11th Symposium on

High-Performance Marine Vehicles

HIPER'17

Zevenwacht, 11-13 September 2017

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Edited by Volker Bertram

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Welcome to the 11th HIPER Conference

Greetings from Giampiero Soncini, Patron of HIPER 2017

The maritime industry faces great challenges which will require bold and innovative solutions. The expectations from politics and customers rise, while the market environment is tougher than it has been in decades. Some giants in our maritime world stumble and fall, while new challengers emerge. The new normal is that yesterday's recipes no longer work. And "disruption" has become a frequently used word in our vocabulary.

Change is in the air and it is encouraging to see that there seem to be at least as many smart ideas as there are challenges in our industry. Just look at the program of this year's Conference for High-Performance Marine Vehicles - Technologies for the Ship of the Future. HIPER has and will continue to promote the dialogue between technology leaders in the maritime industries as well as related fields, building bridges between academia, research institutes and industry. The conference was initiated 18 years ago, and my only regret is that I have not been part of the founding team. As it is, we can build on a proud tradition and expand into the exciting theme of future technologies, where science fiction starts today. And I am proud to be part of it.

While there are many aspects to tomorrow's shipping, the topic of the smart and connected ship is particular to my heart. Big Data analytics, cooperative robotics and application of assorted Artificial Intelligence make rapid progress and we see assorted pioneering applications in the HIPER 2017 proceedings. In 1988, I stated how silly it was to have a crew of 40 to 44 men on the ships sailing back then. I spoke about how ships could have the machinery room totally unmanned. For most of my contemporaries, this sounded as far-fetched as the ideas of completely 3d printed ships and deep-sea exploration by intelligent swarms of robots now. Time was on my side for my visions and I am sure that we will see many of the visions and avant-garde concepts found in these proceedings will not only become reality, but faster than most people think now.

Collectively, we will manage the progress. SpecTec, member of the Volaris Group, is proud to sponsor HIPER 2017 and I am proud that I can be part of this exciting journey towards the future of ships and shipping – our future.

I wish everyone an inspiring exchange of ideas!

Giampiero Soncini
Managing Director Volaris Group

Index

The Democratization of High Performance Marine CFD: A View from the Numerical, the Application and the Business Perspective

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Abstract

The paper describes progress in software and business solutions for advanced CFD applications. Adaptive grid algorithms have proven to be mature for industry applications, refining and coarsening grids wherever it is needed. The implications of adaptive refinement are manifold. On the numerical side, it is a "more bang for the buck" approach (read: better results with less effort), while for the application engineer it also means a more carefree initial mesh generation, since it is the solution itself which will take care of the nitty gritty details of mesh refinement. Finally, the scalable "Numeca on demand" business model grants every user access to the latest high-performance computing hardware along with virtually limitless CFD licenses to compute his resource-intensive applications.

1. Introduction

Democracy [dι`mokrэsi]: Society in which there is treatment of each other […] as equals and absence of class feeling, *Hornby (1974)*.
To adapt [ə`dæpt]: *vt* make (sth) suitable for a new use, need, situation, *Hornby (1974)*.
Adaptivity [ə`dæp`tινιtι]: the ability to adapt.

Access to High Performance (Marine) CFD used to be reserved to an exclusive club. Members only, coming from high profile research facilities or large companies with deep pockets. The need, however, for large computational resources has been growing top down into ever decreasing organisational structures. Today, small shipyards, one-man-show power boat or sporting goods designers and even pool architects all have a need for advanced Marine CFD applications. The requirements are ranging from at least a precise prediction of the free surface shape, but frequently reach much further into 6 DOF simulations or even self-propulsion scenarios. In order to access this level of fidelity three prerequisites are necessary, which usually are – but should not – considered in a separated context. The first one is a technical one: smart, accurate and efficient numerical algorithms. Contemplated superficially the second one – large computational resources – is a technical one as well. But since HPC (high performance computing) can be bought at many places, though with a wide range of quality, HPC boils down to be a commercial topic. The third one is the human factor. Smart minds of scarce and highly paid specialist used to be essential for accurate simulations. A skilful numerical set-up, in particular the mesh generation and the properties of the mesh, can make or break the quality of a high-fidelity simulation.

This paper describes the democratization in the sense of granted access for everybody to High Performance Marine CFD by addressing the numerical, the business and the human perspective. Crucial to this unlimited access in all areas is adaptation and adaptivity. In a broader sense, adaptivity is the key to all life. It forms the basis of evolution. Today, it is widely accepted, that all organisms, are advancing by permanently undergoing selection. Here, organisms also stand for procedures, species, inventions, software codes and technical objects, while selection holds for natural, commercial, environmental or habitual selection. This selection process usually leaves the choice of failing or passing. If an organism passes selection, it will incorporate the lessons learned, hence leading to a fitter and/or more intelligent organism. The ability to adapt to new situations, changing needs or altering conditions, is crucial for survival. Along these lines, new conditions and needs can also mean new flow conditions in a CFD simulation or changing customer demands when it comes to the commercial use of massively parallel hard- and software, or self-learning mesh generation processes. Wherever the challenge for organisms, individuals, organisations or software codes comes from – adaptivity is the key!

In the context of this paper, adaptivity is considered in several meanings and as a reaction to changes coming from different disciplines: First, a technical or numerical one, second the human one and third a business one. All areas cover techniques, procedures and business models of the most efficient usage of computational resources for CFD applications.

Here, technical (numerical) adaptation means techniques and procedures of a most efficient usage of computational resources for CFD applications. Technical (numerical) adaptivity can be accomplished by adapting the numerical accuracy to the changing conditions of a converging (or non-converging) flow solution. Accuracy is expensive to achieve, let it be the scheme or the grid resolution. Therefore it makes a lot of sense to be as accurate as needed – but not more. In other words, being accurate only where it really matters. Good is good enough. Numerical accuracy is driven by a number of factors of influence. The grid resolution and the numerical scheme are two of these factors which are well suited for adaptivity.

Numerical adaptation also reduces the impact of the human component where a user creates a mesh. Even provided that unambiguous rules do exist for mesh generation, and in most organisations, they do not, the user still has the freedom to create the mesh according to his experience (or liking), for the better, or the worse. This human factor largely affects the quality and reproducibility of a simulation. Starting from a simple mesh with little or no refinement and letting mesh adaptation do it the right way is a large step towards improved simulation quality.

The commercial viewpoint is much like the numerical and human ones. Only use, provide and pay for what is really needed. The commercial aspect covers an adaptive business model where the user is no longer stuck with the traditional commercial license models. Software licenses are expensive resources, which are purchased or rented scarcely. In times of high workloads maxed out licenses are quite common, while in other times (or even in other departments within the same company) expensive software licenses are idling. The same holds true for the massively parallel hardware needed for high level CFD simulations.

The paper is structured in three parts. The first part covers the adaptive grid refinement algorithm incorporated in the CFD flow solver FINE™/Marine, illustrated on practical examples. The second part describes how adaptation can minimize the human factor, and the third part describes the commercial adaptivity in terms of intelligent hardware allocation and license management.

2. Adaptivity – The Technical One

General Considerations: Adaptivity always works via two pivot elements. First, there is a driver or trigger, which might be an event, circumstance, gradient or change initiating the adaptivity. The trigger is secondly followed by a procedure or scheme reacting on the trigger and adapting the organism, software code or business model to the changed boundary conditions.

How to apply adaptivity to CFD? The global objective of each numerical scheme is to obtain a sufficiently good overall result with the least computational effort. Numerical adaptivity in CFD describes techniques and procedures to adapt the local accuracy and/or resolution of a flow solution only in regions where it matters. In simple words, this means for mesh adaptation that the mesh should only be refined where high flow gradients call for a high mesh resolution. Consequently, the mesh should be coarsened in flow regions without serious gradients. Therefore, the most efficient use of a given number of – computationally expensive – mesh cells can be ensured. But how does the CFD code know, how accurate it has to be at which location? It is the gradients that matter. For one, gradients can be spatial gradients, e.g. regions in the flow field where severe changes in the flow quantities take place within a very limited spatial region. Examples for high spatial velocity gradients are the boundary layer around the ship hull or on the propeller blades, where the flow velocity changes from zero on the wall to full speed within a very small distance.

Another quite dominant flow gradient in free surface flow is the density gradient at the position of the free surface. Between water and air the density varies approximately by three orders of magnitude. Pressure gradients linked to wave patterns are another prominent example of spatial flow gradients. Similar to spatial gradients, temporal gradients exist in unsteady flow fields. Examples are time dependent events such as impact investigations, or sliding grid propeller simulations.

In general, when talking about numerical adaptation in CFD there are two different techniques, which can be employed either separately, combined or in different space and time combinations within the computational domain. The most influencing factors of numerical accuracy are the mesh resolution and quality and the order of the numerical scheme. Consequently, the numerical adaptivity uses these two key factors to improve or reduce the local accuracy. In most people's mind, adaptation mainly refers to refinement. But it is worthwhile mentioning that adaptation also means de-refinement in regions or in times where a high resolution is not necessary.

Grid Adaptation: Grid adaptation works by modifying the numerical grid, hence the local resolution of the discretization scheme according to the needs – the gradients of the flow as discussed above. There are two different methods for grid adaptation:

1. Adaptation of the mesh refinement by redistribution, also called r-adaptation (Fig.1). Here, the mesh distribution is modified in accordance with the flow gradients. The number of mesh nodes as well as the mesh topology and the connectivity remain unchanged. The redistribution is achieved by moving grid points or lines around, following the flow gradients. This method is in general somewhat limited, since a refinement in one area may result in excessive coarsening in another. An advantage is that r-adaptation can in principle be applied for structured grids also, while most other methods only work for unstructured grids. Grid quality however, might be difficult to control or maintain.

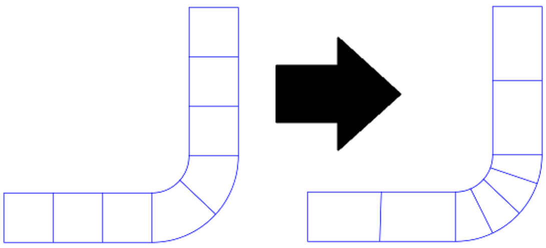

Fig.1: Example of simple r-adaptation, http://www.cfd-online.com/Wiki/Mesh_adaptation

2. H-adaptation adds or removes mesh points. The overall number of nodes usually (although not mandatorily) changes. The node distribution and the mesh topology are altered in any case. Various strategies exist for h-adaptation. Simple procedures subdivide cells, more complex strategies insert or remove or cells (Fig.2). In general, h-adaptation only works on an un-structured level, let it be the overall mesh, or – in case of structured meshes – the block arrangement.

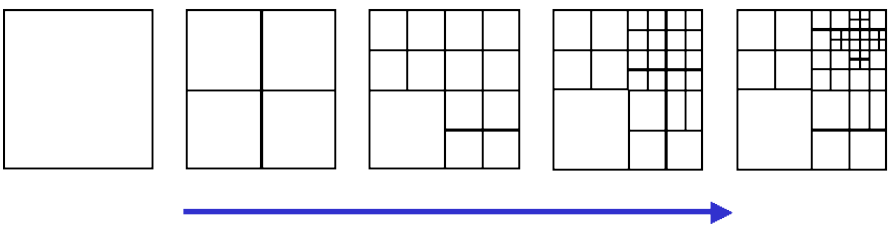

Fig 2: Example of h-adaptation, http://www.mevis-research.de/~tp/LargeScaleFE

Scheme Adaptation: Adapting the resolution of the numerical scheme to the flow gradients can also be achieved by changing the polynomial order of the numerical scheme. Most CFD solvers available today are (theoretically) second order in space. However, hardly anyone reads the small print in the ads, saying that this only holds true for smoothly varying grids. And most practical grids are definitely not smoothly varying. The adaptation of the numerical scheme is also called p-adaptation. When p-adaptation kicks in, the resolution of the numerical scheme is increased from second order to higher orders. In principle, any order can be achieved. Consequently scheme "coarsening" can be accomplished by reducing the order to one. Some numerical schemes such as Discontinuous Galerkin Methods (DGM) are inherently capable of p-adaptation.

Combined Adaptation: Mesh and scheme adaptation can also be combined into the hp-adaptation.

2.1. The CFD System FINE™/Marine

All applications of technical adaptivity presented here are performed using FINE™/Marine, a marine specific CFD system by NUMECA International S.A. FINE™/Marine is a complete CFD tool chain described for example in *Visonneau et al. (2012)* and incorporates the following modules:

1. The mesh generator HEXPRESS™: A full hexahedral unstructured mesh generator, which is capable of solver driven mesh refinement and coarsening (h-adaptation). It features body fitted meshes with a high-quality boundary layer resolution. Grid refinement and coarsening, during the initial generation process as well as in later adaptations is achieved by means of hanging nodes, Figs.3 and 4.

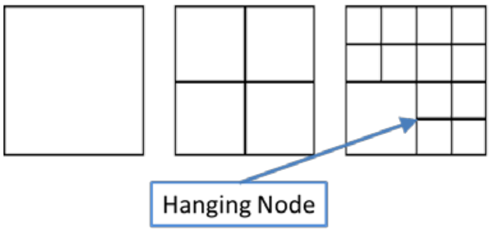

Fig 3: Hanging Node, http://www.mevis-research.de/~tp/LargeScaleFE

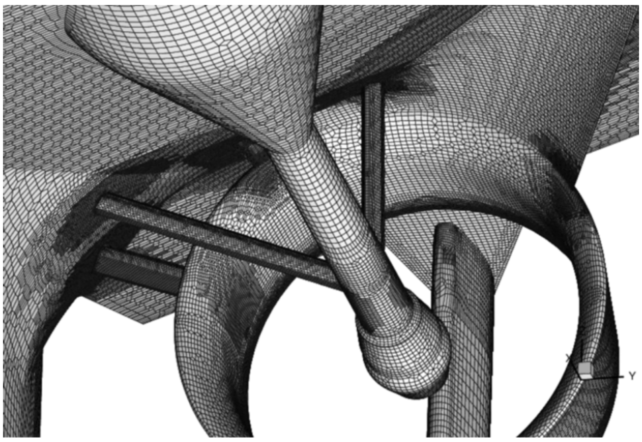

Fig.4: Example of a HEXPRESS™ mesh of ship hull with appendages

2. The flow solver ISIS: The flow solver inside FINE™/Marine is a steady and unsteady incompressible free surface RANS-Code (Reynolds-Averaged-Navier-Stokes) presented in detail by *Duvigneau et al. (2003)*, *Queutey and Visonneau (2007)*. The spatial discretisation of the transport equations is accomplished by a finite volume method. The velocity field is obtained from the momentum conservation equations and the pressure field is extracted from the mass conservation constraint, or continuity equation, transformed into a pressure equation, *Schrooyen et al. (2014)*. Pressure-velocity coupling is obtained through a Rhie & Chow SIMPLE type method. No specific requirements for the topology of the cells are imposed. The grid can be completely unstructured and cells with an arbitrary number of arbitrarily-shaped faces are accepted. In the usual case of turbulent flows, additional transport equations

for turbulent entities are introduced. Several turbulence models ranging from relatively simple one-equation Spalart-Almaras to advanced EARSM (Extended Algebraic Reynolds Stress) models, *Duvigneau et al. (2003)*, are implemented. Free-surface flow is represented by a VOF (Volume of Fluid) technique with an interface capturing approach. Both non-miscible flow phases (air and water) are modelled through the use of a conservation equation for a volume fraction of phase. The free-surface location corresponds to the iso-surface with a volume fraction of 0.5. To avoid smearing of the interface, the volume fraction transport equations are discretized with a specific discretization scheme, which ensures the accuracy and sharpness of the interface, *Queutey and Visonneau (2007)*. Furthermore, the flow solver features 6 DOF motion for the simulation of freely moving ships, *Leroyer and Visonneau (2005)*. Parallelisation is based on domain decomposition.

3. The flow visualisation system CFView™ also incorporates marine specific plug-ins. The visualisation of characteristic features such as wave patterns, the free surface, wetted surface as well as the calculation of forces, momentum and angles is done by a mouse-click.

2.2. Adaptive Grid Refinement

FINE™/Marine incorporates adaptive grid refinement (AGR). When a flow simulation with adaptive grid refinement is launched, the refinement procedure is called every *n* time steps keep the grid adapted to the evolving flow solution. Usually, the flow solver is first run on the initial mesh for a given number of times steps, after which the adaptation algorithm is activated. The existing flow solution is then evaluated and in case one or several adaptation criteria indicate the mesh is too coarse at certain locations, the cells in question are then refined, or cut. The flow solution of the previous step is then interpolated on the refined (=adapted) grid and the flow solver continues for a given number of iterations. Thereafter, the adaptation procedure is called again, and the adaptation criteria are applied. In addition to the first step, all further adaptation steps do not only have the option to refine, but also to de-refine, meaning that earlier refinement steps can be undone. This cycle is then repeated a number of user defined time steps. This technique is described in more detail for example in *Wackers et al. (2010a,b,2011)*. It is designed with a broad range of applications in mind and written in an as general way as possible, *Visonneau et al. (2012)*. To ensure an equal processor load even with adapting meshes, the newly created cells are distributed automatically between the partitions by the flow solver. Hence the total number of cells on each processor is comparable and an efficient usage of all processors is achieved. Several refinement criteria are available and can be selected separately, combined or in succession of each other according to the task at hand. Examples are:

- Free surface criterion, Fig.5: This criterion refines close to the free surface. Since the free surface is clearly characterised by the gradient of the volume fraction normal to the surface, the refinement is employed to refine the grid in the direction normal to the surface only. In large regions of the flow domain this directional (= anisotropic) refinement will be applied in order to keep the number of additional grid points as low as possible. The resulting zone of directional refinement includes the undisturbed water surface, as well as smooth wave patterns. Only in cases where the free surface seriously deviates from the main grid directions, such as breaking waves, isotropic refinement is used, *Wackers et al. (2010a)*.

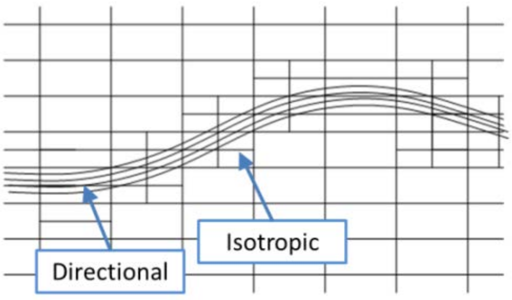

Fig.5: Directional and isotropic refinement at the free surface, *Wackers et al. (2010a*)

- Gradient criteria: A second group of refinement criteria is based on the absolute values of the gradients of solution quantities in each cell. These criteria detect the regions where the flow field changes rapidly; they react to most features of a flow and are thus more general than the free-surface criterion. Also, they are obviously not restricted to the vicinity of the free surface and can refine in the whole computational domain. Three gradient criteria are available in FINE™/Marine.
    1. Pressure gradient
    2. Velocity gradient
    3. Vorticity gradient

- Hessian based criteria: This criterion works with the second spatial derivative of the pressure. It is a very robust refinement criterion, yielding good results for a variety of applications. In contrast to velocity based gradients, it does not introduce any unnecessary refinement into the already refined boundary layer, *Wackers et al. (2014)*.

The effect of mesh adaptation is nicely visible in Fig.6 showing an impacting cone probe, the splashing scheme and the adapted mesh.

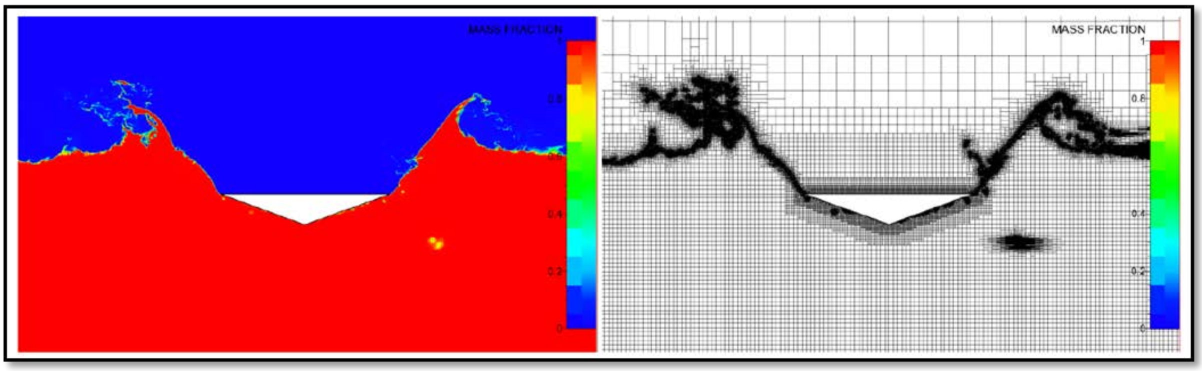

Fig.6: Impacting probe and adapted mesh

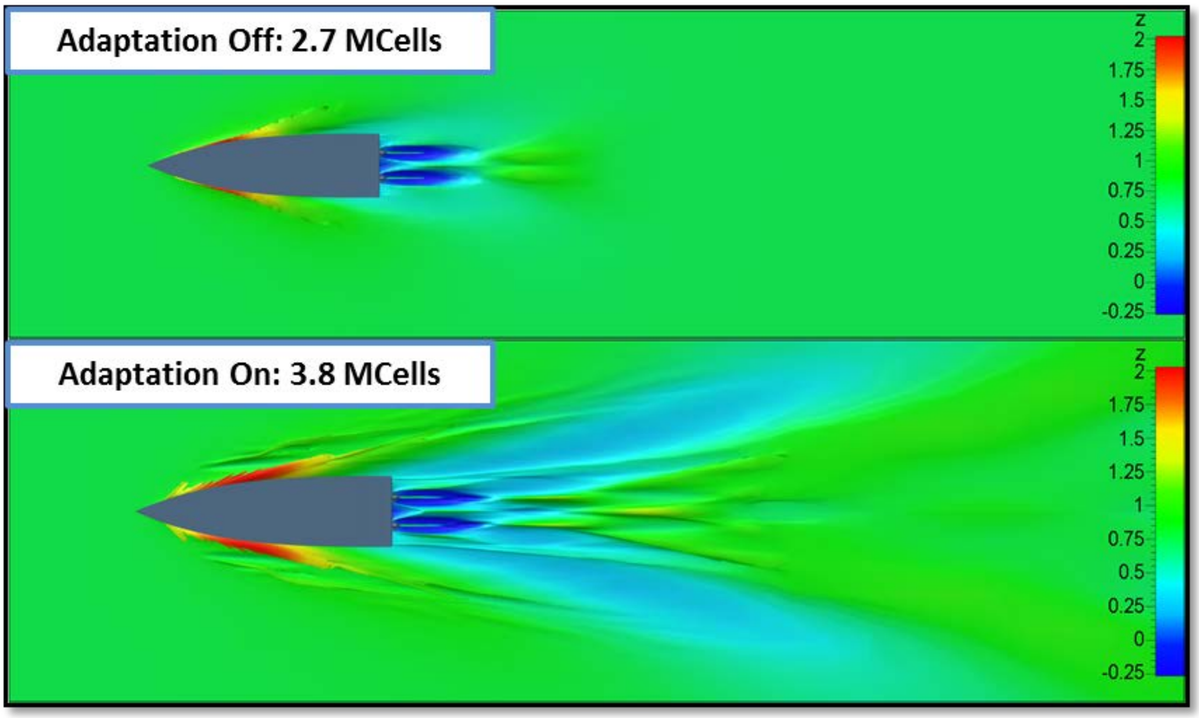

Fig.7: Wave pattern without (top) and with (bottom) mesh adaptation

The efficiency of adaptive mesh refinement is highlighted in Fig.7. In this case, the adapted mesh has only about 40% more cells than the initial mesh, still the surface wave pattern is considerably more detailed showing features which do not appear in the original mesh.

Numerical experiments have shown, that similar or even better resolution of flow features can be obtained on properly adapted grids, having not even a fifth of the mesh count compared to a fine mesh without adaptation.

- Refinement for overset continuity: With the recent implementation of the overset mesh technique into ISIS another application of mesh adaptivity is introduced. This technique, also known as chimera approach, allows to use fully overlapping grids in different computational domains, containing solid bodies or being just a background mesh. In contrast to mesh deformations, the tolerable body motions are limitless, however at the price of an area of interpolation between the overlapping grids. The quality of interpolation and hence overall flow solution is strongly dependant on the difference in cell size on both sides of the overlapping interface. Here, the adaptivity allows to use coarse and efficient cell sizes for background meshes, while the continuity criterion will refine these background cells whenever and wherever necessary, ensuring an ideal interpolation, see Fig. 8: red grid lines indicate cells in the overlapping domain while black grid lines are located in the background; an identical cell size along the overset interface is clearly visible in the right cut view.

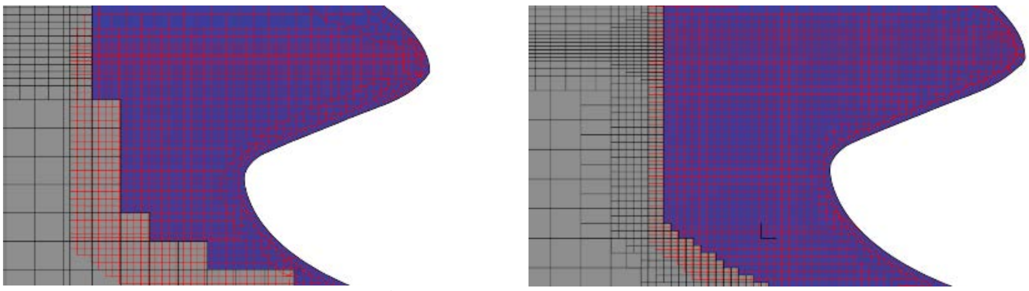

Fig.8: Initial overlapping grids (left) and adapted background mesh (right, black grid lines)

2.3. HPC – and Parallelisation

High level CFD simulations in the maritime field are challenging due to numerous computationally very expensive features. Examples are:

- 6 Degree of Freedom (DOF) simulation for arbitrary movements of multiple bodies.
- Wave breaking and splashing.
- Full unsteady simulations and sliding grid computations of rotating propellers.
- Acceleration and dynamic positioning.
- Seakeeping and self-propulsion.
- Optimisation.

It is very obvious that these tasks, despite all the artful programming of intelligent features which increase the efficiency of computations, call for extreme computing power. Even relatively simple resistance calculations – the bread and butter business of maritime CFD – should be finished in less than one hour. At least, this is what is on the naval architect's wish list. So, High Performance Computing (HPC), and along with it, parallelisation is key.
Full (or more realistically nearly full) and automatic parallelisation is therefore a highly important property of a CFD code. But parallelisation of adaptive grids is not obvious. In non-adaptive calculations, usually a domain-decomposition is performed before the computation is initialised. The decomposed regions (partitions) of the grid are then distributed over the available cores, which may even have different individual performances. The number and size of the decomposed regions depend on the number and performance of the computing nodes. Each domain is then put on one core. The

communication is ensured by parallel libraries, which in the case of FINE™/Marine is MPI (Message Passing Interface). When it comes to adaptive grids, the initially decomposed regions will not remain constant in size. The refinement (or coarsening) algorithm will alter the number of nodes in one partition. Keeping the original decomposition constant, would mean a severe degradation of computational performance due to load imbalance between the processors. Image one region having five times the number of nodes would still run on the same type or number of cores as smaller regions. So, a new decomposition and redistribution over the parallel hardware will become necessary after each adaptation step. In FINE™/Marine the grid refinement is capable of dealing with massively parallel hardware. It includes an automatic dynamic load balancing which redistributes the refined grid over the already allocated cores when some regions have been refined or coarsened.

3. Adaptivity – The Human Factor

Mesh adaptation seems to be a purely technical point, but it is not. It also incorporates a strong human component. Today, nearly all our CFD simulations are still mesh dependent, even if only global quantities are considered. In contrast to the wide spread understanding mesh dependent does not just mean the finer the better, above all it means the better (mesh) the better (result). The mesh needs to have sufficient quality and it needs to have sufficient resolution. Sufficient implies where it is really needed. Not the brute grid count matters, but a smart distribution. Can we assume that an engineer coming fresh from the university will produce the same high quality mesh as a skilled software operator? And can we assume that an aerospace engineer, though blessed with many years of experience in wing aerodynamics will generate a top-level mesh for a planning sailboat? Probably not, and this is a problem. This human factor can largely affect the quality of a simulation and even more its reproducibility. Which raises the question whether a new design is better, or has just another operator performed the simulation and missed to resolve some flow separations? Experiences from TU Darmstadt, *Leichtfuß (2014),* showed a large "human uncertainty" among student classes which were all running the same compressor test-case. Even when using the same tutorial, the individual computed compressor efficiencies produced by the class showed a scatter band of ±2%. This equals about 30 years of compressor development! Obviously, better some sort of algorithm makes sure the mesh is as good as it can be – and if it is not, it should be at least of constant quality.

Herein lies another strong point of adaptation. The probability and severity of user errors during mesh generation is drastically reduced when by default a simple mesh without much refinement towards – rightly or wrongly – assumed gradients is created. The code will take care of the refinements, and it will do so objectively, driven solely by the criteria selected for mesh refinement and coarsening.

4. Adaptivity – The Business Perspective

4.1. General Considerations on Speeding Up CFD Simulations

CFD is certainly one of the CAE disciplines which require the highest level of numerical effort. This holds true despite of all the intellectual effort put into the coding of highly efficient numerical schemes, such as adaptive grids, pseudo time stepping, predictor-corrector algorithms and the more. Therefore, high hardware requirements are quite common in the maritime CFD environment as shown in section 2.3. It is in this region of the highest hardware demands where Moore's law, predicting a doubling of processor performance every 18 months started to lose momentum around 2003. The loophole out of this dilemma is parallelisation. The computational problem is no longer tackled by one single processor, but by many instead. Many can mean several hundreds or even thousands. In exceptional cases, Large Eddy Simulations (LES) of a towing tank model ship on 200.000 cores have been successfully demonstrated, *Nishikawa et al. (2013).*

Parallelisation, also called High Performance Computing (HPC), is based on two pillars:

1. A hardware architecture providing a sufficient number of processors.
2. Software capable of running efficiently on these many processors.

In this context, efficient means scalable. No software ever will run ten times as fast on ten processors as it does on one, although this should be the objective. In this case one would already talk of good scalability, if it would run something like eight times faster than on a single processor, ideally maintaining this ratio independently of an increasing number of cores. One of the reasons for this non-perfect speed-up is that some parts of the software cannot be parallelised while other parts need to do the communication between the processors. By using Amdahl's law, *Amdahl (1967)*, it can easily be demonstrated that even small portions of the software code, which are not running in parallel, will lead to a seriously limited maximum speed-up, which will be asymptotically reached with increasing processor number, but never exceeded, Fig.9.

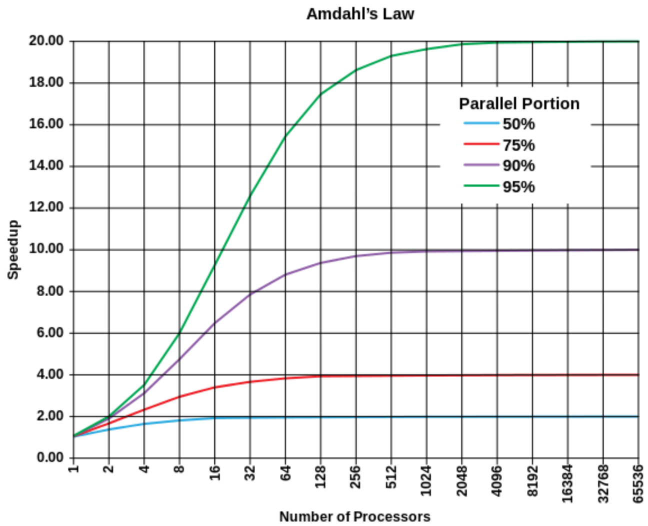

Fig.9: Amdahl's Law – Maximum speed-up as function the parallel portion of a software code

To makes things worse, usually the scalability will go further down when the processor count increases, due to the decreasing volume-to-surface ratio of the single partitions running on each core. More cores mean smaller partitions. The volume of the partitions (= problem size) drops by one over the power of three, while the surface (= communication size) only goes down by one over square.

In any case, if future CFD requirements are to be met, users will find themselves in a situation where to invest in large hardware and, in case of commercial CFD codes, also in licenses. How can be guaranteed that these investments will pay off?

4.2. Adaptivity as a Business Model

As for the numerical adaptivity, the business adaptivity works in a very similar way. Again, there is a driver or trigger, which initiates the process of adaptation in order to match the resources to the expected outcome. When the trigger kicks in, a procedure or scheme reacts on the trigger and adapts the business model to the changed boundary conditions. Now, what is the trigger, or changed boundary conditions and how does the adaptation mechanism look?

Nowadays the use of especially powerful, but also very costly computational resources in industry and academics is standard. In a traditional business model these resources will be bought once, are completely to be maintained during their useful life span and disposed of thereafter. Apart from the costly disposal, the business model for licenses of commercial software is not much different. This traditional business model makes perfect sense, if a constantly high usage of both, licenses and hardware, can be ensured. But if this is not the case, maintaining huge computers and a large license pool becomes uneconomic. Buying computer hardware and licenses will also tie up huge amounts of capital and human resources. Again, as in numerical problems, adaptivity is the solution. The hardware as well as the licenses should be provided only in times when they are needed. Although this option seems obvious and not very new at first it has hardly been applied before.

What do you do with a 2000 core cluster when you do not need it? Shutting it down and mothballing it is probably not an option, if you might need it unexpectedly tomorrow, when model tests have shown that you need to optimise your hull design. Also, the 2000 cores and other hardware architecture are perishable goods. They have a “best before” date stamped on them. So, better use them now. Also, scalability is an issue. You may use 2000 cores occasionally, but only 200 permanently.

In terms of software things are quite similar. You cannot stop paying for annual software licenses just because your CFD team goes to summer holidays. On the opposite side, shortly before the year ends there is usually a peak load, where you might need three times the normal license volume. Usage or non-usage is clearly the trigger of business adaptation. Now, how to realise it?

One viable avenue is to employ an external provider. The self-evident question then is, why should an external provider be able to dealing with fluctuating demands better than oneself? The high volume of these requests with which an external provider must keep up is the key. One strongly fluctuating demand might be a problem for a company, but hundred fluctuating request are standing a good chance of leading to a solid average load with only small seasonal deviations. One single company (or individual, or academic institute) may need 2000 cores for a couple of weeks, which are then on idle for next few months, ready to be used by another client. An external provider who deals with several dozens or hundreds of clients then profits from an averaging effect. It is statistically highly unlikely that all his clients have their up- and downtimes at the same time. While one company’s cores might go idle, they will soon be picked up by another one, who has a peak demand. Clearly, the provider will need a certain overhead which increases the cost slightly, but in total it will be less expensive for his clients than maintaining their own hardware which runs with a much smaller load factor than the provider’s. What has been said for the hardware works out just the same for the software. Ideally, hard- and software will be coupled. They are only employed together and there is no need to have a 2000 parallel license sitting around, when your cluster only features 200 cores.

Key issues of this concept are of course security and availability on very high levels, but this can be accomplished. Equally important are high computational performance and a transparent scheduling and workload sharing. CPU 24/7 is one such provider who offers hard- and software as a bundle. Due to many years of experience and expertise, CPU 24/7 is very conscious about the special requirements of on-demand licensed computing power resources (HPC on Demand), in particular for CAE applications for industrial or high level academic purposes. In parallel to the computer hardware, an intelligent and adaptive license management, which enables a tailored license usage, is desired. The “NUMECA on Demand” concept, Fig.10, combines arbitrarily scalable HPC resources with an on-demand license management for FINE™/Marine.

4.3. Putting Adaptive HPC Resources into Practice

Since 2006 CPU 24/7 has been offering on-demand computing power resources and provides custom-made and dedicated HPC systems and capabilities with a completely pre-configured, secure and easy-to-use remote simulation environment. This is realised as an all-inclusive package taking in the HPC instance on bare metal servers with related CAE applications such as FINE™/Marine. A competent hot-line technical support, sufficient and flexible storage and broad band data traffic are the ingredients to make this concept viable for CAE users.

HPC On Demand has become primarily of interest to those companies, struggling to cope with budget restrictions and a fluctuating demand for computing and licensing capacity. Investing in their own HPC clusters is very cost-intensive, binds valuable capital and expertise as well as requires the services of staff whose skills and capabilities are not central to a company’s core business activities. For such investments to remain profitable, it is essential that all available capacity is constantly being utilised. If this is not the case, renting the access to High Performance Computing capacity instead of binding one’s capital in a complex IT infrastructure and a large license pool might be the smarter option.

It is the temporary, dynamic aspect that makes HPC On Demand so attractive. One advantage of acquiring access to HPC resources for a specified period, for example for a particular project, is that it involves paying only for the capacity and for the duration of the computing services that one actually requires. HPC remote resources are available either as flexibly and online bookable (Fig.10) computing capacities (Resource Area) or also as continuous state-of-the-art HPC systems geared to one's individual needs (Tailored Configurations). In both cases, it is possible to handle the resources due to a cluster management system respectively a job queueing system. This ensures an efficient use considering a dynamic change of hardware requests like number of cores, main memory etc. due to an adaptive resource management. An important aspect is the right setting of several system parameters in the queuing system which is a service from the resource provider. This basic concept fulfils the requirements regarding dynamically changing job characteristics as for example during the adaptation steps of a CFD code.

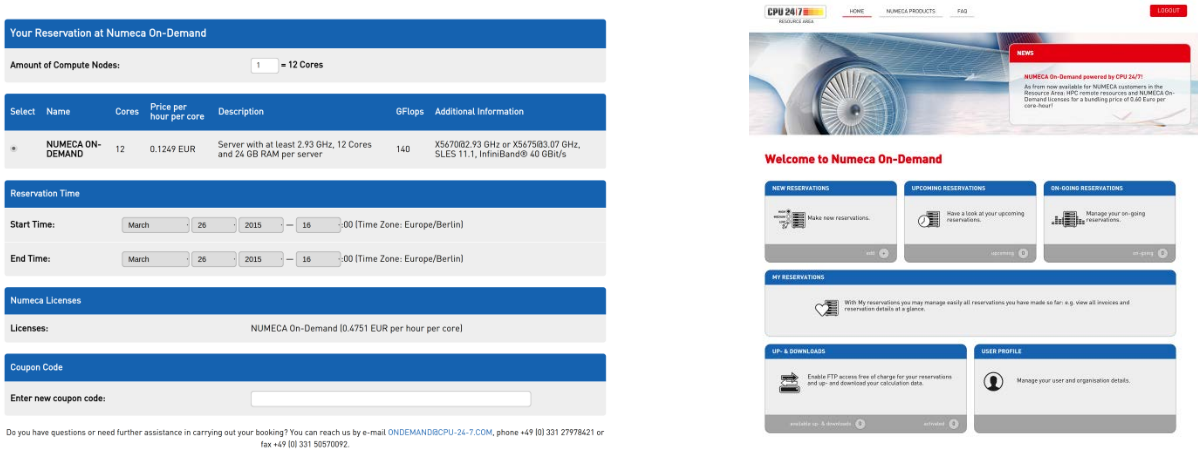

Fig.10: "NUMECA on Demand" @ CPU 24/7

4.4. License Management

The HPC power is just one part of the equation which is necessary for up to date numerical simulations. The second pillar is the CAE software, which is usually licensed, let it be a commercial, in-house, or even your personal version of an open source code. The standard business model during the last years was fixed license contracts over a period of several months or years. Such a static license model does not follow a dynamic and "On-Demand" use of HPC resources and can also hinder the handling of adaptive simulation procedures. Imagine your license features 64 parallel cores, which are fully used at the initialisation of a CFD simulation. Soon, the first adaptation step kicks in and calls for a refinement of certain regions. The job is then automatically re-launched, starting with a fresh decomposition, which would be optimal only for a higher core count, if – your parallel license feature would not be exhausted!

As a response, NUMECA now provides a dynamic and adaptive licensing model which enables the user to get the licenses he needs spontaneously and tailored to the real demand. If more features, such as parallel cores are needed, they will be automatically provided, respecting a user-defined upper (or lower) threshold.

4.5. Commercial Considerations

Also, commercially some fresh thinking is needed. The traditional steps of a commercial sales process starting with a quotation, followed by a purchase order, the delivery and finally an invoice do not fit anymore to a dynamic allocation of hard- and software. Instead, the user books the required resources of hardware and software online, at completely transparent costs. The entire allocation, technically as well as commercially is completed with a couple of mouse-clicks within 10 minutes, Fig.11.

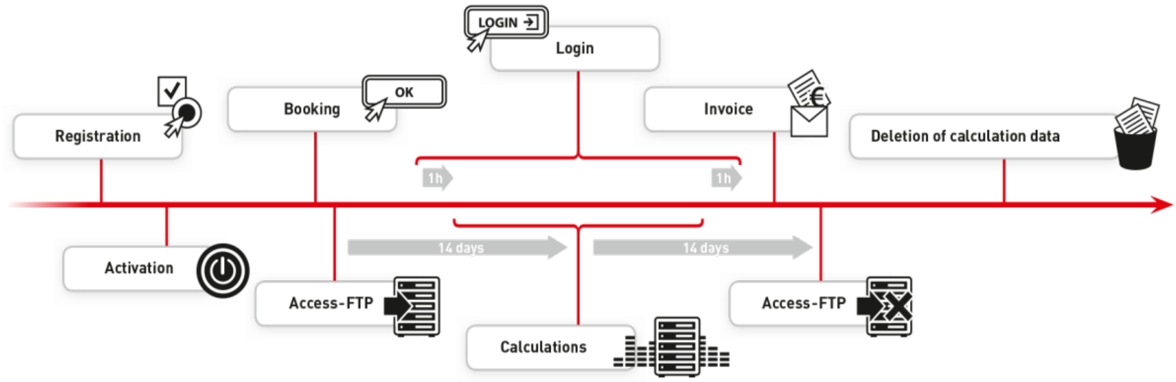

Fig.11: Time sequence of HPC allocation

5. Conclusion

The paper describes the benefits of adaptation for maritime CFD applications. In particular, the mesh h-adaptation driven by various gradient based criteria is discussed. A showcase demonstrates that with only a moderate increase in mesh cell count, a substantial improvement in the quality of the results can be achieved. However, adaptivity can not only be applied to numerical problems, but also is a viable concept if utilized in a business perspective. Hardware as well as software licenses are traditionally purchased in a static business model, which is non-reactive to a fluctuating demand. The "NUMECA on Demand" approach offers a flexible and demand-driven way to allocate computational resources in a tailored way, according to the task at hand. The challenges of aligning adaptivity concepts, the numerical and the business ones, have been addressed. In combination, numerical and business adaptivity offer the potential to achieve the high requirements of full featured maritime CFD at a fraction of the cost of the traditional approach.

Acknowledgements

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Simulation of Ships in Sea-Ice – A Survey

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Abstract

The paper surveys numerical approaches to simulate ships and offshore structures in ice-infested waters, excluding the simulation of actual ice-breaking. Discrete element techniques model many individual ice floes interacting, while classical continuum mechanics model the background flow of water. The state of the art has reached a maturity sufficient for many industrial applications.

1. Introduction

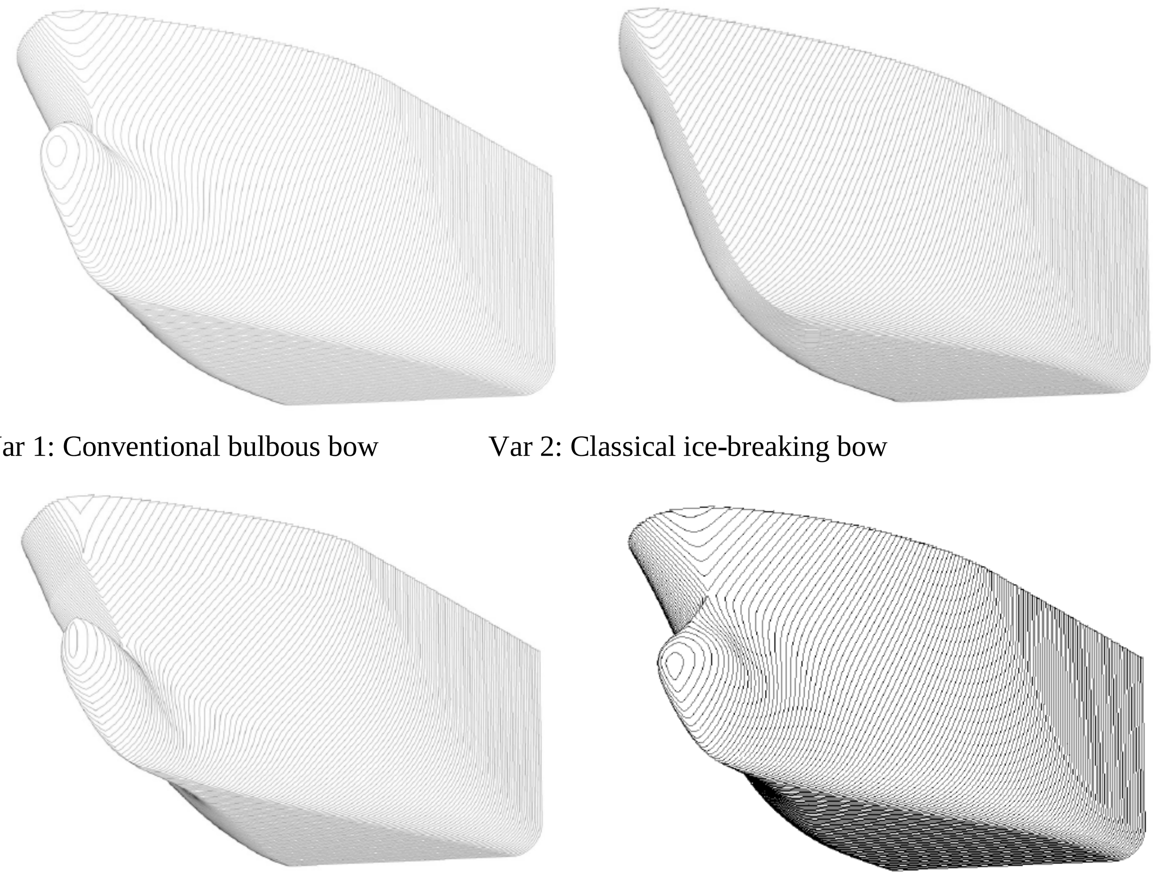
"Climate change will unlock the Arctic, leading to increased activity in ice-covered waters. This includes destination shipping, shipping activities related to offshore oil and gas extraction and transit shipping. There are a series of hazards and uncertainties related to sailing in the Arctic, such as sea ice, […]," *Longva et al. (2014)*. Increased operation in (seasonally) ice infested waters motivates research in design and simulation methods for such operation. The following chapters survey corresponding research and publications.

2. Semi-empirical and qualitative approaches

Martio (2007) summarizes: "During the past decades the main efforts in the arctic maritime research have been concentrated on the development of semi-empirical formulas for the ice resistance. An extensive literature review can be found in *Kämäräinen (1993)*, which includes also several validation cases. The ice resistance components are mainly same in all discussed methods, as the ice resistance is divided into breaking and submersion components. Furthermore, the effect of velocity is usually modelled using semi-empirical formulas."

Rupp (HSVA) gives in personal communication that hull optimizations can use usual parametric descriptions and ice has no influence on the best hull up to ice class E3. (This means most ships except specific icebreakers). *Rupp and Hympendahl (2003)* investigate four different bow shapes with different ice breaking capabilities. One ship was designed for open-water performance; the second had a typical ice-breaking bow. The third and fourth were designed combining open-water qualities with a respectable icebreaking ability. The shown hull shapes could guide qualitative designs depending on the required icebreaking capabilities. The ice-breaker bow of variant 4 had similar open-water performance as variant 1. For formal hull optimization of ice-going ships, an experienced designer may then specify the parametric model and the hull may be optimized for calm-water resistance. "It is difficult to evaluate the performance of an icebreaker through varying many parameters because special facilities and skilled experts are necessary […] Because of these reasons, parametric optimization of icebreaker design is impractical at present," *Konno and Mizuki (2006).* The Finnish-Swedish ice class rules, as incorporated in Class Rules, give semi-empirical formulas for the resistance of a ship in brash ice. Rupp (HSVA) gives in personal communication that these resistance formulas are useful.

De Nucci et al. (2016) describe a design study for US Coast Guard icebreakers, using semi-empirical approaches for open-water resistance and icebreaking resistance. With increasing simulation capabilities, ice-breaker designs and particular ship designs for occasional operation in sea-ice may employ more sophisticated approaches for performance in ice and water, employing formal optimization techniques which are now state of the art for commercial ship design, *Hochkirch and Bertram (2011)*, but not for ships in arctic operation.



Var 1: Conventional bulbous bow Var 2: Classical ice-breaking bow

Var 3: Icebreaking bulbous bow (1) Var 4: Icebreaking bulbous bow (2)

Fig. 1: Bow shapes investigated by *Rupp and Hympendahl (2003)*

3. Introduction to numerical simulation of ice breaking and ice flows

There are various approaches to modelling ice in numerical simulations:

- Continuum mechanics: Level ice is described as a continuous medium with orthotropic homogeneous strength (similar to steel in structural analyses). Continuum mechanics are needed when simulating the actual ice breaking process. The simulation then requires material properties of the ice. Depending on chemical composition of the water and the freezing process, these material properties may widely scatter.
- Discrete element method: Individual ice floes are modelled and tracked individually. Discrete element models are used to track the flow of individual floes. The computational effort increases with the number of floes considered. The floe shape is generally prescribed, with circular floes and rectangular floes as most common choices. These two shapes are considered to be the upper and lower extreme cases of actual ice floes, *Yamaguchi et al. (1997). Konno and Mizuki (2006)* consider also parallelepipeds, *Wang and Derradji-Aouat (2011)* arbitrary shapes.
- Distributed mass/discrete floe model: “This model possesses the advantages of both the continuum and the discrete element models: it can express the discrete nature of pack [= brash] ice, for which it is difficult to use a continuum model, and requires a much shorter computation time than a discrete element model,” *Rheem et al. (1997), Yamaguchi et al. (1997)*. With increasing computing power, the distributed mass/discrete floe model seems to have been replaced by discrete element methods.

Due to the difficulties of modelling ice breaking per se, many applications focus on simpler applications:

- "Pre-sawn" ice: Individual floes are assumed to form an ice sheet, but break on contact (without extra force) into predetermined floes. The topology between the floes is then released and the released floes float freely. This approach is used by *Konno and Mizuki (2006)* and *Puntigliano (2003a,b)*.
- Brash ice: Individual floes are considered with some distance from each other and the ship. The simulation then looks at the flow of the floes, which is driven by the flow of the supporting water, the buoyancy of the floes and the motion (sometimes considered only in 3 degrees of freedom) of the floes.

Numerical simulations for ships in ice have evolved only within the last decade. The state of the art is driven by small specialist communities and the development is too young for consolidation in approaches. There is a multitude of approaches, some based on in-house development, some on commercial software, often focused on sub-problems. The state of the art is thus immature and characterized by research rather than commercial applications.

4. Numerical simulation of brash ice flows and related work

For the simulation of interaction between ship and brash ice, the flow field dominates the ice flow movement. CFD (computational fluid dynamics) can determine the flow velocity field around the hull. However, CFD alone cannot capture the ship-ice interaction, with floes as multi-deformable bodies. The ice floes are subject to buoyancy forces and move in six degrees of freedom when pushed under water. Floes interact with each other and with the ship. *Konno and Mizuki (2006), Konno et al. (2007)* apply ODE (Open Dynamics Engine), www.ode.org, to simulate a ship in pre-sawn ice.

Initially, ODE did not provide applications to obtain contact forces and does not track the floes properly, with floes penetrating the hull in the simulations. "It seems that we must enhance ODE to fit our purpose, or find or implement another physics engine," *Konno and Mizuki (2006)*. Konno continued to refine his methods. *Konno and Yoshimoto (2008)* model a ship in a channel with brash ice, with 1250 ice pieces. *Konno (2009)* extends the approach to 33000 ice pieces and more than 170000 collisions, using a mix of cubic and spherical ice pieces. In the simulations, ice loads decrease with increased numbers of ice pieces. Konno then proceeds to generate irregular brash ice fields by a complex method, releasing packets of cubic and spherical ice pieces from stacks, *Konno and Saitoh (2009)*. The benefit of this approach over using just any random generator algorithm remains unclear.

Watanabe and Konno (2011) and *Konno et al. (2011)* extend the approach further. Up to 126000 ice pieces are considered and the base flow of the water is superimposed, using the open-source CFD solver OpenFOAM. For the considered low speeds (up to 5 kn), the effect of the flow field around the hull against the ship resistance is small.

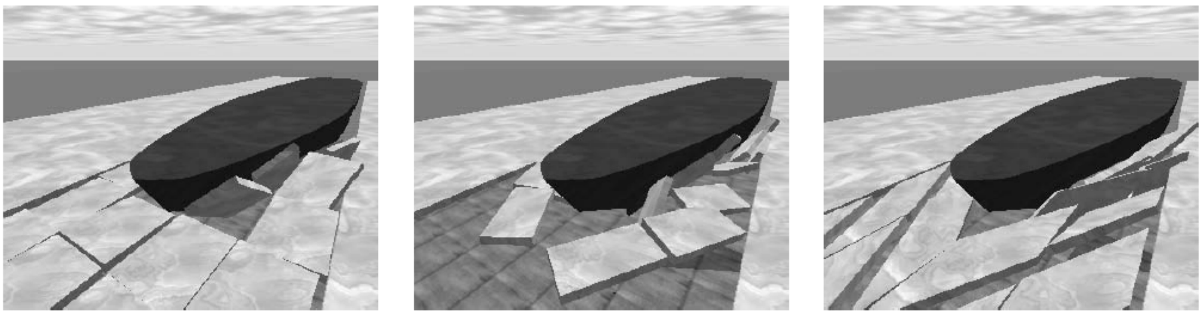


Fig. 2: Numerical simulation of pre-sawn ice test with ODE, *Konno and Mizuki (2006)*

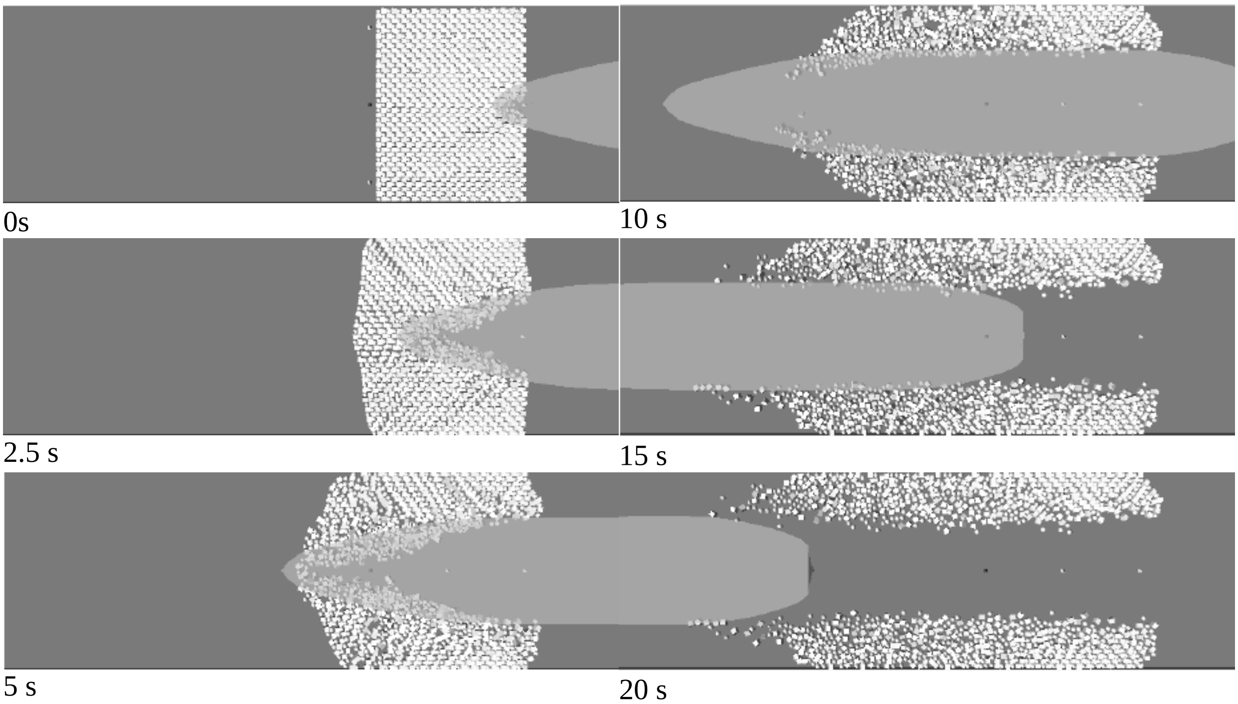


Fig. 3: Numerical simulation in brash ice with ODE, *Konno (2009)*

Wang and Derradji-Aouat (2010) simulate a ship in brash ice. *Wang and Derradji-Aouat (2011)* describe a simulation of ice floes drifting against an offshore structure. The simulation employs the commercial code LS-DYNA, www.lstc.com. Ice floes are represented as rectangular floes and arbitrary-shape floes. The shape has little influence on results. Three different ice concentrations are simulated. Water and air are modelled with the Eulerian method, the offshore structure and pack ice with the Lagrangian method. Interaction between floes and offshore structure is modelled using a penalty method in LS-DYNA. Details of the finite element formulation including the penalty method are given in *Wang and Derradji-Aouat (2010)* and the LS-DYNA theory manual. For the friction between ice floes and the offshore structure, semi-empirical friction coefficients are given.

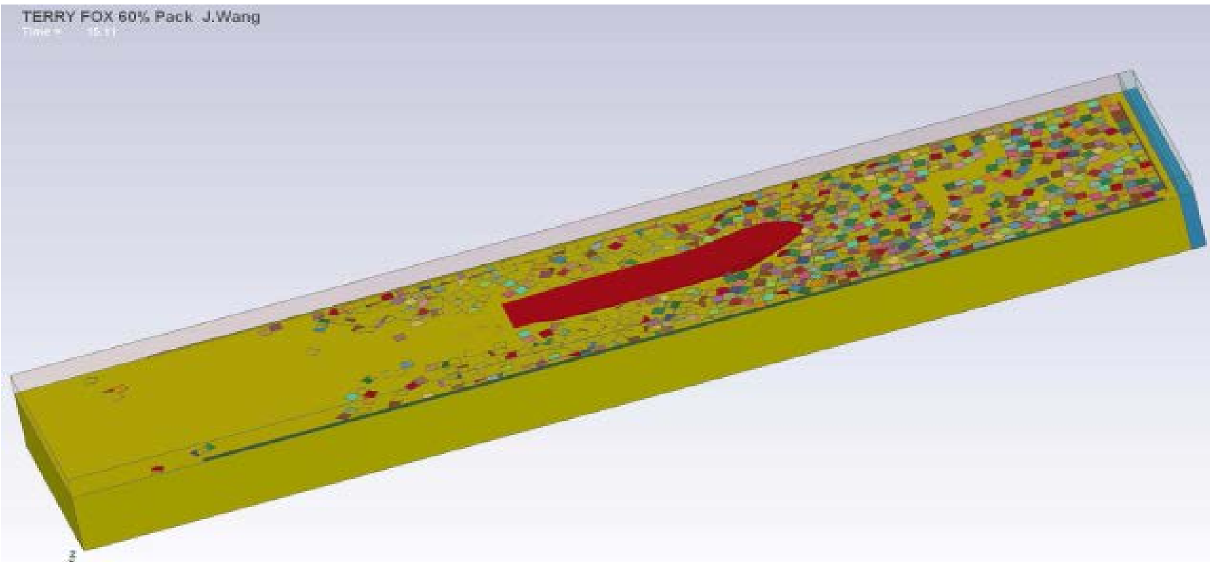


Fig. 4: Simulation of ship in brash ice using LS-DYNA, *Wang and Derradji-Aouat (2010)*

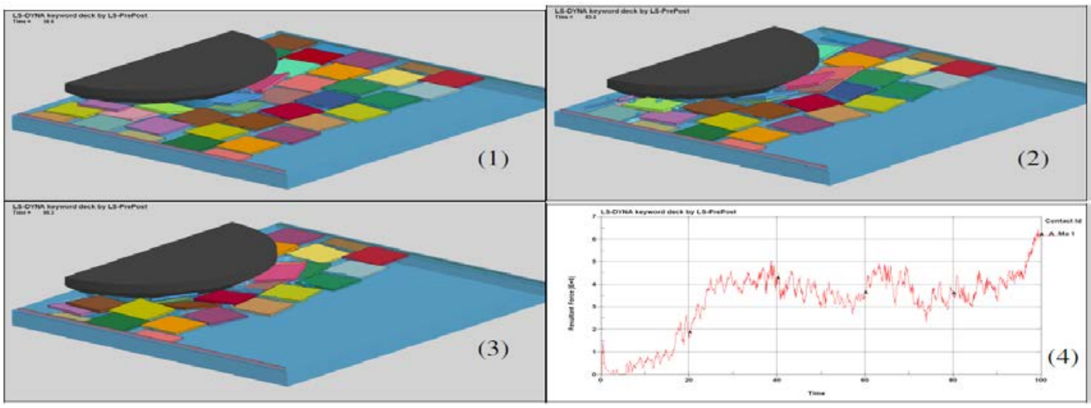


Fig. 5: Simulation of ice floes against platform using LS-DYNA, 80% ice concentration, *Wang and Derradji-Aouat (2011)*

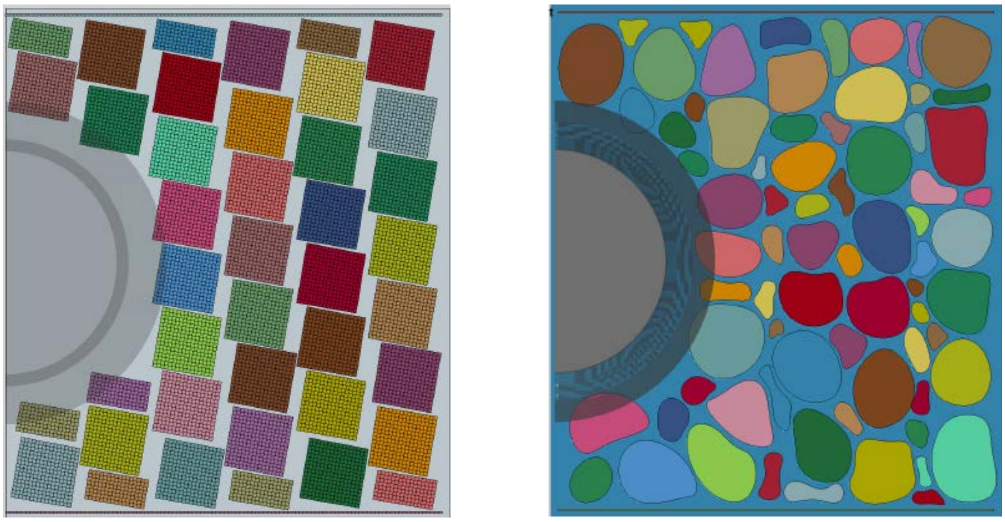


Fig. 6: Regular and irregular shapes gave similar results, *Wang and Derradji-Aouat (2011)*

Vroegrijk (2011a,b) employs the commercial code StarCCM+ with the Discrete Element Method (DEM) option to model brash ice flows around an obstacle. The case study presented aimed to test the application of Computational Fluid Dynamics (CFD) in the calculation of ice particle tracks prior to impact, which will then be used as input in the FEM (Finite Element Method) model. The very recently added DEM option allows only spheres as objects. The spheres can be concatenated to composite particles. In this case, three sphere form the “ice floe”. The obstacle is similarly very simplified, a combination of a prism and a cylinder. The software is still in the early stages of development and is likely to improve, especially if a two-way coupling between the DEM and FEM is realised. This may open possibilities for modelling more complex ship-ice and propeller-ice interaction problems.

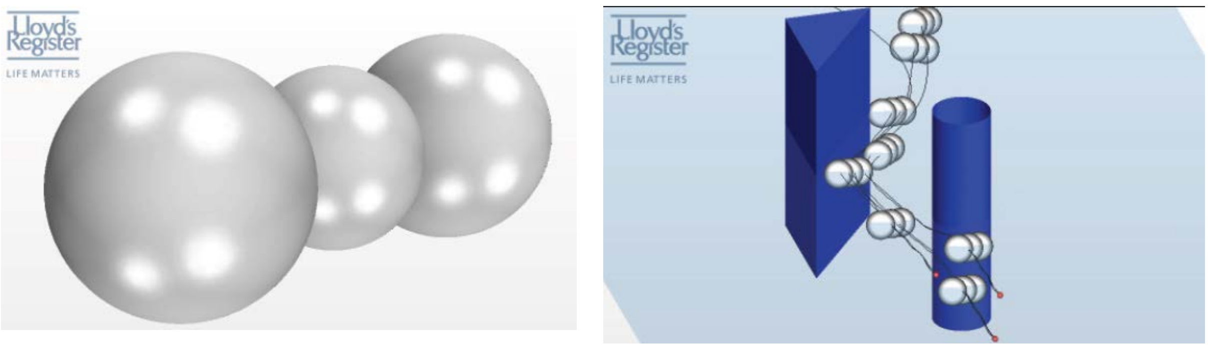


Fig. 7: Ice floes are crudely approximated by composite particles formed by spheres in StarCCM+, *Vroegrijk (2011b)*

Zhan and Molyneux (2010) employ DECICE (Discrete Element Code for ICE related problems), in its 2d version, for ship manoeuvring of tug-tanker in ice. DECICE was developed in the 1980s by Applied Mechanics Inc. The code is now owned by Oceanic Consulting Corporation and also used by the National Research Council of Canada; e.g. *Lau and Simoes Ré (2006)* model a ship navigating in pack ice. In his PhD thesis, *Lawrence (2009*) extended the code in its functionality. *Liu et al. (2010)* simulate offshore structures (including a drill ship) in pack ice using DECICE3D, a 3d version of DECICE. *Zhan and Molyneux (2012)* employ DECICE3D for ship manoeuvring in ice. DECICE is a time-domain solver that uses discrete elements to model ice engineering problems. The elements undergo rigid-body translation and rotation according to classical Newtonian mechanics. Interaction forces, both normal and tangential (resulting from friction) forces, are modelled when bodies contact one another (floe-floe or floe-ship). *Molyneux et al. (2012)* validate DECICE simulations against model tests. The results of the simulations, for three different ship designs and ice conditions, show good agreement with the results of model experiments.

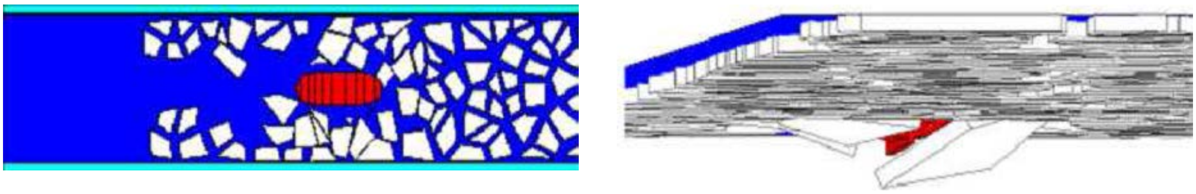


Fig. 8: Simulation in brash ice with DECICE, *Lau and Simoes Ré (2006)*

Alekseev (2016) uses a DEM-based in-house development of the Hamburg Ship Model basin, *Ehle (2011), Myland (2014),* to simulate a ship going through level ice and an ice ridge comparing with model test results. He concludes that “numerical simulation of ship breaking through an ice ridge can be done with DEM as it provides realistic behavior of ship and ice pieces during interaction. However in order to get truly working numerical tool the calibration of the created model of forces calculation in the software is needed.”

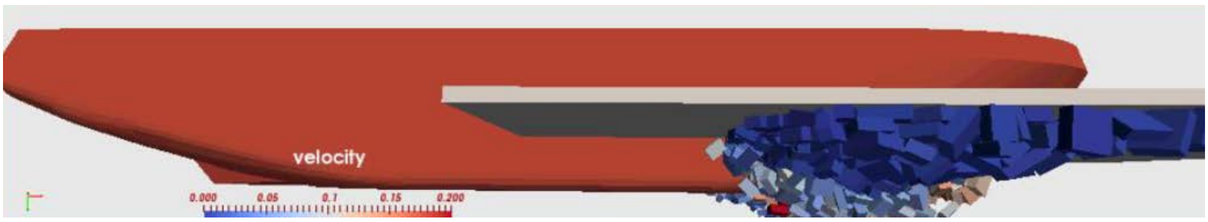


Fig. 9: Simulation of ship going through ice ridge, *Alekseev (2016)*

5. Numerical ice-breaking simulation

As one of the earliest numerical methods to model ice-breaking, *Valanto (1992)* solved 2d ship icebreaking combining numerical simulation and physical considerations on ship-ice interaction. Subsequent work applied 2d simulation to 3d icebreaking to predict the distribution of ice resistance in the waterline, *Valanto (1997)*. *Puntigliano (2003a,b)* developed a method for numerical simulation of ice-breaking which tracked the path of the ice floes along the hull. The method is suitable to predict the ability of a ship to produce an ice free canal behind it (clearing ability) and the amount of ice drifting into the propeller range. Puntigliano points out that, at higher ship speeds, there is a considerable low-pressure field at the bow due to the ice floes and the interaction between the floes is important. However, Puntigliano left HSVA and the method was then no longer supported. The software is no longer used, no longer available and the know-how is documented only in *Puntigliano (2003a)*.

Su (2011) describes simulations for a ship in level ice including ship manoeuvres. He considers essentially a two-dimensional model looking only at the waterplane and the ship in three degrees of freedom (in the waterplane). The work itself does not seem to be of prime interest for this survey, but Su gives a literature overview for ship performance in ice which in itself is interesting.

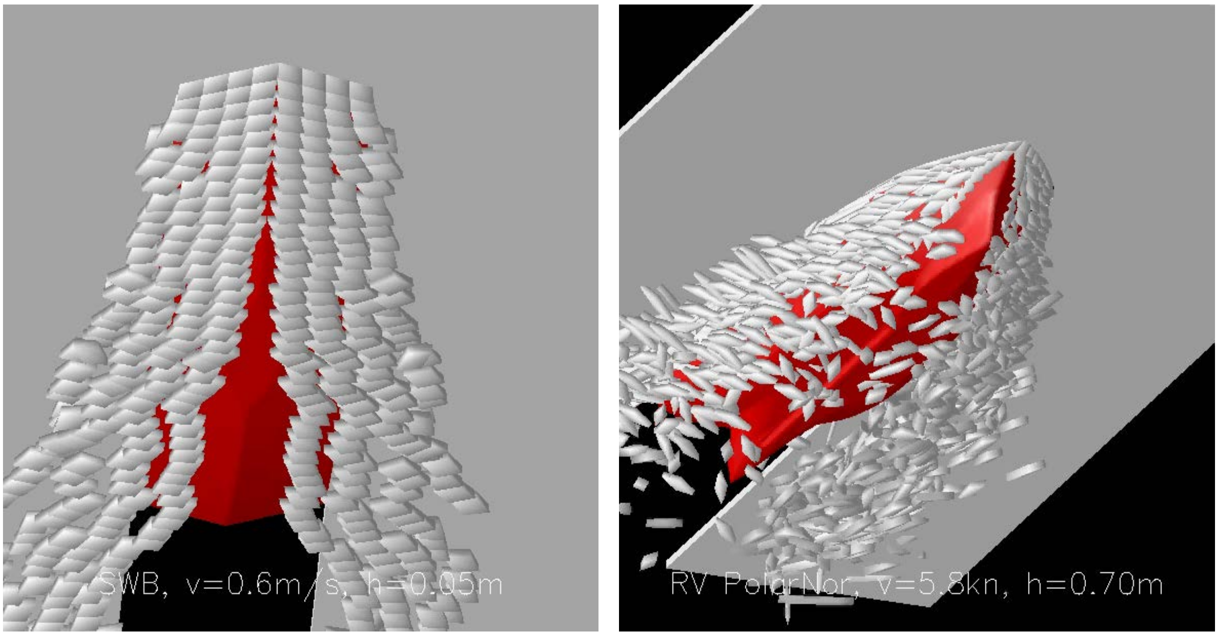


Fig. 9: *Puntigliano (2003a)* compares ice breaker forms capturing the differences in floe paths

Lau (2006) models ship manoeuvring in ice, with focus on the ice breaking. He employs DECICE. The motion of the ship is described and the simulation concerns the ice breaking per se. A penalty function approach is used for the contact forces.

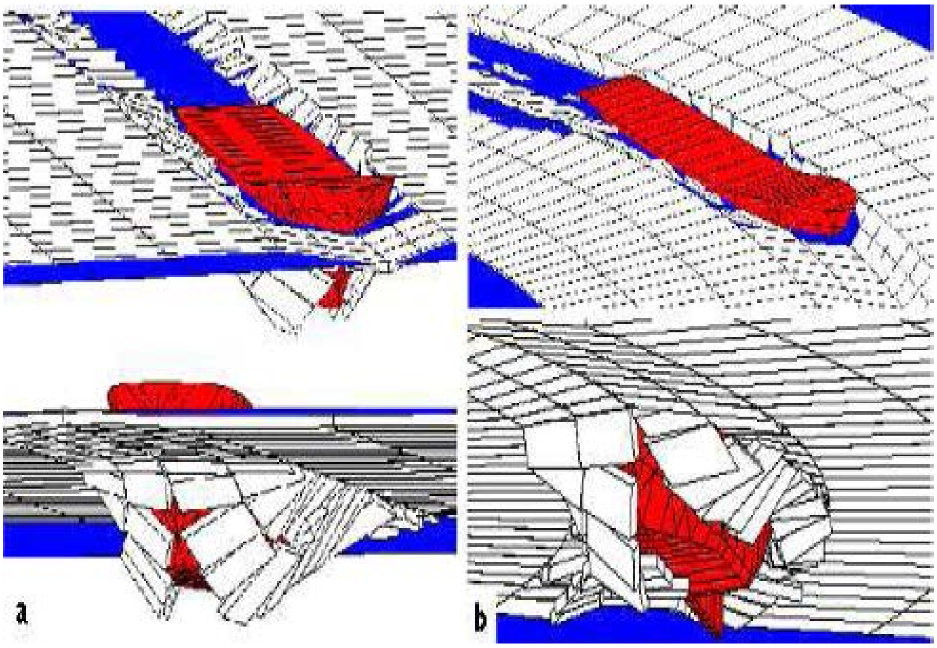


Fig. 10: Numerical ice breaking, *Lau (2006)*

Kämäräinen (2007) employs the commercial code Fluent and an in-house developed CFD code Iceflo to investigate the flow between the hull of a ship and ice floes. The application concerns only the flow in the gap. The aim is the prediction of ice resistance. "The CFD code Iceflo based on the hydrodynamic lubrication theory was written to calculate the flow in the gap between the hull surface and an ice floe," *Kämäräinen (2007).* Iceflo is available in Fortran source code from the author, but as a research tool it is not documented and not user friendly.

Sawamura et al. (2009) simulate a ship advancing in level ice. *Sawamura et al. (2010)* extend the application to manoeuvres in level ice. The work apparently employs an in-house development. The simulation considers three degrees of freedom (in the waterplane). The contact position between the ship-hull and the ice-edge is determined by the circle contact detection algorithm. In order to estimate the ice load, the bending failure of the floating ice plate is focused on. The buoyancy force, the turning and sliding component in the ice load induced by the broken ice pieces during ice breaking process are neglected. The crack pattern of the broken cusp is assumed to be the circular arc.

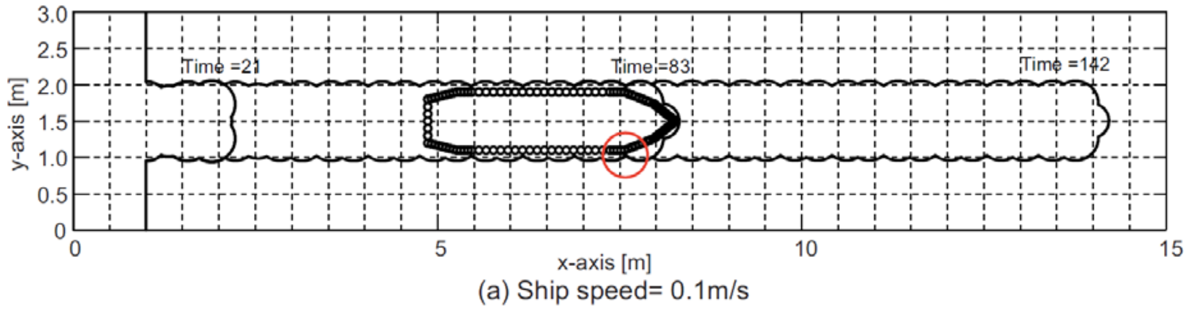


Fig. 11: Numerical ice breaking in head-on motion, *Sawamura et al. (2010)*

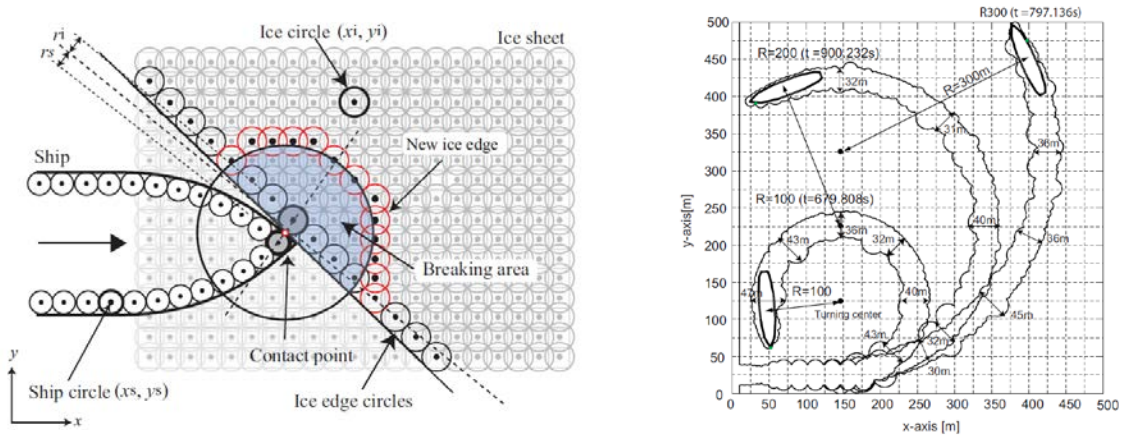


Fig. 12: Numerical ice breaking in manoeuvres, *Sawamura et al. (2010);* circular contact detection algorithm (left) and manoeuvres (right)

Sayed and his collaborators at the Canadian Hydraulics Center (Ottawa) have developed their own software to simulate ice breaking and ship advancing in densely packed ice, *Kubat et al. (2010), Sayed and Barker (2011), Sayed and Kubat (2011), Barker and Sayed (2012).* The simulation can be applied to stationary (moored) structures in a drifting ice field as well as a ship advancing in an ice field. The approach is based on a finite-difference scheme for the solution of mass and momentum conservation. A Particle-in-Cell (PIC) method is used to advect the ice. This method employs discrete particles to represent ice floes and ice cover. Parametric studies show that ship speed, ice density and ice thickness have all significant influence on the ice force, *Kubat et al. (2010).*

Lubbad and Løset (2011) present a simulation of numerical ice-breaking in real-time, comparing the approach with model tests and full-scale observations. They employ PhysX to run their simulations. The results look very realistic, but this may be due to superior post-processing, Fig.16. *Metrikin et al. (2012a)* discuss some potential improvements to the model of *Lubbad and Løset (2011). Metrikin et al. (2012b)* look at various physics engines (= commercial software for simulating the dynamics of multibody systems) for floater-ice interaction, covering Open Dynamics Engine (ODE), PhysX, Vortex and AgX. The conclusion is rather fuzzy: "each physics engine has its own strength and weaknesses and none of the engines is perfect." *Mierke et al. (2015), Huisman et al. (2016)* present a more recent attempt of using the Open Dynamics Engine for ship-ice interaction. The visualization looks at first glance very realistic but ice floes are just pushed aside with no pile-up or floes going underneath the ice breaker.

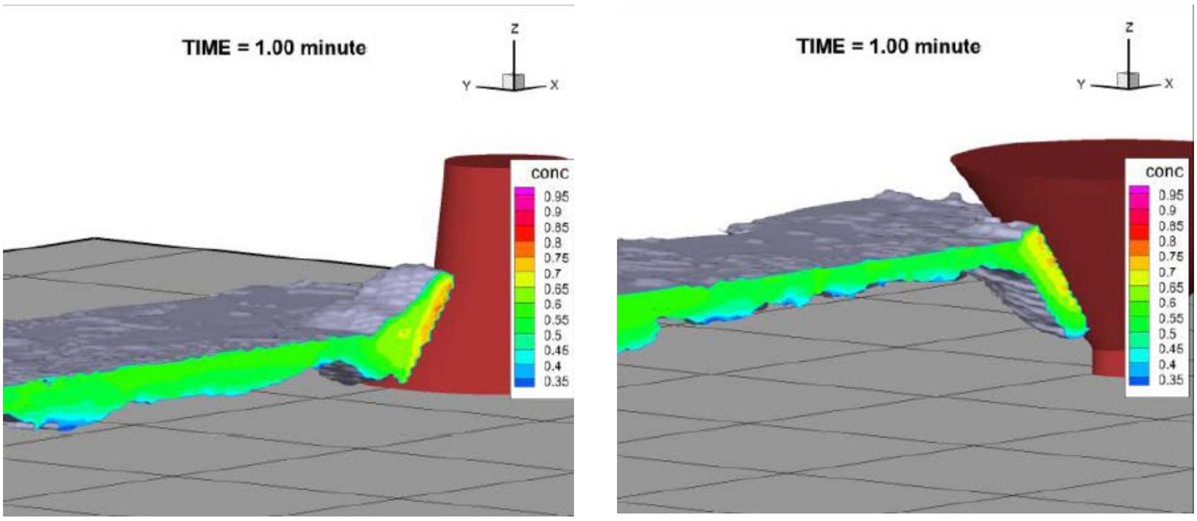


Fig.13: Numerical ice breaking simulation for upward (left) and downward (right) cone, *Barker and Sayed (2012)*

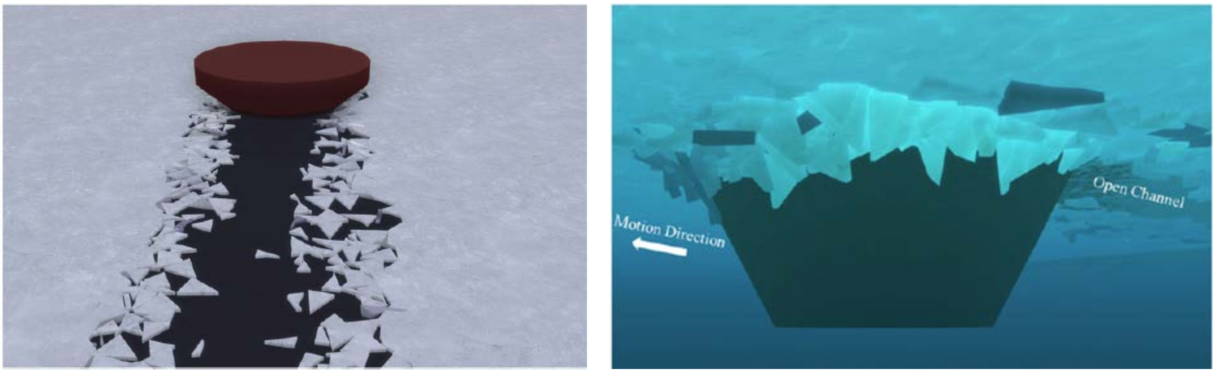


Fig.14: Numerical ice-breaking at NTNU, *Lubbad and Løset (2011)*

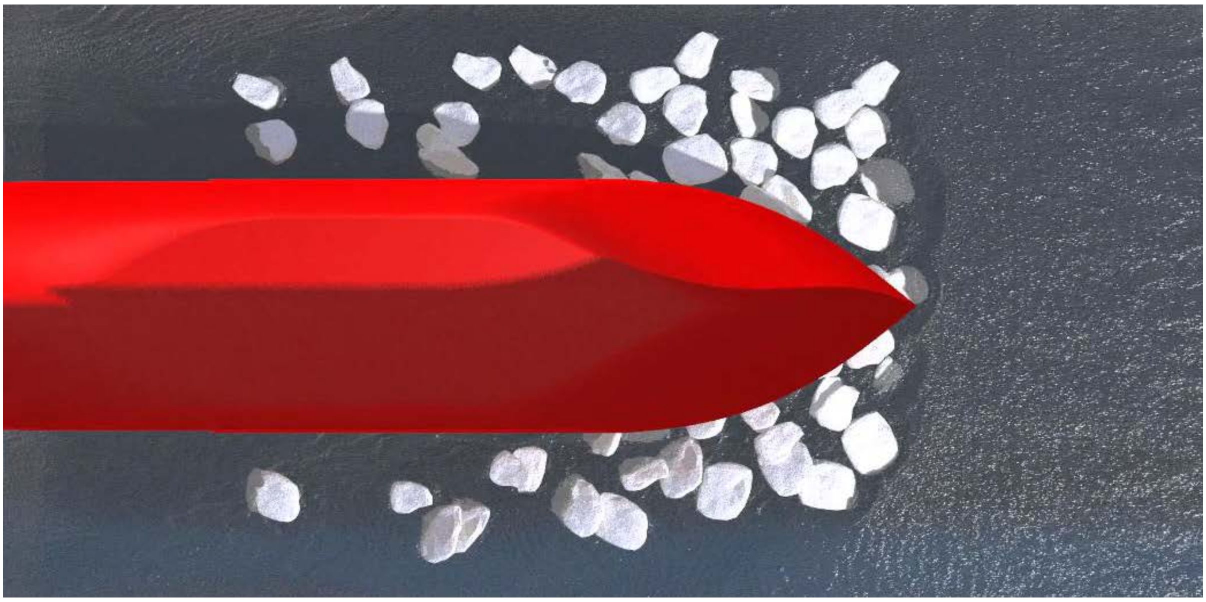


Fig. 15: Simulation of ship-ice interaction, *Mierke et al. (2015)*

6. Conclusions

With climate change, we will see an increase of Arctic ship operation. Simulation technologies for ships operating in sea ice are progressing from research to mature design tools. Increasingly commercial software is used.

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Past, Present and Prospects of Maritime Antifouling

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Abstract

This paper surveys maritime antifouling solutions from a historical perspective extrapolating to the future. "Past" covers the time from first historical records of antifouling B.C. to the ban of TBT coatings. "Present" covers currently popular self-polishing copolymers which are mainly based on copper-compounds and other biocides (boosters). "Prospects" looks at lesser known or adopted technologies. Super-hydrophilic coatings, nano-coatings, surface treated coatings combined with robotic cleaning, flocked surfaces, and ultra-sound transducers are some of the alternatives that have started to emerge.

1. Introduction – Marine Fouling and its impact on ship operation

Fouling, i.e. marine growth on ship hulls and propellers, progresses in stages, Fig.1:

1. Slime: Within hours after a ship has been immersed in seawater, the hull accumulates a microbial biofilm, consisting of bacteria and single-cells organisms. This microscopic slime already reduces the ship's performance by several percentage points. It is widely considered as inevitable.
2. Biofilm: Slime enables the settling of other organisms, such as algae and marine fungi, by providing biochemical cues for settlement and increasing the adherence to the substrate. This biofilm is already visible to the human eye. Light slime may already increase resistance by 10%, *Schultz (2007)*.
3. Soft fouling: Green weed can grow up to 15 cm long and can become a few meters wide at the waterline. It grows rapidly and scrubbing it off triggers even more vigorous growth within a few weeks.
4. Shell fouling (a.k.a. "calcareous fouling" from calcium in the shells) may consist of barnacles, mussels, tubeworms, etc. This hard fouling may penetrate coatings and destroy them. It is also hard to remove, requiring forceful cleaning that may also damage coatings.

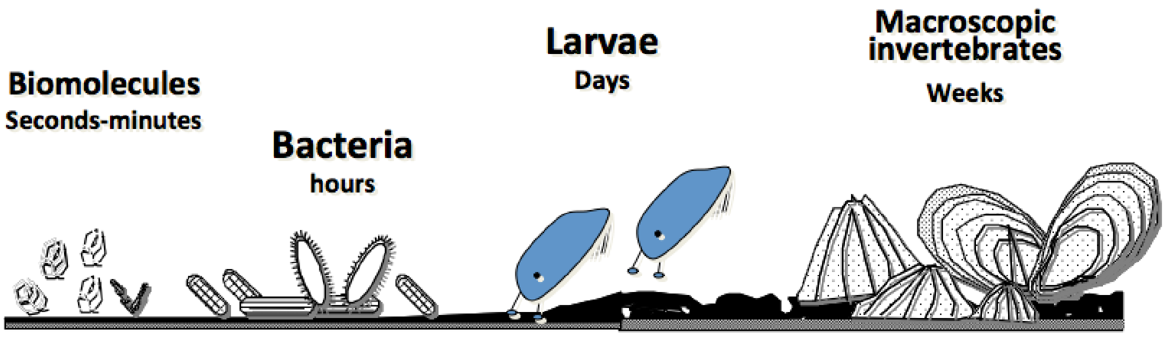

Fig.1: Progressive fouling stages, source: changeantifouling.com

Weed and shell fouling decrease ship performance drastically, typically leading to 30-50% more fuel consumption (and associated emissions) compared to a smooth hull. *Schultz (2007)* give 89% increase for a slender warship with severe fouling. For comparison, many energy saving devices have a target of 3-5% fuel savings. Antifouling, the prevention of marine growth on ships, is thus both an economic and ecological necessity for shipping. In the following we will review antifouling strategies, trying to extrapolate from a historical perspective to the future.

2. “Past” – From ancient Greek to TBT

Fouling has been a headache for shipping since ancient times. Some of the oldest testimonies are Greek texts dating 300 BC describing the use of tar and wax to protect ships. Both Romans and Greeks secured lead sheathing with copper nails. Plutarch (1st century) mentions the hull cleaning for ships “to make them go more easily through water”, http://www.scanz.org.nz/pm/march-antifoulings.

The first record of copper used as antifoulant is in a UK patent by William Beale in 1625. More than a century later, we see copper sheeting evolve for the Royal Navy with the first installation on the HMS Alarm in 1758. Copper sheeting was used by navies and tea clippers (transporting high-value cargo at top speed for a premium) in the 19th century, Fig.2. However, if copper and iron are in contact, this leads to galvanic corrosion. The rapidly increasing demand for steel ships in the second half of the 19th century ended the era of metallic sheeting and the era of antifouling paints started.

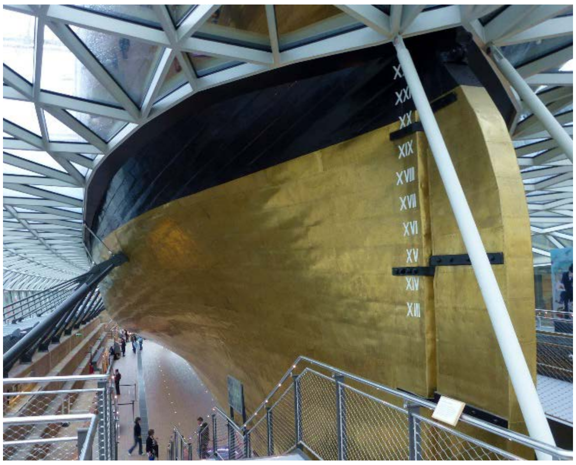

Fig.2: Copper sheeting on “Cutty Sark”, source: wikipedia

Fig.3: Advertisement for “Italian Moravian”, source: unknown

By 1850, antifouling paints had become the predominant way prevent marine growth on ship hulls. In the 19th century, a hot plastic paint called “Italian Moravian” combining a mixture of rosin (natural epoxy) and copper compounds was moderately successful, Fig.3. However, it was relatively expensive, cumbersome in the application process (requiring some heating facilities for the paint at the site of application) and had short life span.

World War II brought important progress also in the field of coating technologies, including modern “cold” paints. The basic principle was the same as in most of today's antifouling paints: In contact with seawater, antifouling paint releases biocides which form a toxic boundary layer preventing marine growth. A certain concentration of these toxins must be maintained for effective protection. As the ship moves through water, the toxins are washed off and the paint must re-supply the protective boundary layer with new toxins. The biocide enters the water through contact and shear forces created while the ship moves through water. The leaching rate depends on the ship’s speed.

The earlier antifouling paints were so-called contact paints. Here seawater penetrates the paint film as the toxins dissolve, leaving a honeycomb structure. This increases surface roughness and thus resistance. It also yields an exponentially decaying leaching rate, releasing far more poison than necessary in the beginning and dropping below the minimum effective level long before all poison in the paint has been released. After about one year, ship performance usually dropped drastically, making a dry-dock interval necessary for re-painting.

The solution came with self-polishing copolymers (SPCs), i.e. a coating matrix that also dissolved slowly in water, Fig.4. As the hosting matrix film (the “co-polymer” in SPCs) dissolves, the surface remains smooth and an almost constant leaching rate is obtained.

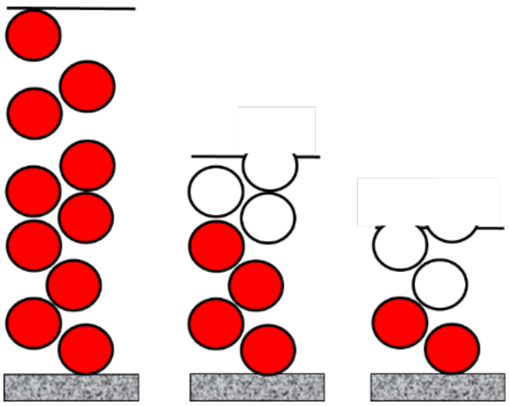

Fig.4: Principle of self-polishing co-polymers with biocides (red) and leached layer (empty circles)

The most popular toxin was TBT (tributyltin), a member of the organotin chemicals family. This tin compound was highly toxic. Hence, small quantities sufficed to protect the hull from fouling. TBT provided up to 5 years fouling-free performance, kept the hull smooth and fuel efficient, and it was easy to apply. The antifouling problem seemed to be solved at last. However, in the early 1980s it became clear that organotin (TBT) not only killed fouling organisms. Its slow release into the water had toxic effects on a wide range of other marine species, particularly mollusks such as whelks and oysters, *Lewis (1998)*. Environmental concerns grew as poisoning of marine organisms including fish had risen to alarming levels. These concerns prompted world-wide regulations restricting the use of TBT coatings, first for pleasure boats, then for commercial shipping. In 2001, IMO (International Maritime Organisation) adopted the AFS Convention, banning TBT for new applications after 1 January 2003 and as active coating on all vessels after 1 January 2008.

3. "Present" – Self-polishing copolymers and low-surface energy coatings

3.1. Self-polishing copolymers

Since the ban on TBT, copper compounds have become the predominant antifouling biocide with an estimated 90% of the world fleet using these, e.g. *Blossom (2009)*. As TBT is more effective (toxic) than copper compounds, copper-based paints require much higher leaching rates than TBT paints. Therefore, usually more paint is required and even then the paints are not 100% effective. Various herbicides and fungicides are added to address plant fouling that is not affected by copper-compounds. These additional toxins are dubbed "boosters".

SPC paints vary widely in price and performance. Differences are due to the matrix (host paint) and the biocides. SPCs may also be classified by the leaching mechanism (depletion, hydration, or hydrolysis). From a customer point of view, the biocides determine effectiveness on given species. The matrix type determines thickness of the leached layer in service (as opposed to directly after application). The leached layer resembles a dry sponge or a raisin bread where the raisins have been picked. The thicker this leached layer is the higher the roughness and thus the frictional resistance of the ship. On the top end of SPC coating, silyl-based matrices offer much thinner leached layers than "standard" coatings. On the lower end, CDP (controlled depletion) matrices are based on rosins, i.e. natural epoxies. Very few significant changes have happened with regards to self-polishing antifouling technology since the overview paper of *Yebra (2004)*, as discussed in *Yebra (2016).*

The wide-spread use of copper-based SPCs has raised concerns about their toxic effects on marine communities, *Chambers et al. (2006)*, *Dafforn et al. (2011)*. Especially some of the boosters (including Irgarol 1051 and Diuron) have come under scrutiny, sometimes resulting in regional bans or curbing legislation. However, it is unlikely that copper-based antifouling paints will be banned by IMO as long as there are no effective and affordable alternatives.

3.2. Low-surface energy coatings

Increased awareness of the impact of toxic antifoulants prompted research into non-toxic alternatives. Fouling may be prevented by making the adhesion of slime mechanically difficult. All marine fouling organisms use adhesive (= sticky) secretions to attach themselves to the hull – and the lower the surface energy of the surface, the weaker the adhesion. Hull coatings with sufficiently low surface energy should prevent fouling because organisms would not be able to adhere to it. The principle is like that of a Teflon surface. Even if fouling is not completely prevented, such “non-stick” coatings make the surfaces easier to clean, e.g. by wiping or low-pressure rinsing. On fast moving boats, they can be self-cleaning, but on slower ships cleaning is necessary, especially in niches with low water speed (such as bow thruster tunnels and sea chests).

These LSE (low-surface energy) coatings are also known as foul release coatings or silicone coatings. Most such coatings are based on fluorinated silicone elastomeric, a chemical cousin to Teflon. LSE coatings contain no biocides and remain active as long as the coating remains undamaged. However, like Teflon, these coatings are mechanically sensitive and fouling starts rapidly after the coating has been scratched. Even if not scratched, the silicone film weathers, i.e. ages with time and becomes less effective. The performance of the LSE coatings degrades over time. In a case study, Hempel reports that a large tanker which used such non-toxic coatings in sea trials achieved 8% fuel savings, but average fuel savings over a five-year period, between dockings, amounted to 4%. For containerships with a much lower share of the friction resistance in total resistance, we may halve these numbers. Initially, the application of an LSE coating will result in a smoother hull compared to a conventional SPC coating, Table I, *Yebra (2016)*. The difference between an LSE surface and an SPC surface becomes larger during operation (and seawater exposure), as the matrix and the embedded biocides dissolve at an uneven rate leaving a rougher leached layer, Fig.5, *Yebra (2014)*.

Table I: Reported improvement in friction coefficients c_f of LSE coatings over SPC coatings

Source	$\Delta\, c_f$	remarks
Weinell et al. (2003)	6.1%	Rotary study; topcoat on smooth PVC
Candries et al. (2003)	3.5%	Rotary study; full system on smooth PVC
Schultz (2004)	3-4%	Full system on 304SS; no sandpaper strip
Candries and Atlar (2005)	5.3%	Topcoat on smooth steel; turbulent boundary layer

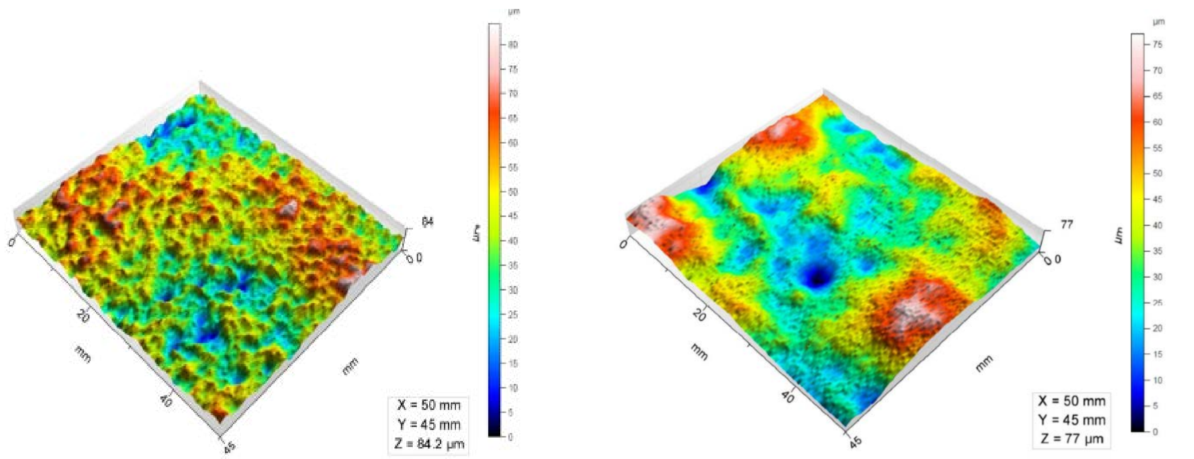

Fig.5: Roughness of SPC (Silyl acrylate) (left) and silicone-based coating (Hempaguard) (right)

4. “Prospects” – A host of options waiting in the wings

World shipping moves slowly, but steadily towards sustainable shipping. Leaching copper and micro-plastics (the dissolved ingredients of today’s standard SPC coatings) into the world oceans is not sustainable. *Dafforn et al. (2011)* argue “that the way forward is to phase-out metals and organic biocides from [antifouling] paints and to adopt non-toxic alternatives. […] However, we call for caution in the time-frame for making these changes." A ban on toxic coatings is unlikely as long as there is no effective and affordable solution for the ship owners on the market. No such convincing alternative has been established so far, but there are many interesting developments as discussed below.

4.1. Superhydrophilic coatings (hydrogels)

Low-surface energy coatings are super-hydrophobic (i.e. water repellent) and inherently (relatively) elastic. The combination makes adhesion by marine organisms difficult, *Yebra (2016)*. However, also the other extreme, namely super-hydrophilic surfaces, impedes settlement of fouling. The working mechanism of hydrogel coatings is threefold, *Yebra (2016)*: "[…] fouling organisms, actively exploring the surface [of a hull], do not recognize the surface of a hydrogel and the opportunistic foulers that do not exhibit exploratory behavior, cannot displace the water-molecules bound in the hydrogel-layer with their glue. As a third level of protection, the silicone-based matrix underneath the hydrogel layer offers very low surface energy for the fouling organisms to anchor their glue, and as outlined above, silicone is well known for its Fouling Release characteristics." The best-known example of this technology is Hempel's ActiGuard®, *Sørensen et al. (2012)*, which is also marketed as "fouling defense". Combined with a mechanism to trap biocides on the hull surface, this approach can reduce biocide leaching by a factor of 10-20 over conventional antifouling coatings with virtual constant performance between docking intervals, *Yebra (2016)*.

To our knowledge, only two such products exist in the market. HEMPAGUARD®, based on the Actiguard® technology, works by forming a biocide-activated hydrogel on the surface of the coating. The hydrogel traps the biocide during diffusion out of the film thereby increasing the surface concentration of the biocide and prolonging the retention time of biocide in the coating matrix and on the surface, Fig.6. The concentration of biocide in the hydrogel surface of the coating increases for a coating based on Actiguard®. This is because the biocide is trapped in the hydrogel on the way out of the coating. In addition to very effectively utilising a minimal amount of biocide, it also means that the biocide concentration can be kept at a level where the silicone coating retains it silicone properties. There is not much public info on the other product claiming similar working principles, Bioclean Plus (ex. Chugoku Marine Paints).

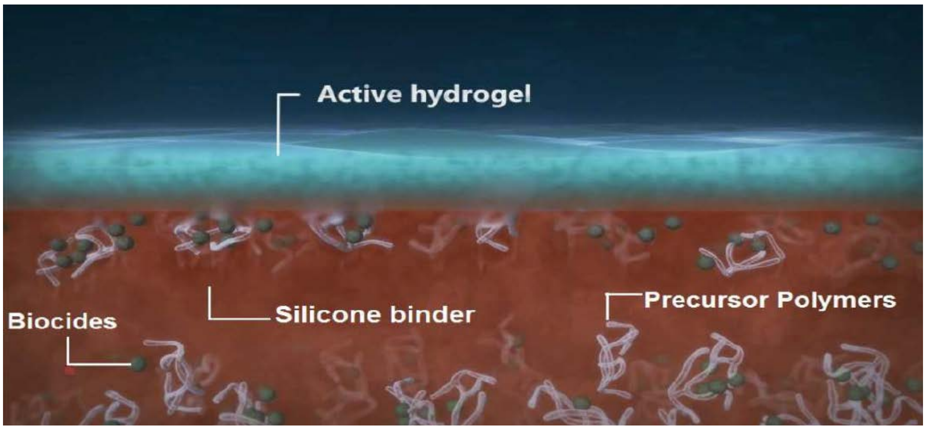

Fig.6: Working mechanism of ActiGuard®

4.2. Pharmaceutical antifoulants

Selektope® (generic substance name Medetomidine, https://en.wikipedia.org/wiki/Medetomidine) has been promoted as a non-toxic alternative to copper compounds, *Dahlström et al. (2000)*. The working principle is described as "pharmaceutical" as opposed to biocidal: barnacle larvae are stimulated to kick their legs, preventing settling on any surface. The substance is rather specific against barnacle fouling with much narrower spectrum of action than e.g. cuprous oxide, *Yebra (2016)*. It thus requires boosters to offer broad-band protection, which come with all the issues of present-day copper-based SPC coatings.

4.3. Nano-coatings and other micro-structured surfaces

Surface structure of e.g. shark skin or lotus leaves makes adhesion difficult for organisms. There are assorted efforts to recreate these effects industrially for ship coatings, e.g. *Stenzel et al. (2016)*. "Nano-coatings" are water-repellent, dirt-repellent paints known as "anti-graffiti" coatings for houses. Nano-coatings are increasingly popular also for ships, gaining market shares while LSE coatings have become less popular.

The German Fraunhofer Institute developed a riblet varnish that mimics shark skin, Fig.7. Recurrent problems with this approach include long-term deterioration, re-application of the coating and application in high-curvature areas. The EU project eSHaRk (eco-friendly Ship Hull film system with fouling Release and fuel saving properties) works on self-adhesive foils inspired by shark skin microstructures, *NN (2016)*. Besides the surface structure to reduce vortex formation, the robotized application of the foil sheets is expected to lead to smoother surfaces and reduced application times.

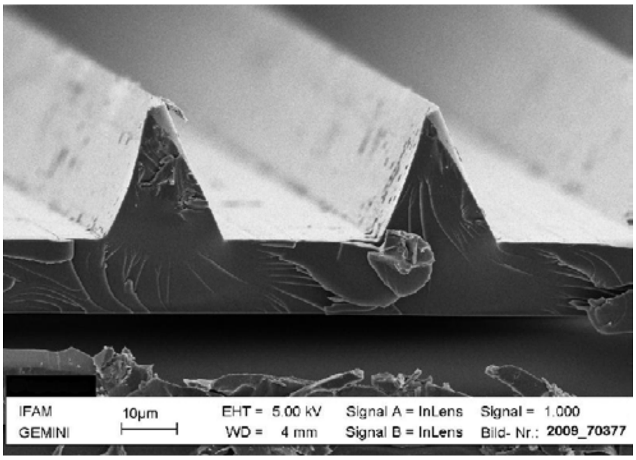

Fig.7: Riblet varnish, *Stenzel et al. (2016)*

Fig.8: Flocked surface (left), source: Micanti

4.4. Flocked surfaces

The Dutch company Micanti offers films with flocked surfaces (resembling Velcro in surface texture), Fig.8. The micro fibers prevent settling of fouling organisms even at zero ship speed. Despite the increase in surface due to the fibers, the company claims that there is no increase in friction resistance and thus no speed penalty, based on tests in the MARIN model basin. A possible explanation is that air was trapped when the test specimen was immersed in water and air lubrication cancelled with added surface. There is no verified performance gain in longer operation (when any initially trapped air will have gone into solution again) yet.

4.5. Surface-treated composites + frequent grooming

As early as 1862, a patent proposed mechanical scrubbing of the hull by rotating knives. This proposal can be seen as the forefather to current developments using robot technology for mechanical cleaning of hulls. Appropriate cleaning strategies depend on the coating used. Copper-based antifouling paints release toxins under shear forces. Thus, any brushing or wiping will release more toxins and each cleaning will deplete more toxins, leading to premature degradation of the coating. LSE coatings are damaged by hard cleaning and require more frequent soft grooming. Hard coatings are suited for frequent cleaning. Surface Treated Composite (STC) coatings, such as Ecospeed by Hydrex, contain tiny glass or platelets to achieve a ceramic-like hard surface. In itself, this surface offers no fouling protection, but allows frequent cleaning. "Frequent" may mean every two weeks, to give an idea. While the coating technology is in place, more work is needed to develop cheap, fast and widely available cleaning. Recent developments on robotic cleaning, such as the HullBUG of SeaRobotics, Fig.9, *Tribou (2006)*, or a Japanese prototype for a ship hull cleaning robot, Fig.10, *Ishii et al. (2014)*, are very interesting in this respect.

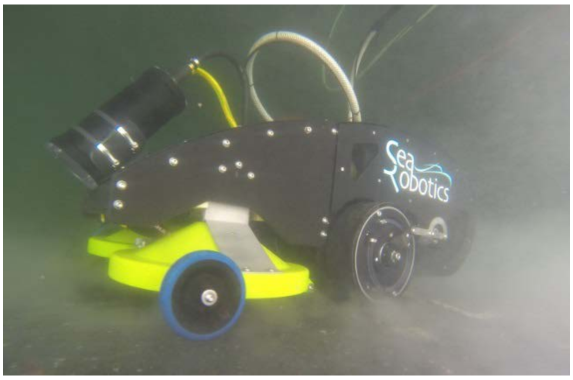

Fig.9: HullBUG cleaning robot for US Navy

Fig.10: Japanese cleaning robot

4.6. Ultrasound transducers

Ultrasonic vibrations cause very high accelerations, which destroy the cell structures of algae and weed. The technology has progressed from research to industrial applications, Fig11, *Kelling (2017)*. However, ultrasonic antifouling requires oscillators (“transducers”) every 6-8 m. The technology has been used for hull protection in yachts and workboats, *NN (2014)*. For large cargo vessels, the application is more difficult, as the many oscillators require a network of electrical supply in areas with difficult access. Here, the technology is most interesting for areas such as pipes or sea chests, where outside access and power supply is easy. If current restrictions for operation in immersed environments (double bottom filled with water or fuel) are overcome, we may see wider applications. A strong point of this approach is that it offers biocide-free protection even for ships at zero speed, e.g. laid up ships.

Fig.11: Transducer, source: Hasytec

Fig.12: HTC application robot, source: Palfinger

4.7. “Conventional” paints and improved application techniques

Regardless of the choice of coating technology, it is likely that the application methods will improve over the next years, making ships more fuel efficient even using with present-day coating products. “Today, hull painting is frequently carried out by unskilled labor under outdoor conditions. Hence, ‘dry spray or spray dust’ due to e.g. poor spraying technique and wind, paint sags (paint running down due to an excess of wet thickness) etc. are frequent defects encountered on hulls. Painting robots, such as the HTC from Palfinger Hubert claim to achieve a very low macro-roughness, in line with the values that can be obtained in lab (ideal) spraying conditions, […] *Hentschel et al. (2016),*" Fig.12, *Yebra (2016).*

4.8. Yet other ideas (and likely dead-ends)

Many alternatives to antifouling paints have been proposed and patented over the years. Ideas which appear at present as impractical or even exotic may be reviewed in the light of changing technology and political mainstream in years to come. Such ideas include:

- Biogenic antifouling coatings - Many sea creatures repel marine organisms without causing widespread harm. Research on the mechanisms of repulsion and chemical agents used by repelling plants and animals continues, e.g. *Qian et al. (2010).* Bio-paints are still a long way away from being a practical alternative. Natural biocides are still biocides and require lengthy and costly assessment and approval processes e.g. in the EU. Natural compounds must be mass produced, either by chemical engineering or farming. And compounds must stay active for several years to become a relevant option for shipping. Overall, biological paints still have a long way to go before they can be considered as a viable alternative.

- Sheeting - The 1980s saw a renaissance of research for the (metal) sheeting approach. Researchers in Japan and the USA found copper alloys that achieved satisfactory antifouling results. For most sheeting systems, the complete hull must be immersed in a bed of the sheeting alloy. Installation costs, both for material and application process, make sheeting unattractive.

- Air or gas carpets - In the 20th century, some patents proposed (chlorous or other) gas insertion at the keel. Also, the use of steam from steam engines was proposed as an antifouling measure. More recently, air lubrication has been proposed to reduce ship resistance. *Silberschmidt et al. (2016)* confirm only that air lubrication has no adverse effects on antifouling, but hint at air lubrication substituting antifouling coatings: "It is too early at this stage to conclude that the air bubbles are reducing the onset of hull and propeller fouling, although evidence points to this significant secondary effect." In any case, this would only apply to the ship bottom, as air lubrication is impractical for the vertical walls where the buoyancy of the bubbles prevents stable coverage.

- Electric protection - In 1891, Edison patented his ideas for an electric antifouling system. In 1907 a US patent was granted for electric protection of the ship hull by forming a boundary layer of antifoulant gases through electrolysis. In the 1960s, these ideas were revived in Japan and the USA, *Benson et al. (1973).* Since the early 1990s, Mitsubishi Heavy Industries commercialized an electrical antifouling system named MAGPET, *Nakao (1992), Bertram (2000).* Using electric hydrolysis, sea water is decomposed forming hypochlorite ions (ClO^-), a well-known antifouling agent. The water contact surface of the hull shell plating is coated with an electro-conductive paint film. A small current is passed through the paint film attracting the hypochlorite ions. This prevents the adhesion of marine growth such as micro-organisms, algae, and seashells. The ions also react to the sea water, when detached from the hull, avoiding long-term contamination. As a limitation, the system requires sea water and does not work in fresh water. Possibly due to high installation costs, it was not accepted by the market.

- UV treatment - Ultraviolet (UV) radiation is widely used in ballast water treatment. It also has been proposed for hull antifouling, *Benson et al. (1973).* However, the rapid attenuation UV radiation and relatively high initial and operational costs make this option rather unattractive for external applications.

- Radioactivity - Using radioactive elements as biocides in coatings has been suggested, e.g. in *Morley et al. (1958), Benson et al. (1973), Wootten (1977).* Thallium 204 was shown to be effective but only at levels which are not safe for human handling.

- Extreme temperatures - Extreme heat (45-99°C), *Benson et al. (1973)*, or extreme cold (cryo-genic treatment) are similarly impractical suggestions for antifouling.

Fig.13: Air lubrication, www.silverstream-tech.com

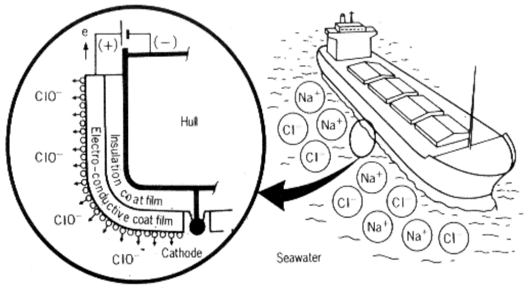

Fig.14: MAGPET system, *Bertram (2000)*

5. Conclusions

Biocide-based self-polishing coatings are widely applied as standard defence against fouling. Performance and price of these antifouling coatings varies largely, depending on base matrix and antifoulants used. Research and development has resulted in interesting low-tox/no-tox alternatives, but so far no dominant challenger to the currently used biocide-based technology has evolved.

We expect that antifouling strategies (which often means a combination of coating and cleaning choices) will be based increasingly on performance monitoring schemes. It is likely that this will promote blasting more frequently and more thoroughly (i.e. increasingly opting for fully blasted surfaces). It is also likely that more expensive, high-performance coatings are increasingly employed. Application and cleaning will be robotized, where more frequent milder cleaning ("grooming") will be the optimum choice.

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Appendix 1 – Historical development of antifouling solutions

The following table gives a rough timeline of marine antifouling strategies combining information from *NN (1952)* (Chapter 11 – The History of the Prevention of Fouling), *Omae (2003), Readman (2006), Dafforn et al. (2011),* https://reactiveresins.com/history-copper-resin-antifouling.html, http://www.international-marine.com/antifoulings/history-of-fouling-control.aspx

1500-300 BC	Use of lead and copper sheets, e.g. by early Phoenicians
15th Century	Chinese Admiral Zheng He has his ships coated with lime mixed with toxic oil
	Columbus uses tallow and pitch coatings and regular scrubbing
1625	First record of a patent for antifouling paint by William Beale (UK); many more patents follow, all essentially ineffective
1761	British Navy reports corrosion problems on iron bolts in copper clad ship
	Due to cost and corrosion issues, metal sheeting declines until 1900
19th Century	Heavy metals (copper, arsenic, mercury) incorporated into coating
1854	James McInnes patents first practical antifouling paint. This is soon followed by a similar product called “Italian Moravian”, a hot plastic paint used well into the 20th century
1906	US Navy begins to manufacture its own antifouling paint, tests shellac and hot plastic paints
1940s	“Modern” cold paints developed
1952	Extensive US Navy research results in handbook of antifouling
1960s	Development of TBT conventional coatings
1974	Oyster farmers report abnormal shell growth
1977	First low-surface energy (foul release) patent
1980s	TBT linked to shell abnormalities in oysters
1987-1990	First regional bans on TBT for pleasure craft;
	introduction of non-toxic foul release coatings
1990s	Copper release rates restricted regionally
2001	IMO adopts “AFS Convention” fading out TBT by 2008

Towards Future Hull Surveys based on Virtual Reality, Drone and Digital Twin Technologies

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Abstract

Today, assessment of the structural condition of a vessel mostly takes place during survey, i.e. during physical tank entry. The presence of the surveyor reduces the need for the recording of condition – assessment can be performed on site. Upcoming inspection techniques such as drones and self-localizing cameras potentially enable cost efficient full visual mapping of tank condition on a 3D ship model. The paper explores in how far such techniques could allow structural condition assessment to be performed remotely, thereby prospectively avoiding human tank entry.

1. Hull surveys of ships in service – common practice

Structural integrity of a ship is today ensured through hull maintenance performed on behalf of the ship owner. In this process, which is characterized through periodic inspections and repairs, the actual condition of the structure may not fall below a certain level. This level is specified in rules and regulations, see e.g. *IMO (1993), IACS (2003)*. Through periodic surveys, classification societies verify that appropriate structural condition is maintained.

The maritime industry is under continuous cost pressure. This leads also to a search for more efficient means for performing surveys. Today, survey of the hull structure requires the physical presence of a surveyor.

A key aspect of hull surveys for ships in service today lies in the extensive on-board activities of class surveyors. A main portion of hull surveyor's activities on board is related to physically accessing the structure for assessing hull condition. This typically comprises the overall and close-up visual inspection of hull structures as well as monitoring and evaluating of thickness measurements. The need for surveyor's presence on board also implies cost and time loss due to travel. Time efficiency of the hull survey itself is normally low because of difficult access conditions: narrow manholes in double bottom ballast tanks, or 20 m high elevations in cargo holds, Fig.1. Reporting of findings furthermore requires good orientation skills when e.g. examining a double bottom tank.

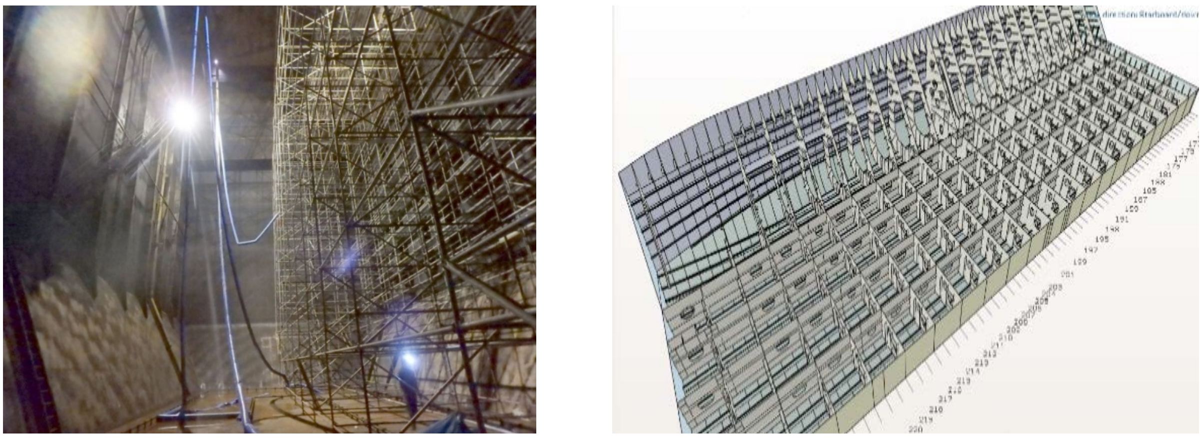

Fig.1: Staging erected for accessing and surveying bulkhead of cargo hold (left); ballast tank with high number of bays to be examined during survey (right)

Moreover, the survey preparation on board is in many cases even more time-consuming than the examination of the hull condition itself. In particular, the internal examination of spaces, such as ballast and cargo tanks, requires the tanks to be extensively prepared for physical entry. This comprises emptying the tanks, cleaning the structure from e.g. oil and sediments, gas freeing and maintaining continuous ventilation, and installing sufficient access means such as scaffolds. Thus, class hull surveys typically cannot be initiated and carried out on a short-term basis to make use of e.g. vessel's unplanned waiting time for new cargo. Although this preparation effort does not affect surveyor's time, it is an effort and operational interruption for the ship operator.

Finally, physical tank entry in many cases is hazardous: typical dangers are falling from height, lack of oxygen and presence of toxic gases. This clearly points towards the question: can the need for tank entry be reduced or be avoided altogether?

2. Remote hull surveys

Based on the above description of the current situation regarding hull surveys it is attractive to consider replacing human tank entry through alternative techniques. This also reflects existing ambitions in land based industries which target at avoiding human entry of enclosed spaces (e.g. pressure vessels) altogether in the future. In this paper, we are drafting a scenario for remote hull surveys based on several technological elements. Before describing the changed survey process in more detail, we list what could or should be available when we want to consider such procedure:

- Access to structure would be provided by an autonomous vehicle. This can be a drone or a diving or crawling robot. We will refer to a drone in the following to simplify the text but alternatives are possible.
- The orientation of the drone is enabled through automatic indoor positioning technology
- Image capturing methods allow taking photos or hyperspectral images
- Optionally, flight path is guided through a pre-existing map which can be a 3D model, possibly in a simplified format. This model would also serve as a map for marking potentially critical areas before tank inspection
- Optionally, historical findings, experience databases, or Risk Based Inspection (RBI) survey plans aid in programming specific flight paths
- Through an image mapping algorithm, captured photos can be displayed on the model, thereby comprising an updated "digital twin"
- Image recognition methods identify photos for marking necessary follow-up and/or prioritize them for additional human assessment
- Remote connectivity allows a user to interact with and guide the drone for additional close-up capturing where found necessary
- Virtual Reality (VR) techniques facilitate access to the pre-scanned tank information
- Optionally, measurement gear is carried by the drone for measurements of thickness and deformations and/or detection of cracks
- Optionally, captured images are used to automatically reconstruct a 3D model which refines the existing coarse structural model

Note that no storage of captured video material (other than for backup purposes) is proposed as it appears to be more appropriate to navigate freely in the mapped 3D output via VR rather than needing to linearly scan video material.

3. VR aided remote hull survey

The VR aided hull survey process is illustrated in Fig.2 on a high level. The main process phases – survey planning, pre-scan on board and remote hull condition assessment – are described below.

3.1. Survey planning

In general, the survey planning and preparation aims at selection of spaces for overall external and internal examination and of locations for close-up visual inspection and thickness measurements (what, where, how to inspect). For this purpose, the surveyor would explore the vessel's digital twin enriched with historic data, including results of previous class surveys and owners' inspections, as well as related data for sister vessels.

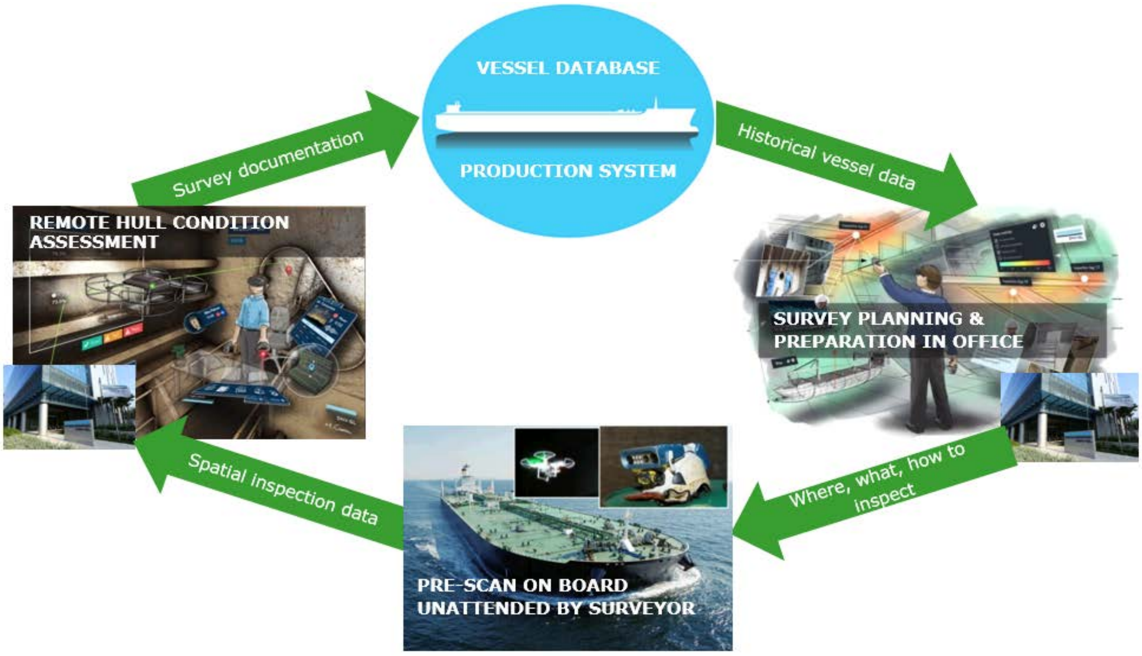

Fig.2: Remote hull surveys with VR technology

Fig.3: Examining hull structure in VR

In a virtual environment, the class surveyor can be provided with advanced abilities of viewing, interacting and navigating through the vessel's virtual twin in real scale and model scale, Fig.3. Different types of structural representation, e.g. transparency mode showing structural arrangement e.g. behind the tank boundaries, Fig.4 (top), support a quick and comprehensive insight into vessel's tank arrangement, structural arrangement, hull equipment, etc. Orientating and navigating in the virtual vessel may be further supported by displaying frame numbers, structural member labels, position above the base, etc.

VR supports different strategies for long, medium and short range locomotion. For long range, the user may "jump" to a hull compartment of interest by selecting it from the small-scale model, Fig.4 (bottom). For the medium range navigation, fly mode and teleport mode may be available. Short range navigation is supported in VR by tracking the physical motions of the surveyor in real scale.

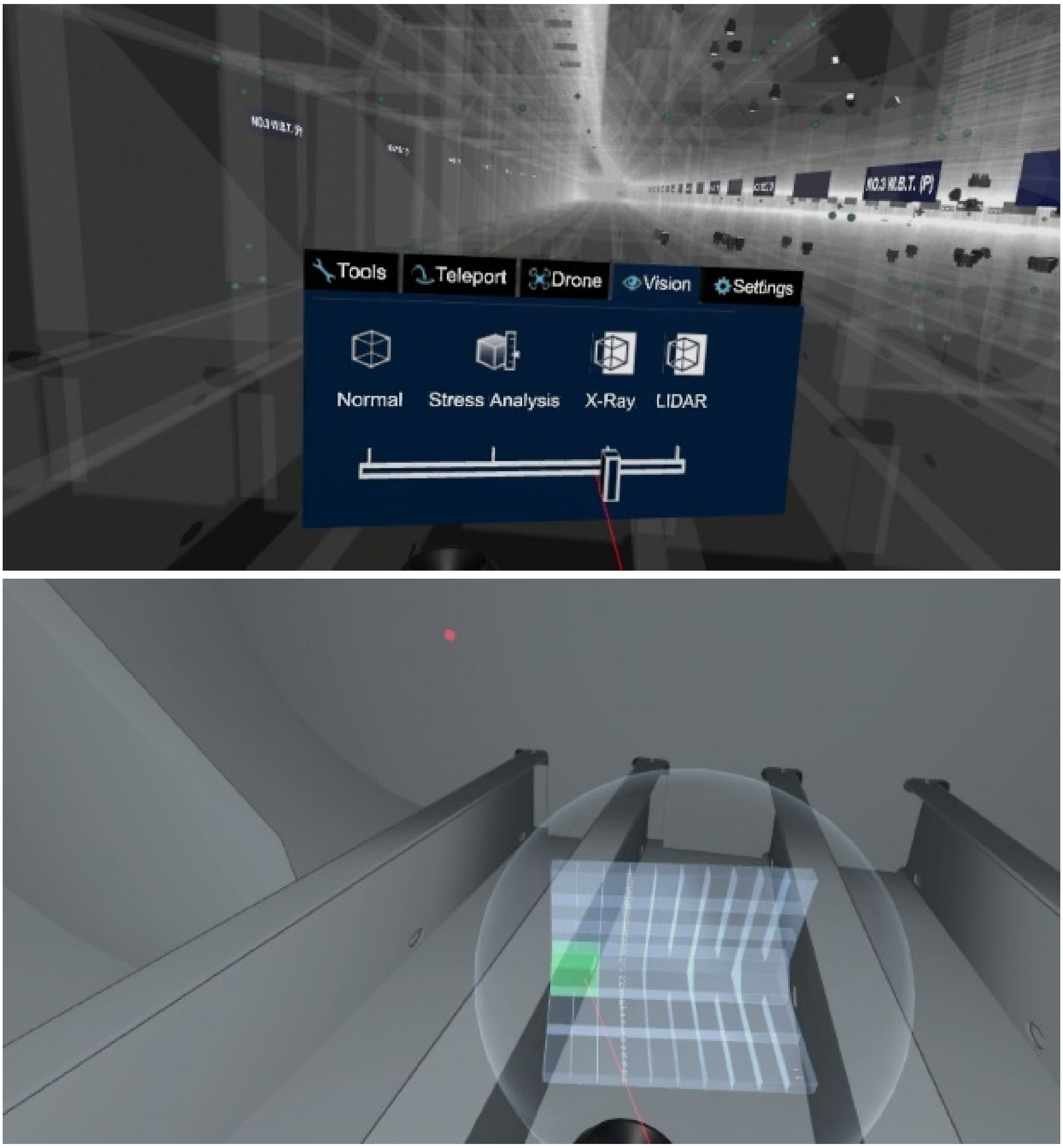

Fig.4: Setting control and X-ray mode for fast overview (left). Changing location by selecting target in mini-map(right).

In the different representation scales, different detail levels of information are provided. For instance, in the model scale representing the general hull form and compartmentation, the surveyor would be provided with the high-level information such as main ship data, list of relevant codes, tank arrangement, etc. In real scale representation of a specific location like a tank, the surveyor would be provided with detailed information associated with this location, e.g. the most critical weld connections in the tank, details on previous repair measures in the tank, etc. In VR, the surveyor can be provided with information in form of virtual documents/lists which can be arranged in the virtual space as appropriate for the surveyor. In addition, spatial data like locations of substantial corrosion, cracks, deformations, etc. can be displayed on the corresponding locations in virtual tank. By selecting such items on electronic lists in VR, the surveyor can be guided to the corresponding location in the virtual hull structure. Photos of the structure captured by a camera with tracking system, e.g. during previous class surveys, can be mapped on the associated virtual structure resulting in a realistic representation of the structural condition at a given date.

Provided with the above means in VR, users can efficiently extract insights relevant for specifying the survey scope like selection of spaces for overall internal examination, and of locations for close-up visual inspection and thickness measurements. The surveyor can instantly document the survey plan and other relevant documentation for the owner's survey preparation note. In particular, the surveyor would determine and record in VR the sequence for entering the spaces for overall internal examination and the optimum path for the drone (or as an intermediate development step for the technician with e.g. helmet camera) through those spaces during inspecting. Moreover, the surveyor would make marks on the virtual structure and prepare check lists and action lists for each location to be inspected as appropriate. This would be available in VR in execution phase for efficient surveyor guidance and progress documentation.

3.2 Hull inspection as pre-scan

Hull inspections would be performed with the help of remotely operated or even autonomous inspection means, like camera equipped drones, crawlers, etc., combined with an indoor positioning system. For higher time efficiency, hull inspections would be preferably done in a pre-scan unattended by the class surveyor, following the inspection plan prepared in planning phase. As the drone or crawler would carry an automatic indoor positioning system, inspection photos could automatically be mapped onto a 3D model. Fig.5 shows an example for this procedure based on image capturing with the IRIS system, *Wilken et al. (2015)*.

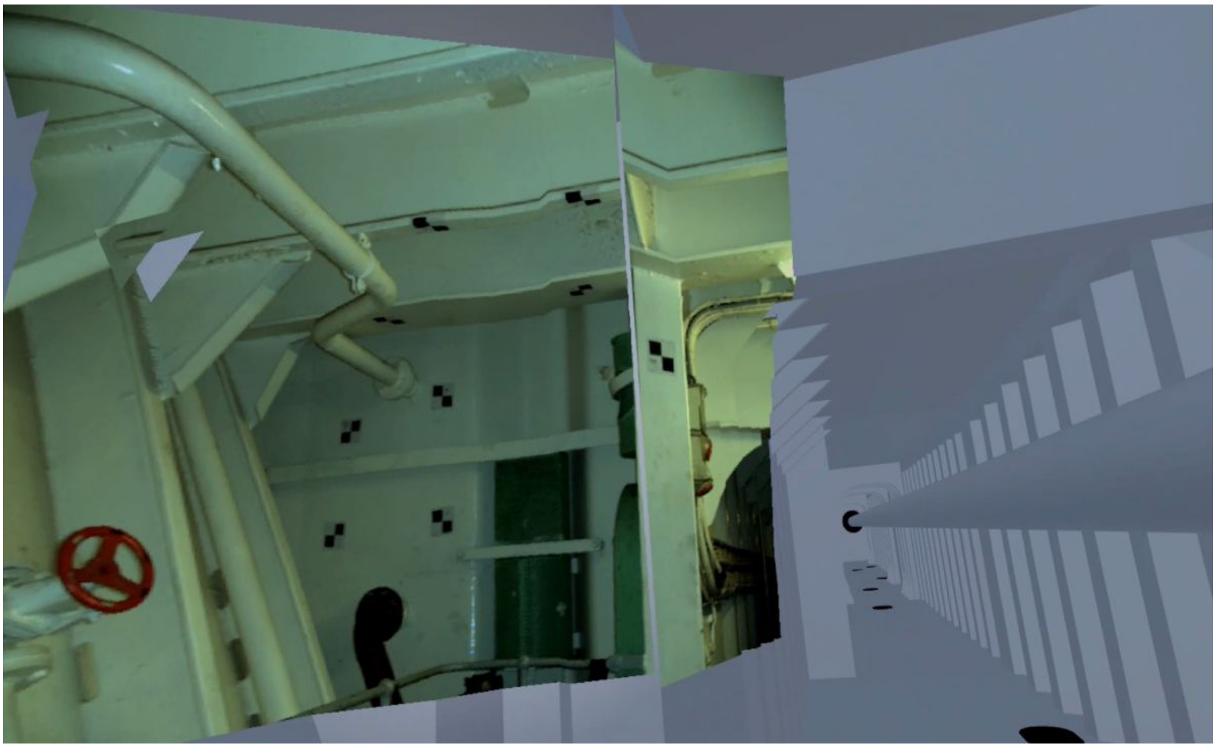

Fig.5: Inspection photo taken with IRIS inspection camera positioning the photo automatically. The photo is projected in VR onto the existing coarse 3D model.

Camera equipped drones can already today remove the necessity for installing scaffoldings. This is the case when visual confirmation of good condition is sufficient. Crawling robots or lightweight contactless thickness measurement could prospectively abandon the need for physical tank entries. The effort for survey preparation on board will thereby be dramatically reduced allowing voyages or even short unplanned downtimes of the ship to be effectively used for the pre-scanning of the hull structure.

As long as autonomous drone flight is not possible, pre-scanning can be performed through a remotely guided drone carrying the indoor positioning system. Here, human tank entry is still avoided, but the remote pilot can watch the drone's position in the virtual model. If the positioning system is still too heavy for carrying by the drone, pre-scan can be performed by a service technician carrying a camera system. Through equipping the carried camera system with indoor positioning technology, image capturing towards a 3D model still is very efficient.

Already today, drones far outperform humans when it comes to quickly accessing structures. For this reason, it becomes viable to scan a larger area of the tank surface at low cost. Depending on degree of automation, it could therefore become possible to reach 100% surface coverage from a distance, possibly even full close-up imagery.

3.3 Hull condition assessment and reporting

After the pre-scan, inspection data captured on board (overall and close-up footage and measurement readings) is spatially allocated to the ship's 3D model. In a more prospective view, a complete 3D scan of the tank may be generated during the tank inspection and, thus, remove the need for building a separate 3D model in advance.

The ship's 3D model – populated with the new inspection data (image footage and measurement results) – can be explored by the class surveyor in virtual space using the VR capabilities for navigating, orientating and interacting with data in the virtual tank as described in section 3.1, Fig.6. That is, the surveyor can assess the actual hull condition based on an accurate virtual twin of the real ship reflecting the actual hull condition. Thus, the surveyor can attend the survey remotely from any office worldwide using VR.

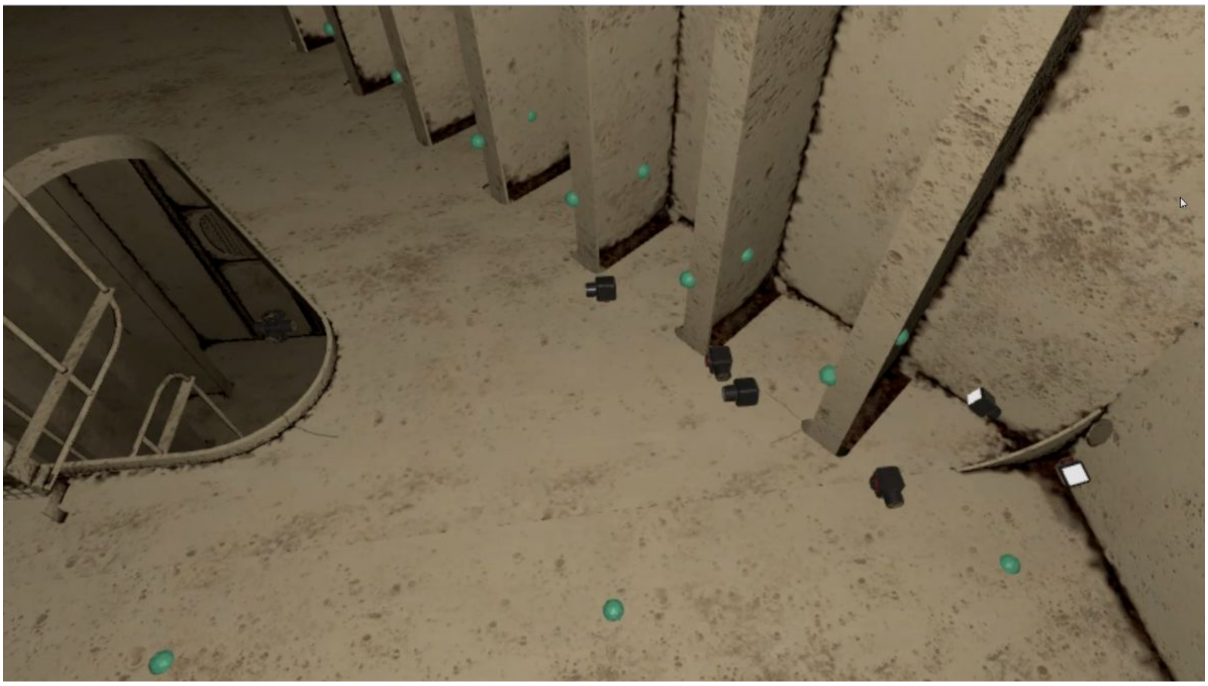

Fig.6: Indication of thickness measurement points and camera positions for close-up imagery viewed in VR

Consequently, remote hull survey techniques would reduce travel and would allow a higher degree of surveyors' specialisation – on specific ship types or even individual ship series.

Although a fully automatic pre-scan might become possible in the future we assume that in the medium-term scenario, a surveyor would still need the ability to interact with the drone in the tank. The reason is the need for additional close-up photos in case of uncertain assessment. In this scenario, suspect areas detected in VR in the pre-scan imagery is followed up through remotely advising the drone to re-visit specific locations and obtain more detailed imagery. See Fig.7 how this process can be visualized in VR.

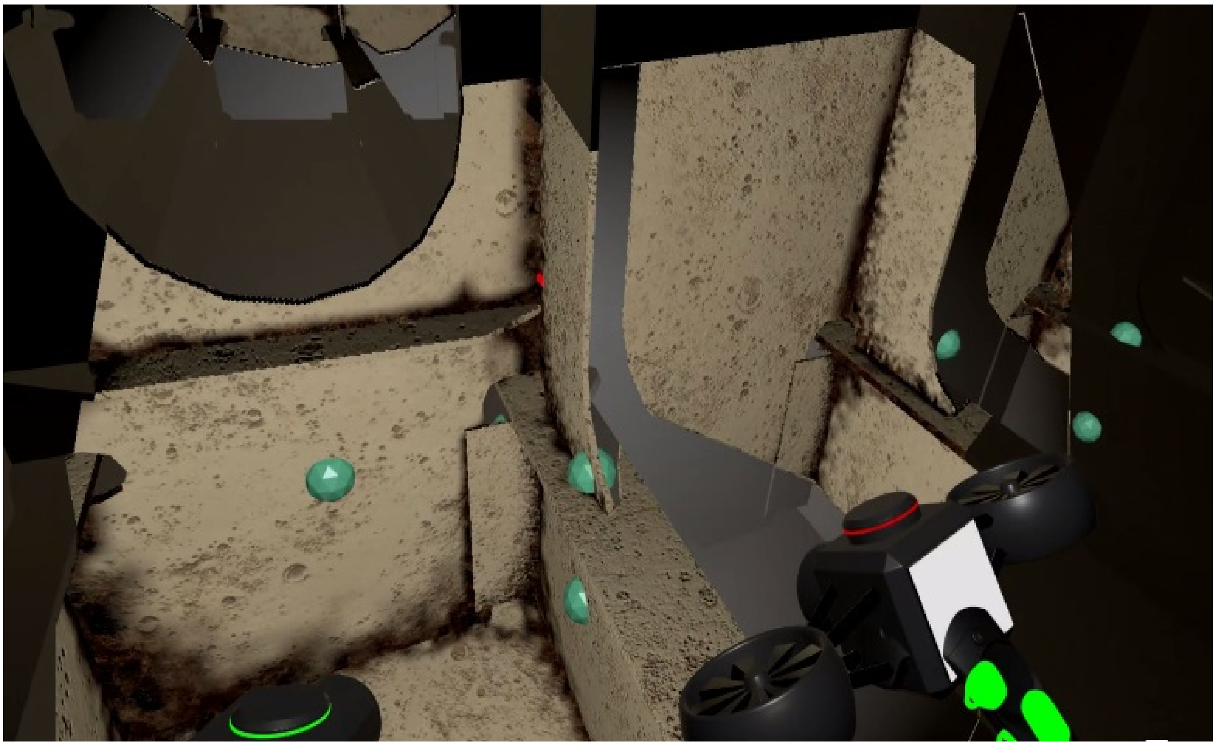

Fig.7: Scenario in VR showing real-time interaction with drone for additional close-up photo

In the virtual environment, on-board the virtual ship, hull condition can be assessed and documented very quickly. Moving around (e.g. examining bulkhead plates from both sides by simply walking through the virtual bulkhead and turning around), accessing thickness measurement results, comparing to previous records, etc. becomes fast and easy. Automated algorithms for image recognition can direct the surveyor to locations with suspected cracks, deformations, heavy corrosion wastage, coating break-down, etc. and would therefore accelerate the process of hull condition assessment.

Inside the virtual tank, the surveyor is efficiently guided in terms of all relevant data from vessel database like design analysis data, risk-critical areas, ship operation history (trading pattern, encountered wave climate, loading pattern), survey and inspection history (condition of hull at last survey), condition of sister ships, etc. In complicated cases, an expert from helpdesk can be brought into the same virtual space for decision support.

Findings, repair measures, memo to surveyor, etc. can directly be recorded on the structure and linked to the production system. Voice notes and text dictation further facilitate instant reporting. No additional work is necessary for the surveyor after leaving the virtual ship – documentation is done when survey is done.

Results can be presented and necessity of possible maintenance and repair measures can be explained to the superintendent/ship owner representative in a virtual meeting on-board the virtual ship in an efficient and most intuitive way.

4. Remote hull surveys – technological status

Today, hull inspection techniques using remote means like camera-equipped drones are starting to be accepted on a case-by-case basis. They might e.g. be used for the overall and close-up visual inspections of large hull compartments. Drone inspections currently require two persons to be present during the survey: the drone pilot with clear line of sight to the drone and the surveyor interpreting the screen image. The surveyor also needs the line of sight to the drone to understand its current position. Drone inspection techniques for narrow spaces – where no line of sight to the drone is possible – are a matter of research.

From the perspective of a class surveyor, thickness measurements in the context of class hull surveys are performed today de facto remotely as well: third party technicians carry out the thickness measurement at designated locations inside the hull compartments, while the class surveyor monitors the thickness measurement process and later evaluates the measurement results. Prospectively, remotely operated or even autonomously operating robots may play a key role for remote thickness measurement techniques and for avoiding human tank entry. Currently, crawling/rolling robots (using magnets), diving robots, and floating robots (internal examination through gradually filling tanks) are tested and partially used in the industry for thickness measurements. Thickness measurements via drones are in an early development stage.

While remote inspection devices like drones and robots equipped with cameras and sensors are fundamental prerequisites for remote hull inspections, the automated spatial allocation of imagery and measurement data captured e.g. inside a ballast tank is essential for documentation and (visual) representation of the hull condition. Accordingly, several systems for automated indoor positioning of cameras and sensors are currently under development. For instance, the IRIS system enables photos captured in closed spaces to be properly associated to 3D models, *Wilken (2015)*. The same technique would allow the drone to orient itself in space. Further development of indoor positioning technologies for cameras and sensors (e.g. UTM sensors) is needed regarding their precision and portability by drones and robots. As an intermediate development step, IRIS or other existing systems can be used by inspectors/surveyors for capturing (visual) inspection data inside hull compartments.

Remote connectivity can further leverage performing remote hull surveys. As stated above, techniques for remote inspections of closed spaces available today and those under development are expected to reduce the need for physical tank entries by humans soon. The remote connectivity between back office and ship capable of two-way audio and video transmission would even enable the hull survey (as a follow-up to pre-scan) to be performed in real time remotely from the back office. Although technology for two-way communication between surveyor in the office and persons in closed spaces on board has already been tested, the capability of remote connectivity technology of data transfer at rates appropriate for large amount of inspection data is uncertain today. In particular, live connectivity to a ship on voyage would require further technological progress. In the medium term, follow-up to hull pre-scan would be performed by the surveyor being on-board. Without the need to enter the tank, the on-board surveyor could connect to the drone flying in the tank and guide it to suspect areas for further close-up.

5. The role of VR

The technologies described above are in different development stages – between prototype and testing – their further development in the near future is expected. The detailed scenario how remote surveys could be realized will very much depend on actual availability and maturity of each technology over time. Eventually, remote hull condition assessment would be enabled based on visualisation of spatial inspection data, captured by (autonomous) drones and robots inside the hull compartments, by mapping them on a ship's 3D model. Thus, the need for physical tank entries and even for surveyor's presence on board would be avoided in many cases. This would not merely increase the time efficiency of hull surveys but also reduce the health risks surveyors and inspectors are facing today when working inside the tanks.

On the other hand, being outside the tank and, thus, being not able to use all human senses, see section 6, involves potential difficulties for the surveyors to comprehend the inspection data and draw insights regarding the actual hull condition. The unique capabilities of VR technology for visualisation and interaction with spatial data can be used to partially compensate for this deficiency.

The realistic immersive simulating of an interactive environment with VR enables an accurate replication of e.g. ballast and cargo tanks in a virtual space. It allows the surveyors to be immersed in a virtual tank populated by imagery and measurement data captured inside the real tank, and to explore it in the most natural and safe way. In other words, VR brings the remotely captured (spatial) inspection data closer again to surveyors' human senses. Moreover, VR combines the natural human perception with augmented spatial data sets and improves surveyors' ability to draw insights from multiple data sources. For instance, in VR, the current hull inspection data can be aggregated and compared e.g. with the data from previous inspections, including sister vessels, or with strength calculation data from the design phase.

The potential of VR technology is not limited to enhancing the remote hull condition assessment only. Benefit with respect to time efficiency and quality is also seen in the use of VR for survey planning enabling quick insights e.g. into required survey scope and critical locations inside the tanks under consideration. In addition, surveyors can be provided with all necessary (virtual) tools for instant, largely automated recording and reporting of findings during the hull condition assessment in the virtual tank. Thus, follow-up activities for survey documentation after the survey, which make up a significant portion the total survey process today, could be substantially reduced. Finally, VR offers new opportunities for collaborative working. Surveyors can invite other users like Helpdesk experts or ship owner representatives, who are physically somewhere else, into the same virtual space for e.g. decision support and sharing insights.

6. Can a drone replace physical tank entry?

A class surveyor, being physically present on board during survey, uses more than his/her visual sense:

- Touching/feeling objects and substances to examine their condition and nature (Is the surface smooth? Is it wet? Is this water or oil?)
- Use of hammer or other impacting force, e.g. to remove scaling or to test the mechanical and acoustical response of structure for indication of deficiencies
- Testing the smell, e.g. as indication of smoke or cargo vapours in a space, etc.

As autonomous vehicles today typically cannot perform these actions, we need to understand whether other capabilities could compensate this so that this lack of information from autonomous pre-scans does not lead to less safe structures. Today, the survey regime requires partial examination of tanks at given time intervals. E.g. after five years (first class renewal) selected transverse shell frames in one forward and one aft cargo hold of a general dry cargo hold must be examined through close-up visual inspection. This inspection scope increases with ship age. If – through automatic scanning – visual scan of the structure becomes easy, a more frequent and more extensive examination of the structure becomes feasible. More frequent and more extensive inspections will increase the structural safety of the hull. Therefore, infrequent partial check with all human senses would be replaced by frequent complete visual check with e.g. a drone – combined with image recognition techniques to increase probability of detection of structural deficiencies.

Another option is to fit additional imaging techniques on the drone such as hyperspectral imaging – being able to analyse the full spectrum of the light reflected by the structural surface. Thereby corrosion or coating breakdown could be detected with higher likelihood than with the naked eye.

7. From idea to prototype

DNV GL have developed a working prototype demonstrating how hull condition can be assessed and documented in a virtual space. The prototype allows VR users to experience a water ballast tank of a large crude oil tanker. They can enter the tank virtually and explore the structural arrangement in real scale. Navigation and orientating are supported by various navigation and visualisation modes like teleportation and transparent view. Users can spatially display and examine emulated thickness measurement data and drone footage (360° view, close-up photos and a complete 3D scan). They can search for locations with corrosion, cracks or buckling and document possible findings. Emulated data from previous inspections of the ship and her sisters can be displayed and compared with the actual tank condition. See Fig. 8 for visualization of the environment.

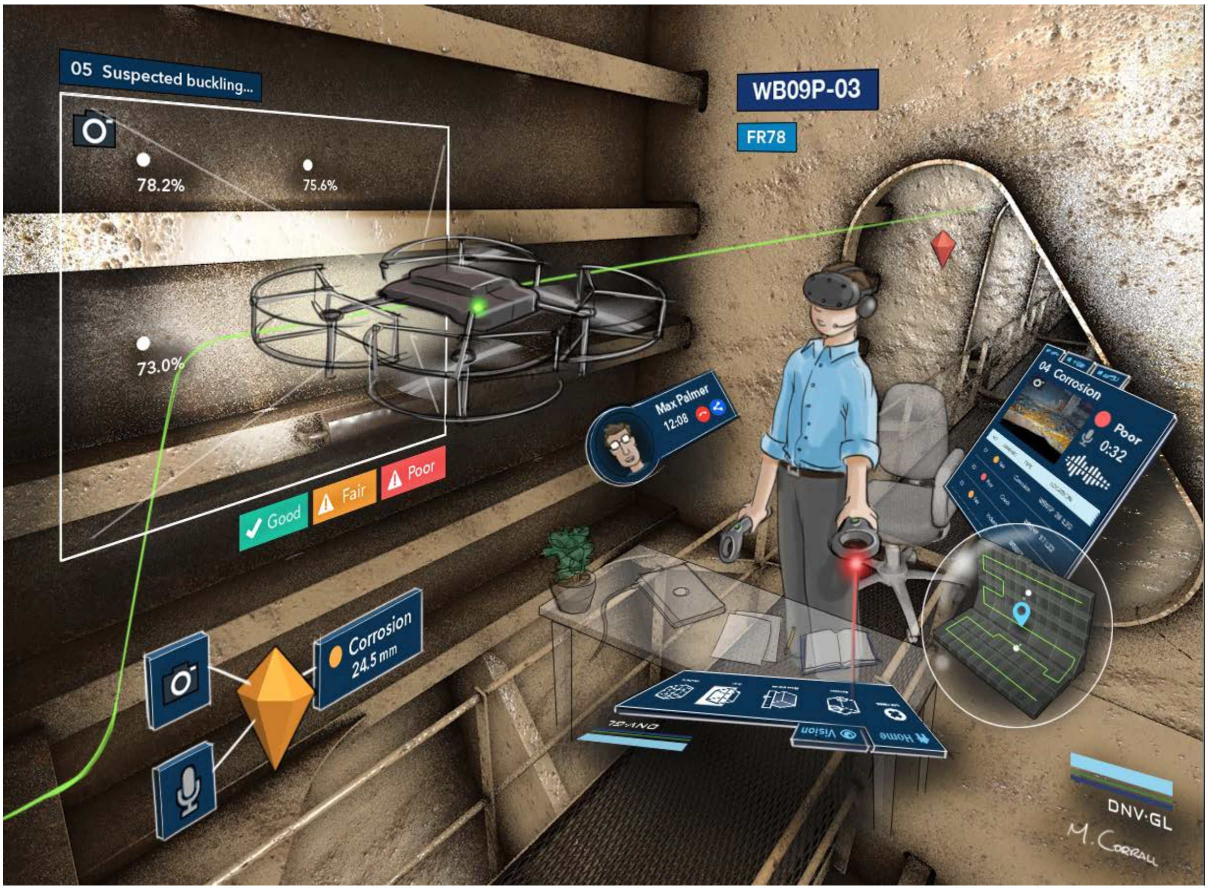

Fig. 8: Concept image of realized VR environment for remote hull surveys. (Image by Matt Corrall)

For actual inspections performed by a person using the IRIS self-localizing camera system, photos can be uploaded to the ShipManager Hull model of the vessel. The photo results can be examined in VR using the developed prototype. Therefore, without drones the system can be used in pilot studies on-board real ships.

8. Summary and conclusions

Avoiding human entry into enclosed spaces is a valuable ambition. Technological developments in many areas deliver the elements which will make this possible while at the same time reducing cost level and service interruptions of the ship. By automating hull pre-scans with the help of drones, the surface coverage and frequency of inspections could be increased. This, and the use of new imaging and image recognition technology then has the potential to compensate for the missing human perception of the tank environment. Thereby, the proposed procedure could result in the same or a higher safety level than reached today through assessing the less frequent inspections carried out by crew, superintendents, UTM operators and class surveyors.

It is not yet clear when a full autonomous scan of a ship compartment might become reality. But the maritime industry is clearly working towards this. Further conceptual work should be performed to investigate safety equivalence. VR will bring the captured images as close to physical presence as possible. Thereby, VR might turn out to be an important element in making remote hull surveys possible.

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Maritime e-Training – Matching Requirements to Solutions

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Abstract

The paper discusses expected or desirable changes in teaching engineering, in particular post-graduate and professional training in maritime technologies. Several factors drive the developments: changes in students, changes in technology, changes in expectations from industry and governments. These factors determine what we need to teach and how we need to teach. A different teaching infra-structure with possibly different providers is expected to evolve. The paper discusses both market and technological aspects, highlighting challenges and pitfalls of new technologies commonly referred to as "e-learning". The paper argues in favor of pedagogy-driven education rather than technology-driven education.

1. Introduction

A new method to the 3d flow around a ship on shallow water and in oblique waves is a safe topic for an engineering conference. An estimated three colleagues may be interested to start with. A suitable mixture of complex equations, daunting diagrams and colorful displays will evoke admiration, little interest and no aggression. In comparison, education in engineering is a dangerous topic. All engineers have been exposed to the topic (as students). It is a bit like soccer:

- It used to be better in the past.
- The players (students) today just do not want to work anymore. Shame on them!
- The coaches (professors) are incompetent. We could do a better job.
- It is still great fun to talk about…

Teaching environments and techniques have changed over time, Fig.1. In Germany in the early 1980s, all professors used blackboard and chalk. Today, a mixture of PowerPoint and blackboard (or white-board) prevails. Discussions about future teaching employ terms like "web-based teaching", "e-learning" or "m-learning" (e-learning describes learning (or teaching) through the use of assorted technologies, mainly Internet or computer-based. Students rarely, if ever, are face-to-face with each other or teachers. m-learning describes learning through the use of mobile devices, particularly mobile telephones.) This comes typically with reorganization of departments and curricula, introduction of further quality management procedures and reduction of budgets. One must be a politician or university president to understand how this will result in better engineers for our industries.

Fig.1: Teaching over time (around 1940, 1975 and 2008)

A lot of the new teaching technology has been driven by mass markets like language teaching. Here the financial incentives are higher due to much higher numbers of students. In addition, there is a traditionally much higher focus on pedagogy and openness to multi-media teaching. Much of what is now discussed for maritime teaching has been tested in other fields like language teaching, law, and medicine. Highly specialized engineering (like graduate and post-graduate training in maritime technologies) is different from these fields in required skills, available market size, and other aspects. Some approaches that work for example in English language teaching do not work for teaching naval architecture.

Despite changes in students and technologies, there are some constants in our fundamental guidelines to teaching:

- You learn by doing and face-to-face time with teachers is expensive. So we need to encourage students to work outside class time.
- Students should use tools that they are familiar with. For our generation, that meant books. For the new generation of students, this may increasingly mean computers and even smart phones.
- Communication with peers should be encouraged. This happened too little in classical engineering training, where frontal teaching has ruled supreme. Internet technology allows virtual meeting spaces for students. While popular for "net-working" (gossiping), we are not aware of any real academic benefits in the maritime field. However, traditional teamwork continues to work well and team communication is then automatically based on internet and mobile phones.
- Modern teaching approaches advocate: Make teaching competitive, make it fun! We are supposed to move from education to edutainment, where students are entertained while learning quasi without noticing it. This is easier in language education than in engineering. Material science was no fun 30 years ago, still is no fun, and is unlikely to ever be fun. No pain, no gain.

2. Changing conditions

The introduction has already mentioned several of the driving factors shaping our teaching: budgets, technology, and politics. The demographic and political changes are fairly universal. They will be discussed in the following subsections.

2.1. Different students

"Students these days are not what they used to be." We heard this sentence when we were students from our professors. We hear it today, and it is the same the world over:

- They do not want to study as much as we did.
- They cannot write properly even in their mother tongue.
- They only want to play with computers; they are not interested in "real" science (i.e. the mathematics involved in fluid or structural analyses).

These are not senile professors ranting, with a selective memory of their past. There are real changes, due to changes in the way of life and upbringing of children. Today's children are exposed to computers before they go to school. *Prensky (2001,2011)* calls them "digital natives": "Today's average college grads [in the USA] have spent less than 5,000 hours of their lives reading, but over 10,000 playing video games […] It is very likely that our students' brains have physically changed […] ." These digital natives are our raw material and they are different from us, with strengths and weaknesses:

- They are used to getting information fast. They google rather than open 20 books in a library.
- They prefer graphics to texts.
- They prefer random access to information (like hypertext links).
- They function best when networked.
- They thrive on instant gratification.
- They prefer games to serious work.

Does any of this sound familiar? Our generation of teachers is called "digital immigrants" by *Prensky (2001).* We are always one generation behind in the latest technology tools. Digital Immigrants have to teach Digital Natives. We cannot change the students or course participants we get. Instead, we should work on understanding them better and try to adapt our teaching to them, without sacrificing our goal to teach them what we know (or believe) to be important in their professional careers.

2.2. Changing political frameworks

Several political trends influence the evolution of teaching in general:

- There is an increasing demand for life-long training, with upgrades on new developments in legislation and technology. Industry engineers looking for continuous professional development are willing to spend more money, but less time and will favor on-site training rather than on-campus training. The demand for distance learning will increase.
- The transition towards a unified bachelor-master-PhD system in Europe (following the Bologna treaty) has reduced thresholds between the various states in making university degree compatible. This means that students will have more choice in where they can study. The winners of the resulting competition between universities are likely to be large Anglophone universities.
- Funding for education is reduced in most countries. There is a trend to "privatize" state universities, cutting their budgets and encouraging them to generate more own income.

2.3. New media

"New" media invariably involve computer technology. Technology develops and new terms come and go. After initial hype and large investments, universities and other higher learning institutes frequently experience a sobering disillusion.

An example may illustrate the problems encountered: "Self-access centers" (SACs) are educational facilities designed for student learning that are at least partially, if not fully self-directed. Several websites promote SACs as follows: "Self-access learning gives you the opportunity to develop initiative, responsibility, self-awareness, confidence and independence in learning. It is about making choices and having flexibility in learning." This sounds great in theory, but SACs often do not live up to these expectations, for a variety of reasons:

- It is expensive to set up a good SAC. Learning institutes like to boast having an SAC, but do not want to pay much. Token efforts are a waste of money when it comes to SACs.
- SACs are frequently poorly staffed. Some existing teacher or technician gets tasked with running the new multi-media lab. There is no budget for hiring a dedicated expert or even for training the person responsible.
- Material gets stolen or vandalized.
- SACs are set up as a once-off prestige object, often with external once-off funding. There is no budget for maintenance and upgrades. As a result, half the computers do not work after a short period or have outdated and incompatible software.
- Students have no time or no motivation to use SACs, at least not for studying.

3. Challenges and Trends

The requirements for future engineering teaching involve some changes in infrastructure and teacher profiles:

- More teaching will have to be based on e-learning and short courses. We have observed course times moving from 1 week, to one day with demand increasing for 5 to 45 minutes e-learning solutions to respond to industry demand for continuous professional development. So units of learning become ever shorter. Similarly, expectations for development times become ever shorter: "Can we have training on latest XYZ developments next week?"

- Teachers will continue with some traditional tasks (selection or creation of appropriate teaching material, checking that learning goals have been achieved (tests), monitoring of results, evaluation of learners), even if based on different media.
- “Edutainment” will require more frequent changes of media (more video) and topics than traditional teaching.

New media may or may not offer better ways of teaching, but pedagogy comes first. First we must decide <u>what</u> to teach, and then we can decide <u>how</u> best to teach it. Poor pedagogy results in poor training, regardless what media is employed. No doubt we have all seen more than enough useless e-learning courses.

The appendix lists some goals compiled during a workshop on training future ship designers, *Rusling et al. (2005)*. The elementary learning techniques to teach these goals are (largely) media independent and migrate naturally into web-based teaching:

	Traditional	e-learning
watching	Blackboard	PowerPoint embedded videos
reading	Books Lecture notes	Books Online texts
doing	Exercises Assigned homework/projects Laboratory work	Exercises (web-based) Assigned homework/projects Virtual lab visits
testing/evaluating	In class	On-line Homework submission

Here the pedagogy remains largely the same. The change is gradual and there is better acceptance among the traditional trainers/teachers. In principle, all traditional elements in our curricula could migrate to digital form, except for laboratories and visits to industry sites. The vast majority of the “digital immigrants” defend traditional laboratory time, but personal experience is that they are expensive and ineffective in teaching. If you really want to learn experimental techniques, make an internship or project in a professional testing facility. If you just want some hands-on feeling on some physical behavior then a virtual (numerical) lab could serve a similar purpose. So, in principle, migration to e-learning should be feasible in most cases. Then, why don’t we see widespread e-learning activities in the maritime world and why do many efforts fall well short of their targets?

There are many factors contributing to the slow transition in our field:

- Often, there is no or insufficient budget for the conversion to electronic teaching.
- Our best teachers are often not 100% computer savvy and the computer gurus lack competence in the subject matter and in pedagogy.
- E-learning is frequently not desirable:
  - You have no feedback from the learners (do they understand the material?)
  - E-learning requires self-discipline and maturity, frequently not found in our average high-school graduate;
  - E-learning requires more technological skills from teachers and students.

Some web-based means to support teaching are found in most universities today. At ENSTA Bretagne a decade ago, we employed Moodle (http://en.wikipedia.org/wiki/Moodle) as a platform for the teaching of naval architects and offshore engineers. Students accessed teaching schedules, lecture notes, assignments, and even grades via this platform. The project was moderately successful. The “download” center was readily accepted. Moodle also made it easier to integrate special students who were part time in industry (in other cities) and followed part-time courses at ENSTA Bretagne.

In Germany, four universities offering naval architecture and ocean engineering at graduate level and the research group “instructional design and interactive media” joined forces within the multi-million project mar-ing to develop e-learning infrastructure and material, *Bronsart and Müsebeck (2007).* Some years later, the video conference facilities were used for occasional lectures by visiting lecturers from industry or academia. Each university continued to use the developed material, but no mention of core lectures being offered in distance learning could be found.

We should not be surprised. The same mechanisms have prevented a text book culture in our field:

- The considerable effort to develop and update material for specialized topics cannot be recuperated.
- Teachers like to use their own material, because some topics are not covered in a book, or not explained in a way the teacher likes.

We will therefore not see a rapid e-learning development as e.g. in English language teaching. Still, the demand (and pressure) is there to develop web-based courses, which may come in the form of e-learning or webinars or evolving other forms. As universities do not reward effective teaching, much of this development towards web-based training will be driven mainly by industry providers.

4. Our own experience

Until fairly recently, DNV GL’s Academy and our own training experience was based on classroom courses, where frontal teaching is interspersed with various tasks to actively involve and engage the learners who are usually limited to 15- 20 people to allow small-group interaction. Over the past few years, our Academy has responded to the increasing demand for “e-learning”, which is a frequently used term by our customers expressing “something on the computer where my employees don’t have to travel and sit in your classroom”. Often the real training need and most suitable form of training require further elucidation through discussion of available options and constraints. We discuss our experience with various options in the following subchapters.

4.1. Classical e-learning courses

Some years ago we developed our first e-learning course on energy efficiency in ship operation. The course was rolled out via USB sticks branded with the customer’s logo. The focus was on having a training solution that could be used anytime and anywhere, targeted at ship crews who would not have (easy and cheap) access to the internet. The course was subdivided into modules of typically a few minutes’ duration with small tasks or quizzes to keep the participants’ attention and to provide feedback on achieved learning goals. Since then technology platforms have progressed with web-based solutions and more user-friendly software to create small cartoon-type videos, Fig.2.

Fig.2: Stills from e-learning videos merging cartoon-like animations with tailored image elements

We have seen an exponential growth in demand for e-learning solutions both for internal and external training, the goal always being to save costs. But e-learning is neither cheap nor fast to produce. It requires a team of domain experts, pedagogical experts and programming experts. Once produced, the solution is more rigid than classroom training. In this respect, producing e-learning resembles writing a textbook. For example, local trainers can easily conduct classroom training in the native language of participants using PowerPoint material in English. Translating e-learning to multiple languages is usually prohibitively expensive in the limited maritime market.

A key lesson learnt over a variety of projects is that costs and time for e-learning are easily underestimated:

- Scope creep is frequently an issue in e-learning projects, especially if there is no designated single point of contact on the customer side. Change requests should be budgeted in and made explicitly clear in terms of time and cost to the customer. It is a good idea to have a script similar to a movie with sketched stills before producing any video. Only after such a script (or storyboard) has been mutually agreed upon should the rather expensive video production commence.
- Customers mostly have no idea about video production effort. Costs depend on many factors, but as a rule of thumb 1 minute of video costs 1000-3000 € to produce. It should thus be considered in each case whether a video is “nice to have”, “important” or “essential” in the context of the learning goals.
- Costs for e-learning production vary globally and depend on the sophistication of original classroom material and desired e-learning material, but in a 2017 market survey transposing a 40 slide presentation into e-learning gave costs of 7500 to 15000 €.

We would propose that E-learning is suitable for the following cases:

- There is a clearly defined topic where the state of the art does not change rapidly. E.g. non-destructive testing of welds is suitable as it has used the same technologies for decades and the fundamental physics do not change.
- There is a large and distributed pool of learners, with economies of scale justifying the relatively high initial production costs.
- The reason for training is compliance. A typical example is the instruction by airlines on safety procedures. “In the unlikely event of a sudden drop in cabin pressure…” Do all passengers really know what to do in an emergency? Of course not, but the airlines need to have proof that passengers were “instructed”. Training employees across a corporate empire on compliance issues (company mission, anti-corruption policies. etc.) is often based on e-learning. Record keeping of “successful instruction” can be automated, making it a popular option with human resource and compliance departments.

E-learning generally has less impact than classroom training where individual feedback is possible and where learners generally have a higher attention rate. It is an unlikely candidate for once-off trainings, as the initial development investment can rarely be recovered. It is not suitable when a fast response to a new training need is called for.

4.2. Virtual Reality based training

Gamification of teaching using video game technology has attracted a lot of attention. Virtual Reality is seen as a key technology for (maritime) training, and this has been reflected in various COMPIT papers, *Doig and Kaeding (2007), Katzky (2014), Venter and Juricic (2014), MacKinnon et al. (2016).* Virtual Reality is not only fascinating and fun; it is indeed also a powerful tool for training, especially when it comes to visual assessment and human interaction, e.g. judging when to initiate action in maneuvering, crane operation, etc.

However, the price of developing Virtual Reality-based training is high. Creating virtual worlds has become easier, faster and cheaper, but it is still far from being easy, fast and cheap. Models need to have the right level of detail, balancing realism and response time. Import/export from CAD systems or other models (e.g. finite-element models) may save time, but in our experience is never as straight-forward as hoped for or promised by vendors. Having a ship modelled over several decks, along with equipment, interactivity, etc. may run into 5 or 6 digits of Euros. Such an investment needs either subsidizing from R&D projects or a suitable mass market willing to pay premium fees for training, such as firefighting. Often solutions have been developed for larger industries and are then adapted to maritime applications, reducing the development effort.

DNV GL has developed a Virtual Reality-based training solution for ship inspections, called SuSi (Survey Simulator), https://www.dnvgl.com/services/survey-simulator-for-ship-surveyor-training-in-virtual-reality-shipmanager-survey-simulator-2173. SuSi provides realistic and cost-efficient 3D training software for survey inspections, using Virtual Reality technology and detailed models of ships and offshore structures, Fig.3. The virtual inspection gets trainees exposed to deficiencies that would take years for a surveyor to experience in real life. An inspection run can be recorded and discussed in a debriefing with an experienced supervisor/trainer, pointing out oversights and errors by the trainee.

Fig.3: Level of detail in SuSi (Virtual Reality based survey simulator)

SuSi offers a variety of interactive elements, such as a virtual camera, virtual smartphone with product data information and access to DNV GL Rules, virtual spray to mark deficiencies, Fig.4, and obviously navigation control to explore the virtual ship or offshore platform.

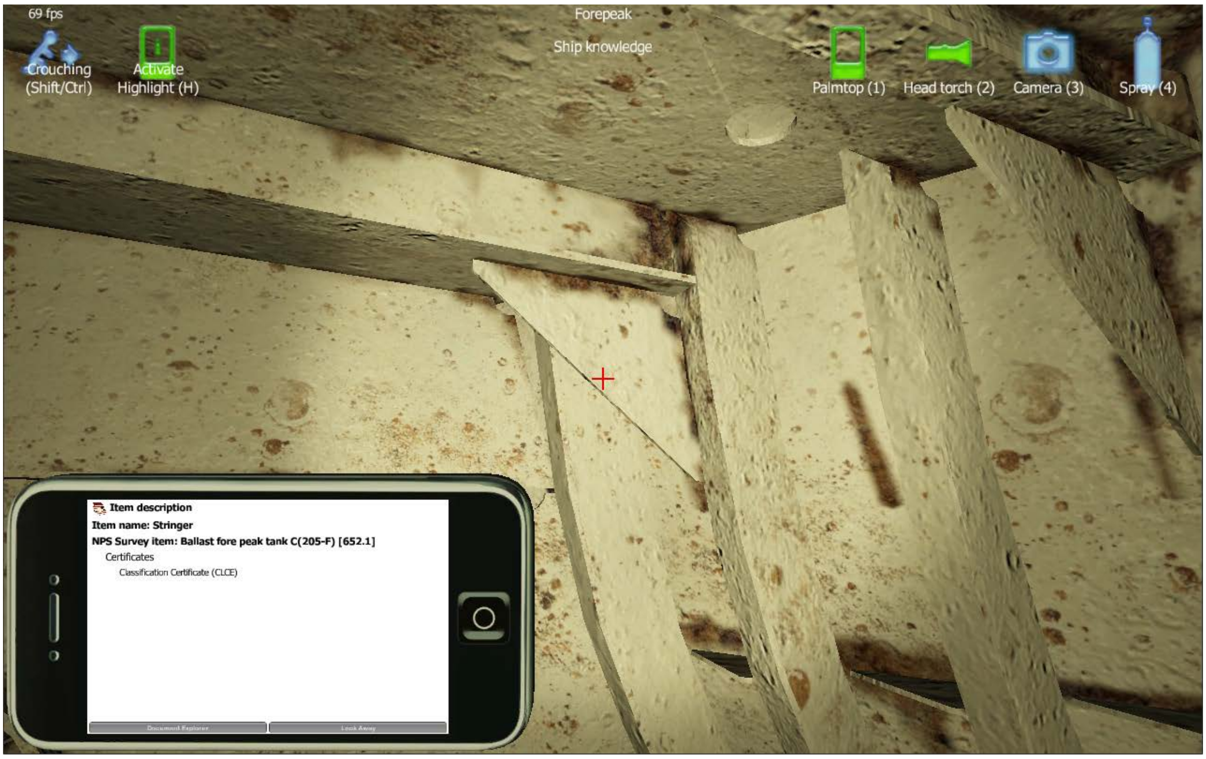

Fig.4: Virtual Reality based training with DNV GL's SuSi (Surveyor Simulator)

Initially, the designers of the software envisioned trainees running the software from individual PCs or laptops and exploring in parallel "their" ship in a rather self-centered learning approach. The user interface was deemed to be so intuitive that - after minimal instruction - each trainee would embark on his survey. But practice revealed that to be too optimistic. The user interface was intuitive for digital natives, but "digital immigrants" struggled with the video gaming controls and navigational concepts and got lost in the virtual world, often leading to frustration and missing the training goals. The solution has been to adopt a pragmatic approach where the trainer guides the class collectively through the ship (with a single PC and a data projector) and trainees shout out when they spot a deficiency which can then be discussed. Such a blended approach of classroom instruction and Virtual Reality tour may be frustrating for the video game programmer, but achieves the training goal for all trainees. It also requires fewer licenses and hardware. This approach has been very well received by participants from industry across a wide range of nationalities (cultures), educational backgrounds, management levels and age groups.

The lesson learnt in this case is that less is sometimes more. Never fall in love with technology, but look first at the pedagogy. Also consider heterogeneity in trainees and possibly hardware and think about possible hurdles.

4.3. Webinars

In our line of training, we often have to respond rapidly to new developments, e.g. new regulations coming into force. Domain experts in the specific field of competence are scarce (say 1-2 key experts in the company) and their time is in high demand. Customers need training quickly as e.g. non-compliance may lead to costly detentions. Traditional classroom training and e-learning are not suited to such requirements. We have found that webinars are an attractive addition to our toolbox of training solutions in this respect. DNV GL's line of external webinars is called "smart-ups", https://www.dnvgl.com/maritime/maritime-academy/smart-ups.html.

In 2016, we delivered 10 smart-ups, reaching out to customers around the globe. We also used webinars internally to support the training needs that came with new Rules of DNV GL (merging the rules of the two Class societies) and training colleagues on new developments, such as our cyber-security training or advances in performance monitoring with the ECO Insight solution.

Key lessons learnt were:

- Domain experts are generally neither communication experts nor webinar technology experts. Raw material (PowerPoint) needs more or less extensive reworking for a webinar and delivery is similar to being on the radio: domain experts need technical support and possibly some coaching on how to speak during a webinar.
- Domain experts are much more willing to take the time for a webinar than for the development and wide-scale delivery of classroom training. Once made aware that the option exists, we encountered general enthusiasm for this training solution.
- Webinars should be designed for maximum 20-30 minutes presentation time. Beyond that audience attention cannot be maintained and the message is lost.
- Powerpoint slides used for webinars should have even less text than the classroom version and rely much more on visual language to convey the message, Fig.5.
- After a maximum of 10 minutes speaking time, an interactive element ("poll" in the jargon of webinar designers, Fig.6) should stimulate the audience to refocus on the topic. Otherwise the temptation to multi-task (i.e. read incoming emails, etc.) becomes overwhelming for most people.
- While recordings of webinars were offered after the event, the live versions were clearly more attractive. Consequently webinars for a global audience need to be offered several times "live" to cover different time zones. Extra resources then need to be allocated for the repeats.

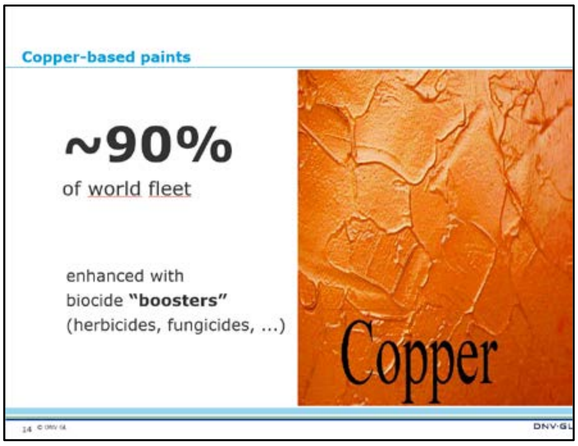

Fig.5: Typical webinar slide

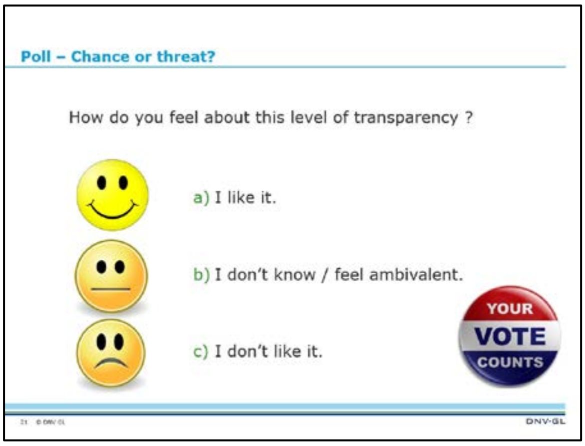

Fig.6: "Polls" stimulate audience to think

5. Conclusions

Content is more important than means of transmission. Flashy e-learning portals do not substitute qualified teachers. E-learning is particularly interesting for commodity subjects (English, business administration, mathematics, etc.). Webinars, often overlooked as a training solution, offer more flexible and cost-efficient options for global maritime training needs than e-learning courses.

The private training market is expected to gain in importance with life-long learning in incremental steps on latest industry developments. DNV GL's Academy will continue to play an important role in this regard.

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Appendix: Requirements for Naval Architects

The following is based on an ONR workshop on Future Warship Designers, *Rusling (2005).* In discussion between (mostly US American) representatives of industry and academia, the following items were listed as guidelines for future curricula for naval architecture:

- Good base in naval architecture / engineering principles
  - strength analyses, structural design and production
  - hydrostatics / stability and ship design (rules, layout, estimation methods)
  - hydrodynamics
  - marine engineering
- Computer literate
  - CAD proficiency seen as main gap
  - Level of competence (hours spent with specific software) should be recorded
  - Naval architecture is increasingly applied computer science and less mechanical engineering
- Hands-on experience
  - as worker and as engineer
  - at sea / at shipyard
- more specialized knowledge 7 more mathematics at post-grad level
- soft skills
  - ability to study independently
  - creative with feel for viability of solutions
  - enthusiastic
  - team capability
- management skills
  - project management
  - communication
  - basic legal frameworks for contract / work laws
  - motivation
- engineering English
  - vocabulary (incl. mathematical expressions)
  - technical / scientific communication in English

Cloud-Based Numerical Towing Tanks – Anytime, Anywhere and for Anybody

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Abstract

The paper presents a web-based application for virtual sea trials. The application incorporates proven techniques for robust CFD simulations for propulsion tests. Macros make performing CFD computations for standard applications straight-forward for anybody. Users specify scope of analysis (number of speeds, drafts, trim) and get immediately the costs for the Virtual Trials. The online booking, cloud computing and standard electronic reporting is seen as 21st century equivalent of model basin tests.

1. Introduction

Computational fluid dynamics (CFD) denotes collectively techniques solving equations describing the physics of flows. As any other simulation technology, CFD has progressed rapidly over the past decades, evolving from a research tool to a widely accepted tool in industry, *Peric and Bertram (2011), Hochkirch and Bertram (2012).* The term “Numerical Towing Tank” has been used for many years now to denote the simulation of resistance and propulsion tests as alternative to classical model basin tests, *Bertram (2000).* The progress in the numerical techniques can be seen in the annual Numerical Towing Tank Symposium series, https://www.uni-due.de/IST/ismt_nutts.shtml, and the CFD in Ship Hydrodynamics workshops which are held approximately every 5 years, e.g. www.t2015.nmri.go.jp/. However, as *Peric and Bertram (2011)* pointed out, the progress in user-friendliness and ease of access is arguably even more important. Commercial CFD solvers have become more user-friendly and pay-as-you-use schemes have reduced barriers for small and medium enterprises, e.g. shipyards and design offices. *Hildebrandt and Reyer (2015)* present such a scheme for the maritime industries, where high-performance computing hardware (in the cloud) and parallel licenses for the CFD solver can be rented by the core-hour. However, the user still needs to master the CFD software and generate the grid and input specifications.

The idea of the “Virtual Trial” takes the development to the next level as part of DNV GL’s push towards maritime digitalization. Digitalization describes collectively approaches that employ new business processes to exploit digitization, the process that turned analog-paper technology into digital-computer technology. Digitization converted classical model tests into CFD simulations. Over the years, the processes have been streamlined and completely automated for selected applications, such as numerical simulations of resistance and propulsion tests, e.g. *Hansen and Hochkirch (2013).*

With My DNVGL, https://my.dnvgl.com/, our company has created a central digitalization platform with a multitude of app(lication)s, *Dausendschön (2016).* Offering fully automated CFD simulations to assess the resistance and propulsion aspects of ships now brings the various elements together, allowing “Virtual Trials” at any time, from anywhere and by anybody as no CFD specific input is needed. In essence, ship designers or other interested parties can then launch “Virtual Trials” in complete anonymity and with results within one week, i.e. much faster than in classical towing tank business.

2. The Virtual Trial development

Key elements of the “Virtual Trial” concept are as follows:

- The “Virtual Trial” is a fully digital service from data submission to reporting. It is offered via the My DNV GL portal.

- The “Virtual Trial” offers full-scale RANSE (Reynolds-averaged Navier-Stokes equations) VoF (Volume of Fluid) CFD, resistance and propulsion simulations for ships. RANSE means that viscosity is directly reflected in the basic physics, i.e. boundary layer formation and flow separation can be captured by the fundamental equations. VoF means that complex wave formation including breaking waves is accurately reflected in the numerical model. And “full-scale” means that the simulation mimics sea trial, avoiding the notorious scale-effects that come with model test extrapolation to full scale. This is especially important if larger breaking waves appear, e.g. at intermediate drafts or blunt foreships, *Hochkirch and Mallol (2013)*.
- The customer uploads the ship geometry as STL file (STL = Standard Tessellation Language, a format that describes the surface by many triangles; all commonly used CAD software tools allow export to STL) or IGES file (IGES = Initial Graphics Exchange Specification; vendor neutral format and frequently used for hull shape exchange between CAD and CFD software) and defines the scope of simulation runs (variations of draft, trim, speed) in My DNV GL web interface and launches the simulations, Fig.1. Project information and status is visible for customer in My DNV GL portal throughout the entire project.
- Web based reporting via the My DNV GL portal allows for 3D visualization of CFD results and hull lines giving more insight into the flow details. The standardized report format shall become an industry accepted reference for comparison and benchmarking. Ship designs can be compared against each other consistently, even if the projects are submitted from different parties. The outcome is impartial and consistent. Own designs can be compared against anonymized state-of-the-art designs from our database, Fig.2. This best-practice comparison gives rapid and intuitive insight into improvement potential for investigated designs.

The service offering is open to anybody who owns ship lines. This will be predominantly ship yards and design offices, but could also extend to ship operators who might be in need for independent power predictions for given hull forms.

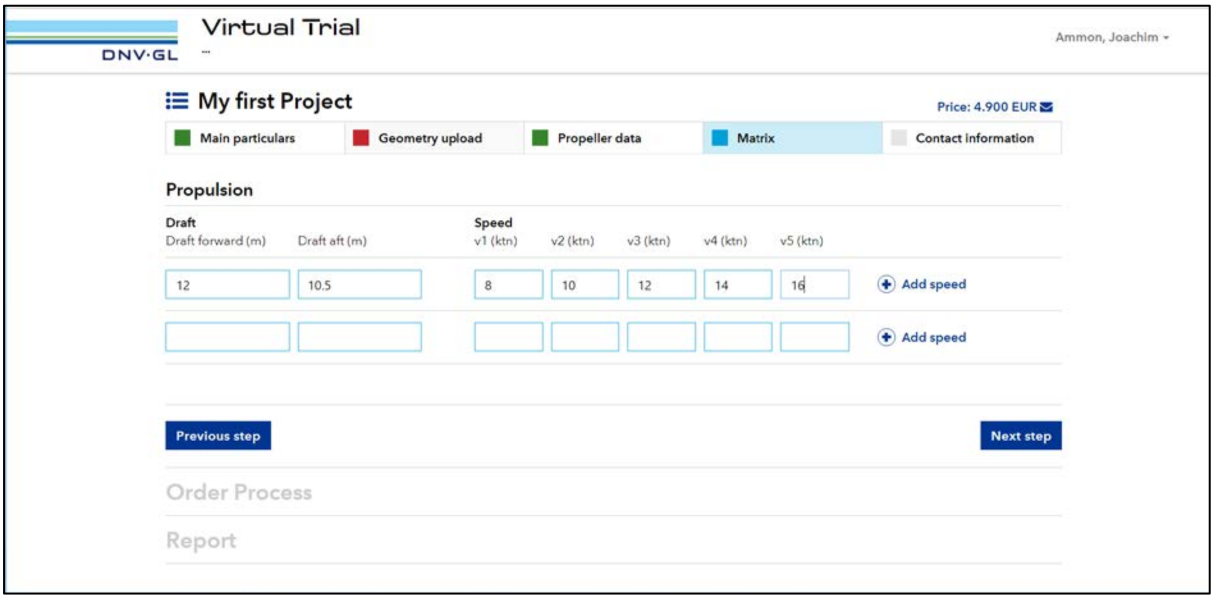

Fig.1: User interface in My DNV GL application allowing detailed case specification

The “Virtual Trials” offer tangible benefits from a customer points of view, mainly in terms of time and cost. This is best illustrated by a typical project where a shipping company wants to evaluate three shipyard proposals for a newbuilding project, each at design and ballast draft and over a range of five speeds. For each combination of draft and speed, the company wants to look at the required power demand. We assume that the shipping company has the lines, respectively imposes upload of the lines from each shipyard as part of the bidding process. Table I compares then the “Virtual Trial” with a typical ship model basin in central or northern Europe.

Table I: Time and cost involved in "Virtual Trials" vs. classical model testing

	"Virtual Trial"	Model Test
Lead time	1 week	~10 weeks
Costs	17100 €	~80000 €
Propeller	Wageningen CD-series	Stock propeller

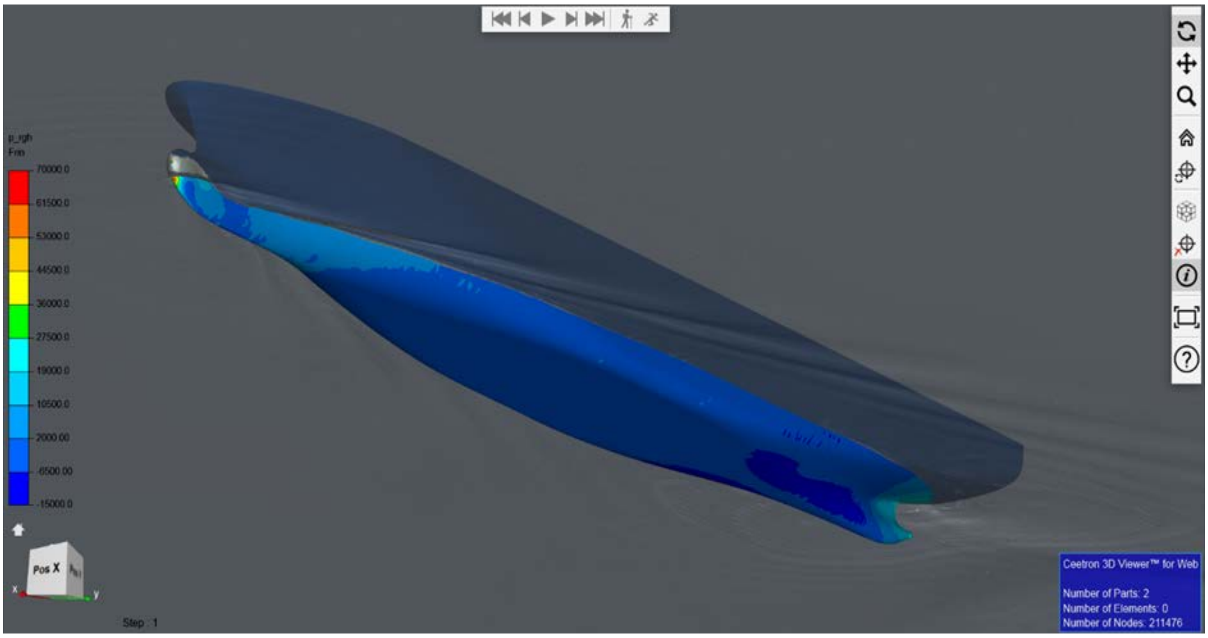

Fig.2: 3D visualization of CFD results in Virtual Trial application

We conducted specific interviews with key ship operators, yards and design offices to sound out the market response to the "Virtual Trial" service. The service received generally positive feedback. The interviewees liked specifically:

- Short response time and low costs
- The benchmark functionality which allows competitor comparisons
- The fresh reporting style

3. Conclusions

The "Virtual Trial" assesses hydrodynamic characteristics of hull forms with significant advantages in terms of costs and response time compared to model tests. Such web-based, completely digitalized services are expected to disrupt hydrodynamic consultancy. The initial customer response indicates that such online services will be embraced rapidly, mirroring similar trends in consumer goods.

Acknowledgement

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Ultrasonic Technology for Biocide-Free Antifouling

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Abstract

This paper gives an overview of upcoming new antifouling regulations, different ultrasound working principles, examples of applications and results, and benefits leading to a lower Total Cost Of Ownership.

1. Introduction

HASYTEC carries out maintenance and start-ups for military and civilian ships. When it comes to repairs and modernization measures regarding the whole electronic systems for cargo vessels or military vehicles we have always been the right partner. Mainly we perform repair works on ships for the German Navy. We've specialized in electronic systems and devices of submarines and benefit from more than 20 years' experience. However, our technical support is not limited to 'undersea'. We also provide support for mine warfare systems, tenders or combat support vessels when it comes to electronic systems or battery management solutions.

For some time, we have been dealing with ultrasound devices which we found on the market for antifouling solutions. On this base, we founded a research department which has provided us with serious knowledge and insight about this innovative antifouling solution.

2. Upcoming new Antifouling Regulations

In relation to the IMO convention "International Convention on the control of harmful Anti-Fouling Systems on Ships (2001)", the European Union finalized the EU Regulation No. 528/2012. This regulation on biocide containing products regulates the marketing and use of biocide containing products, which due to the activity of the active ingredients contained in them for the protection of humans, animals, materials or products against harmful organisms such as pests or bacteria, may be used. The aim of the Regulation is to ensure a better functioning of the biocide containing Products market in the EU, while ensuring a high level of protection for human health and for the environment. As an example, almost no copper based active substance will get permission to be used in the future. Every system has to be approved to be marketed and the environmentally harmful systems shall be sorted out. This leaves essentially two options:

- taking the risk of using less effective antifouling systems which leads to higher costs for maintenance and repair as well as to higher fuel expenses
- looking for alternatives to replace the currently used antifouling systems

3. Different Ultrasound Working Principles

3.1. Biofilm in general

The biofilms are formed when bacteria adhere to a solid surface and enclose themselves in a sticky polysaccharide. Once this polysaccharide is formed the bacteria can no longer leave the surface, and when new bacteria are produced they stay within the polysaccharide layer. This layer, which is the biofilm, is highly protective for the organisms within it. In fact, it is considered a fact that many bacteria could not survive in the environment outside of biofilms.

Biofilms are ubiquitous in the environment. They form on our teeth, inside our bodies, in our streams and oceans, on natural surfaces continually wetted by dripping water. They also are formed inside of all of our water pipes, toilets, and drains, and, in fact, everywhere where there is persistent water.

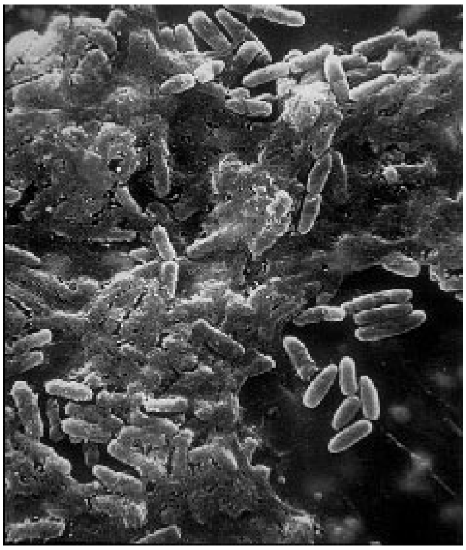

Fig.1 Biofilms under the microscope

In general, while a few fungi can form their own biofilms, and a few inhabit bacterial biofilms, the so-called "moulds" generally do not grow in or even on the surface of biofilms. This is because there is generally too much water. The majority of fungi will not grow under water, while biofilms are always under water at least most of the time. Biofilms will not go away on their own, and considerable effort is required to eliminate them. Biofilms on teeth, components of which contribute to plaque formation and tooth decay, are removed by diligent scrubbing with somewhat abrasive materials. Unfortunately, the biofilms return within hours, and teeth cleaning is an endless process.

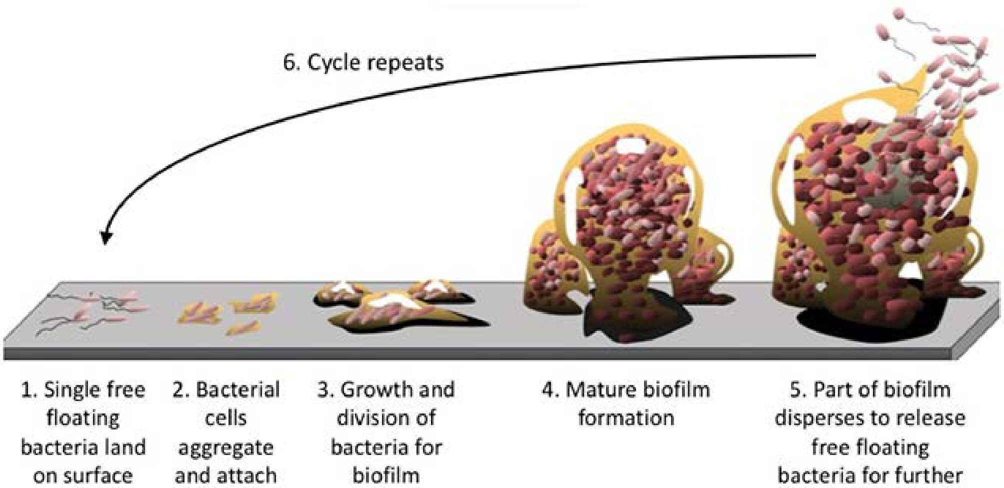

Fig.2: Biofilm growth cycle

Biofilms on other surfaces can be scrubbed away, or can be disrupted using very hot water (steam is best) and concentrated oxidizing agents. However, they will return quickly unless the water source is removed. Hence, there are always biofilms present where, by definition, water is always present (e.g., in the ocean, rivers, our mouths, and our water pipes).

3.2. High-powered ultrasound causing cavitation

Older ultrasound methods followed the idea of getting rid of hard growth which had already attached. Using hard cavitation, this working principle might work in certain situations but may also damage the vessel's steel itself. As a consequence, this approach was not accepted by the market.

3.3. Low-powered ultrasound not causing cavitation

Using low-powered ultrasound (which does not cause cavitation in a certain combination of frequencies, altitudes and power consumption) follows only one idea: avoiding biofilm on every liquid carrying surface. Avoiding biofilm means at the same time avoiding marine growth as barnacles, shells and algae. This working principle is relatively new and unknown on the market. But this new kind of antifouling system has a huge potential regarding protecting the environment, being sustainable and not harming either humans or animals.

4. Response of fish to low-powered ultrasound

Fig.3 shops the startle response of fish to the low-powered ultrasound. The fish that responded to the stimuli increased their swimming speed and often made tight turns. No startle response was ever seen during test periods apart from during signal presentation. In almost all cases when a startle response was seen, the fish swam away from the sound source. The fish always resumed normal swimming behaviour within a few seconds of the end of the 900 ms acoustic stimulus presentation.

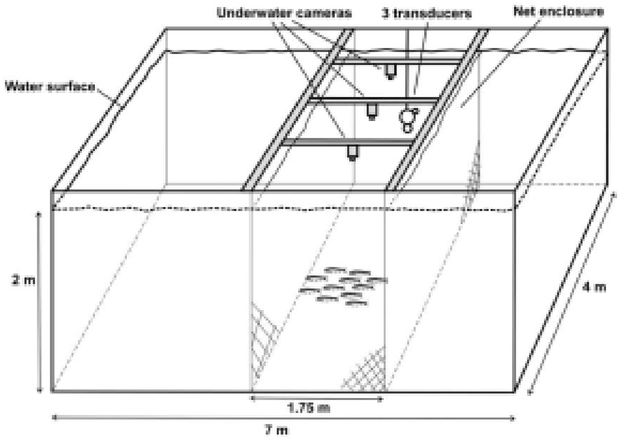

Fig.3: Startle response of captive North Sea fish species to underwater tones 0.1 to 64 kHz, source: Science Direct from 7.9.2008

For sea bass, 50% reaction threshold ranges were reached for signals between 0.1 and 0.7 kHz, Fig.4A. The sea bass did not react to the maximum received levels that could be produced for the higher frequency signals. For thicklip mullet, 50% reaction thresholds were reached for signals between 0.4 and 0.7 kHz, Fig.4B. The fish did not react to the maximum received levels that could be produced for the other frequencies. However, the mullet reacted to one of the twelve 0.1 kHz signal trials and two of the 0.125 kHz signal trials, which suggests that the 50% reaction threshold level for those frequencies was only a few dB above the maximum level that could be produced with the available equipment. For pout, 50% reaction thresholds were reached for signals between 0.1 and 0.250 kHz, Fig.4C. The pout did not react to the maximum received levels that could be produced for the higher frequency signals. For Atlantic cod and common eel, no 50% reaction thresholds could be reached with the maximum levels for the frequencies that could be produced with the available equipment, Fig.4D and E. For Pollack, no 50% reaction thresholds could be reached with the maximum levels for the frequencies that could be produced with the available equipment, Fig.4F. However, there was some reaction to the maximum levels that could be produced for signals of 0.1 kHz (reaction in 4 of the 15 trials), 0.125 kHz (4 trials), 0.250 kHz (2 trials) and 0.4 kHz (3 trials). For horse mackerel, 50% reaction thresholds were reached for signals between 0.1 and 2 kHz, Fig.4G. The horse mackerel did not react to the maximum received levels that could be produced for the higher frequency signals. Atlantic herring reacted to two frequencies. The 50% reaction threshold was reached only for the 4 kHz signal, Fig.4H. There was also some reaction to the 0.4 kHz signal (in 2 of the 12 trials). The herring did not react to the maximum received levels that could be produced for the other frequencies.

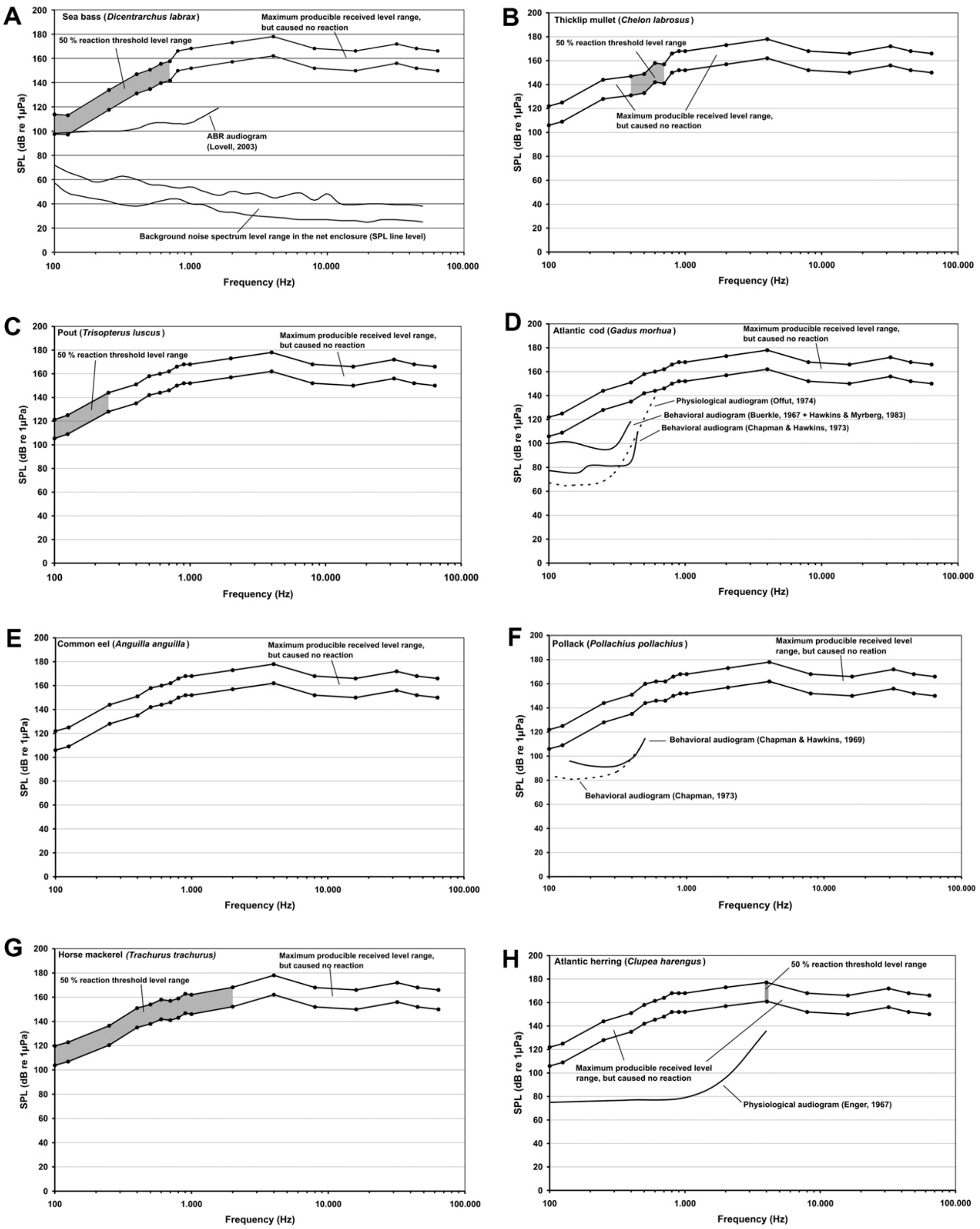

Fig.4: The maximum received level range that could be produced in the tank for the test frequencies causing no reactions, and, for some species, the 50% reaction SPL ranges (shaded areas represent ±8 dB of average received level).

(A) Sea bass (0.1-0.7 kHz; school size: 17 fish), and the background noise range in the net enclosure, which applies to all species. Also shown is the auditory brainstem response (ABR) audiogram of sea bass. (B) Thicklip mullet (0.4-0.7 kHz; school size: 11 fish). (C) Pout (0.1-0.250 kHz; school size: 9 fish). (D) Atlantic cod (school size: 5 fish). Also shown thresholds of Atlantic cod. (E) Common eel (school size: 10 fish). (F) Pollack (school size: 4 fish). There was some reaction (<50%) to the maximum levels that could be produced for signals of 0.1 kHz, 0.125 kHz, 0.250 kHz and 0.4 kHz. Also shown are two hearing thresholds of pollack. (G) Horse mackerel (0.1 2 kHz, school size: 13 fish). (H) Atlantic herring (4 kHz, school size: 4 fish). Also shown is the hearing threshold of Atlantic herring

We judged that the researchers used consistent criteria for classing a trial as a response trial or a non-response trial, because their classifications were always identical, and the startle response was very obvious (not a subtle increase in swimming speed or swimming depth as was observed in a previous study; *Kastelein et al. (2007)*.

The size of their tank influences the general swimming behaviour of many fish species. Before the fish were put in the test tank, they were kept in much smaller circular tanks, in which they swam very slowly or not at all. In the net enclosure in the large test tank, the fish were much more active; they behaved in the same way as fish in the previous study in this tank, which had the entire tank available to them, *Kastelein et al. (2007)*. So, although the test tank was far from a natural environment, it was a much better study area than the smaller tanks used in several previous studies on reactions of fish to sound.

The study fish had been housed, for at least part of their lives, in tanks at aquaria and fish farms. However, those facilities had water filtration systems that were relatively quiet, so the study animals had probably not been exposed to higher sound levels than wild conspecifics. As the location of the study site was selected because of its remote location and quiet environment, the tank was designed specifically for acoustic research, and the area around the tank was strictly controlled (nobody was present within 100 m of the tank, except the researchers who sat quietly), there was little background noise, and startle responses were not observed outside the signal presentations.

The reactions of the fish in the present study were probably dependent on the context in which the sounds were produced, and the fish probably responded differently than would wild fish. Even in the wild, animals behave differently depending on location, temperature, physiological state, age, body size, and school size. So, even if the present study had been conducted in the wild, the findings may not have been of universal value.

5. Examples of applications and results

Figs.5-7 demonstrate the effectiveness of the ultrasound solution.

Fig.5: Tugboat without (top) and with (bottom) ultrasound protection

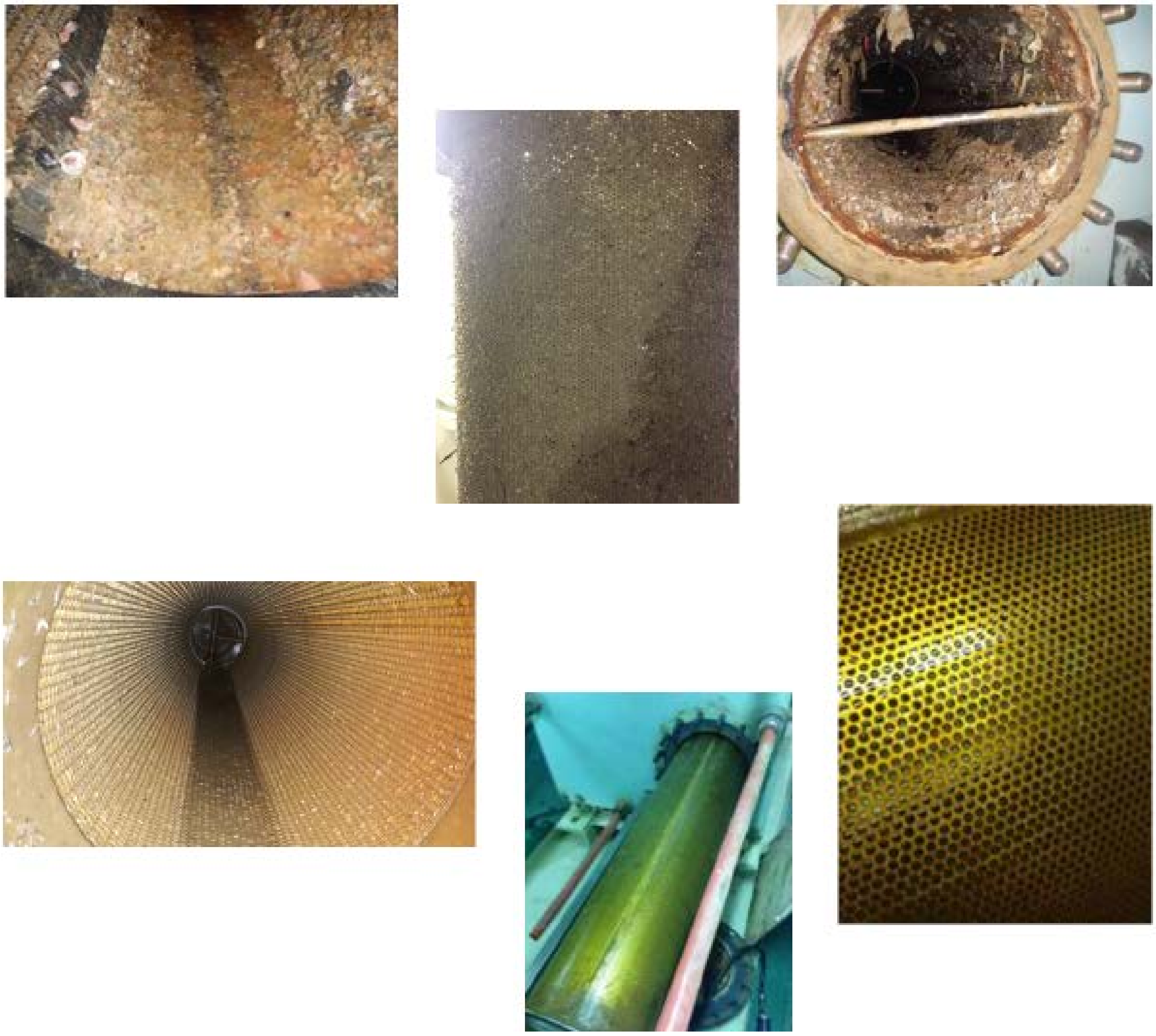

Fig.6: Low-temperature cooler on 13000 TEU containership without (top) and with (bottom) ultrasound protection after 13 months trading Europe / Fareast Asia

Fig.7: Boxcooler on anchor handling tug with ultrasound protection after 24 months trading West-Africa and Caribbean

6. Benefits leading to a lower Total Cost Of Ownership

There are clear advantages of using ultrasound for antifouling:

- ✓ Maintenance free
- ✓ Environmental friendly
- ✓ Sustainable
- ✓ One-time investment
- ✓ No running costs for consumptions or maintenance/repair

The following calculation example refers to the “MV Öland” of Reederei Danz & Tietjens, as given in private communication by the captain of the vessel. The difference in fuel consumption for the hull free of growth compared to the hull with a lot of growth was given as 2 t/day. For 220 days/year at sea this gives 440 t saved. At 500€/t fuel cost, this converts to 220.000 € saved per year.

The investment for the ultrasound system involving ~140 transducers (for hull, bow thruster, sea chests, coolers and inner vessel pipes, incl. installation) are ~183.000 €, leading to a return on investment of 10 months. This estimate ignores the advantages of savings in copper anodes and chemicals, but also the running of the system which leads to reliability.

In the future, the savings should be quantified more reliably using performance monitoring.

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Computer Aided Ship Design 2030 - I Can See Clearly Now

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Abstract

This paper sketches an image of the near future of Computer Aided Ship Design (CASD). It starts with a reflection on the model of ship design methodology, followed by several technical CAD-related individual subjects, such as advances in virtual and tactile modelling methods of the ship hull, tools for data representation and processing and the organization of heterogeneous software components into one (virtual) CAD system. Other subjects are of more general nature, such as a plea for the return of empirical methods in ship design, and hardware support for computation-intensive tasks. Finally, three possible future scenarios are elaborated, which reflect general trends in programming and the daily use of computers, and their impact on CASD.

1. Introduction

This paper is an update of *Koelman (2013)*, and contains an outlook on Computer Aided Ship Design (CASD). I restrict myself to the mid-term — say the next decade — because a longer period cannot be foreseen. The basis for the outlook is threefold: (1) our experience with software development and contributions to research projects, (2) some notions from literature and (3) personal observations and projections. Addressed will be six, more or less disconnected subjects:

- The model of the ship design process.
- Contemporary methods for design and representation of the shape of the ship hull.
- Product Data Technology; data exchange and inter-program communication.
- A plea for the revival of empirical prediction methods in ship design.
- PC hardware support for computation-intensive tasks.
- Scenarios on the use and advancement of computers and their impact on CASD.

2. Ship design methodology

When it comes to design methodology, the design spiral always surfaces. This familiar model of ship design activities, which is attributed to *Evans (1959)*, shows the distinct design phases (initial design, embodiment design, contract design, detailed design) and suggests a fixed sequence of activities. It is a bit funny that this model is still so often referred to in these years, because its reality level is low. After all, in practice we don't see fixed sequences of design activities, while design phases may overlap or merge. Also in literature, the concept of the design spiral has been criticized, see e.g. *Nowacki (2009)*, *Harries et al. (2011)* and *Koelman (1999)*. In the latter, a toolbox is proposed as model for ship design activities, Fig.1, although this can hardly be considered to be a structured model, because summarized it expresses that "every activity can be performed an undetermined number of times in an arbitrary sequence".

In this respect, we can question the use of these kinds of models anyway. See e.g. Fig.2, where the model of a company is represented (in Dutch). What is its use? It might be that it has a certain descriptive value, e.g. for a novice in the company, or an external party. On the other hand, such a model is also conservative, in the sense that it conserves the present state of the company. And, as a consequence, suggests that the company should be organized according to this scheme. Or that the implementation of company automation is done according to this model, while the automation could enable a new, better, organization structure.

Fortunately, making these models is a bit of a hobby for academics, without much consequences in practice. However, in the ship design practice some other concepts or abstractions exist, which are not holistic models, but which are guiding decisions nevertheless, such as:

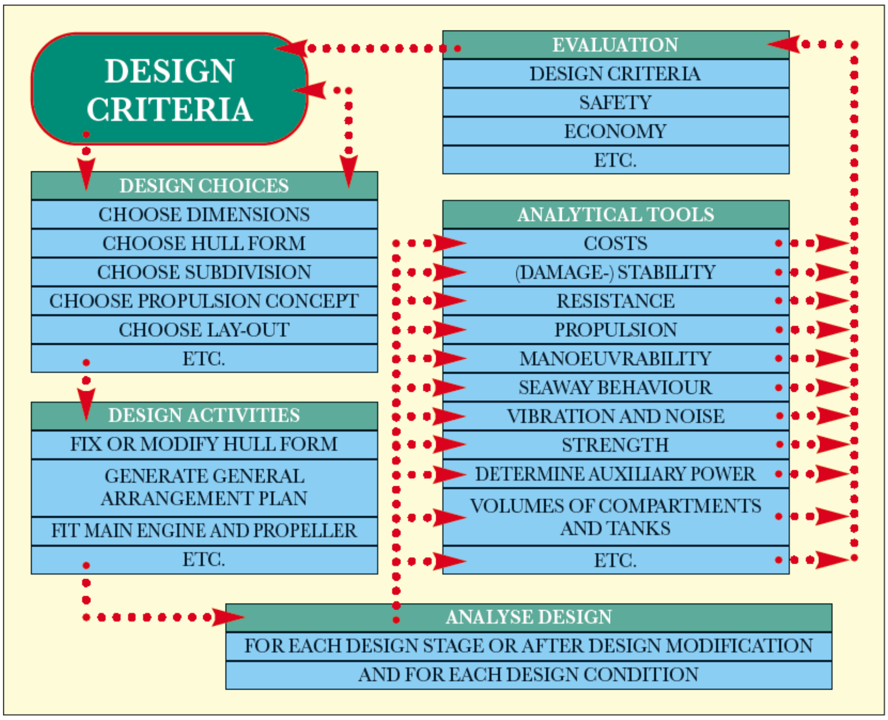

Fig.1: Toolbox metaphor of the ship design process

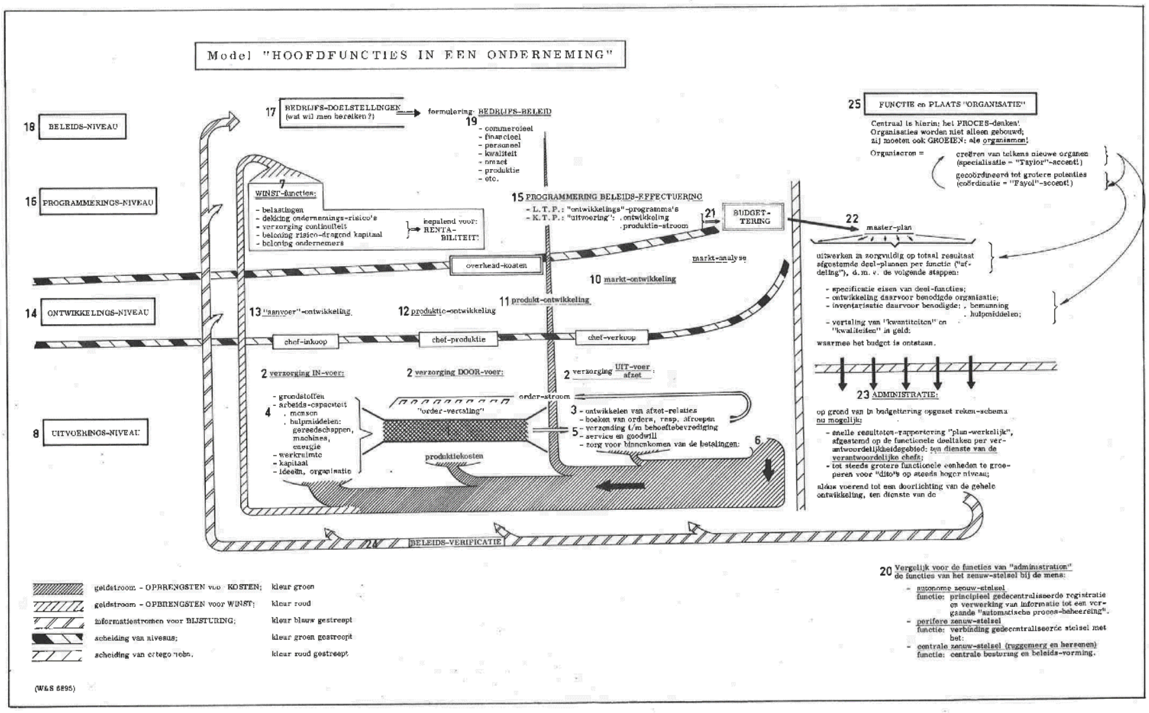

Fig.2: Main functions in a company (TU-Delft lecture notes, 197X)

- The question whether to use 2D or 3D (computer) representations for the ship design. This is really a question from the 1980s, every decent CAD or dedicated ship design program from today has an underlying 3D coherence, although the workbench or output (the “drawing”) may just show a 2D intersection or projection. An occasional genuine 2D software program that has escaped the author’s attention can be considered to be ripe for the museum.
- The concept of “design phases”, which we also encountered in the ship design spiral. There might have been days that the only way to manage the complex task of ship design was to

divide it into phases (and correspondingly divide the design office into departments), but improved CAD modelling methods and communication facilities make such a strict discrimination between design phases a bit obsolete. E.g. moving a pipe line a short distance in the “detailed design phase” may bring it - unnoticed and undeliberate - into another damage stability zone, and consequently may have a large impact on damage stability characteristics. While damage stability is an aspect of “embodiment design” as well as the final trim and stability booklet, which is in its turn part of the “post-detailed design phase”. So, this simple action affects all design phases.

- The idea that the major purpose of a piece of software is its only role. Obviously, in some cases this statement is correct, after all nobody would like to make a lines plan with MS-Paint. However, in other cases this is a simplification. E.g. the main purpose of our ship design software is to make all kinds of ship design computations, so it can be labelled as a “calculation package”. We have seen users defining hull form and compartments with a general-purpose CAD-system - because of its label of being a “design package” - and subsequently typing over or exporting coordinates and bulkhead locations to the “calculation package”. While the other way round - defining in the “calculation package”, with its dedicated and optimized definition methods, and then exporting to the CAD-package for the fringes and details - is faster, more pleasant and more robust.
- The notion that information which is available electronically is generally usable. This idea is stimulated by the nice flow diagrams in leaflets of software suppliers, which often put their products in the core of a network of arrows and circles. We will revert to this subject later on…

The conclusion is a bit that all models and abstractions might on the one hand add guidance and structure to a confusing reality, but on the other hand lead to suboptimal decisions because people might think that the model is reality.

3. Hull shape

The prevailing hull shape representation method is by B-spline or NURBS surface. That method has its merits but certainly also its disadvantages, on which we will not re-iterate because it has been duly reported in literature, e.g. *Koelman (1997), Sharma et al. (2012), Koelman and Veelo (2013)*. In the latter, also an alternative method is presented, which is implemented in the ship design suite from my company, already quite some years ago. So, there is sufficient material to reflect on the reception of this method, and the conclusion is that in particular by the users the method is praised for its flexibility and preciseness, but that recognition in general goes slow. For which a reason will be that many people have become so accustomed to the prevailing NURBS method that they don’t see their drawbacks; we have seen nicely rendered NURBS-based hull shapes declared to be fit for production with gaps of a decimetre, with waterlines containing multiple deflection points, or with buttocks in the parallel body that where just not straight but oscillating up and down. Another reason can be that users, without realizing, work around the limitations of the NURBS method. For example, by introducing chines, which are not present out of naval architectural necessity, but because in that way the program limitations can be circumvented.

Concerning export of surfaces to IGES, our company has experienced a bit of a drama. After a ship hull has been designed with our ship design program, the result has to be exported to other tools, e.g. for engineering, CFD, FEM. And many of those accept import preferably in NURBS format. So, through a backdoor the NURBS re-enter! In principle, our modeller can readily export a NURBS model through the IGES-NURBS standard, that function is already available for many years. However, it also results in a vast number of small NURBS surfaces, and quite some software packages have problems with that amount, which hampers a fluent data transfer. In order to smoothen this process, our modeller is at this moment being equipped with a postprocessor which provides two functions:

- Recognition of larger four-sided regions (which is one of the limitations of NURBS, to be four-sided). Take the example of Fig.3, where without special provisions each face between the curves would be converted to an independent NURBS surface, where the nonfour-sided faces would be split into multiple four-sided ones. For the relatively simple example of this figure this process would lead to some 80 NURBS surfaces in the IGES file. With the four-sided recognition feature the number of surfaces will be decreased to some 11, as depicted in Fig.4.
- These regions are being converted to NURBS by means of a special algorithm, which guarantees a set of NURBS surfaces which are guaranteed to be gap-free (which is a prerequisite for some CFD programs).

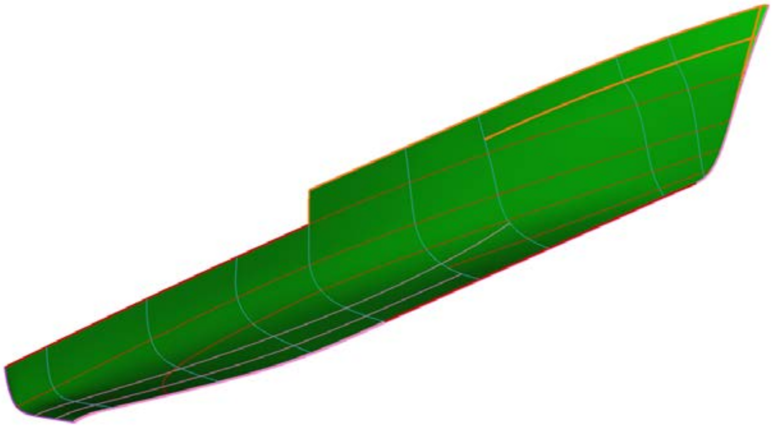

Fig.3: Some 80 surface patches between the curves of this ship hull model

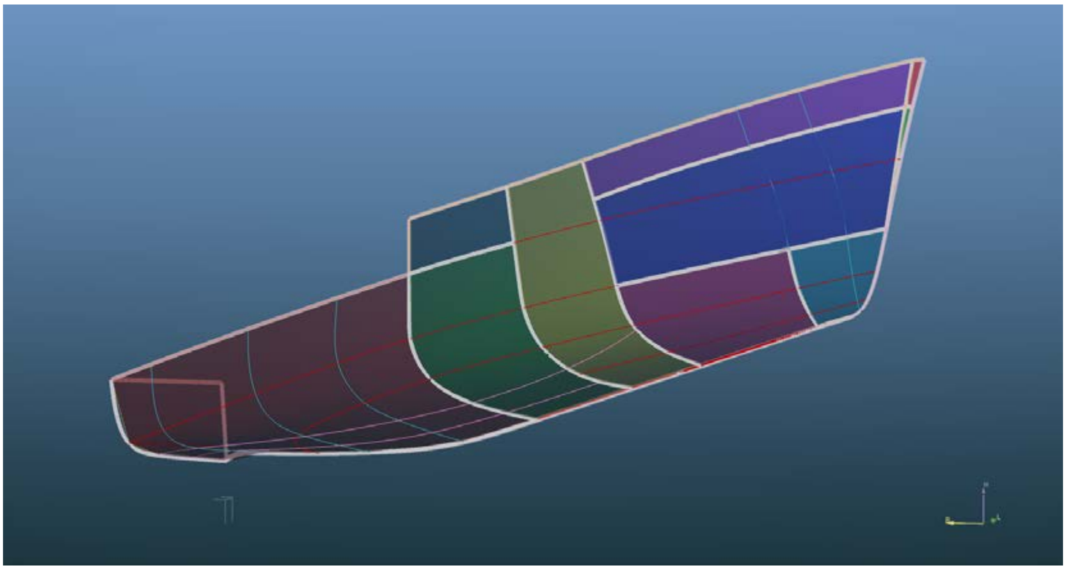

Fig.4: Some 11 four-sided patches covering the same surface as depicted in Fig.3

It will be a bit of a sour remark, but these features may repair some of the difficulties caused by the employment of methods of limited capabilities in other software.

The final question is whether the ship design community will stick to the NURBS method, or will eventually switch to something better. That is not easy to predict. On the one hand, it could be expected that ship designers with an independent state of mind critically evaluate their present tools and methods. On the other hand it could be that a generation has already become so custom with the NURBS method, that they do not realize that alternatives do exist. A phenomenon known in psychology as imprinting, https://en.wikipedia.org/wiki/Imprinting_(psychology).

4. Don't Let Me Be Misunderstood (On PDT)

PDT, Product Data technology, is the common denominator used for data exchange, data sharing and collaboration between computer programs. This subject is perhaps the determining factor for CASD development in the years to come. However, littered with some major misunderstandings. When it comes to communication, three layers can be distinguished, ordered top-down in Table I.

Table I: Layers of communication

	Inter-human		PDT for CASD	
Layer	Embodiment	Applicable standard	Embodiment	Applicable standard
Semantics	Knowledge of the world	A system of values and believes	Knowledge of the ship and her parts	High-level agreement on the ship and her components
Representation language	E.g. English	E.g. the Oxford dictionary	E.g. STEP, XML, DXF or IGES	Dictionary
Communication channel	E.g. radio waves	E.g. modulation and frequency	E.g. discfile, USB-stick, Tcp/ip or Internet	E.g. volt, tesla, bit-coding and tcp/ip protocol

The lowest level, which is the hardware level of the communication channel, can easily be established; it appeared to be easy for mankind to set standards on frequencies, disc file formats, volts and bit coding standards. However, one level higher, on the language level, this become more difficult; you cannot understand the Korean TV news if you don't master the language. But even if you understand the language, inter-human communication and understanding fails without a common set of values and beliefs; I understand the words of the US press officer Kellyanne Conway if she comes up with the concept of "alternative facts" in January 2017, but lacking a shared system of values I fail to understand the point she is trying to make.

Applied to PDT similar conclusions can be drawn. A shared communication channel implies that the raw data are present "electronically", however, as such that does not imply their usability. One level higher, by using the same representation language, is a prerequisite for successful data exchange, but not sufficient. E.g. STEP and IGES contain many representation variants, and only with agreement on all variants the exchanged data is usable. An example is that an IGES file can contain a faired lines plan, represented by construction frames and many waterlines and buttocks. However, if the importing program's internal representation is a NURBS surface, then the received data are not readily usable. They will have to be converted, which is not a trivial task, in this example.

Why is this so surprising? After all we already know that computer communication often works faulty. If you try to import a nicely formatted Word document in OpenOffice the whole document format will be destroyed; pictures are shifted to the edges of the pages, often illegible, font features are gone etc. Or take the title of this section, it is a song title, and for convenience I copy/pasted it from Google, with the result you see (the reason is that decimal 39 is ASCII coding for the single quote ' character, but that is not the question). Apparently, mankind is not able to transfer a line of text or a flat A4 paper from one program to another, but we still expect that 3D product models can be communicated meaningfully? The remarkable thing here is not that shit happens, the funny thing is that people persist in expecting flawless program interoperability "because the data are available electronically" while the practice shows so many examples of the opposite.

What can we do now after this gloomy conclusion? Try to find an alternative interoperability solution. Standard data exchange formats, such as STEP, DXF or IGES, drop out, firstly due to the representation variation issue (the fact that so many alternative representations exist), and secondly because they carry only geometry, and no semantics (e.g. a file can contain a plane. What is that plane, a bulkhead? Watertight or not? Or fire-resistant? Is the bulkhead from the type "collision bulkhead"? Does it require corrosion allowance? Etc. etc.). Emerging standards are 3D PDF, X3D and JT (Jupiter Tessellation), however these are just viewer standards, and do not contain a complete geometric model (let alone semantic information). So, these formats also drop out. Instead, for the past years we have realized a collaborative system based on:

- Direct communication between multiple applications, over TCP/IP.
- No common product model.
- Exchange of higher-level entities, such as “a transverse bulkhead”, or “sewage piping system”.
- Coding in XML, on the basis of a dictionary, where all semantics are written down. For the sake of convenience these definitions are as much as possible extracted from STEP (notably AP215 and AP216), extended where required.
- Communicate not only product model data, but also request/replies (of derived, volatile data).
- Exchanging bulkheads and decks, restricted to two systems.

While, at present, the system is being extended with:

- N-system communication.
- System management.
- Compartments.
- Piping details, to be used for e.g. damage stability, progressive flooding, time-domain analyses (such as time-to-evacuate) and engineering, Fig.5.

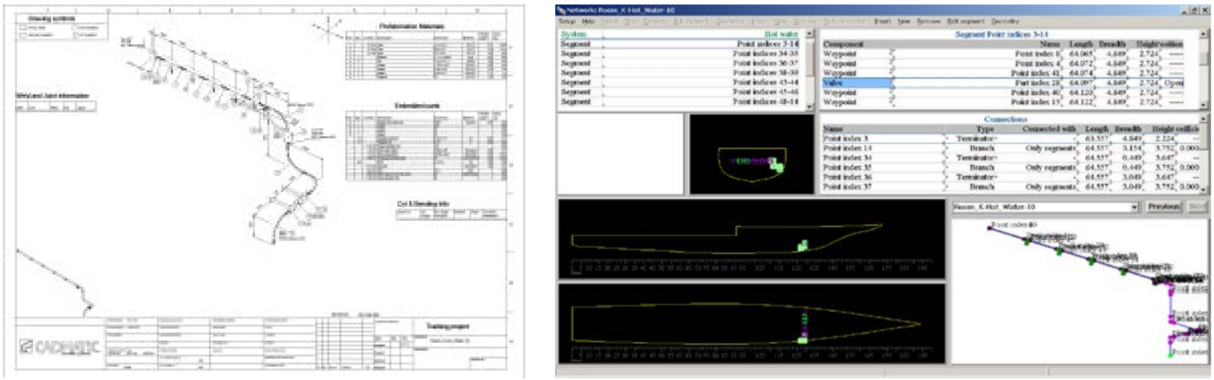

Fig.5: Experiment with piping system shape and meta-information in CADMATIC (left), shared by XML with PIAS (right)

A screenshot of the two GUI’s of the system is depicted in Fig.6. According to pilot users, the present development version of this system works quite satisfactorily. At this moment suggestions are being compiled for auxiliary user functions, in order to be able to offer a comprehensive product to the market. The conclusions on this development are:

- This initiative is different from earlier central product model concepts.
- A strong aspect is not only data sharing, but also commands.
- It relies on high-level semantics (e.g. the concepts “transverse bulkhead” or “sounding pipe”).
- So, it requires willing partners. Computer communication relies to a large extent on human communication.
- It is a powerful approach, but won’t conquer the whole world. The roughly estimated maximum number of connected computer programs will be some 10, perhaps 20.

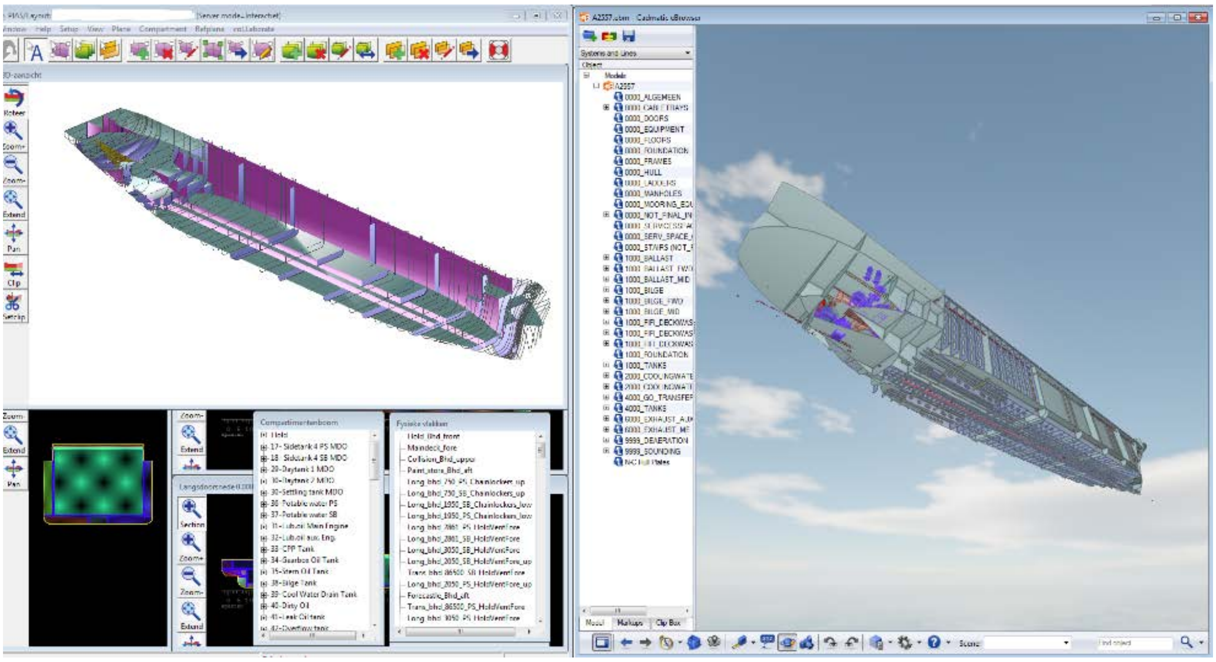

Fig.6: Screenshot of two systems, simultaneously working on the same ship design, left PIAS and right CADMATIC

5. 3D printing

Koelman (2013) reported some experiments on ship design support with 3D printing of cheap desktop printers. It was anticipated at the time that desktop printers would emerge for design support applications, but in our direct environment we see little sign of that. Although the technology has become much more mature and reliable. E.g. the printer we used was a Do It Yourself Ultimaker Original, which has initially a fail rate of some tens of percents. Newer models are version 2, which comes assembled, and 3, see ultimaker.com/en/products/ultimaker-3. The applied Ultimaker technology is Fusion Deposit Modelling (FDM), which is essentially layered manufacturing with one source of material. This method requires a flat base layer of sufficient size, for example, it will not be possible to print an Eiffel Tower model upside down, because due to the lack of a base layer the object will turn over. This might be solved by segmenting the model, but that requires additional processing as well as post-printing assembly. Version 3 has two print heads, one with the conventional construction material, and the other with water soluble support material. The latter can be used to support the artefact during printing, and washed away later on, thus allowing many more shapes to be printed in a single run. Also, larger manufacturers enter this market, for example Hewlett-Packard, although their Jet Fusion 3D printer, www8.hp.com/us/en/printers/3d-printers.html, is with a price tag of $200,000 a bit expensive for common desktop use.

Although penetration of 3D printing for design support may go a bit slow, its application in manufacturing is presently boosting, *Economist (2017)*. A typical marine manufacturing application is printing a propeller by Wire Arc welding, www.imarest.org/themarineprofessional/item/3364-3d-printing-takes-the-next-step-in-the-maritime-industry.

6. The return of empiricism

The advance of the computer has opened up new possibilities for the ship designer and brought many handy tools, such as CFD, advanced optimization algorithms and product model sharing. However, with the emphasis on these new possibilities an elder class of tools, the empirical prediction methods, is being neglected. In particular, for concept studies and the early design stage, such methods have proven to be extremely useful. Take for instance resistance prediction methods such as from Savitsky and Holtrop & Mennen, or steel weight approximations by Schneekluth or Westers. Unfortunately, these methods have not been updated for modern designs or construction methods. The most recent Holtrop & Mennen publication is from 1984, and the steel weight approximations date back to the early 1960s. This is peculiar, not only because the need for such methods is compelling, but also because now empirical methods could be built with today's possibilities, such as:

- Massive statistical analyses, such as regression models with a large degree of freedom, or response surface models.
- Collecting empirical material used to be tedious, for example doing model experiments. However, numerical experiments based on FEA or CFD could generate "numerical series".
- In 'those' days a prime requirement was to communicate the method in a condensed way, by using equations with only a few coefficients or graphs. But nowadays things are much easier. Large amounts of numerical data can easily be distributed and just as easy being read into a computer program or a spreadsheet.
- The increased processing power brings additional features within reach. For example, by extending the prediction method with confidence limits. In this fashion a probabilistic steel weight method might be possible, where not only the steel weight is predicted, but also its probability distribution.

In this respect, the occasional publication with a fully elaborated empirical method is a delight, e.g. the compact overview of empirical prediction methods for catamarans in *Haase et al. (2013)*. And notably *Hekkenberg (2013)* and *Rotteveel et al. (2014)*, which contain quite some useful empirical material for steel weight and hydrodynamics of inland waterway vessels. Another example of recent application of empirical methods, in the field of seakeeping and stability, can be found in the contemporary development of second generation intact stability criteria, *Umeda and Francescutto (2016)*. I hope that these efforts will be an inspiration to other scholars to work in this area. And remember: Eternal fame will be yours. For what is the reason we are still familiar with the names of e.g. Puchstein or Lap?

7. Hardware-supported accelerators

Distributed processor power supply has become abundant for the past decades, but processor power demand has increased in more or less the same pace. Reasons for the latter are for instance the increasing computation load as required by the legislation - probabilistic damage stability, 2nd generation intact stability criteria - and the application of optimization methods; genetics algorithms are powerful, but require many generations to find the optimum. Until some ten years ago that was somewhat automatically compensated by the autonomous increase of PC processor power, because every two or three years a new generation of processors was released with more or less double speed. Unfortunately, that effect has grinded to a halt, processors running single-core tasks are not significantly faster today than ten years ago.

For this problem, a solution may be found in High Performance Computing or Cloud Computing, *Mallol et al. (2016)*, an approach which brings huge time savings for tasks that can be massively parallelized, such as CFD, FEM and, potentially, probabilistic damage stability. However, there are also tasks that play predominantly on the desktop, in an interactive fashion, with a short burst of computing power demand. For example, a surface rendering task, dozens of stability calculations in a series of waves (such as required for second-generation stability criteria) or a series of some 100 damage stability calculations, as may be required to assess compliance with damage stability requirements on an on-board loading computer. So, demand for high-performance desktop processing power remains. Modern processors offer three facilities for that:

- Spreading the workload over multiple processors (multi-threading).
- Using Advanced Vector Instructions (AVX) on the Intel processor family, en.wikipedia.org-/wiki/Advanced_Vector_Extensions. With this feature, arithmetic operations on Floating Points (FP's) can be done in parallel, as depicted in Fig.7. Depending of the AVX-version a

maximum of four or eight simultaneous operations can be performed. The reason that AVX is dedicated to FP's multiplications, divisions etc., is that those are relatively time-consuming operations.

- Using Graphics Processing Units (GPUs). This facility may rely on the availability of a GPU of a certain brand or family, although standards are emerging, such as CUDA, en.wikipedia.org/wiki/CUDA, and OpenCL, en.wikipedia.org/wiki/OpenCL.

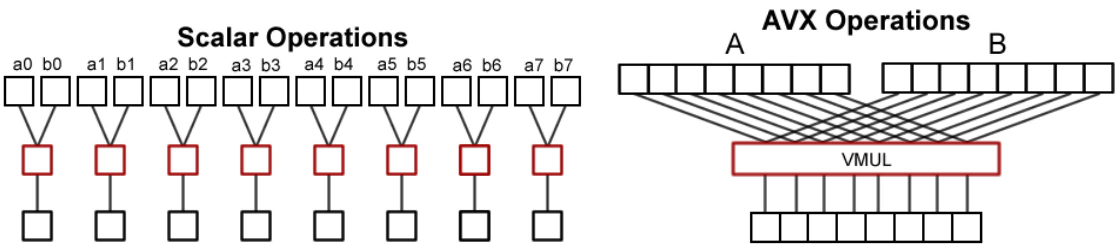

Fig.7: Eight multiplications sequentially (left), and parallel with AVX (right).

The GPU solution is reported to deliver quite some performance. However, two factors make it less suitable for standard application. The first is the requirement of a powerful GPU to be installed, which may not always be available on e.g. a laptop computer, and the second the lack of a uniform standard for the communication with the GPU. So, for our software family we have only investigated the first two options, which led to the following conclusions:

- Contemporary standard Windows multi-threading facilities perform reasonably well. The original Win95 CreateThread had quite some overhead, hampering its use for short tasks. In the best Microsoft tradition, this phenomenon was not solved by improving the multi-threading functions as such, but by adding a complete new design and function set, called Thread Pools. With the latter, also shorter tasks can be efficiently parallelized, although finding the balance between speed gain and overhead still requires quite some experimenting.
- Also in an application that was originally not design for multi-threading, sufficient tasks can be identified for and adapted to parallel execution.
- Because some practical implementation choices have been made, based on experiments, the maximum number of supported cores is eight. A higher maximum will be feasible, but will also require re-tuning.
- On a computer with N cores, speed gain is ≈ 0.75-0.90 N, where a core is a real, independent core, and not the kind of pseudo-core as Intel provides with its 'hyperthreading' technology.
- AVX may in theory provide a performance gain of a factor 8 on FP operations, however its application in practice is slowed down anyway because the numbers have to be shuffled and rearranged before presenting it to the processor. However, a major governing factor is that even programs that do a lot of arithmetic also spend quite some processor cycles to administrative tasks, such as the transfer of data between CPU and memory. In our application, some hyper-frequently executed, FP intensive, tasks have been identified and adapted to explicit AVX processing. The AVX speed improvement of the entire program is with 5-10% a bit disappointing, on the other hand, every contribution counts, and if you are working against a deadline…

8. Scenarios on the use and advancement of computers and their impact on CASD

Koelman (2013) postulated three mid-term scenarios on the use and advancement of computers, and their impact on CASD. The world has not changed much since 2013, so these scenarios, updated to the 2017 insights, are still deemed to be realistic:

- **Fragmentation, symbolized by the collapse of MS-Windows**. Time was that Microsoft (MS) ruled the world. However, in the technology battle of today its role seems to be over; for example a briefing on future platforms, *Economist (2012)*, reports in depth on Apple, Amazon, Google and Facebook, but spends only a single word on MS. A possible reason for the silence around MS was given in the *Financial Times (2017)*: "The Microsoft future epitomises the economist John Hicks's quip: 'the best of all monopoly profits is a quiet life'. Microsoft in the 1990s became famous as a once-brilliant company that decided to pull up the drawbridge, locking in consumers and locking out competitors". Although as such the downturn of MS might be a relief for many, the annoying undertone is that no prevailing platform will arise that can mature to mainstream. As such, the lack of a clear winner is not a big disadvantage, it might even be healthy for innovation. But consequences might be that PDT and collaborative design will become tedious.

- **The standstill era**. In the Netherlands, the 18th century is known as the 'wig age', the 'pruikentijd'. This is generally considered to have been a standstill era, where the country still floated on its successes of the Dutch glorious Golden Age, however, with little innovation. The same might be the future of computing: overwhelmed by the magic of the computing and connectivity power the strive for innovation is lost for the moment. Or to condense this scenario in a rhetorical question: Do you think that our common desktop tools, such as spreadsheets, word processors and databases have significantly improved since 1986? I don't. Admittedly, we have gained e-mail and Internet, but for the rest my office productivity was higher in 1990 than it is now. A second example of standstill is the unconnectiveness of apps. It is often said that an iPhone or Android device makes you a member of the connected world, and that is true, but at the same time you are the endpoint, the terminal. The apps themselves are not interconnected, all connection must pass through and be interpreted by the human being. In some sense, it is a reminiscence of the mainframe model of the 1960s and 1970s; a powerful computer at the center and many dumb terminals at the spokes of the wheel.
- **A bright young world**. In this scenario, the focus lies not so much on computer programs, but more on methodological advancement; the development of methods that assist the ship designer in the daily practice, but also at a deeper level help to make our industry more competitive and more pleasant. Obviously, the results will become available as computer applications, however, with more attention to the methodological user-friendliness than to appearance and user-interface wizardry. This kind of user-friendliness also stimulates a common ground for interoperability technologies.

The advantage of scenarios is that we do not have to choose. It is likely that a mixture will become reality. Obviously, everybody will favor the third scenario. But please see that such a choice is not without engagement. This scenario can only become reality if we actively contribute to it and stimulate others to do so, too.

9. Conclusion

Looking back, the outlook is sometimes a bit grim, summarized:

a) all ship design model disposed,
b) an awkward but popular ship hull representation method might continue to haunt us,
c) even in simple 2D cases data exchange may fail and
d) office PC's have lost their autonomous performance increase.

On the other hand, there is progress:

1) a better hull form method does exist,
2) for collaborative design a workable framework has been sketched,
3) PC processors offer alternative performance increasing facilities, and
4) 3D printers gradually become more reliable and more abundant.

So, a bright future may lie ahead, but will not arrive without us pursuing it. In the words of *Popper (2001)*: "When I say, 'Optimism is a duty', this means not only that the future is open but that we all help to decide it through what we do. We are all jointly responsible for what is to come. So, we all have a duty, instead of predicting something bad, to support the things that may lead to a better future".

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Hathor - An Event Cruise Ship

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Abstract

This paper presents a new concept for the cruise ship, which has been developed from our thesis work. A typical cruise ship docked at port does not interact with the city, but remains a guest in transit. Why not then take on the challenge of designing a functional entity that transports events, culture and entertainment? The ship would then become an extension of the city, offering a different experience each time to suit the tastes of all the family. If a ship can be 'inhabited', a city can be 'inhabited on the water'. The ship does not have a particularly residential facade but it has a multifunctional body.

1. Premise and Metadesign

Our design work began by analysing the current cruise sector and how it has evolved in recent years. We analysed all aspects of mass-market cruises, luxury cruises and river cruises to help develop an innovative concept. Our initial analysis of mass-market and luxury cruises revealed that the principal aim of cruise companies is to make the customers feel at ease, looking after their primary needs (food, rest) and desires and trying to convert these into purchases. All of this with the aim of pleasing and entertaining.

In this regard, modern cruises are very similar to shopping centres, places that meet the needs of various target customers, and where advertising is fundamental to attracting potential customers and trying to get them on board to try out new experiences.

We then conducted some market research to help us develop the concept. It focused on mass-market and luxury cruises on one hand, and yachts and mega yachts on the other: the first two to find out what facilities are available on board, and the second two for form and aesthetics. Future, recognisability, flexibility, comfort and exclusivity were the keywords that came out of the market research and which were later used in putting together the concept for the project. The research also looked at other sectors, beyond naval and nautical, for ideas from contemporary architecture as identifying elements for the project which would be immediately recognisable and have an aesthetic value in themselves, independent of the activities that take place inside.

We realized that the reasons behind the continuous development in the cruise tourism sector must be traced back to the versatility of that sector over the years in meeting the increasingly diverse and complex needs of their customers, satisfying them with a mix of attractions which motivate the client through:

1) an image of luxury and glamour, generally associated with holidays on large cruise ships,
2) accommodation on a par with superior and luxury hotels, particularly in terms of communal services, with standardised restaurants and no distinctions made based on expenditure, except for the layout and presentation of the cabins,
3) an ‘experiential’ offer based on a mix of destinations, some within the categories of the great cities of art and political capitals, and others which are more obviously holiday destinations,

4) a combination of cruising and themed activities (cultural tourism, shopping, entertainment, etc.) which is made possible by the geographical mix of destinations on a cruise itinerary, with on land excursions and various other options available in the itinerary.

This is all offered at a price level which is competitive with other all-inclusive forms of tourism.

After completing the market research, we moved on to the meta-design phase to identify the context of our ship and the target customers. Our target customer base is wide and diverse so as not to exclude anyone and to get a large slice of the potential market that might be attracted to the project: families with children, couples, groups of friends and older people, all attracted to living differently for a day and being able to customize the experience to their own liking. Attention to the customer and his wishes are at the center of the project and consequently on-board activities are centered on these: entertainment, relaxation, culture and all round wellness.

Naturally this all leads to high management and maintenance costs, raising the price range and attracting medium to high-income customers. We decided to borrow some aspects of the classic cruise, such as the communal areas and some of the attractions on board, and redesign and adapt them for our project. The main difference is the absence of passenger cabins which provides more space for communal areas on board as, in our concept of the day vacation, no space is needed for overnight stays. The only cabins on the ship are for the crew who, of course, remain on board throughout the cruising period. To compensate financially for the lack of cabins, the periods spent between ports must necessarily be kept short, avoiding dead periods and spending long periods docked in the port. The envisioned ship only makes a profit when it is docked in a port or natural harbour, i.e., when there are passengers on board who have booked the day, therefore it is essential to respect the points listed above. Moreover, the route the ship will take is limited by the fact that the ports must be close to populations which are interested in the activities on board.

The destinations will be a mix of coastal metropolitan cities (e.g. the ports of New York, Miami, Barcelona, Genoa) and interesting areas of countryside where passengers can board the ship in the harbor and then go out to sea to spend the day on board and get a different perspective where the sea is the centre of attention. Keeping the target customer and type of cruise in mind, we focused on the activities which should be available on board. First of all, a preliminary study was carried out dividing the day into four parts to understand the customers' interests and requirements and so meet their needs and demands. A range of activities were drawn up for morning, afternoon, evening and night, some of which are already available on common cruise ships while others are new ideas. For each activity, we identified the target customer, the age range, and the requirements in terms of elements, materials, requirements and performance.

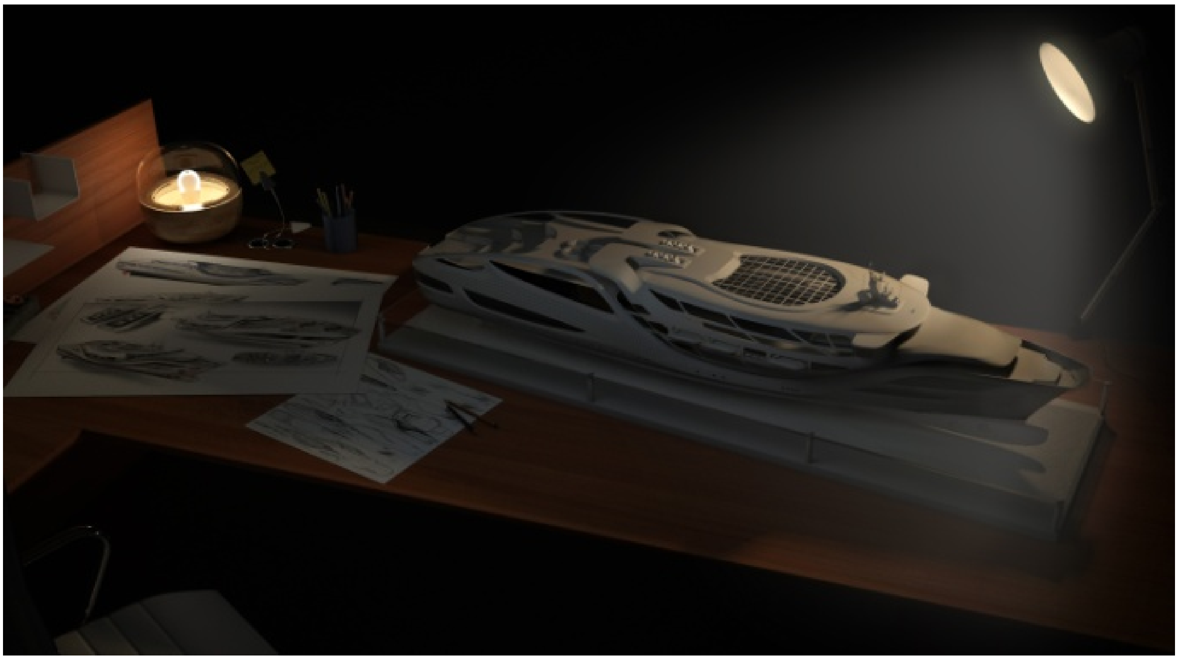
From this study, we were able to choose the final activities based on various considerations ranging from the financial to the functional. We tried not to have any areas that were dead at certain parts of the day, and to have areas that could accommodate different customers at the same time, or areas of various kinds that involved people with different interests. The activities were divided into four macro categories: services, culture, wellness and entertainment; four themed areas that intersect on the ship's decks to involve customers throughout the day. The services were designed as areas where there are bars, restaurants, reception, bathrooms and changing rooms.

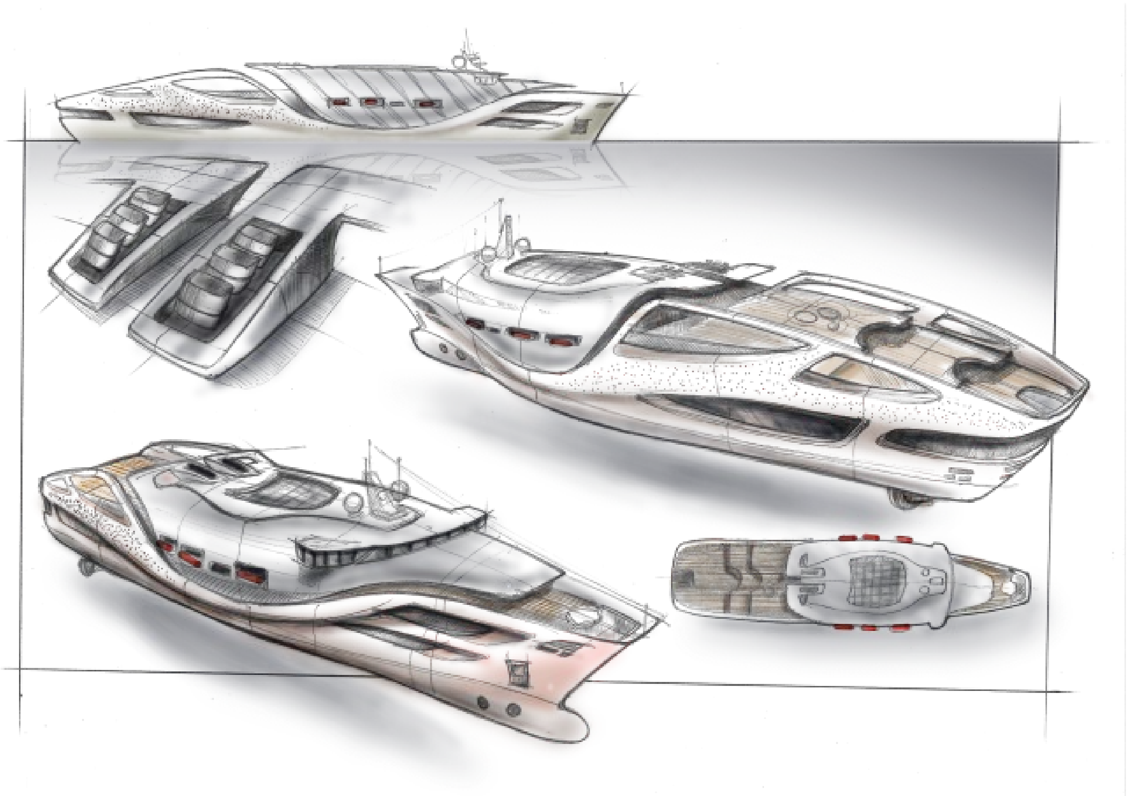
Culture includes areas for exhibitions and installations, a theatre, a multimedia room. For wellness, there are various outdoor sunbathing areas with swimming pools and hydro massage tubs, a spa, a gym, individual relaxation areas and a lounge with panoramic views. Of course, on board a cruise you also need entertainment areas, and indeed we have included areas for children's entertainment, a disco, a concert theatre and shops.

2. Design

The whole ship has been designed within the concept guidelines which have provided us with certain points of reference. The principle innovation compared to a classic cruise ship, the absence of cabins for overnight stays, has allowed us to have large internal spaces that can be used for the various activities selected, all of which are for public use, and to remove the private areas of the boat. The exterior has been designed with a contemporary aesthetic for two main reasons: the first was to look towards a new aesthetic concept for cruises which moves away from the traditional idea of a floating palace designed to carry the maximum number of people; the second was to make our project recognisable so, at first glance, it can be easily distinguished from the background of ships. We felt it was essential to make the design stand out, to arouse curiosity and astonishment in those seeing it for the first time and to make it well known and continually interesting for those who already know it. It has quite an aggressive shape with clean, angular lines and soft curves, and several aesthetic architectural and naval references which call to mind some elements of the cruise ship, some features from yachts, and others from contemporary architecture, the most obvious style influences being Zaha Hadid's fluidity and Norman Foster's high tech. The classic, very visible funnel of the cruise ship (e.g. Costa Crociere's yellow funnel) has disappeared to give way to a more "veiled" outlet which has a lesser impact on the already recognizable aesthetics of the boat. There is a clear intention to create a strong link between the ship and the external landscape with large openings, broad windows and spacious outdoor areas. The ‘transparency’ of many areas is deliberate and has been made possible because of the lack of private areas which would have required more privacy.

With a total length of 161 m and a maximum beam of 39.5 m, the ship has quite a low length/width ratio; this was to create large spaces on board and therefore comfort and space for all the passengers. Two azipod ABB engines allow a maximum cruising speed of 20 knots and a maximum speed of 24 knots. Based on the attractions and the space available, the maximum capacity is estimated at approximately 1,030 people, which includes 800 customers and visitors and 230 crew. Compared to normal cruises where the crew/passenger ratio is around 1/5, our concept has a ratio of around 1/4. This was a deliberate decision to ensure that customers receive more attention and more refined and exclusive service. As for the external paintwork, the superstructure is petrol blue while the rest of the hull is light metallic gray. This delineation was designed to visually separate the two parts.





3. Conclusions

In conclusion, our intention, right from the beginning, was to work within the cruise sector to find a new way of looking at and experiencing the cruise ship. We therefore set ourselves the objective of developing a concept to apply to a newly conceived ship where a customer can have a different and unusual experience. The starting point was the cruise ship which, after appropriate modifications, becomes a 'new' ship with innovative features which meet traditional requirements in a different way. Our idea was conceived as an alternative to the cruise holiday; a customisable Fast Holiday for people who want to enjoy a day of relaxation, wellness and culture on board without having to go away for a few days. It can be summed as a desire to create a new ship market which offers services in a different way and provides a new experience.

Concept Design of Transformable Submersible Hydrofoil Trimaran

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Abstract

In the current political and socio-economic climate, it is imperative that countries can protect their sea lanes and coastal zones from surveillances and infiltration from foreign entities. As a result, developed and developing countries must be able to show their might and capability with blue water naval forces. Hence there is a need to develop innovative hull forms which would possess elusive ability and capable of hot pursuit. This paper attempts to focus on a new type of ocean going vessel, a transformable submersible hydrofoil trimaran (TSHT) which can travel both on the surface and underwater as necessary. With a transformable device and foldable hydrofoils between main hull and side hulls, TSHT has the ability to change from submarine under water to a trimaran on surface. This article will mainly focus on introduction of TSHT and also make an attempt to compare hydrodynamic characteristics against similar types of displacement trimarans.

1. Introduction

The clear majority of today's ships, both commercial and military, would be described as having hulls of conventional design. Within this group there are numerous sizes and configurations, so what does constitute a conventional hull form? This question will be answered by an assessment of the hull configuration, the type of support and its speed potential. Other aspects influencing the classification of a design concept include facets such as the means of powering, construction and materials used. These however, are not related to the resistance and seakeeping characteristics as these areas will be extensively explored in the feasibility of this concept, namely Transformable Submersible Hydrofoil Trimaran (TSHT), which was patented by *Pan (2015)* CN104787275(A). TSHT is a kind of marine craft whose displacement can vary between 200 and 800 t and will be able to operate as a trimaran on the surface or as an underwater submersible vehicle by changing the configuration of the outriggers. Equipped with two types propulsion systems (gas and electric), it is expected that TSHT can achieve a speed of 50 kn on the surface using gas engines and proceed with low noise signature profile underwater using electric power.

This paper introduces TSHT's theory and operational feasibility. Initially this paper attempts to determine the resistance using the CFD code of STAR CCM+. Also examined is the lift force of hydrofoil on TSHT to see whether the force can support the weight of TSHT. The initial concept TSHT has been molded using RHINO and AUTOCAD.

2. Background

The usual methods to decrease the resistance especially in high-speed craft using multi-bodies, is to increase length/breadth ratio and decreasing displacement. Numerous hull configuration concepts employed in this quest appear in Fig.1 over a 20-year period. They include planning craft, multihulls, hydrofoil ships, hovercraft, and hybrids. Fig.1, the so-called Sustention Triangle, *Clark et al. (2000)*, shows the lift forces raising the hulls above, or partially above, the water surface.

Because of TSHT's complex nature, there is no available literature in public domain. However, there are several studies on hull vane, hydrofoil supported catamaran and hydrofoil assisted trimaran sailing boat.

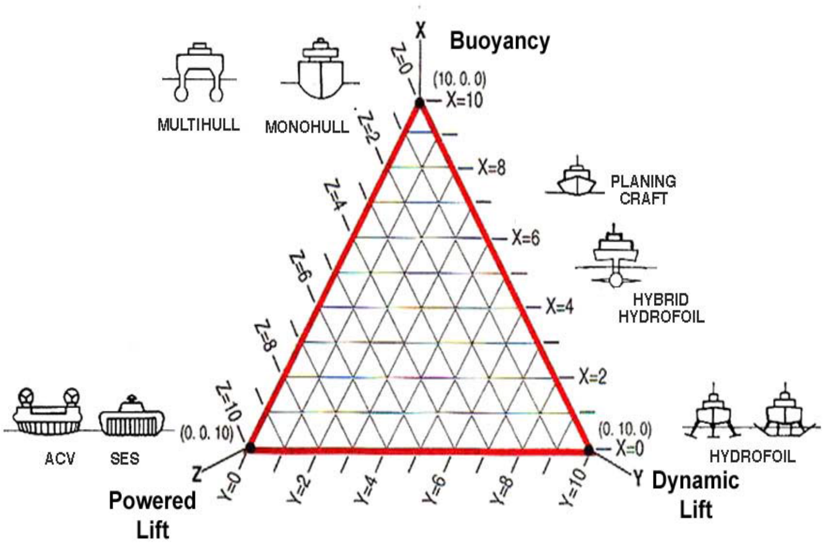


Fig.1: Sustention Triangle, *Clark et al. (2004)*

3. Hydrofoil ship

A hydrofoil is a thin sheet of material submerged in flowing water which is inspired by an airfoil. But the hydrofoil can provide more lift force than an airfoil because water's density is greater than air. In the paper of The Quest for Speed at Sea presented by *Clark et al. (2004)*, some methods to increase the speed of ships have been mentioned. Multihull ships such as catamaran and trimaran, and the hydrofoil ships were also described. Therefore, hydrofoils designs have been included to produce lift on the concept TSHT.

3.1 Hull vane

Uithof and Oossanen (2015) carried out research on the advantages and disadvantages of applying the Hull Vane® and the result shows a trimaran yacht equipped with the Hull Vane® performs better in lowering resistance than an equivalent mono-hull. The concept of Hull Vane® was presented in 1992. It was applied on a catamaran vessel to reach the required speed. The foil can reduce the bow-up trim and the resistance significantly. In 2003, the Hull Vane® was fitted on 'Le Deft Areva'. The Hull Vane® was outfitted on vessels 'Karina' and 'Alive' in 2014, *Uithof and Oossanen (2015)*.

3.2 Hydrofoil supported catamaran

Hoppe (2001) summarized some of the applications of hydrofoil within the time region between 1998 and 2001. The HYSCUCAT principle was also mentioned. *Migeotte and Kornev (2004)* presented a paper about the development of hydrofoil applications. *Migeotte (2015)* carried out research on Hydrofoil Supported Catamaran. He indicated that the problem of applying hydrofoil as a complex technology.

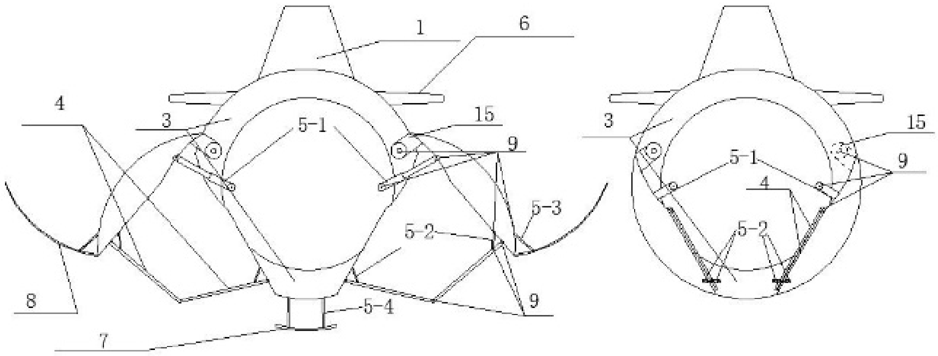
3.3 Hydrofoil trimaran

The calculation of the trim and sinkage on the trimaran resistance was presented by *Deng et al. (2015)*. In this paper, the viscous flow field of T-foil-trimaran was simulated and the resistance calculated. It showed that the T-foil works well on mitigating trimaran motion.

Speer (2000) describes the BASILISCUS project and covered the scaling laws for model hydrofoils, the baseline design and preliminary CFD modeling of the hydrofoils. Another application of hydrofoil on trimaran is 'L'Hydroptère'. The original idea was developed in 1975 and its first flight occurred in 1994. Under high speed the foil allowed the boat's hulls to come out of water. In 2005 it broke the record of crossing the English Channel between Dover and Calais. The speed was over 33 kn. In 2004 it became the fastest sailing craft with an average speed of 41.69 kn. In 2009, the ‘L’Hydroptère’ smashed the 500 m and the nautical mile record outright.

4. TSHT Working Theory

TSHT can be transformed via the open/close of the side hull (ballast tanks inside) into a submarine or trimaran. In the submerged condition, Figs.2 and 3, water is filled in the ballast tanks. In afloat condition, water will be expelled from ballast tanks. In floating condition the two side hulls will open and hydrofoils will be deployed. With increase in speed hydrofoils lift force will be generated to support the vessel. In this condition, it is expected that the total resistance will decrease. TSHT structural configuration has been shown in Figs.2 and 3. TSHT main parameters are shown in Table I.



1	control tower	6	front horizontal rudder	11	pod propeller
2	side body	7	bottom hydrofoil	12	vertical tail rudder
3	water ballast tank	8	side body hydrofoil	13	tail horizontal rudder
4	folding hydrofoil	9	bearing	14	water jet propulsion device
5	hydraulic driving mechanism	10	supporting rod	15	main hinge

Fig. 2: Hinged Arrangement of TSHT

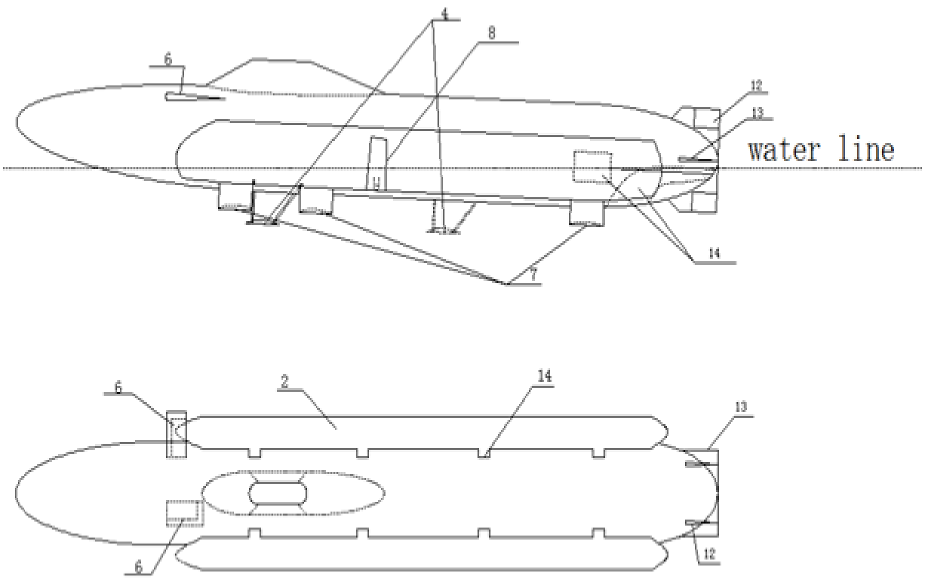


Fig. 3: TSHT structural configuration

5. CFD Model Domain and Boundary Conditions

STAR CCM+, a CFD modelling software has been utilized for preliminary resistance evaluation. To simulate the fluid field around the hull, a computational domain was first established. Due to the symmetry of the geometry and simulation time, only half of the hull was modeled. The domain size has a significant impact on the accuracy and computational cost. In the current study, only one half of model was included in the simulation as the other could be a mirror image. The dimensions of the computational domain around the hull are given in Table II. The boundary conditions are specified as follows: At the inlet boundary, the velocity (both for water and air) is specified by the velocity of the hull. At the outlet, hydrostatic pressure is applied. Symmetry condition is used at the central plane of the hull. The hull body is considered as a rigid body and no-slip condition is imposed on the hull surface. Free slip condition is used for the other boundaries.

Table I: Parameters of concept TSHT

Overall Length	37.40 m	Surface cruise speed	33 kn
Beam	4.40 m	Maximum speed	50 kn
Beam open	7.60 m	Hydrofoil number	2 pairs
Draft	3.05 m	Hydrofoil type	NACA 6409
Displacement	490 t	Hydrofoil Chord	1.5 m
Displacement on surface	335 t	Hydrofoil angle of attack	2°
Under water speed	<10 kn		

Table II: Limits of Domain

X (longitudinal)	-80 m	80 m
Y (beam)	0 m	50 m
Z (height)	-50 m	50 m

6. Mesh Generation

The domain is divided in two regions. Due to the complex geometrical characteristics of the hull, a kind of trimmed cell mesh is used in meshing structure and hulls. The resolution of the mesh near hull has evident influence on the computational accuracy. In this paper, the boundary layer mesh was refined with prism elements. A mesh-dependent analysis was conducted for the non-dimensional wall distance of the first cell center y+ and the surface mesh size of the TSHT surfaces to ensure that the selected mesh produces accurate results. The domain volume is divided into small cells to generate the mesh. The largest cells on the hull are approximately $\Delta(X, Y, Z) \approx 0.36$ m in size. In areas with large curvature and small features, cells as small as $\Delta(X,Y,Z) \approx 0.003$ m were used to ensure that flow features have a good resolution. Extra cells were added to the hydrofoils to ensure a good resolution in the boundary layer. The first cell near the wall was set to have a size of about 0.00064 m, such that its non-dimensional distance (y+) to the wall was approximately 50 m. Cells near the air-water interface were refined to have a size of 0.006 m in z-direction. Fig.4 shows the mesh generated and boundary domain around the surface of the hull.

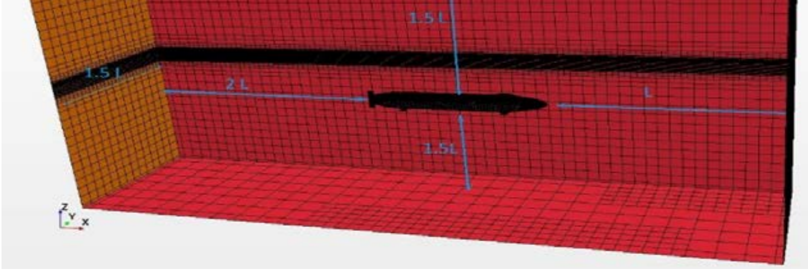


Fig. 4: Mesh and computational domain

7. Results and Discussion

The resistance to displacement ratio (R_T/Δ) value of the model in open and closed conditions on the surface obtained from CFD simulations have been compared. The results have been computed for Froude number (Fn) values of 0.1, 0.4, 0.7, 1.0 and 1.3. The physics of the model used an implicit unsteady, Eulerian multiphase, standard k-ε turbulence model with wall functions.

When navigating on the surface, TSHT can be deployed in either of the two conditions. In open condition the outriggers are extended which depicts TSHT in open configuration. When side hulls are not extended the TSHT exhibits closed configuration. Table III shows the resistance and effective power results of CFD simulation. The comparison between the TSHT open and close conditions are shown in Figs.5 and 6.

Table III: Resistance data from Simulation

Fn	V (knots)	R_T/Δ (open)	R_T/Δ (closed)	P_E (open) (kW)	P_E (closed) (kW)
0.1	3.7	0.0020	0.0007	12.65	4.289
0.4	14.9	0.0584	0.0352	1470.4	886.9
0.7	26.1	0.0960	0.1050	4228.8	4627.1
1	37.2	0.0668	0.1369	4207.2	8619.5
1.3	48.4	0.0646	---------	5288.1	-------

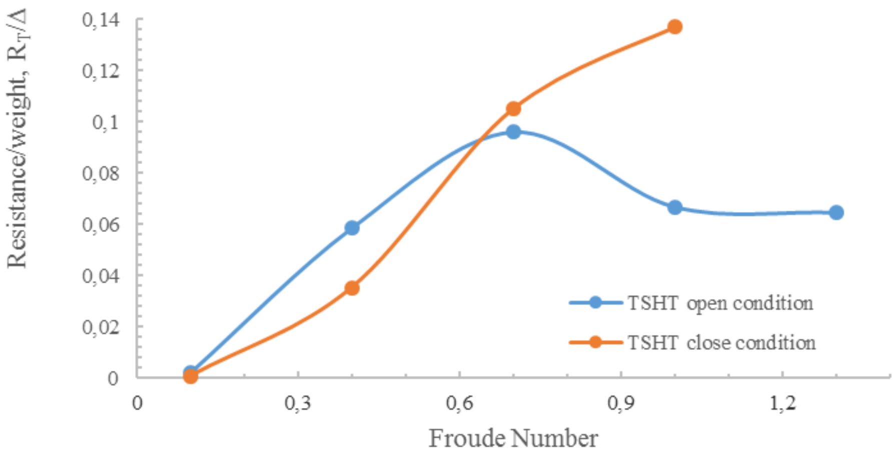


Fig.5: Resistance comparison in open and closed condition

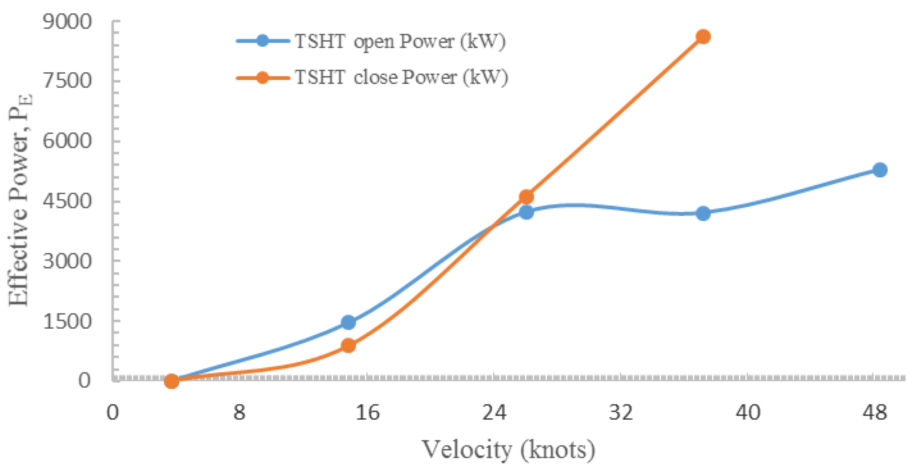


Fig.6: Effective Power (open and closed condition)

Fig.5 shows that the TSHT in closed condition has an advantage below Fn = 0.65. Due to reduced wetted surface area, the total resistance of TSHT in closed condition is about 30% lower than the TSHT open condition at Froude number Fn = 0.4. The total resistance of TSHT open condition reaches a peak at Fn ≈ 0.7 which is 10% lower than the TSHT in closed condition. However, the total resistance of TSHT in open condition drops by 30% when Fn increases from 0.7 to 1.0 and thereafter remains fairly constant up to Fn = 1.3. At Fn = 1.0 open configuration R_T/Δ has reduced by almost 50% when compared against the closed condition.

Fig.6 illustrates the relationship of effective power between the two conditions. It is obvious that effective power of TSHT in closed condition exhibits a linear growth. The power of TSHT in open condition reaches a peak of 4228 kW at 26.1 kn (Fn 0.7) subsequently decreasing to 4207 kW at 37.2 kn (Fn 1.0), which is less than half of the effective power of TSHT in closed condition. The effective power increase in open condition is almost 25% when vessel progresses from 37.2 to 48.4 kn.

8. Conclusions

The results of simulations with respect to R_T/Δ and P_E prove that the type of transformable submersible hydrofoil trimaran can reduce resistance in high-speed condition, especially at Froude numbers above 0.6. While traversing on the surface, TSHT has the option of choosing open or closed condition according to the speed requirements. Besides, on the surface, it would be beneficial for TSHT to operate in high-speed with low power consumption preferably at Froude number greater than 0.9.

Acknowledgement

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Software Developing in a Distributed Environment Exemplified for a Propeller Damping Tool

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Abstract

This paper explains, on the basis of a propeller damping tool, a way of developing software within small and distributed teams of engineers. An overview will be given about the technical problem, the theoretical background and the technical need of the developed tool. Furthermore, there will be an introduction of the ship design framework E4. A focus is on the coordination between different teams of developers. There are special requirements to maintain a software framework across different organisations. It will be discussed, how teamwork is possible although the involved organisations have to protect their intellectually property.

1. Introduction

Ship design needs complex software. But in the same way as other technical products, software design requires a special knowhow. Commercial software is built by companies with big IT departments and a clearly structured development strategy. An organisation can concentrate on questions of their naval architectural core competence by using such software. The disadvantage is a limited flexibility. Commercial software has limitations in adapting it to special features of the own organisation. Sometimes it is very useful to implement an own physical model to analyse special technical problems which are relevant for a project.

But it is not easy to handle software projects in-house with limited resources for software engineering. Besides physical and numerical problems, software design has to handle many IT tasks such as data handling, communication and user interfaces. A concept is needed for the distribution, bug fixing and documentation of different software versions. These topics are important for a software product. But most companies only want to use software for solving a special technical problem and do not have enough financial and technical resources to handle all these aspects of software engineering.

In contrast to commercial software, the ship design software E4 is a product which is developed by a group of independent partners from the maritime industry. The E4 framework is no monolithic software. It is a software system which contains many tools for different topics of ship design. Depending on the technical problem a single tool is more or less complex. Each partner is able to develop and support own tools and adopted them to their specific problems.

Propeller damping is such a problem, which shows the advantage of own software. An important question is in which way propeller damping affects propeller shaft vibrations. Prof. Schwanecke solved the interaction of hydrodynamic mass of a propeller with the blades by an analytic description of the propeller and water interaction. Beside the sophisticated physical and mathematical background, the developed model is small and easy to use. Coding in the computer language FORTRAN needs no explicit IT knowhow. The implementation has been done within the ship design framework E4 and could be realized in a short time. This was possible because all main functionality like data handling and user interface were already part of the framework and could be used by the developer.

The E4 framework is supported by a group of organisations who share their resources for software developing. In addition to someone's own interests and situations of completion, each partner has the benefit to be able to use a software framework to realise own software projects. The main resources can be focused to solve technical problems. The necessary work for supporting the basic system is shared with the partners and reduces the effort for each partner.

2. The E4 framework and partner group

The ship design software E4, *Bühr (1988)*, *Krüger (1999)*, has been developed over a period of 30 years. The focus was to build a software framework for ship design. Therefore, many different types of numerical methods have been developed and integrated into this system. The framework has the task to support the design engineer, especially during the early design as described in *Krüger (2003)*. It is a set of many different tools, which are working on the same database. This concept allows different engineers and scientists to integrate their own knowledge to the framework by developing special methods. As symbolized in Fig.1, there are different types of "first-principle methods" available. The framework has a strong modular structure. All methods can be used as single programs. For each method, permissions for sharing can be defined individually. This allows a good control over the own knowhow and an individual distribution of the own software.

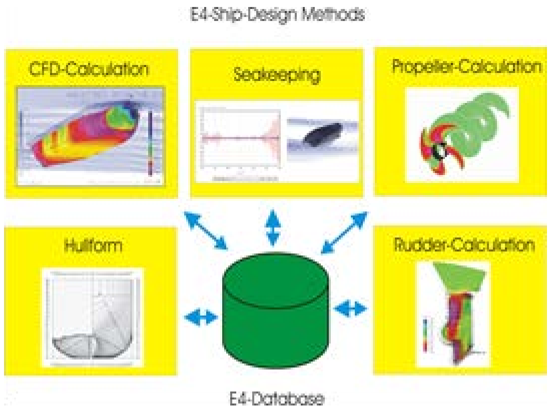

Fig.1: Principle structure of E4 ship design framework

2.1 The developer structure

Within the E4 group there are partners with different requirements. Sometimes methods should be used by others people who are not the developer. Sometimes a development in cooperation is wanted. In this case source code has to be shared. For such purpose, it is necessary to exchange own developed tools. Therefore, the E4 framework needs a permission system, which allows every partner to control the distribution of the own software. Two aspects have to be taken into account:

- Software tools and/or software libraries have to be distributed as a precompiled binary package.
- Source code should be developed together with other partners.

In contrast to classical software, there is no single organisation which handles the whole developing. This means, the developing process needs a decentralized procedure. Engineers have to develop their own tools without having access to the whole framework. Consequently, it is not possible to store the complete E4 framework on a single source code control system.

Corresponding to the decentralized approach, every partner has the ability to use an own subversion server for the source code of their tools. Fig.2 shows the structure of the E4 marketplace and developing environment. Although the framework operates totally decentralized, the TUHH offers some services for the community. Not every partner has the resources and/or knowhow to run an own server. In such a case, it can be hosted by the TUHH. Additionally, a central build and testing server has been implemented. Sometimes a partner has an agreement with another partner for using the software without having access to the source code. In such a case, it is necessary to distribute parts of the E4 framework as a binary package. Every partner is free to exchange own software with each other as one like. Consequently, the needed binary packages are different for every partner. The TUHH as a neutral non-commercial partner has access to all source code of tools which should be exchanged within the E4 community. The process of configuring and compiling has been automatized by server called “Build-Bot”. This Build-Bot has the task to control every change within the source code, whether it is correct or not. Now two compilers are used for checking the source code. First the open source GNU-Fortran compiler is used. This compiler has the advantage of being very critical. It can be configured to control many aspects of modern FORTRAN and to give warnings about discrepancies to the standardization. As a second compiler we use a commercial compiler for packaging. The optimization features are much better. The combination of both compilers has the advantage to have a good control about the quality of the source code in combination with a highly optimized method for the user of the distributed tool.

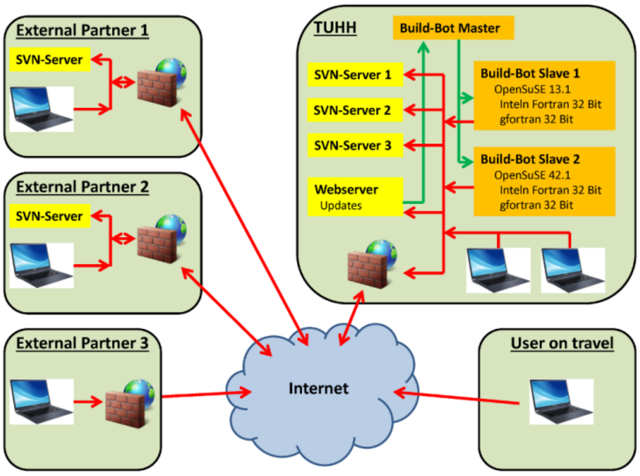

Fig.2: E4 marketplace

Beside the advantage of having control over the own developments, the decentralized approach has the disadvantage of a more complex environment. Every partner has different access to source code and binary files. Fig.3 shows a typical structure. An engineer needs to check out a set of different source code repositories. Additionally, often binary libraries are needed. The source code will be synchronized by subversion and the libraries have to be downloaded from the Update Server of TUHH.

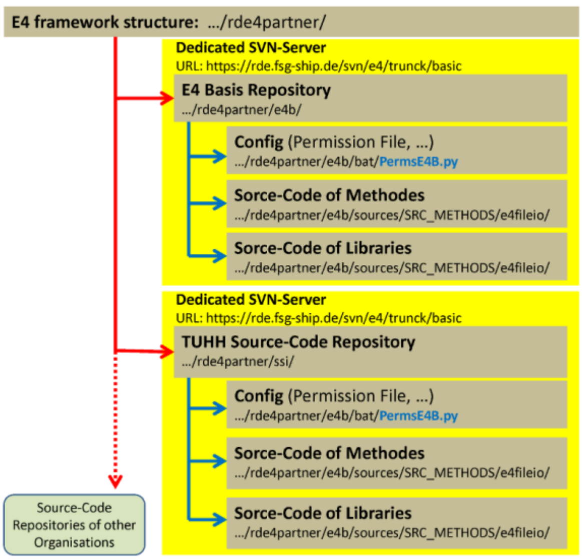

Fig.3: E4 source code structure

The configuration of permissions is handled by text files stored in the config-directory of each subversion server. Each partner can define which libraries and methods are distributed to which other partners. The permission system is based on a simple set of rules. Every source code directory can be characterized by four flags.

- The “read” flag allows to get read access to the source code directory.
- The “write” flag allows to get write access to the source code directory.
- The “binary” flag allows to get a precompiled binary file of the specified library or method.
- The “documentation” flag allows to get access to the documentation of the specified library or method.

This mechanism of permission files, allows an infrastructure where different partners can cooperate in an individual way. Each partner can focus on their own task. Basic functionality of the E4 framework is stored in a special repository, which is open for the community. This repository contains the primary functionality. Libraries for reading and writing data, GUI and basic naval architect functionality are in this open pool. This pool is supported in cooperation by the group. In this way, restricted resources can be used more efficient for such a task which is not part of the core business. The main resources can be investigated in the not public parts of special naval architect tools. If and under which conditions an own development should be shared, can be decided later on.

3. Method of propeller damping calculation

Now it should be explained in which way such a framework can be used for special developments. The actual trend to operate vessels in the so-called slow-steaming mode has posed a lot of complex problems to the naval architects, as the ships operate far away from their design condition. This is of most importance for the operation of the engine and the propeller. When the propulsion system is operated at low revolutions, it is at the same time operated closer to the torsional vibration resonance, because the drive train is designed with a resonance frequency at low revolutions. During run up or slow down, a so called barred speed range is passed to avoid permanent operation close to the resonance. As a consequence, the layout of the drive train with respect to torsional vibrations must be carried out taking this operational boundary condition into account. With respect to torsional vibrations, the propeller – besides the engine – is the main source of excitation as well as the most important damper of the drive train. Furthermore, the mass moment of inertia of propeller – including the so called added mass moment of inertia (MOI) due to forces of the entrained water – dominates the resonance frequency of the drive train. To compute hydrodynamic damping, there are some semi-empirical theories available, where the most advanced method was developed by Schwanecke and Grim. Even though there was a significant development in both numerical and experimental techniques, there are no such applications used for the calculation of propeller damping. *Steen (2015)* has reported that RANS applications can presently not be used to predict propeller damping due to numerical difficulties, and also model tests failed to properly predict propeller damping. Consequently, there are only a very few publications which deal with this problem. Additionally, only a few full-scale measurements are available for this problem. For these reasons, the authors have chosen to investigate the Grim/Schwanecke method.

The theory of Schwanecke and Grim is based on the established theory of the oscillating airfoil. As the practical application of the theory published by Schwanecke and Grim resulted in complex and time consuming computations, Grim and Schwanecke had introduced some simplifications into the theory. This resulted in quite simple formulae which allowed the computation of hydrodynamic damping and added mass or MOI in an easy way for all six degrees of freedom. However, since these developments screw propellers have been subject to a continuous development, where the aim was mainly to reduce pressure pulses and to increase the efficiency. The most important developments were the introduction of the propeller skew and the application of radially nonuniform pitch distributions. Both measures were intended to increase the comfort level of modern propellers, posing the difficulty to the propeller designers to keep the efficiency at least constant. This resulted in more cambered propeller profiles and lower blade area ratios. All these developments have not been foreseen by the simplified formulae published by Schwanecke and Grim.

Due to the new operational challenges of the ships, propeller damping and added MOI have to be computed more accurately, while at the same time it is not clear whether the simplified formulae published in 1963, 1973 and 1983, respectively, are still able to cope with modern screw propellers. As computational power is not a problem anymore, it was found useful by the authors to reformulate the original theory by Schwanecke and Grim in the context of an updated lifting line model for modern screw propellers. If this has once been done, it is also possible to analyze the propeller in the wake field of a modern ship design in any propulsion condition. It is then further possible to analyze controllable pitch propellers in off-design pitch conditions, too.

3.1. Harmonic forces acting on an oscillating hydrofoil of infinite span

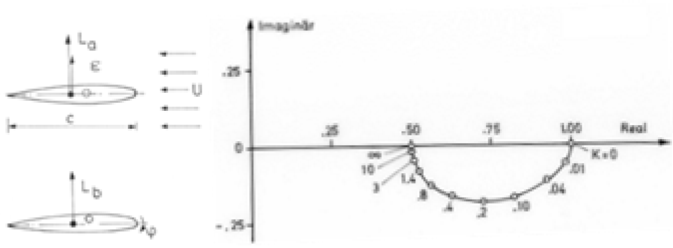

Fig.4: Definitions of flow around oscillating airfoils (left) and complex function C(K)

An airfoil of infinite span in a parallel inflow U is exposed to harmonic lateral or rotational oscillations of the amplitudes ε_A or φ_a. The motion equations read:

$$\varepsilon = \varepsilon_A \cdot e^{i\omega t} \; resp. \; \varphi = \varphi_a \cdot e^{i\omega t} \qquad (1)$$

Assuming the transversal velocities to be small compared to the inflow velocity U, the problem becomes independent from the mean angle of attack of the airfoil as well as from the thickness of the airfoil. The harmonic hydrodynamic forces L rectangular to the parallel inflow can be obtained from the theory of conformal mapping as follows *Grim (1983), Karman (1938), Küssner (1936)*:

$$L_\varepsilon = -\frac{c_a'}{2}\rho l U \dot{\varepsilon}\left(i\frac{k}{2} + C(k)\right) \; resp. \; L_\varphi = -\frac{c_a'}{2}\rho l U^2 \varphi\left(i\frac{k}{2} + \left(1 + \frac{ik}{2}\cdot C(k)\right)\right) \qquad (2)$$

In Eqn. 2, L_ε denotes the harmonic lift forces due to the lateral motion, L_φ due to the rotational motion. In Eqn. (2) c denotes the chord length of the airfoil, U the inflow velocity and ρ the density of the fluid. c_a' denotes the gradient of the lift coefficient, which theoretically amounts to 2π. In practice, values between $(0.87 \ldots 0.93)\cdot 2\pi$ are obtained. k is the nondimensional frequency of the oscillation and it is defined as

$$k = \frac{\omega c}{2U} \qquad (3)$$

$C(k)$ is a complex function which is shown in Fig.4, right. From Fig.4 and Eqn. (2) the fact can be derived that the magnitude of the harmonic hydrodynamic forces actually depends on the frequency of the oscillation. From Fig.4 it can also be seen that the imaginary part $C(k)$ becomes zero if k equals either zero or infinite. If $k = 0$, the problem becomes stationary, and with $C(k = 0) = 1$ the stationary solution for the profile lift is obtained, *Grim (1983)*. If on the other hand the reduced frequency k becomes large enough, the oscillating lift forces do also become independent from k as the imaginary part vanishes and $C(k = \infty) = 0.5$. For the screw propeller this means that the frequency of the oscillation ω must be sufficiently large against the inflow velocity U. If we assume an aspect ratio of $c/D = 0.25$ for a modern screw propeller blade, where c is the mean chord length of the propeller blade and D the propeller diameter, and if we introduce the advance ratio J=v/(nD) into Eqn. (3), we obtain $c/D = 0.25\, K = 0.785\ N/J$, where N is the order of the oscillation with respect to the number of revolutions. We can therefore conclude that for a screw propeller, the harmonic forces due to torsional vibrations are practically independent from the vibration frequency.

If we assume a four-bladed propeller operating at an advance ratio J of about 0.8, k becomes about 4, and from Fig.4(right), the fact can be derived that this condition is close to the vanishing of the imaginary part of $C(k)$, which is equivalent to the fact that the harmonic forces become independent from the frequency of the oscillation.

3.2. Harmonic forces acting on a propeller blade

Fig.5 (left) shows the inflow condition to the blade of a screw propeller. The direction of the flow with the velocity U_I is given by the hydrodynamic pitch angle β_I. U_I is the vector sum of the rotational speed of the blade section ωr, the (local) inflow velocity V_A and the sum of the propeller induced velocities, here denoted by U_N. The angle of attack of the blade is given by the difference of the blade angle (δ) and the hydrodynamic pitch angle β_I. For the moment, it is assumed that the flow around the propeller blade is 2d, so that the formulae for the foil of infinite span (Eqns. (1) and (2)) can be applied. The propeller blade now performs a harmonic torsional oscillation. For the resulting hydrodynamic force element, the component rectangular to the inflow velocity $U_I$is relevant, which means that all translational force elements have to be multiplied with $\cos(\beta_I)$, and all rotational elements with $-\sin(\beta_I)$. From Eqn. (2), we obtain for the torsional harmonic moment due to a torsional oscillation by integration over the propeller radius:

$$M_{\varphi\varphi} = -\frac{c_a'}{2}\rho N \int_{r=R_N}^{R_a} r^2 \left(\ddot{\varphi}\frac{c^2}{2} + \dot{\varphi} c U\right) sin^2(\beta_i) \cdot dr \qquad (4)$$

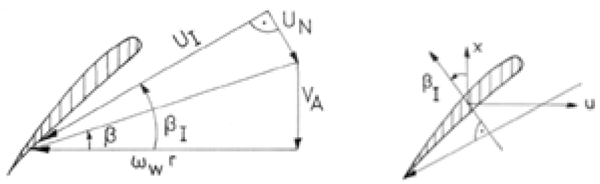

Fig.5: Inflow conditions at a propeller blade, *Grim (1983)*

In Eqn. (4), N denotes the number of blades of the Propeller. Eqn. (4) now includes terms which depend on the first time derivative of φ; they can be interpreted as damping terms. Terms depending on the second time derivative of φ can be interpreted as inertia terms. If we use the notation introduced by *Schwanecke (1973,1963)*, then we obtain the hydrodynamic damping ($b^{\varphi\varphi}$) and the hydrodynamic MOI of the propeller ($a^{\varphi\varphi}$) from the radial integration of all force elements, *Grim (1983)*:

$$a^{\varphi\varphi} = -c_{stat} \cdot c_{AR} \cdot \frac{c_a'}{4}\rho N \int_{r=R_N}^{R_a} r^2 \frac{c^2}{2} sin^2(\beta_i) \cdot dr \qquad (5)$$

$$b^{\varphi\varphi} = -c_{stat} \cdot c_{AR} \cdot \frac{c_a'}{4}\rho N \int_{r=R_N}^{R_a} r^2 c U sin^2(\beta_i) \cdot dr \qquad (6)$$

In Eqns. (5) and (6) R_N denotes the hub radius and R_a the half of the propeller diameter. Eqn. (4) has been developed assuming a purely 2d flow around the propeller blade. Therefore, corrections have to be made for the foil of finite span in Eqns. (5) and (6). This has been accounted for by introducing the correction factors C_{Stat} and C_{AR} . C_{Stat} takes into account the fact that the 3d flow around the propeller blade leads to a reduction of the effective angle of attack and therefore to a reduction of the stationary propeller thrust and torque. C_{Stat} can be computed for each propeller e.g. by using the lifting line method (see below). As a rough approximation, Schwanecke has proposed a C_{Stat} value of

0.85 *Schwanecke (1973,1963).* C_{AR} takes into account that also the harmonic oscillatory forces of the propeller are subject to a reduction by 3d flow effects. This has been computed by *Breslin (1970)*, and values for C_{AR} can be taken from Fig.6(right), *Grim (1983)*. In this diagram, Z denotes the number of blades, and Ae/A0 is the expanded area ratio of the propeller. r_0 denotes the hub radius of the propeller and n is the order of vibration. Except for the correction of c_a'; viscous effects have not been included in the theory so far, because the viscous influence is known to be small. However, *Isay (1963)* showed that the influence of the viscosity on the torque of a screw propeller can be included by multiplying the radial torque coefficient with $\left(1 + \epsilon\, cot(\beta_I)\right)$, where Є is the lift/drag ratio of the profile at the given (mean) angle of attack. In this sense, Eqns. (5) and (6) can be corrected accordingly.

After some simplifications and some assumptions for the propeller blade geometry, the inflow velocity and the hydrodynamic pitch angle, the following simple formulae have been obtained for $a^{\varphi\varphi}$ and $b^{\varphi\varphi}$ by Schwanecke and Grim:

$$a^{\varphi\varphi} = -c_a \cdot \frac{\rho}{N} \frac{D^5}{\pi} \left(\frac{P}{D}\right)^2 \left(\frac{A_e}{A_0}\right)^2 \tag{7}$$

$$b^{\varphi\varphi} = -c_b \cdot \omega \frac{\rho D^5}{\pi} \left(\frac{P}{D}\right)^2 \frac{A_e}{A_0} \tag{8}$$

Schwanecke (1973) has proposed values for c_a and c_b of 0.0703 and 0.0231, respectively. In a later publication, *Grim (1983)* revised these values to 0.052 and 0.017, and also later publications by Schwanecke mention theses revised values. In Eqns. (7) and (8), P/D means the pitch/diameter ratio of the propeller. This is often given at 0.7R, and this value is at the same time the maximum P/D of the propeller. In the sense of Eqn. (7) and (8), the correct mean pitch of the propeller could be used instead of the maximum pitch at about 0.7R. It must further be understood that these formulae are not applicable for controllable pitch propellers in off-design pitch conditions.

Nevertheless, it is of course possible to directly solve the Eqns. (5) and (6) for any screw propeller. This requires the exact computation of the (local) inflow velocity of the propeller and the hydrodynamic pitch angle. Both require the calculation of the propeller induced velocities denoted by U_N in Fig.5. U_N is the vector sum of the axial induced velocity U_Q and the circumferential velocity V_Q. Both can be computed by means of the lifting line theory with sufficient accuracy. This is at first done for the stationary propeller inflow, *Isay (1963), Karman (1938), Krüger (1998).*

3.3. Stationary lifting line theory

From Biot-Savart's law, the vortex induced velocities can be computed for any propeller assuming that the free vortex sheets are located on regular helices of constant pitch k_0 by the following integral-differential equations, expressed in cylindrical coordinates (x,r):

$$u_Q(x,r) = \frac{1}{4\pi} \sum_{n=0}^{N-1} \int_{s=Rh}^{R} \frac{d\Gamma(s)}{ds} \cdot \int_{\psi=0}^{\infty} \frac{\left(r\cos\left(\varphi-\varphi_0-\frac{2\pi n}{N}-\psi\right)-s\right) s\, d\psi\, ds}{\left[\left(-x-x_p-k_0\psi\right)^2+r^2+s^2-2rs\cos\left(\varphi-\varphi_0-\frac{2\pi n}{N}-\psi\right)\right]^{3/2}} \tag{9}$$

$$v_Q(x,r) = \frac{1}{4\pi} \sum_{n=0}^{N-1} \int_{s=Rh}^{R} \frac{d\Gamma(s)}{ds} \cdot \int_{\psi=0}^{\infty} \frac{\left(s\cos\left(\varphi-\varphi_0-\frac{2\pi n}{N}-\psi\right)-r-s\psi\sin\left(\varphi-\varphi_0-\frac{2\pi n}{N}-\psi\right)\right) k_0\, d\psi\, ds}{\left[\left(-x-x_p-k_0\psi\right)^2+r^2+s^2-2rs\cos\left(\varphi-\varphi_0-\frac{2\pi n}{N}-\psi\right)\right]^{3/2}} \tag{10}$$

In Eqns. (9) and (10), N denotes the number of propeller blades where φ_0 is the phase angle of the key blade. $\Gamma(s)$ denotes the radial distribution of the bounded vortex circulation representing the propeller blade, and according to Helmholtz' law of vortex conservation, $d\Gamma(s)/ds$ is the vortex strength of a free vortex thread starting at the radial position s at the bounded vortex. It should be noted that the integrand becomes singular if the collocation point coincides with a vortex point, which means that the velocity is to be computed exactly in the free vortex surface. A detailed mathematical discussion of these singularities was treated by *Isay (1963)* and *Lerbs (1955)*.

For the computation of the propeller damping and added MOI, it is sufficient to compute the circular average of the propeller induced velocities. Further it is sufficient to compute these averaged velocities on the key blade at the position of the bounded vortex. In this case, Eqns. (9) and (10) simplify to:

$$u_Q = \frac{r}{k_0}\frac{N\Gamma}{4\pi r}\frac{1}{\kappa} \tag{11}$$

$$v_Q = -\frac{N\Gamma}{4\pi r}\frac{1}{\kappa} \tag{12}$$

In Eqns. (11) and (12), κ is the Goldstein Factor which can be taken from *Isay (1963)* or from *Lerbs (1955)*. Now it is possible to compute the hydrodynamic pitch angle β_I and the inflow velocity U_I if the radial distribution of the circulation distribution of the bounded vortex $\Gamma(r)$ is known. According to the law of Kutta-Joukowski, we obtain for the radial circulation distribution:

$$\Gamma(r) = c_a' \frac{c}{2} U\, sin(\delta_0 - \beta_i) \tag{13}$$

From Fig.5 (left), we obtain for the composition of the inflow velocities:

$$U\, cos(\beta_i) = \omega r + v_Q \tag{14}$$

$$U\, sin(\beta_i) = u_0 + u_Q \tag{15}$$

Introducing Eqns. (14) and (15) in (13) using Eqns. (11) and (12) at the same time, we obtain for the radial circulation distribution $\Gamma(r)$:

$$\Gamma(r) = \frac{\omega r\, tan(\delta_0) - u_0}{\frac{2}{c_a'}\frac{1}{c\, cos(\delta_0)} + \frac{N}{4\pi\kappa}\left(tan(\delta_0) + \frac{r}{k_0}\right)} \tag{16}$$

The pitch of the free vortex sheets k_0 can be computed from the hydrodynamic pitch angle as follows, see also. Fig.5, left:

$$k_0 = r\, tan(\beta_i) = r\frac{u_0 + u_Q}{\omega r + v_Q} \tag{17}$$

Using Eqn. (17), Eqn. (16) can be solved iteratively. For the 1st iteration, u_Q and v_Q are set to zero. This allows to compute the Goldstein factor κ and the circulation distribution $\Gamma(r)$. With $\Gamma(r)$ the induced velocities u_Q and v_Q are determined. Using these values for the induced velocities, the next iteration for k_0 is obtained. The computation usually converges after about 20 iterations. Although the theory requires that the free vortices are located on regular helices having a constant pitch $k_0 = r \cdot tan(\beta_I)$ which requires light propeller loading, it was found by many authors that the results are also acceptable when the free vortex sheets are significantly deformed, which coincides with a heavy loading of the propeller. From the results of Eqns. (16) and (17) it is now possible to compute the hydrodynamic propeller damping and the added MOI according to Eqns. (5) and (6).

3.4. corrections for modern propeller designs

So far, no corrections for the 3d flow have been made in the lifting line theory. These need to be considered now, as damping and added MOI for modern propeller designs shall be computed. Two major corrections should be made to the theory to better cope with modern propeller designs:

- A correction which considers the propeller skew.
- A correction which considers the reduction of the angle of attack due to the three-dimensional flow around the propeller blade.

Weissinger (1949) and *Gersten (1961)* have developed a nonlinear lifting line theory for airfoils. As many practical airfoils are inclined by the so-called sweep angle ϑ, Weissinger has found that the lift of an airfoil is decreased when the foil is inclined by a sweep angle. This is because, due to the inclination of the foil in direction of the flow, longitudinal vortices occur, inducing velocities which decrease the effective angle of attack of the foil. The lower the aspect ratio of the foil, the larger is the lift reduction. From the complex theory, Weissinger has developed the following simplified formula to account for the sweep angle of the foil:

$$\frac{c'_{a,\vartheta}}{c'_a} = \frac{\Lambda + 2}{\frac{\Lambda}{cos(\vartheta)} + 2} \tag{18}$$

In Eqn. (18), Λ denotes the aspect ratio of the foil, the ratio on the left side of Eqn. (18) expresses the lift gradient of a foil with nonzero sweep angle and the lift gradient of a foil with a sweep angle. Eqn. (18) can be applied now to a screw propeller if the sweep angle is computed from the difference of the maximum skew angle (usually at the blade tip) and the minimum skew angle (usually at the hub). The aspect ratio of the blade can be obtained from the averaged chord length c of the blade and the difference between R_A and R_{Hub}. The reduction ratio according to Eqn. (18) is computed once in our method and then applied to the ca'- values of all radii.

Lerbs (1955) pointed out that the 3d flow around the propeller blade reduces the effective profile camber. Consequently, the geometrical profile camber needs to be reduced. This artificial correction of the effective camber would result in a corrected zero lift angle of each profile. As the blade angle δ_0 is measured against the zero lift axis of each profile, it is equivalent to correct the local blade angle δ_0 accordingly. This correction must be considered during the application of Eqn. (16) to obtain the corrected circulation distribution. At the same time, the hydrodynamic pitch angle β_I needs to be increased accordingly in Eqns. (5) and (6). *Lerbs (1955)* has suggested the following relationship for the effective angle of attack in 3d flow α_{3D}, where $\alpha = \delta_0 - \beta_I$:

$$\frac{\alpha_{2D}}{\alpha_{3D}} = F_1\left(\frac{r}{R_a}\right) \cdot F_2\left(\frac{r}{R_a}, \frac{A_e}{A_0}\right) \cdot F_3\left(\frac{A_e}{A_0}, J\right) \tag{19}$$

F1 and F2 can immediately be taken from the original publication from *Lerbs (1955)*. F3 was recalculated for the purpose of the present analysis. The calculation procedure was such that for a series of selected propellers of the Wageningen B-Series, the value of F3 was adjusted in such a way that the measured propeller thrust was exactly met. This was done to better compare the values we have obtained with the results of Lerbs. During the computation of F3, a correction for the propeller skew according to Eqn. (18) was also not made to keep the results comparable. The resulting values of F3 are shown in Fig.6, left. Like in the original publication by Lerbs, we have made the values of F3 dimensionless with those obtained for J=0.4. In addition, we have extended the computations for the J-values 0.0 and 1.0. The comparison of Fig.6, left, with the original data published by *Lerbs (1955)*) shows a good agreement.

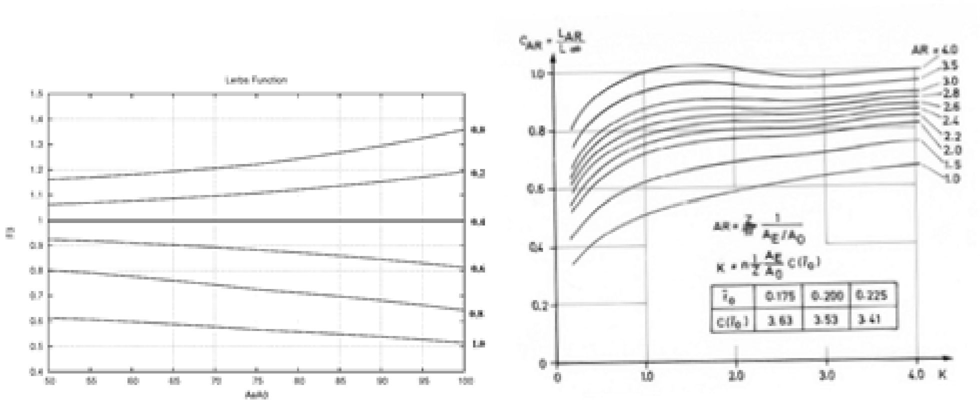

Fig.6: Recalculated correction function F3 according to LERBS (left) and correction function C_{AR} for the instationary part according to *Breslin (1970)* and *Grim (1983)* (right).

3.5. The screw propeller behind the ship

Hydrodynamic propeller damping and added MOI can be computed using Eqns. (5) and (6) if beforehand the propeller inflow conditions have been computed, using Eqns. (16) and (17). However, these computations require the propeller rpm and the propeller inflow condition as an input. These can only be computed if the propulsion condition of the ship is known. At a given floating condition and ship speed, the ship has a specific resistance R_T, which also may include additional resistances due to environmental conditions. The revolutions of the propeller must now fulfill the propulsion equilibrium condition, which means that the propeller thrust T must equal the sum of ship resistance R_T and thrust deduction, $T \cdot (1 - t) = R_T$. The inflow condition to the propeller for the stationary case is defined as $V_A = V_S \cdot (1 - w)$, where w is the effective wake fraction, typically obtained from a model test. It will later be shown that the wake distribution has a small effect on the damping only and can therefore be taken into account by the relative rotative efficiency. The calculation procedure for each calculation speed is as follows:

- Determine the ship resistance R_T for the actual floating condition and environmental conditions
- Determine thrust deduction fraction t and effective wake fraction w
- Find the rpm of the propeller which fulfills the propulsion equilibrium $T \cdot (1 - t) = R_T$
- For the computed combination of ship speed and propeller revolutions, solve Eqn. (16) iteratively.
- Then solve Eqns. (5) and (6) to obtain the propeller damping and added MOI.

If the propeller is a controllable pitch propeller (CPP), the propulsion equilibrium must be obtained from the correct combination of pitch setting and rpm, which must be taken from the ship´s propulsion control system settings.

For the screw propeller behind the ship, the values obtained for damping and added MOI should theoretically be corrected for the relative rotative efficiency (η_R) of the ship, as η_R expresses the relationship of the propeller torque behind the ship compared to the J-equivalent open water condition. However, as η_R is typically close to 1 for the cases examined below, this effect was neglected.

3.6. Validation

Full-scale Measurements of propeller damping are difficult to conduct and they are therefore very rare. Additionally, many of the data are confidential and therefore difficult to obtain. For the purpose of the present analysis, measured data are fortunately available from sea trial measurements. The validation has been published in *Krüger S. (2017)*. The propeller is a fixed pitch propeller with four blades, diameter 6m, area ratio 0.5, pitch ratio (at 0.7R) 0.7. The measurements by *Orthmann (2017)* and the computations are shown in Fig. 7. The black curves show the results for the presented method, for reasons of comparison the results obtained from the GRIM method are shown.

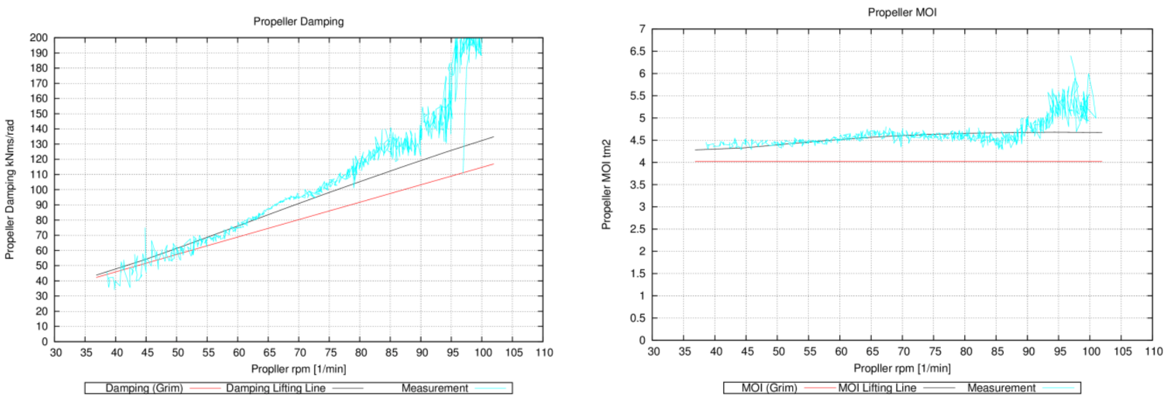

Fig.7: Measured and computed propeller MOI and damping (blue) during a sea trial run up according to *Orthmann (2016,2017)*. red: Grim's method, black: present method

4. Conclusion

The development of software tools is often necessary, if special technical problems have to be solved. The presented lifting line model allows the computation of hydrodynamic damping and added MOI for any type of screw propeller. The proposed method is based on the theory on propeller damping published by Schwanecke and Grim, who have applied well established methods from the airfoil theory to the screw propeller. Both authors also have developed simplified formulae to avoid the complex computation of the propeller inflow conditions.

Besides the complex physical modelling, the implementation of software needs special knowhow and a lot of human resources. For many organizations, it is not possible to provide such resources alone. A sharing of resources for pure IT tasks is useful, because a cooperation in this topic means no loss of own intellectual property. The E4 framework bases on a grid of individual source code servers. The access to these servers can be configured by every partner self. Standard functionality is stored in a special repository and is supported in cooperation for the whole group of partners. Further a central server exists for checking the software and for assembling binary software packages. This approach of a distributed software development allow sharing resources by still keeping control about the own intellectual property.

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Future of Autonomous Shipping from an Administration Point of View

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Abstract

This paper presents the future of digitalization from an administration point of view. What is the administrations responsibility, and how do we cope with innovation and new technology within the scope in Norway.

1. Introduction

The national authority has a social, financial and ethically responsibility towards its citizen. When it comes to the maritime authority there is no exceptions. The Maritime authority is the administrative and supervisory authority in matters related to safety of life, health, material values and the environment on vessels flying the national flag. The administration also need to ensure that foreign ships in the flag states waters are acting save, secure and environmental in accordance with international agreements. In addition, the administration has a responsibility for ensuring the legal protection of the national fleet, sailing with the flag of convince.

2. The Authority's responsibility

2.1 Adviser

National and international interests will always be complexed and due to various maritime perspectives, the administration may have different prioritized agendas. Depending of what kind of clients or customers it has, the flag state take a stand. However, the authority will always have a duty to provide guidance to its customers. Regulations and instructions need to be available for the relevant stakeholders. Guidance to governmental organizations is offcouse a part of this.

2.2 Driving Force

The authority should also be a driving force for the industry and political authorities in the safety and environmental activities. It should encourage the maintenance and development of a strong national flag. The administration should be a visible and clear participant in the national and international regulatory work. In my opinion, this is one of the clearest indicator of a quality flag! Attitudinal measures should also be a central issue to its work. Research, innovation, risk assessments and lessons learned from accidents/ incidents should form the basis for its priorities.

2.3 Supervisory authority

In most cases the administration also has the supervisory authority pursuant to the national

- Ship Safety and Security Act,
- Product Control Act and;
- Act relating to Recreational and Small Craft.

The supervision includes certification, document control, inspection and auditing to ensure compliance with the legislation. The supervision contributes to the creation of strong behavioural attitudes with regard to health, safety and the environment.

2.4 Register

To maintain control over the flag vessels, the administration need to manage the function of real property register, a registration which ensures the legal protection of registered rights and is maintained by correct and updated registers of the national ships. In Norway, this is covered by law, in the Norwegian Maritime Code to manage the function of real property register.

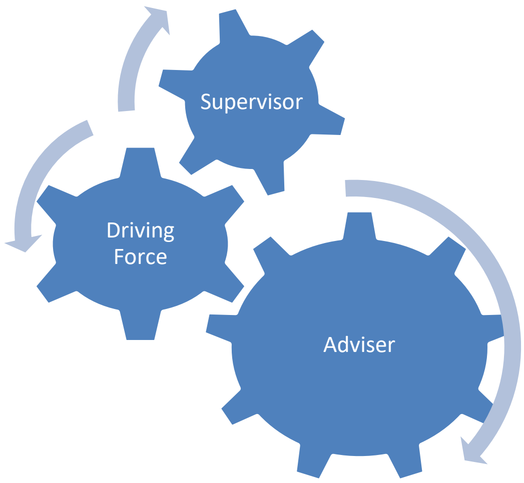

Fig.1: The cog-wheels of a quality Flag

3. The preferred maritime administration

To achieve the center attraction and become a preferred flag - both for shipping and maritime industry. The administrations need to make a difference. It cannot be passive. If you like to be a preferred stakeholder, you cannot be a free rider! If you do so, your effort will limit itself. The future of shipping holds new segments of which flags of convenience will have great difficulties to obtain if they are not dedicated and active. It's not enough to hold a management regime.

The administration need to be:

- Available to its customers. 24/7.
- It will not be enough in the long run, just to have protocols, regulations and acts.
- The owner's need a competent and experienced administration, which can make safe and secure decisions on, contravenes of established routines and regulations. As the maritime domain is moving into a significant change. The administration need to hold a relevant expertise and be recognized for its competence in the maritime cluster.
- The administration need to act and contribute to the development of new and advanced technology. To make it safe and secure. WE need to be committed and serious.
- Administration with significant influence need to use their channels and co-work with other administrations to make common ground.
- Hopefully good reputation is worth something. And quality will concur simplicity and greed. Safety need to be a part of the development.
- Countries with ability to take decisions and create sustainable ways ahead will be preferred partners as they can set the premises.
- Administrations, which has the ability to think new, turn around and make innovation and new technology available for its users, will become attractive for the new shipping era.
- We need to be somehow pre-active, dynamic and looking ahead for technology, which can make the oceans more reliable, safe and secure. With low environmental risks.

Of course, the relations to the economy also need to be in line. The flag need to offer a competitive services so that the industry chooses to register it's vessels in respectively flag. We need a blue economy in a green and secure shipping environment!

4. Contribute to making National innovation to international standard

In Norway, we have the benefit of being a small but complete cluster within the maritime domain. We have a chain of participants from the industry research and development (R&D), manufactures, makers, insurance, management, union, class societies and authorities working together. We have arenas of cooperation capable of concluding. The Norwegian Maritime Authority encourage the industry by:

- Stimulate to innovative thinking. We strive to be open minded, always looking ahead for better and safer way to operate.
- We Coordinate and facilitate ideas which seems to be sustainable.
- We actively participate in international forums, promoting safe, secure, environmental and sustainable ideas, which have beneficial potential.
- Invite the industry to participate in the Authority's international work
- We even take the initiative in many ways, which earlier were unthinkable.
- Active and Participate in many development projects.

4.1 Innovation and new technology

Norway sees itself as one of the big contributors in the international shipping and maritime industry. We therefore have taken an enterprising initiative with concern to sustainable new technology. Megatrends within "innovation" which we see today is mostly triggered by "new technology & Environmental requirements". These megatrends are seen as the main drivers towards new maritime innovation. Within the terminology of new technology, we have concepts as:

- e-Navigation
- Digitalization
- Automation
- Autonomous ships

Digital Ship
e-Navigation
e-Maritime

Increased environmental requirements is also drivers for these megatrends. Concepts, which will minimize human environmental footprints. By establishing regulations for Ballast water management and reduction of Greenhouse gases. Together with Establishment of an Energy Efficiency Design Index (EEDI), a Ship Energy Efficiency Management Plan (SEMP) to reduce emissions and create a more efficient and cleaner shipping. And by creating a designated Emission Control Areas (ECA) to reduce Sulphur content we have achieved great environmental benefits of these megatrends already.

4.2 New Technology - Driving Forces

Due to these trends, Norway has developed many new achievements in the name of innovation. To mention a few, we were the first to build:

- LNG tug boat - Borgøy with gas turbines delivered by Rolls-Royce.
- The very first UECC's LNG car carrier.
- And the first methanol tank boat
- The first battery ferry in operation – "MF Ampere"
- The first battery small smack vessel
- The hybrid "Vision of the Fjords"
- And hopefully the very first autonomous zero emission container vessel – "Yara Birkeland"

4.3 Automation, digitalization and Remote functionality

One of these new megatrends is driven by the new technology within the revolution of global digitalization. The technology has already started making Man superfluous and obsolete in many ways. The machine has started to take intelligent decisions by its own. Processes which earlier where dependent of a human interfering, the machines are now able to make their own decisions based on calculated algorithms or pre-programed behavior pattern.

The digitalization trends, which we see on the near horizon, have an autonomous approach. Where the human machine interface is moved from the decision making and operational to the supervising table.

- Artificial intelligence (AI)
  AI as we call it seems to be the goal. We are moving from SIRI to self-driving cars, the new self-learning technology is progressing rapidly. The technology can now encompass anything from Google's search algorithms to autonomous driving. Even though the self-learning technology today is designed to perform a narrow task, e.g. facial recognition, internet searches or driving a car or vessel, it seems like the long-term goal is to create a technology, which will outperform humans in whatever the specific task is. Soon and if we let it, the technology will be able to outperform humans at nearly every cognitive task there is.

  Areas of expertise where man already is outperformed in many ways include banking, insurance, brooking, travel agencies, cashiers. Also, automated industry assembly work, which earlier was tantamount with poor safety, or work related to repetition causing fatigue or inattention is replaced by robotics.

- Why the eager towards autonomous system
  Nevertheless, and despite these circumstances, we still see an eager towards a digitalization from the industry in general, but now also in the maritime industry. We can see that new segments of businesses which eager to make a soon approach. We actually see a potential of new business models emerging, which can be a competitor to traditional trade as we see it today

  This may be one of the reasons why we do not see the biggest enthusiasm towards autonomous systems from the owner's side. Another reason is probably the fact that the shipping industry is deep into a low conjecture, and for the time being have enough just to get the wheels running.

  The maritime industry has been shielded from many of these new technology developments for better or worse. The digitalization and automation in the maritime segment has been regulated through IMO and strong type approval regimes, and have therefor been held back. The technology has not been prioritized for commercial use even though it has been available for some time.

5. Benefits

When it comes to the potential of the autonomous systems – in my opinion, few industry segments can achieve bigger benefits than the maritime industry and shipping. Benefits such as

- Cost efficiency
  - When constructing autonomous vessels, there will be lower building cost due to less superstructure and no accommodation; there will be less to maintain.
  - The reduced superstructure construction will improve aerodynamics and stability.
  - Digitalization and optimization of the power management will reduce fuel consumption and emissions.
- Safety;
  - With fewer people on board there will be fewer accidents involving humans and to evacuate in case of emergency.
- Security

- Both cyber-security and general security will be at a higher standard than today. Because we can build the system around the concept and from scratch, we can adjust and interface cybersecurity for a digital approach.
- Physical security will be better by making vessels unboardable, and therefore of no interest for hijackers or stowaways.

- Environment
    - These vessels will most likely to have an environmental footprint with zero emission as a goal. That means less emission to air and water.
- Efficiency
    - The administration on board is digitalized and taken care of ashore or automated on board. This enormously impact the administration burden.
- Digitalization
    - All systems on board will be harmonized and interfaced. The systems will work together and make the navigation more exact and safer.
- Reliability
    - Because all operation scenarios must have been gone through thoroughly, the reliability is better. The fact that autonomous vessels need to have compensating measurement to achieve better safety and reliability gives these vessels an advantage.
    - Also redundant systems make it more reliable.
- Reduction of Human errors
    - Reduction of human errors is obvious.
    - Continuity – Non-stop process is also a benefit.
    - Machines do not need breaks as humans. There is no fatigue and operations can go on 24/7.
- Automated Logistics
    - The logistics is calculated and put into transportation chains, automated and available for all relevant stakeholders.
- Shore-based control stations
    - Control stations onshore will be a big contributor and take care of incidents which may occur accordingly, and if necessary take over control of the vessel.

Fig.2: Cost-efficiency equals quality

6. From concept to project

Even though we have a lot of enthusiasm around the autonomous trends today, I think it still will take some time until the world is ready for a general fleet of commercial autonomous ships. The future is still unknown! All future views are tentative assumptions based on the development trends. Even due to the circumstances that we see a rapidly development today around the subject. I think general automation and digitalization of navigation and communication equipment will come first. New technology will pave the way for the new era of automation. When the bridge is harmonized, integrated and automated, we will harvest experience and statistics that will make the change possible. R&Ds will lead an important role in this development. Project based experience will help with showcases that will show us that autonomous systems can be made safe and secure in a cost-beneficial manner.

7. When and Where

7.1 Test areas for autonomous and remote ships

The future will hold an interaction between unmanned and manned vessels operating. Vessels which is navigating safe and secure and in accordance with COLREG! The autonomous vessels will behave as they were manned, and the manned vessel, which will be very much automated, will navigate in accordance with the traffic pattern and COLREG as today.

At the start of this maritime autonomous era, we will need dedicated areas to operate these vessels. Dedicated areas so that we can supervise and take necessary precautions in a period to provide tests and to collect data from these.

Due to these circumstances, Kongsberg Seatex in Trondheim took the initiative in August 2016 to establish such a location for new and innovative technology to operate under restricted conditions, and under authorities' supervision.
And on 30.09.2016, the Norwegian Maritime Authority, Norwegian Coastal administration, NTNU, Kongsberg Seatex, Kongsberg Maritime, MARINTEK, Maritime Robotics and the port of Trondheim signed an agreement of intent to make the Trondheim fjord available for testing of remotely controlled and autonomous systems. This became the start of the new era for autonomous shipping in Norway. The first test area of this kind in the whole world were established! There will also be new test areas as the need arises. Grenlandsfjord in the southeast part of Norway is most likely the next test area to be considered. These test areas will be the first locations which we will see Autonomous vessels in action. Much likely, will these areas also grow into commercial areas as well.

7.2 When

When will this take place? When will the first autonomous vessel sail? Well, there are stages to climb. There is complexity to define and there are regulations to make. Even though Norway has Sovereignty over its own territorial waters, it does not so in international waters. Due to these circumstances and the nature of convenience, national trade will be made available first.

Nevertheless, the unmanned autonomous vessel is the goal. We will first see a growth of automation in general. Already existing vessels and new buildings will be equipped or built with new and more complexed equipment making an efficiency footprint. We will see:

- More advanced DP systems with sailing modes, which will be functional for voyages from A to B, operating with an eco-efficient pattern.
- automated crossing systems based on
  - advanced autopilots,
  - DP (dynamic positioning) system,
  - Collision avoidance systems with integrated algorithms making safe real-time decisions based on the vessel's maneuvering characteristics, local traffic, topographic and weather conditions
  - complexed sensor-fusion functionality going beyond GNSS references systems (e.g. gyro, radar, laser, spot track, RADius (relative position reference system of Kongsberg), hydro-acoustic positioning systems, etc.)

We will also see

- Automated docking systems, taking the vessel safe and secure from end of voyage to all fast at the berth, based on sensor fusion.
- harmonized bridges (e-navigation/ INS) built for a digital and interfaced purpose

- de-centralized navigation tasks
- wider communication carriers
    - Capable of transmitting and receiving
    - IoT (Internet of Things) or “Internet of Sea” if you like
    - Big data and such

Interfacing of data received both from shore and interoperations between the equipment on board will make the steps towards autonomous and remote operations available.

7.3 Sustainable Innovation

In Norway, the authorities has acknowledged that the digital world is imminent and already here. It is no use stopping it. Why should we prevent new technology and innovation if it is safe, secure, beneficial and sustainable? Of course, there is social aspects in this matter, which we need to consider. However, I think that this is an issue that will be taken care of and standards and limitation will be defined as we go.

We think that the safety of sea in general is dependent of a co-working between governmental organization, industry and R&D institutions with regard to automation and autonomous systems. We need to work in close relation and take advantage of the complete maritime chain to achieve a sustainable result. The Norwegian Maritime Authority is working in parallel with national and international organizations and maritime governments worldwide to make a safe approach towards an autonomous shipping.

We are still at the Conception stage of these innovation, but we are preparing. NMA have an obligation and a corporate social responsibility towards safety of life at sea, health, material values and the environment on vessels flying the Norwegian flag. And it is therefore important that we make the process safe, secure and sustainable.

Parallel with these obligations we also see a responsible to obtain a Norwegian maritime quality reputation. And we like to see the maritime industry succeed making safe Norwegian innovation into international standard.

8. Norway’s adoption of new technology

8.1 The leading innovative maritime nation

Due to the Maritime Cluster in Norway, we need to take a proactive role. As one of the mayor maritime Flag states in the world, we - together with other have a responsibility to prepare the future with a safe and sustainable maritime industry. The Norwegian government therefor has made a political statement of being “the leading innovative maritime nation”, given significant amount of founding to Research and development (RD) within innovation and new technology.

8.2 Strategy

Ocean Strategy 2017 (Hav strategi 2017)

Maritim21 

Maritime Strategy 2016 (Maritime strategi 2016) 

National Transport Plan 2018-2029 (Nasjonal Transport Plan) 

Fig.3: Norwegian strategy documents

8.3 Funding

MAROFF – 137.5 mill. NOK 10/19 approved project is automation related project

ENNOVA – 2.3 billion (2017) Financial support to innovative, environmental and sustainable creations.

Innovation Norway – ~930.2 mill. NOK (RD)

In Norway, there is a big activity with concern to autonomous and remote shipping and Automation in general. There are several projects, which have a multimillion funding from the Norwegian Research council Innovation Norway and ENOVA. There is a considerable turnover of funding in the Norwegian maritime cluster. The funding is meant to stimulate the industry during a phase of significant change.

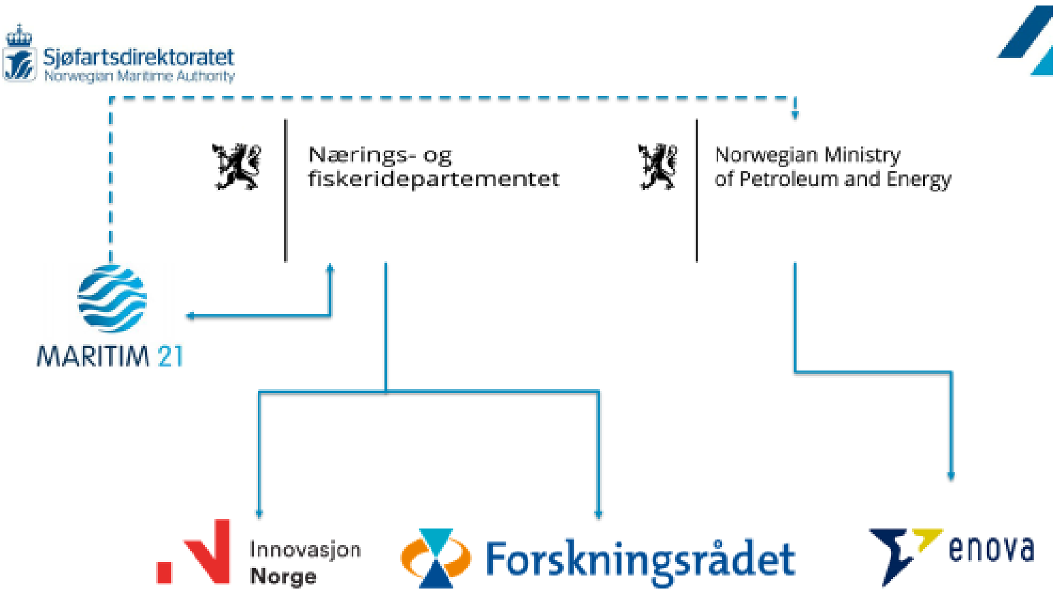

Fig.4: Norway's R&D founding

9. Projects in progress

9.1. Connection studies

- SIMAROS - Safe Implementation of Autonomous and Remote Operations of Ships (DNV GL)
- ROMAS - Remote Operation of Machinery and Automation Systems (DNV GL)
- Open Bridge (VARD)
- ASTAT - Autonomous Ship Transport at Trondheimsfjorden (Kongsberg Seatex)
- SAREPTA (SINTEF OCEAN)
- EGNSS H2H (SINTEF OCEAN)
- Autonomous Zero emission container ship (DNV GL) from the green coastal program at the west coast of Norway

Fig.5: Green coastal shipping – DNV GL

9.2 Newbuilding projects for autonomous or remote ships in Norway

There are several projects scheduled for newbuildings of autonomous and remotely controlled vessels. Not yet for approval at the administration, but conception studies at consultancies, where the Norwegian Maritime Authority is involved, and we see the potential in the near future.

10. Regulation Framework

As per today, we do not have any regulations that cover vessels sailing without an officer on watch (OOW). Before we have a national regulation framework to build autonomous and remotely controlled operation upon, we need instructions and precautions made available to set the premises. These premises are the Authority's responsibility.

- National regulations
  In national waters, Norway can decide where and how to operate its vessel. Nevertheless, even in national waters we have international traffic, which we need to pay attention too. So, national regulation is not preferable. However, national regulations or temporary instructions can be an option in the vacuum of existing regulations. However, the goal is to achieve an international regulation regime also for autonomous shipping. To achieve this, we need to go through the United Nation's – International maritime organization (IMO)

- International regulations
  International regulation will take time. Based on experience, it takes between 10 to 15 years to get a new regulation regime established in IMO, if there is a need for one! I think there will be established bilateral agreements between national coasts before we see a full-scale international regulation and standards regime. Due to the fact that the process in IMO is very slow, we have already started the approach towards autonomous regulation international. Strategic adjustment was notified to IMO at council last year, and were acknowledged. The Council decided that "Automation and remote operations" should be included in the IMO's strategic framework for 2018-2023 and will therefore be a considerable agenda item for MSC and the sub-committees and put in the High-Level Action Plan accordingly.

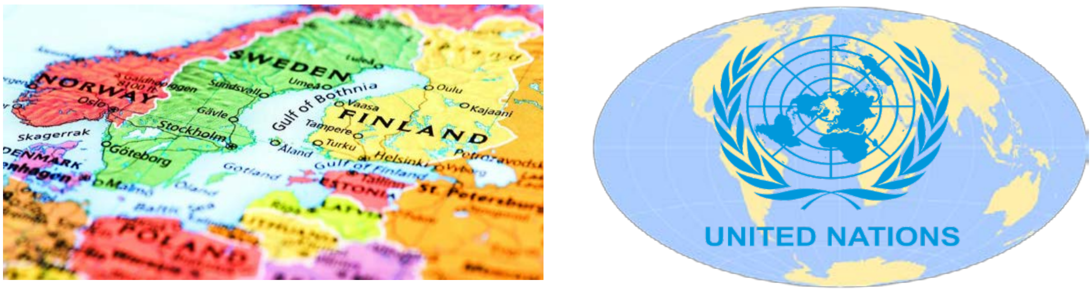

Fig.6: Regulations will move from national to regional to intzernational level

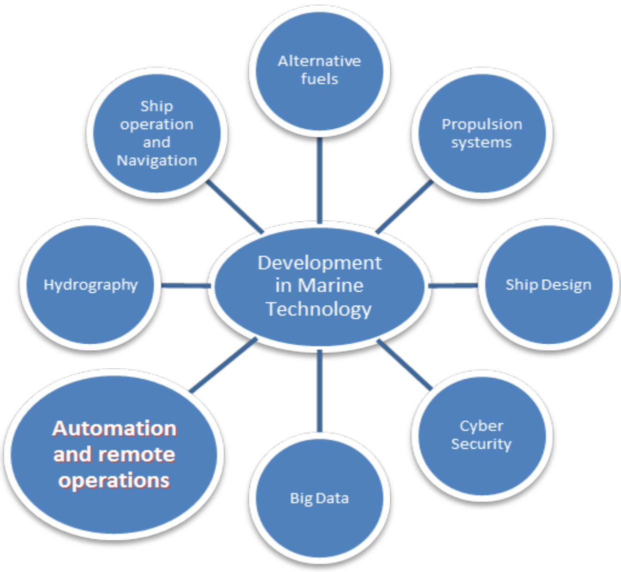

Fig.7: IMO decided to include "Automation and remote operations" in its strategic framework

11. Conclusion

We will see a change! It will make the shipping more Digital and automated. The extent of the automation is dependent of the trade area and the type of vessel. National small coastal trade of container vessel and general cargo ships will have an easier way of approval than a Passenger ship. International regulations will take time while national adjustment may be possible in a shorter period. Even though national legislation is easier to achieve, we need to stress the international legislation despite a national regulation regime.

Success is dependent of a safe and secure way to approach autonomous- and remote operations, and a co-working with R&D, Industry and authorities. Norway will keep on supporting innovation, which is beneficial, safe, environmental and sustainable. We see the potential of digitalization and automation. The maritime authority will facilitate and prepare for a blue shipping in a green environment. And the industry in Norway is pushing forward.

Ship Design Technologies – A CAVE-Man's View

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Abstract

This paper presents a perspective on modern ship design looking at four key tasks collected under the acronym CAVE: creating design alternatives, analyzing them, visualizing options and results, and deriving enlightenment (or knowledge) from design exploration. The paper gives some historical perspective before reviewing some modern developments in computer-aided ship design, drawing frequently, but not exclusively, on the experience of the author.

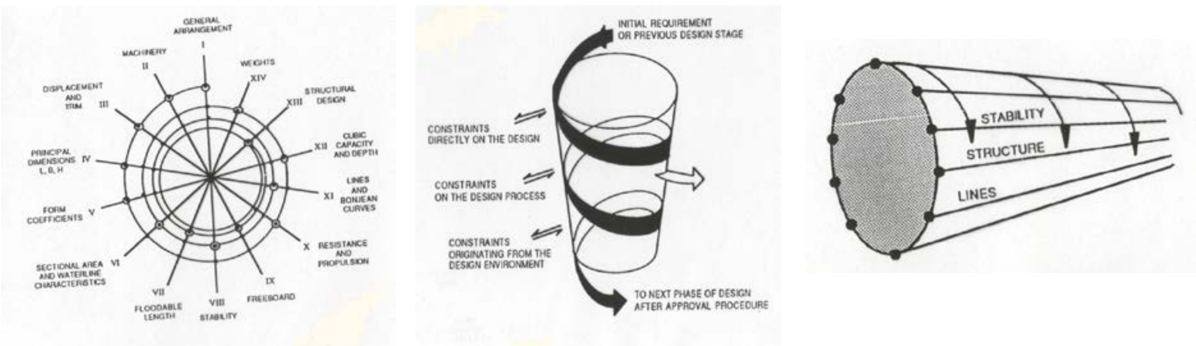
1. Introduction

The design process is often described as a design spiral following the initial model of *Evans (1959).* This model has been "refined" by proposing spiraling cones, *Andrews (1981)*, or interconnected spirals, *Mistree et al. (1990)*, but in essence it was the spiral in disguise, Fig.1. This model for ship design has been rejected frequently, as the sequence of analyses and decisions is not as sequential as the spiral models suggest. Ship design seems to be instead a rather chaotic process of combining various analyses with 'intelligent' or 'creative' generation of solutions, sometimes in parallel, which are then analyzed, evaluated, possibly rejected or modified. The sequence of these elements in the design process changes even for absolutely the same design task from designer to designer. There is no absolute criterion what is the best design process sequence.

While different designers may well apply the same tools (or at least tools of comparable performance power), some designers manage to get better results. I see this in rough analogy to nature. The DNA is composed of the same four basic elements, whether it is the DNA of a bacterium or the DNA of a Nobel Prize laureate. Apparently the proper combination of the same four simple elements can make a big difference. Rather than speculating whether computers in the (distant) future may outperform humans in the design process, I focus on the "basic elements" of ship design and highlight advances in computer technology supporting the ship design process. The ship design process remains human-centric, but the computer accelerates processes and improves the "classical toolkit" of the designer.

Repeatedly performed tasks of the designer may be grouped into the following four key CAVE tasks:

1. Creation (creative, intelligent or systematic creation of solutions)
2. Analysis (evaluation, simulation, computation)
3. Visualization (representation, communication)
4. Enlightenment (knowledge, identification, learning)



Evans (1959) *Andrews (1981)* *Mistree et al. (1990)*

Fig.1: Ship design has been frequently described as a design spiral process

2. Creation

The generation of solutions is rather a creative task. While “Artificial Intelligence” is by now widely accepted as an additional useful tool also for naval architects, nobody contemplates (seriously) “Artificial Creativity”. And yet the computer may help us to generate better solutions, namely in the context of concept exploration and/or optimization, *Bertram (2003)*, *Hochkirch and Bertram (2012)*, *Bertram and Hochkirch (2015)*:

- Concept exploration
  Concept exploration models (CEMs) have been proposed as an alternative to ‘automatic’ optimization. More recently, “design of experiment” (DOE) has been used as a term for the same design strategy: A large set of candidate solutions is generated by varying design variables. Each of these solutions is evaluated in key performance indicators and stored. CEMs thus generate a “map” of the unknown design space. Using suitable graphical displays, the designer gets a feeling how certain variables influence the performance of the design. The approach was deemed impractical for ship design in the 1990s due the then excessive computational requirements, *Erikstad (1996)*. However, parallel computation has changed this and concept exploration is now used in commercial projects.
- Optimization
  Optimization looks at thousands or even tens of thousands of designs and uses an optimization algorithm to find the best design. For many modern optimization problems, genetic algorithms (GAs) or related evolutionary optimization algorithm are the preferred choice these days. GAs are significantly less efficient than older gradient-based search algorithms. However, they are easily parallelized and robust in finding global optima, i.e. they do not get stuck at local optima. (Single-objective) optimization is in theory a mathematically well-posed problem. However, objective and all constraints must be expressed as mathematical functions. This is not easy in practice.
- Multi-objective optimization
  Optimization for multiple objectives is strictly speaking nonsense. Mathematically you can only optimize for one objective, respectively an optimum is only defined for one objective function. In layman terms, finding the fastest (objective: speed) and cheapest (objective: price) car will result in the question: Make up your mind, what do you want? Multi-objective optimization in practice is short for a combination of concept exploration and optimization. The concept exploration helps in making up one’s mind (requirements elucidation in the words of David Andrews of UCL). Then objectives may be reformulated as constraints or combined in one artificial objective function using weights for the individual objectives. The “best compromise” objective function can then be determined formally by the optimization algorithm of choice.

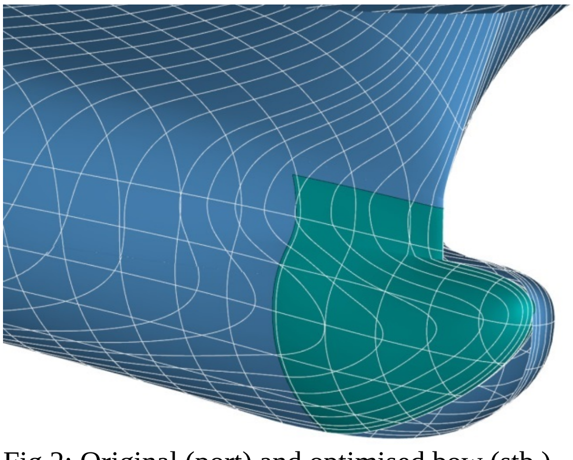


Fig.2: Original (port) and optimised bow (stb.)

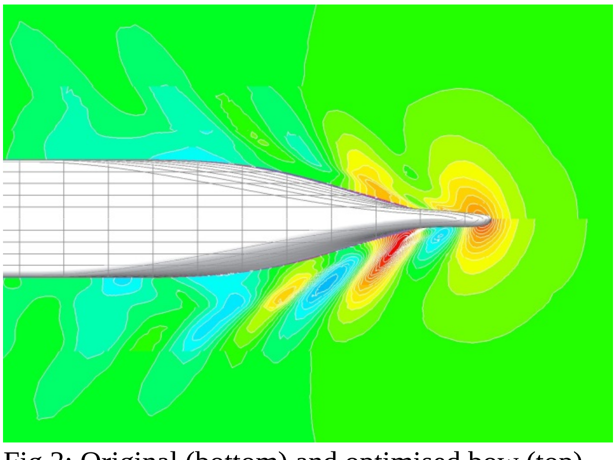


Fig.3: Original (bottom) and optimised bow (top)

Integrated design optimization frameworks, such as CAESES, www.caeses.com or modeFRONTIER, http://www.esteco.com/modefrontier, allow designers to focus on the design task and are in standard use in industrial ship design projects, achieving typically gains of 4-6% in energy efficiency, Figs.2 and 3, *Hochkirch and Bertram (2015).*

Possibilities are as numerous as the rapidly developing simulation tools which will be discussed later in the chapter on analysis. Applications include optimization of

- Hull for calm-water power requirements, *Hochkirch and Bertram (2015),*
- Hull for seakeeping, *Harries et al. (2012),*
- Internal subdivision for minimum oil spills, *Harries et al. (2011),*
- Funnel for smoke propagation, *Harries and Vesting (2010*).

New and improved simulation tools can be integrated in optimization models allowing new or more realistic applications.

Ship hull optimization and design in general has benefitted from advances in hull description, namely parametric hull description, e.g. *Harries (1998,2014).* A practical problem is that the hull description requires consideration of the intended optimization at the time of setting up the parametric model. Thus existing CAD (Computer Aided Design) descriptions are usually of little value and a new hull description (of an existing hull) is required for an optimization. *Butruille (2002)* compared three commercial CAD systems (NAPA, CATIA, CAESES (then Friendship Framework)) offering parametric descriptions using a generic ro-ro ferry geometry as test case. Table I gives his (subjective) evaluation.

Table I: Evaluation for parametric ship hull description benchmark study, *Butruille (2002)*

	NAPA	CAESES	CATIA
Ability to approximate given surface with parametric description	Not tested. Handling of parameters does not seem simple.	average (good for conventional forms)	good
Facility of parameterization (time needed for user)	quite slow	fast (GUI needed)	average (conventional forms)
Grid generation for CFD code	simple	simple	average
IGES export	good	good	average
Surface quality	average (too sensitive on changes in parameters)	average (some problems at junctions)	average (sometimes bad w/o apparent reason)
Robustness on parameter variations	poor	quite robust	poor
Proper program end in case of error in attempt to create parametric surface	no (sometimes program not closing in case of error)	yes (often without error message)	yes
Duration for surface generation	1 minute	some seconds	2-4 minutes

3. Analysis

The word simulation is derived from the Latin “simulare” which can be translated as “to mimic”. The Oxford dictionary defines "to simulate" as "to imitate conditions of a situation or process", specifically "to produce a computer model of a process". In this sense virtually all computer models used in the design process of ships would qualify as simulations. The field of such computer models in modern shipbuilding processes covers a wide field, including from transport economics, CAD models involving Virtual Reality (VR) and ergonomics, finite element analyses, hydrostatic and hydrodynamic analyses, production analyses, etc.

Stability analyses were among the first applications of computers in naval architecture. Today, the naval architect can perform stability analyses in intact and damaged conditions quasi at the push of a button. Two other "classical" applications of computer simulations for ships are CFD (computational fluid dynamics) and FEA (finite-element analyses). Both have been used for several decades now to support ship design, but today's CFD and FEA applications are far more sophisticated than 20 years ago. In CFD, we see today unsteady viscous flow simulations with complex two-phase flow simulation (wave breaking, cavitation) and complex ship geometry including propeller, appendages and hull, *Peric and Bertram (2011)*, Fig.4. Massive parallel computation has opened the next era of CFD with significant progress in computing accuracy, *Nishikawa (2015).* Cloud computing, flexible licensing schemes and software connections are expected to lead to a democratization of CFD, where small and medium design offices and shipyards may have direct access to the technology, *Hildebrandt and Reyer (2015), Gentzsch et al. (2016).*

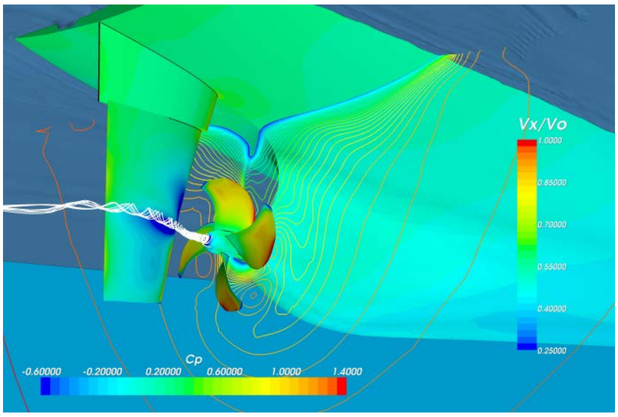


Fig.4: CFD simulation for aftbody with propeller, hull, appendage interaction

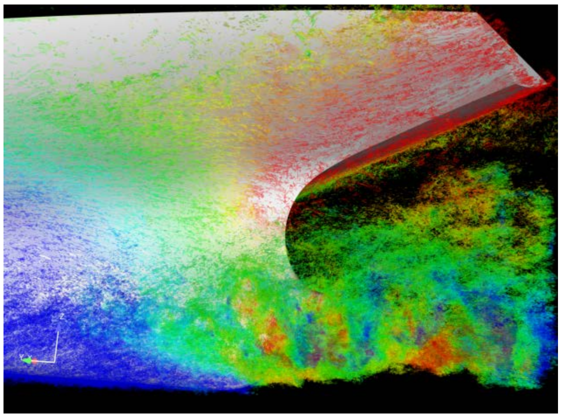


Fig.5: CFD simulation with fine resolution of turbulent structures (35 billion cells), *Nishikawa (2015)*

In structural analyses, frontiers have been pushed similarly to new applications or ever increasing level of detail, including:

- highly nonlinear analyses are feasible, e.g. for collision analyses with hulls rupture, Fig.6
- anisotropic FEA for composites, *Bertram et al. (2010)*
- high-frequency analyses (e.g. sound propagation in structures)
- fluid-structure interaction coupling CFD and FEA, e.g. *Schellin et al. (2015)*

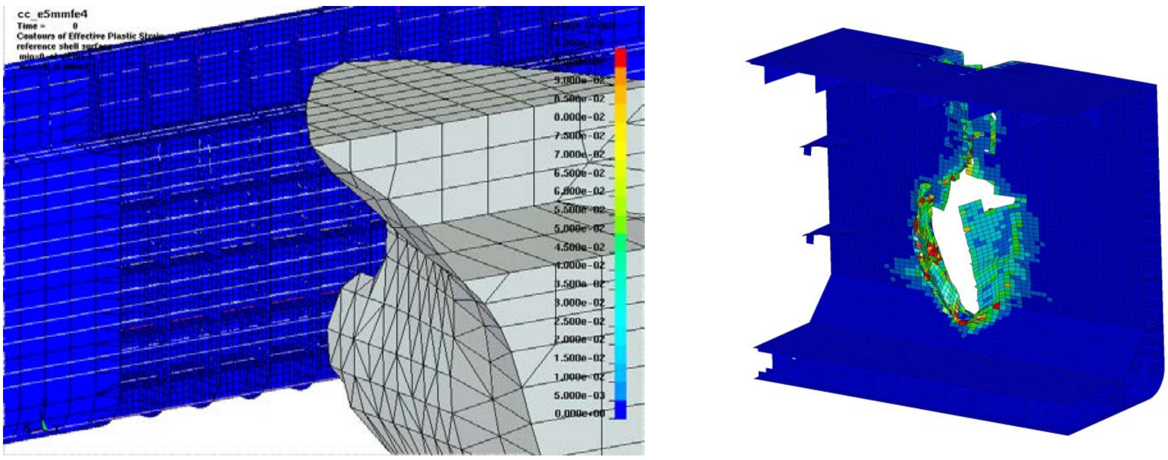


Fig.6: Collision analysis using nonlinear finite-element methods

The last decade has seen a rapid profusion of a plethora of simulation techniques and applications for ships. Flow simulations have been extended to "wind, fire, and ice":

- aerodynamic analyses of ship superstructures and ventilated rooms, Fig.7 – for aerodynamic drag, smoke propagation, helideck operation, etc.
- simulations of fire in ship rooms, Fig.8 - Despite impressive progress, fire simulations for ships face many problems. Classical zonal models are efficient, but questionable in tall rooms with strong 3-d effects. Standard CFD codes are not able to reproduce the evolution of large eddy structures observed in most fire plumes. The direct resolution of these eddies is prohibitively time-consuming. Ship fire simulations face thus the classical dilemma of large complex geometries (if e.g. a whole deck or even several decks are to be simulated) with strong local changes in the simulated properties (temperature, smoke density, etc.). Appropriate compromises between available resources and accuracy of the model will change in time as more powerful simulation tools gain practical application maturity.
- numerical ice-breaking, Fig.9, *Bertram (2017)* – simulations combine continuous mechanics (as in CFD) and discrete elements
- production simulations, Fig.10, *Steinhauer (2011)* - Discrete Event Simulation (DES) combines discrete events of a multitude of objects that are associated with specified characteristics or parameters. DES is increasingly used in production planning on advanced shipyards, but can be used for a wide scope of applications from design to operation. Despite a relative simplicity of the fundamental theory, simulation for complex systems offers considerable benefits in qualitative insight (e.g. identifying bottlenecks) and quantitative information (e.g. times to perform an assembly or to unload a ship).
- traffic flow simulations, Fig.11, *Povel and Bertram (2010)* - DES simulations become more complex if human behavior is included automatically in the simulation (via intelligent agents, i.e. small expert systems following some simple rules), as in the case of traffic flow simulations. Traffic flow analyses can be used also for the optimization of boarding and de-boarding processes. Advanced systems can combine dynamic simulations of fire and smoke propagation, seakeeping, dynamic flooding simulation and passenger traffic flow. Such multi-agent systems can be used for a variety of other simulations with relevance to ship design. *Simpson et al. (2003)* present a DES system combined with expert system elements mimicking port management decision in assigning ships to berths, Fig.12.

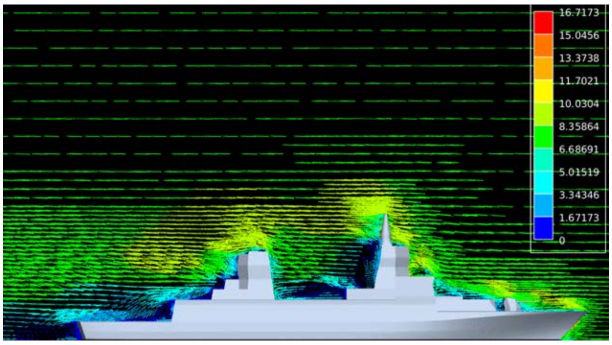


Fig.7: Aerodynamic simulation for frigate

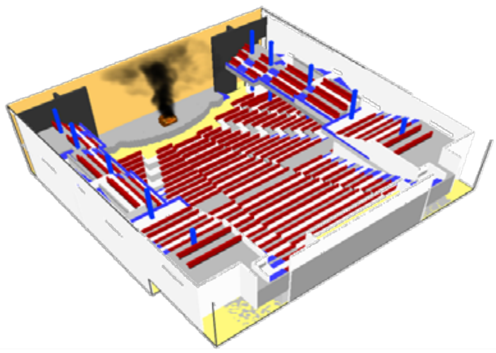


Fig.8: Fire simulation for cruise ship theater

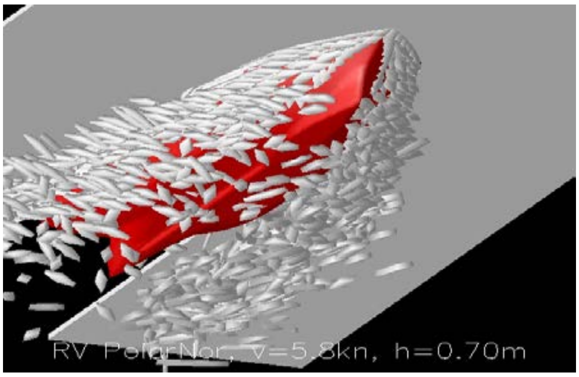


Fig.9: Ice-breaking simulation, *Puntigliano (2003)*

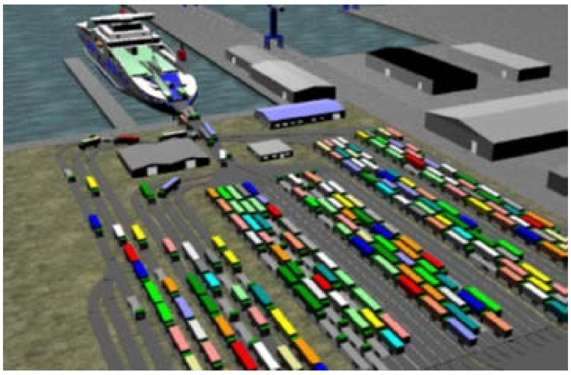


Fig.10: DES simulation for port operation,

Steinhauer (2011)

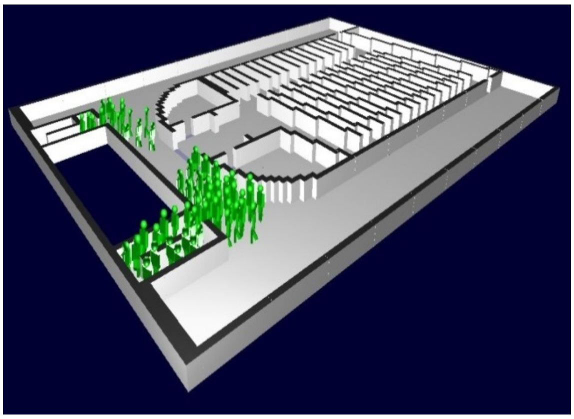


Fig.11: Traffic flow simulation for passenger evacuation

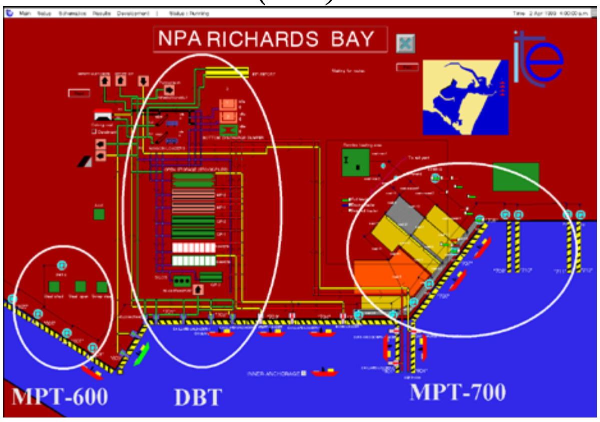
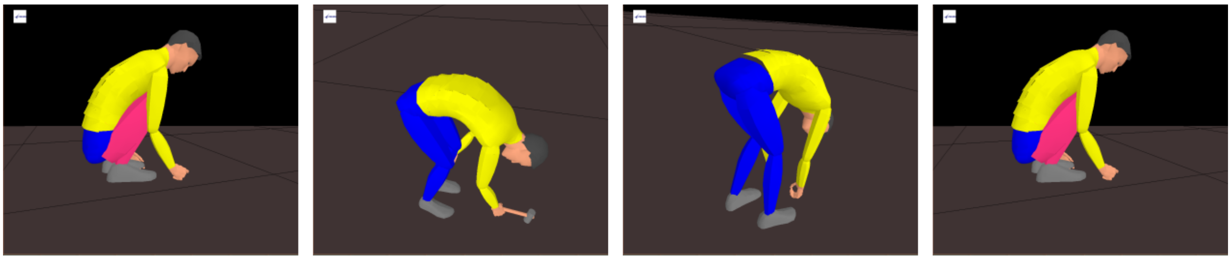


Fig.12: Expert system DES for port simulation, *Simpson et al. (2003)*

Simulation may also be combined with virtual reality if ergonomics are important. Virtual mannequins can then be studied in performing tasks in the building or operation of ships, e.g. for a shipyard simulation of certain assembly tasks, *Sasaki (2003)*, Fig.13. Similarly, virtual reality mannequins have been used to study feasibility of torpedo loading in confined submarines and crew operation in engine rooms.



Set the small parts **fixing the parts position** **check the parts position** **welding**

Fig.13: Examples of mannequin simulating basic tasks in ship sub-assembly, *Sasaki (2003)*

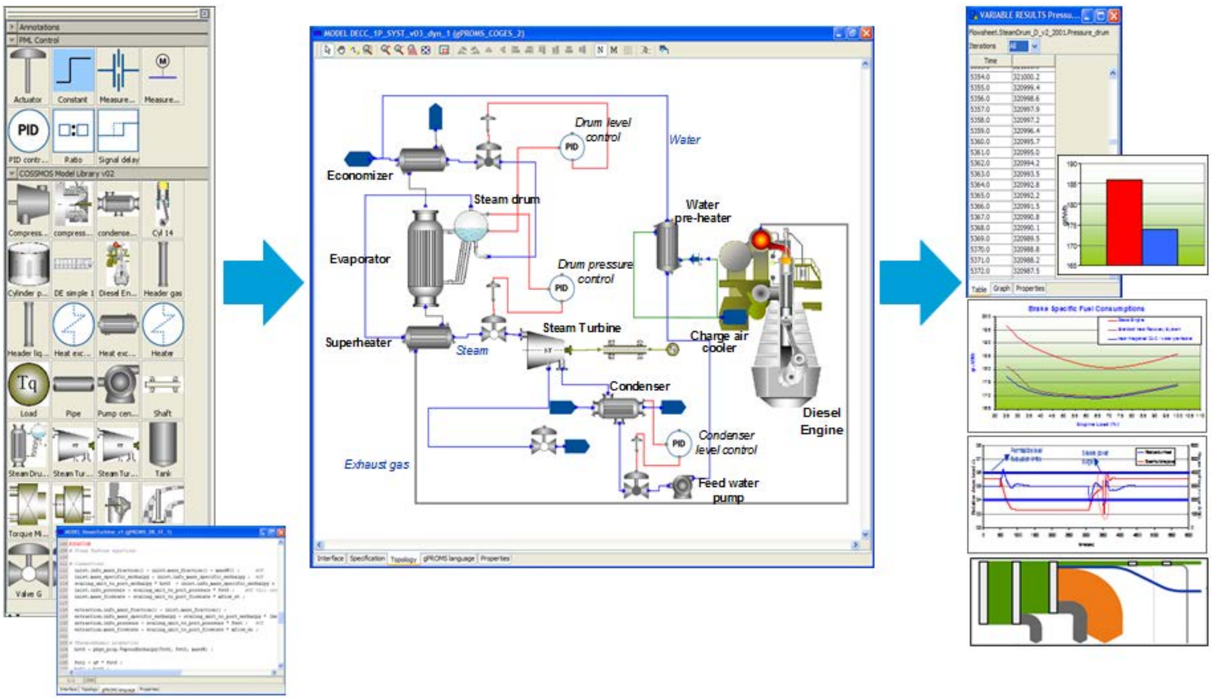


Fig.14: Energy flow simulation set up from object library to insight, *Kakalis et al. (2014)*

Energy flow simulation is a relatively new addition to the suite of simulations used in design and operation of ships. In essence, the simulation model considers energy providers (= main engine and generator sets) and energy consumers (propeller, pumps, heat exchangers, ventilators, cargo handling gear, etc.) in a graphical network, Fig.14, *Kakalis et al. (2014)*. Ambient conditions and operational profile are input dynamically (i.e. changing over time) and the simulation reveals energy flows and utilization rates (with bottlenecks and idle over-capacity). The detailed insight can be used to improve designs or operations.

4. Visualization

Wooden ships of the 16th century used already the ship definition based on cross sections erected on the longitudinal keel. The hull planks were aligned along thin wooden splines over the cross sections, Fig.15. These splines can be regarded as the forefathers of the splines used later on drawing tables to create ship lines on paper, Fig.16, and the mathematical splines used in CAD programs. *Harries (1998)* and *Bole (2012)* are recommended for a good overviews of the state of the art in ship hull design systems.

Fig.15: Cross sections and splines, ca.1700

Fig.16: Ducks and wooden spline, TU Berlin, ca. 1995

While we retained essentially the same representation of ships over centuries, the way we design ship hulls has moved from a curve-driven process to three-dimensional models even in the conceptual stage. Parametric modelling is a powerful concept in this respect, supporting rapid exploration of design spaces interactively in CAD or automatically in optimization, Fig.18, *Harries (1998,2012), Abt et al. (2003)*.

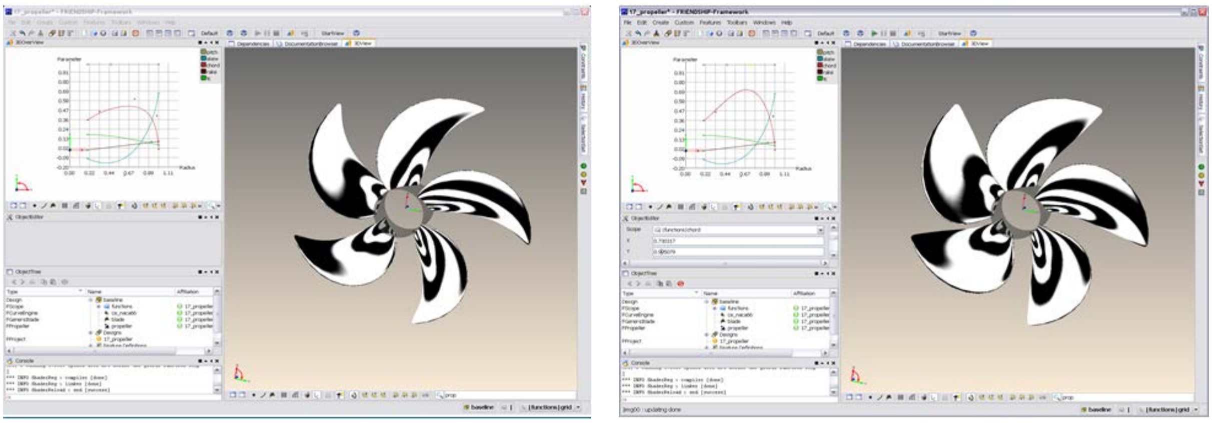


Fig.17: Variation of propeller with parametric form description, Source: CAESES

A more recent development is using 3d laser scans and automatic surface fitting to recreate complex surfaces, *Bole (2014)*. While this may raise concerns with intellectual property, it is important and required for many retrofit applications where original information is no longer available.

The progress in CAD systems towards three-dimensional product data models, Fig.18, allows today not only performing a large variety of analyses and simulations, but also advanced representation in photo-realistic displays or in Virtual Reality, Fig.19. While better visualization options are a bonus, the main benefit of 3-d design lies in data management and advanced simulation options supporting first-principle design.

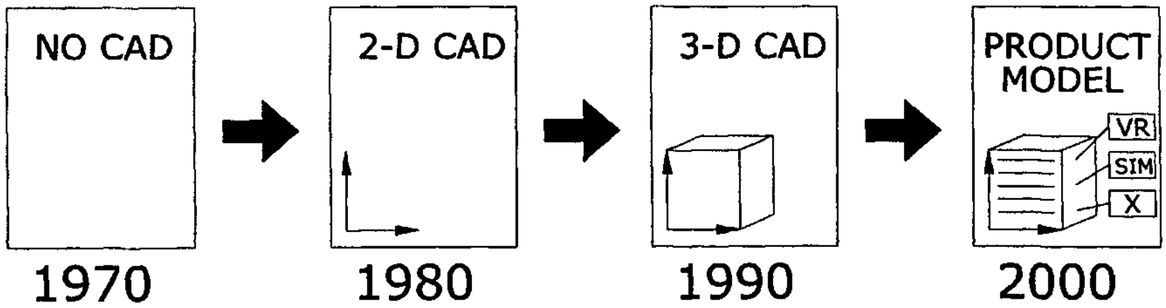


Fig.18: Development of ship CAD systems towards three-dimensional product models, *Aarnio (2000)*

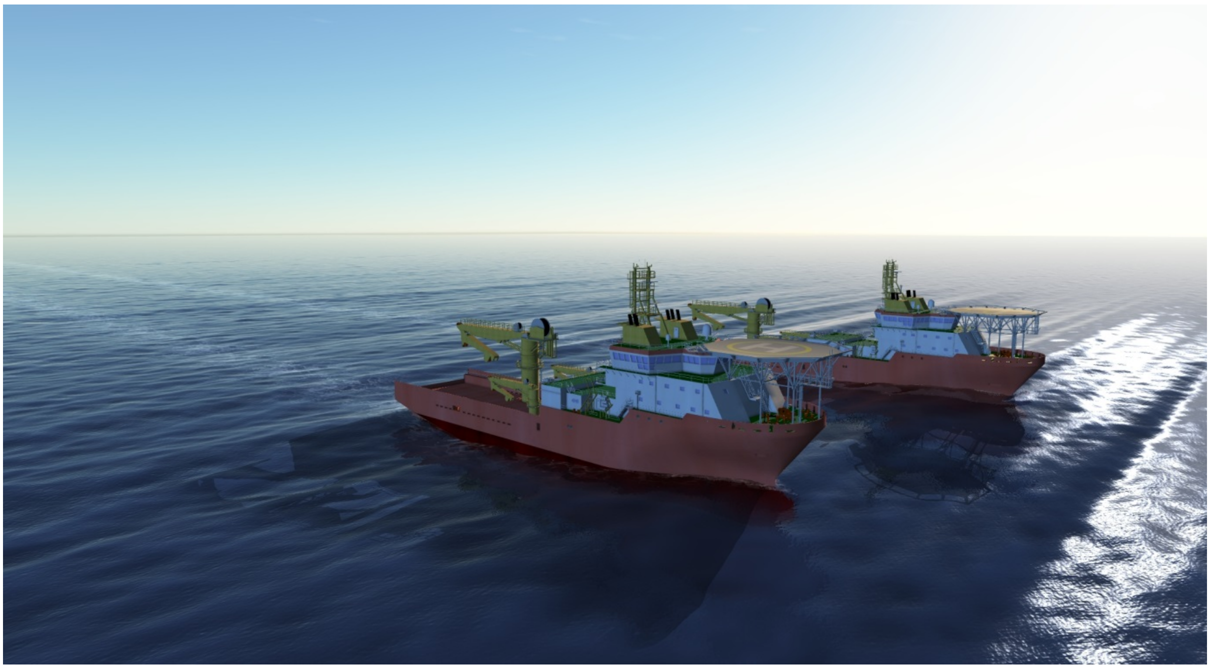


Fig.19: Photorealistic representation of offshore supply vessels in waves, source: CAESES

Virtual Reality uses 3D models of the world with fly-through or walk-through capabilities, and typically some user interaction; in essence, it is the same technology used in video games. This technology is gaining popularity for training, but also for aesthetics (interior design), Fig.14, orientation in ships (cruise vessels or large navy ships) and operational aspects in design (reachability, visibility). Considerable progress has been made by adding real-time physics, thanks to "physics engines", fast emulators of typical kinematics and dynamics of objects. This progress in simulations has been accompanied by similar advance in visualization techniques. Direct export of CAD descriptions or simulation models (grids) to VR results generally in unsuitable models. Directly exported models are typically far too detailed and big for the purposes of Virtual Reality viewing, *Lindenau and Bertram (2003), Wauchope et al. (2003)*. Dedicated export facilities in 3d CAD systems have improved the time required for creating 3d worlds. However, visualizing time-dependent engineering simulations in VR style involves an effort that is often underestimated.

Fig.20: Virtual Reality for interior design of a megayacht, *Lukas et al. (2015)*

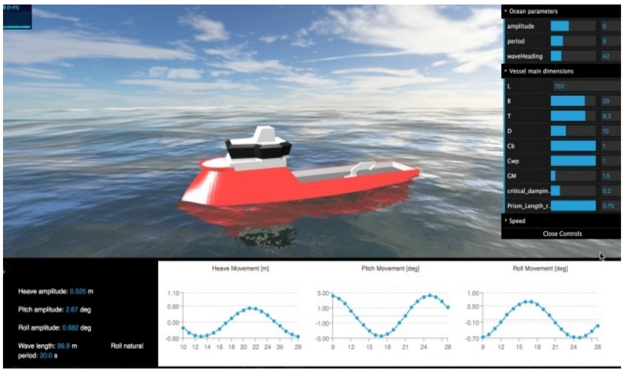


Fig.21: Game technology allows rapid and intuitive assessment of design performance, *Chaves and Gaspar (2016)*

5. Enlightenment

Knowledge remains at the heart of design. Knowledge comes largely from education and work experience. However, machine learning may support human knowledge in ship design. Artificial neural networks (ANNs), *Mesbahi and Atlar (2000)*, *Mesbahi (2003)*, allow very general functional fitting to data sets. ANNs can be applied if the functional relation between data is unknown or too complex to be explicitly specified. However, as with most Artificial Intelligence techniques, ANNs benefit from adding human knowledge. If human knowledge can e.g. eliminate irrelevant parameters or supply already a good approximation e.g. from theoretical analysis, the ANN will perform that much better in approximating the residual quantities. ANNs and related response surface techniques can be used to derive empirical design formulas which allow fast estimates in very early design stages, as envisioned by *Koelman (2013)*. In my experience, this approach has worked well for a variety of special applications:

- Bulbous bow design, *Mesbahi and Atlar (2000)*
- Propeller design, *Mesbahi and Atlar (2000)*
- Power prediction for tugs, Fig.22, *Mesbahi and Bertram (2000)*
- Power and resistance prediction for planing and semi-planing monohulls and catamarans, *Bertram and Mesbahi (2004)*
- Power prediction for SWATHs, *Bertram and Mesbahi (2006)*

User-friendly free software has certainly promoted the use of ANNs in the maritime community. My recommendation here is ICE (Intelligent Calculations of Equations) provided by William Faller (Applied Simulation Technologies), *Roddy et al. (2006)*. The software is user-friendly and allows exporting the derived formulas for use in other design software.

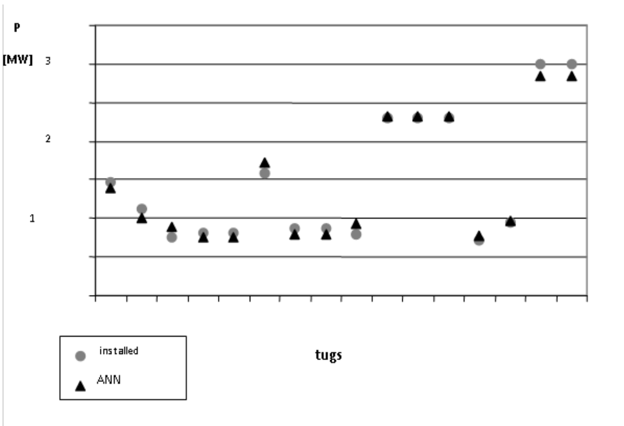


Fig.22: ANN predicted and actual tug power, *Mesbahi and Bertram (2000)*

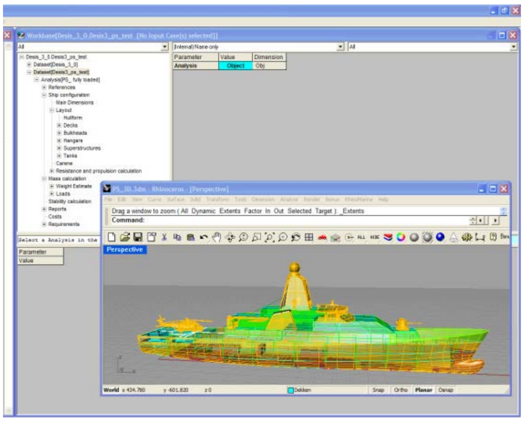


Fig.23: QUAESTOR expert system, source: MARIN

Parametric designs and simulations can be combined to create "numerical series" for a given ship type, a term chosen in analogy to classical ship design series such as the Series 60 of the 1960s. The resulting database can then be used to fit a neural net or other response surface. Once this has been done, designers can quickly extract data from the numerical model series to substantiate their design during the bidding and tendering process (which normally takes place under considerable time pressure). The approach is described in more detail in *Harries (2010)*, *Couser et al. (2011)*.

Knowledge-based systems (KBS) a.k.a. expert systems have been successfully applied to a wide variety of marine applications, *Bertram (2000)*. However, applications to ship design are rare and mostly disappointing. This is not really surprising. Expert systems support best tasks that are relatively simple and do not involve common sense or a "wide picture". Ship design is a largely unstructured and creative task, where even human experts have difficulties describing how they proceed in their design work. However, partial support can be given and aid the designer in practice as demonstrated by the Dutch navy in applying QUAESTOR, a design expert system with focus on ship hydrodynamics, Fig.23, *Es and Hees (2003)*.

6. Conclusions

Design combines the elements high-lighted above: creation, analysis, visualization and enlightenment. None of these should be seen by themselves. Only in proper combination is the full potential for advanced designs revealed. The individual chapters showed already on occasion the general trend towards combination of techniques. This trend will continue: simulation tools with Virtual Reality displays, expert systems with simulation tools, simulation-based virtual experience for training neural networks, etc. Stand-alone techniques have reached a high degree of maturity and further progress is best obtained by combing techniques. This requires often interdisciplinary cooperation and funding frameworks as well as modern communication possibilities allow increasingly sourcing the best partners worldwide for a given problem, Fig.24.

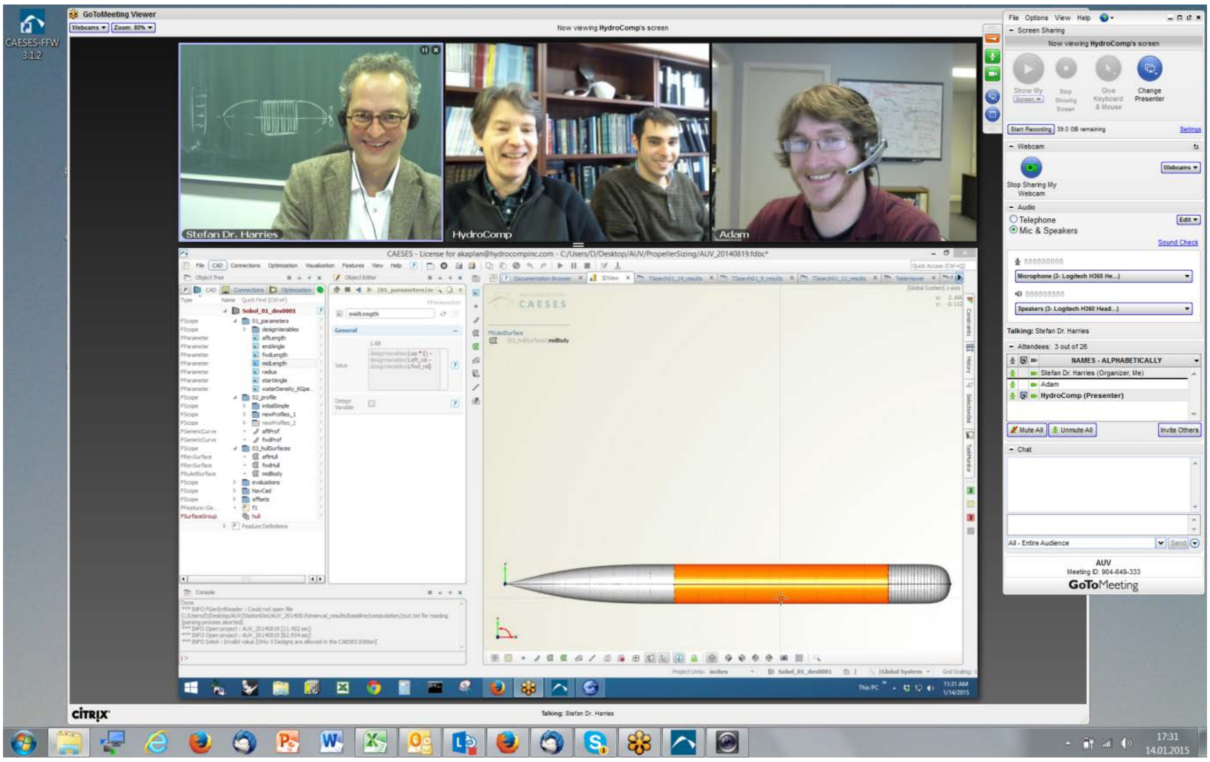


Fig.24: Web-based transatlantic cooperation between CAESES and HydroComp combining best-of-breed software, *Harries et al. (2015)*

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Merging Physics, Big Data Analytics and Simulation for the Next-Generation Digital Twins

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Abstract

A digital twin is a model capable of rendering the state and behaviour of a unique real asset in (close to) real time. Thus, it offers opportunities beyond the capabilities offered by traditional CAD, CAE and PLM. In this paper, we will lay out the core principles on which digital twins are founded, pointing to its history from engineering analysis and simulation models. Further, we compare a physics-based digital twin solution with artificial intelligence and machine learning. Our proposition is that while the two are fundamentally different in how knowledge and insight is generated, they at the same time offer opportunities for innovative complementary solutions based on big data sensor platforms.

1. Introduction

In the maritime industries, there is a considerable focus on the "Internet of Things" (IoT) and Digital Twin (DT) technologies. In the wake of this hype there is a multitude of technology and solution offerings, with corresponding inflated expectations. Retrofitting existing assets with sensors are supposed to make them "smart". Connecting assets to existing workflows are supposed to make them "intelligent". And further, by capturing exabytes of sensor data we suddenly have "cognitive systems", *Datta (2015)*.

Looking beneath the hype in order to assess what is the real, tangible contribution, a more nuanced picture emerge. To a large extent, it is the "emperor's new clothes" – an array of technologies that are mature and firmly established, such as advanced physics models, simulation, multivariate data analysis, signal processing, to name a few. At the same time, there is a momentum and scale behind this that by itself provides opportunities for new insights and new business processes. Gartner, *Geschickter (2017)*, has named Digital Twins as one of the top ten strategic technology trends for 2017. They expect 21 billion IoT endpoints by 2020, and a 35% annual growth rate in years to come.

2. Digital Twins – What, Why and How?

The term "digital twin" is relatively new, and we already see multiple flavours of how it is used. General Electric, in their Predix IoT platform, denotes DTs as "dynamic digital models of physical assets and systems", https://www.predix.io. Siemens describes the concept as "…a digital copy that is created and developed simultaneously with the real machine". DNV GL terms it a "…virtual image of an asset, maintained throughout the lifecycle and easily accessible at any time", *DNV GL (2017)*. SAP defines it as a digital representation using real-time data from sensors to continuously represents a physical reality, *Magyar (2017)*.

To some extent, the term "digital twin" is in itself flawed. Real-life twins don't even have to be similar. Even when we assume monozygotic twins, the digital twin concept bear little resemblance with real life. First, in real life, twins are two separate and unique identities - there is not one original, and the other being a reflection of the first. Further, after creation, there is no connection between them from a behaviour/state point-of-view. If we should continue to use biological metaphors, "digital clone" would be closer, where we have one original and one copy. Physical concepts have been used to describe the concept, such as digital mirror model, digital reflection, and digital shadow, but without having settled as an alternative. Still, the term "digital twin" seems to have settled for now.

In order to define what is a digital twin, there are several aspects that should be covered. The "What" perspective identifies the intrinsic characteristics that characterises DTs. The "Why" perspective focuses on their purpose and role, to make them a useful part of a business or engineering landscape. The "How" perspective describes the architecture and technology platform needed for their realization. In the following, each of these perspectives will be described in more detail.

2.1 The "What" perspective – Intrinsic characteristics of DTs

A Digital Twin can be defined as "a digital model capable of rendering state and behaviour of a unique real asset in (close to) real time". A further dissection of this definition points to the following five core characteristics:

- Identity, by connecting to a single, real and unique physical asset, such as a ship, a semisubmersible, a riser, or a wind turbine. When we observe a state on the DT, it corresponds one-to-one with a potential observation on a particular physical asset. In an ideal world, a 1-to-1 cardinality between asset and twin would be preferable. However, pragmatic considerations may imply a 1-to-N cardinality, with several more-or-less well-connected twins, each covering a subset of relevant physics dimensions, IP scope, stakeholder perspectives, sub-systems or processes.
- Representation, which implies the capturing of essential physical manifestation of the real asset in a digital format, such as CAD or engineering models with corresponding metadata.
- State, which demarcates a DT from a traditional CAD/CAE model, by having the capability to render quantifiable measures of the asset´s state in (close to) real time.
- Behaviour – reflecting basic responses to external stimuli (forces, temperatures, chemical processes, etc.) in the present context.
- Context – describing external operating context, such as wind, waves, temperature, etc., in which the asset exists in or operates within.

2.2 The "Why" perspective

"Why" is linked to the opportunities from a continuously updated digital model, as opposed to assessing the real asset directly. There are many aspects to this. It makes it possible to do monitoring and inspection on the digital twin instead, thus saving (part of) the effort to do this by physically inspecting the real asset. This is of particular importance when access is a challenge, such as for instance offshore structures or subsea installations. It makes it possible to aggregate data at relatively high fidelity, such as stress cycle counting in fatigue life utilization calculations.

Examples of useful applications of a Digital Twin for a high value, high complexity asset include:

- Remaining life assessment of structure
- Inspection/maintenance planning based on true load history
- Relationship between loads and power production for control system policies
- Early damage detection for pre-emptive maintenance and shutdown prevention
- Hindsight to foresight – access to (aggregated) time series for design feedback
- Virtual inspection support
- Predict consequences of (adverse) future operating conditions
- Multi-asset orchestration/control and synchronization
- Inspection/monitoring process support (cost reduction)
- Visualization and inspection of stresses at inaccessible/hidden locations

2.3. The "How" perspective - Digital Twin development and implementation

Implementation will depend on asset type, linked to the needs for accuracy, quality, availability, feasibility and similar parameters, traded off with cost and technology readiness. A minimum Digital Twin implementation must at least comprise the following parts:

- Edge capabilities for observing key aspects of the real asset's state and behaviour. This typically implies sensors with corresponding edge processing capabilities for data quality enhancements, such a calibration, filtering, time synchronization, etc.
- The Digital Twin core runtime, using the input stream from the edge to render a (near) real-time digital reflection of the asset's state.

The application layer subscribes to selected data streams from the Digital Twin as an integral part of different business processes. This can be specific end-user applications for monitoring and control, it can be legacy applications for maintenance and asset management, or the data stream from the twin might feed into data analytics and machine learning stacks for pattern recognition and decision support.

2.4. A digital twin example: SAP Digital Twin for Wind Power

An example from the offshore renewables domain can illustrate what a digital twin solution can look like. Traditional condition monitoring solutions for wind power systems are developed to report the operational state with the objective to understand changes which may occur over time. The main purpose of the monitoring is to prevent damage to the system and to ensure efficient operation of the asset. Control systems are traditionally based on generic algorithms and maintenance actions are often following pre-defined plans. The concept of real-time structural integrity management has not been implemented in condition monitoring solutions.

SAP's Digital Twin for Wind Power monitoring enables operators to implement adaptive control strategies as well as improved predictive maintenance tactics based on the physical condition of the system at any time, using a digital representation of the real asset. Control actions such as yawing direction of a wind turbine can be simulated in advance of a control decision, considering consequences for both power production and structural life-time. A yaw misalignment for example to the incoming wind direction can lead to a decreased power production. At the same time, the blade root can become sensitive to the yawing direction by in- or decreasing the overall fatigue loading of the system. Engineering simulation also allows operators to record structural loading throughout the asset lifecycle, enabling operators to increase the uptime by a better overview of the structural integrity, and by this the option to react preventively.

Already implemented in a pilot project with Arctic Wind, this wind turbine digital twin solution supports maintenance operations and structural capability utilization. The application screen-shots are intended to give an overview of a typical domain specific Digital Twin application.

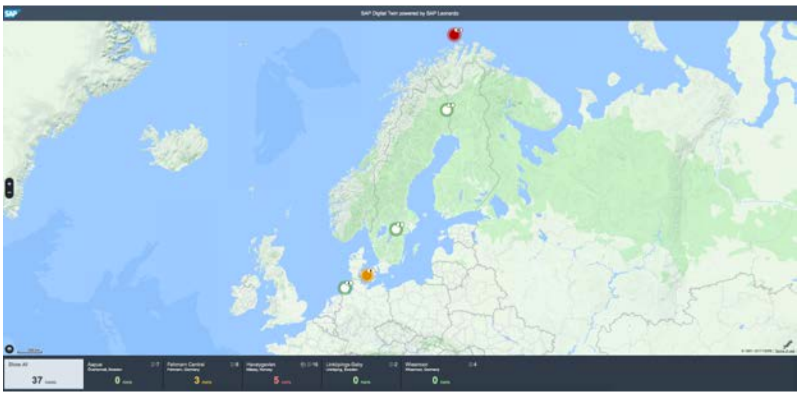

Fig.1: The landing page gives an overview of the operations, with indicators for events to be followed up.

Fig.2: The site overview page outlines a specific wind farm, where high level details on individual assets can be summarized upon selection

Fig.3: When selecting a wind turbine in the farm, details on structural alerts including 3D real-time visualization can be investigated.

Fig.4: Asset Component Analytics & Model-Based User Experience

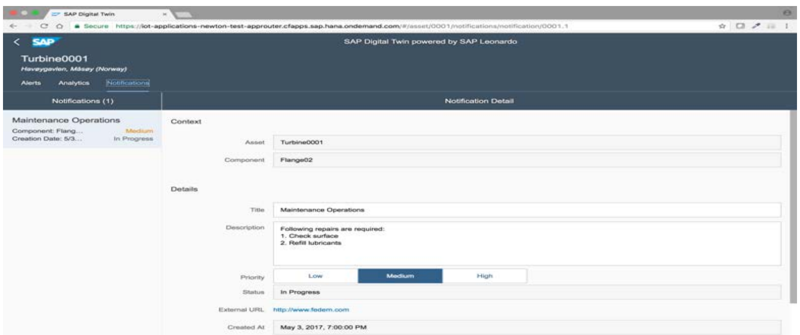

Fig.5: Additional information on components is supported by SAP Enterprise Asset Management Integration

3. The Digital Twin origin – physics and simulation

Though the concept of a physics-based digital twin, at least as it is understood here, is relatively new, its foundation can be traced back well-known constructs that have been widely used in the engineering community, as illustrated in Fig.6. It is based on engineering analysis and its foundation in Newtonian physics. By adding time as a dimension, asset behaviour can be assessed, allowing for the analysis of operations based on anticipated load cases. From here, the further evolution of the digital twin is based on two fundamental contributions; switching from (anticipated) load cases to sensor-based observations as the main input for the model, and switching from simulated time to (close to) real time.

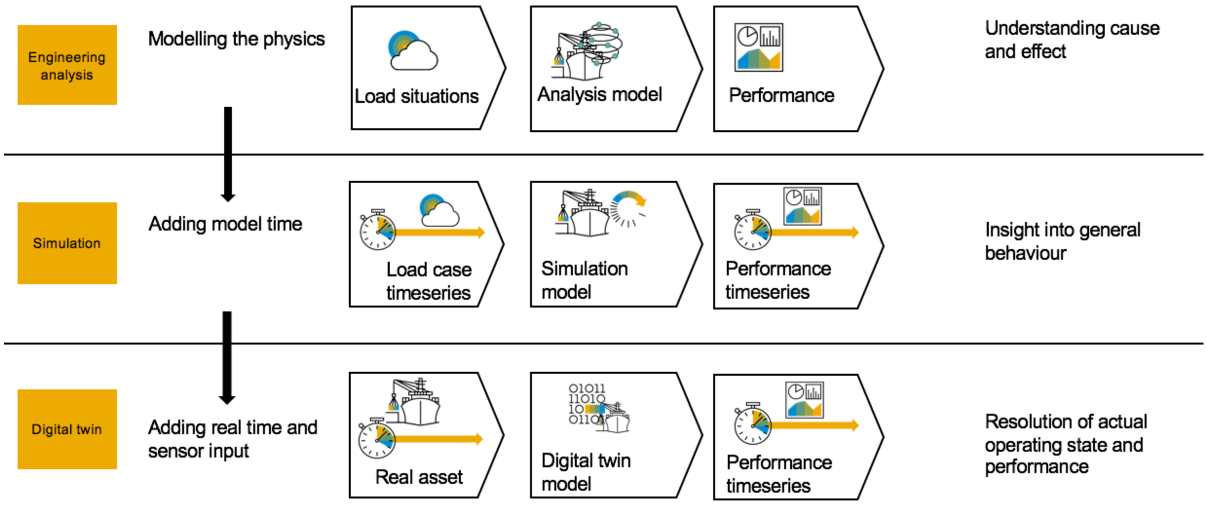

Fig.6:Digital twin foundations in simulation and engineering analysis

3. Machine Learning and Data Analytics – complementary or alternative?

Even more than physics-based digital twins, big data technologies, such as machine learning and data analytics, has received considerable attention, and is an important part the IoT landscape. They play a vital role in extracting insight and knowledge from the massive amount of data that are created by the extensive installation of sensors in the hull, machinery systems and deck machinery. The potential use of machine learning models as the foundation for digital twin solutions would be based on quite different principles than the physics-based solution presented here. This is summarized in Fig.7.

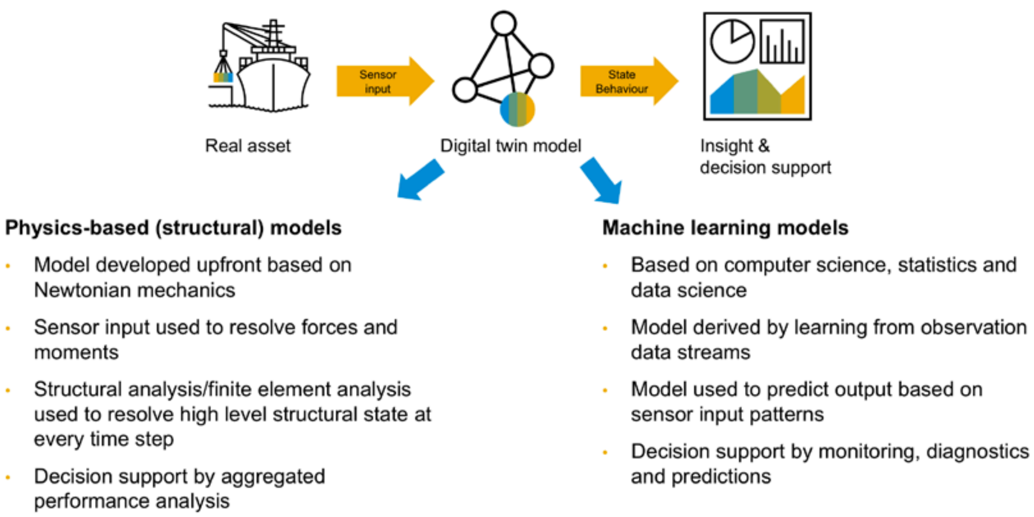

Fig.7: Physics-based vs. machine learning based digital twin solutions

In Table I, the advantages and disadvantages of these two approaches are summarized.

Table I: Comparing physics-based and machine learning based models

	Machine learning based	**Physics based**
PRO	• Model derived from data only – no need for domain knowledge • Generic and flexible - handles heterogeneous data streams (also non-physics) • Model improves over time (reinforcement learning) • Good at discovering complex relations and patterns	• Models capture deep existing knowledge based on Newtonian physics • Causal relationships provide insight and understanding • Uncertainty controlled by input and modelling accuracy • Model has universal validity – predict any point covered by model
CON	• The availability of training data needed to develop model • Correlations, not causality. Blackbox, no explanations (in particular, deep learning) • Approximation methods, no exact mathematics • Predictive capabilities deteriorate quickly outside training set scope • Difficult to predict extreme/critical conditions (few observations)	• Require extensive domain (physics) knowledge • Computationally intensive, challenge in real-time • Complete assumptions about input-output must be made upfront

In the digital twin the basic laws of physics and structural mechanics is embedded in the behaviour of the twin. Thus, it is possible to assess the performance, such as stress level or accumulated fatigue, independently of experience data from the same or similar assets. Such performances can be resolved at any position on the structure. The flip side is that physics based twins is more complex to implement than a data analytics solution since it requires a relatively detailed structural model of the asset, combined with powerful analysis capability to solve the state of the model in real time based on sensor input.

So, it is fair to say that even if a Digital Twin driven by the laws of physics and a twin driven by data analytics are to some extent alternative approaches, they are largely complementary. Yet we believe that the future for “intelligent” IoT applications lies at the intersection of these two, combining the strengths of each approach.

Based on the provision of a (close to) real time digital representation of the state of an asset, a Digital Twin offers hindsight on the operational history of the asset, making it possible both to aggregate behaviour and performance over time, as well as going back in time for understanding root causes and patterns of behaviour. In principle, this can be done without an (extreme) big data approach – by storing only the defining sensor input stream, which typically amounts to one single stream per degree of freedom, we can replay the model on the input data providing the required state and behaviour for any previous point in time.

For the connection to simulation, this capability is turned around. Along with the accumulation of insight into the relation between operating conditions and ship system behaviour, we can also predict the asset's response to anticipated future scenarios. Combining this with the explicit modelling of the ship´s control system, we can be better prepared for upcoming critical events, as well as having the ability to tune control system settings to optimize operational performance.

In the following sections, several conceptual solutions on how big data analytics, physics-based behaviour prediction and simulation will meet in a digital twin model.

3.1 Continuous response surface generation for computational offloading

In stable, non-critical load situations the continuous computation mode can be switched to an auto-generated response surface (regression model). The model can either re-sample or switch back based on elapsed time or prediction deviation. This will not replace the need for a physics-based model in the first place – without it we would not be able to derive this response surface (fitted curve) in the first place.

Fig.8: Computational offloading by continuous sampling and learning

3.2 Creating low-fidelity surrogate models for limited footprint time series storage

Generally, for a digital twin, we assume we store all sensor input data. Thus, for the DT output (from asset parts/virtual sensors), we will have the following choices:

- Store none. This implies that if we want to go back in time to inspect historic output data, we would need to regenerate this by the DT based on the sensor input stream, which is possible but typically computationally costly.
- Store all. This implies a high storage cost, especially at high resolutions/frequencies)
- Store at low resolution, which implies a data loss cost)

Alternatively, time windows of data can be stored by using machine learning on the combined input-output stream, and only the fitted model parameters need to be stored. The complete data stream can then be regenerated at relatively low cost.

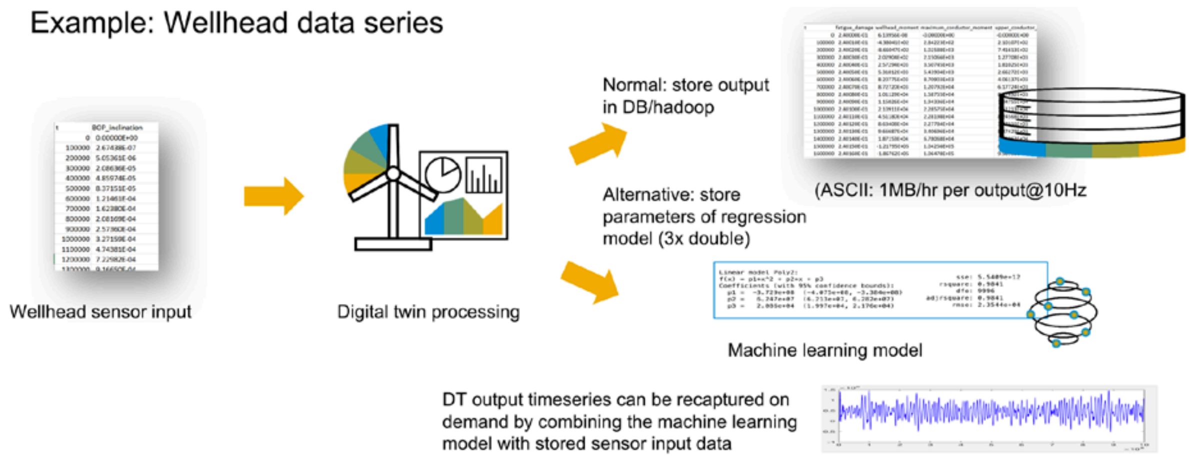

Fig.9: Limiting storage footprint by storing ML-based model parameters

3.3. Multi-asset prediction

Central to the concept of a digital twin is the principle of representing a unique asset in the real world, where the combination of description, state and behaviour is different from other assets. However, often we want to monitor and understand systems of things beyond their individual contribution, such as a collection of production robots on a production line, or a complete electricity transmission line with many utility poles and cables. The system may comprise predominantly similar asset types, say, wind turbines in a wind farm, or a large set of different asset types, for instance the tracks, switches power lines, bridges, etc. in a railway network.

A common denominator for complex systems is that they exhibit behaviour beyond what can be assessed by simply adding the contributions from the individual assets – what is termed emergent behaviour. For instance, understanding, and not the least predicting, the energy production performance of a single wind turbine, we need to understand how the wind field pattern is influenced by the operations of the other turbines in the farm. The motion behaviour of a platform supply vessel will be influenced by the waves generated by the motion of the semi-submersible platforms it serves.

It is not always obvious when we should consider a thing to be a component, thus part of a larger system, and when we can consider the thing to be a complete system by itself. For example, considering a marine riser for oil production. In some cases, it is useful to create a digital twin that is limited to the riser itself. In other cases, we need to consider the riser as part of a wider system that also comprises neighbouring systems such as the BOP, the well-head, and ultimately the platform.

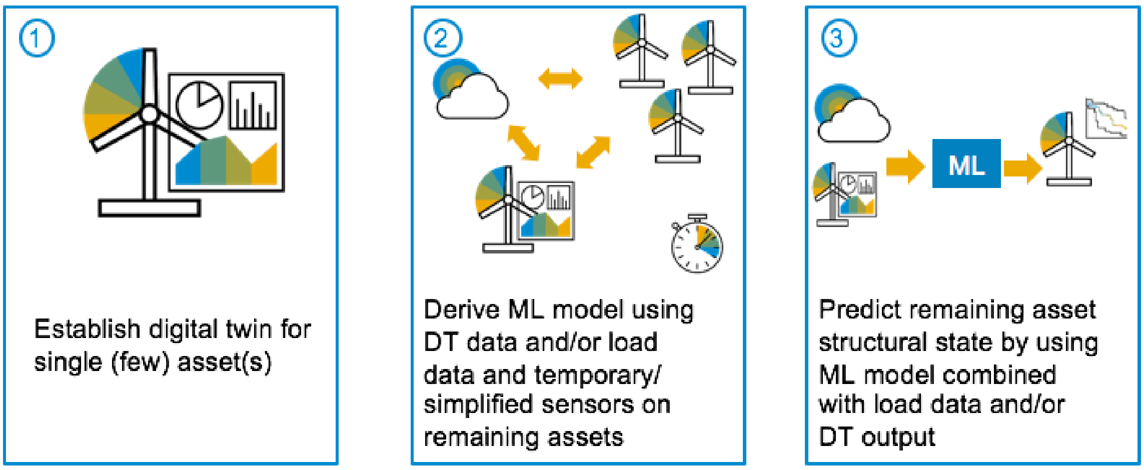

Fig.10: Combining a digital twin and machine learning for multi-asset prediction

We believe that in the future digital twin solutions need to be able to traverse different system levels. This implies being able to easily switch between considering individual twins in isolation and considering the twin as an intrinsic part of a larger system that exhibits behaviour emerging from the interaction between multiple twins and their operating environment.

For multi-asset installation, cost considerations may limit us to install a full sensor configuration only on one or a few assets. We may be able to establish a sufficiently accurate load situation on the remaining assets by machine learning models based on their correlated structural behaviour. For instance, this can be based on temporary/portable sensor installation on neighbouring assets.

3.4. The digital twin as a simulation model for supervised learning

Supervised learning can extract patterns linking different load situations and structural performance, including failure situations. These patterns can be used to detect deviations, i.e. if similar load situations result in different structural behaviour.

In Table I, the availability of relevant training sets was identified as one of the challenges of using machine learning based models. Here, the digital twin can be used in a simulation mode to produce such training sets, i.e. producing many load situations with corresponding expected structural behaviour and failure situations.

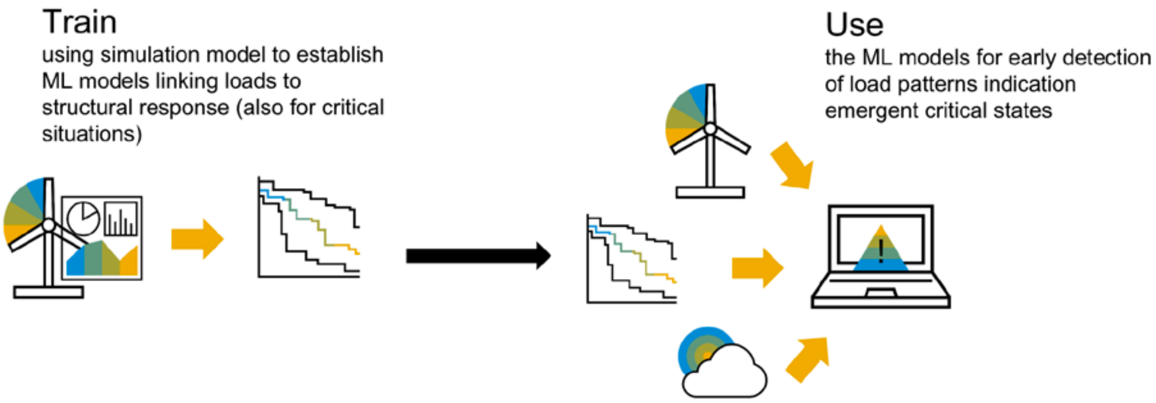

Fig.11: Using the digital twin as a simulation model for machine learning training

3.5. From insight to foresight

The primary role of a digital twin solution is to provide a (close to) real time digital representation of the state of an asset, that enables valuable operational insight that can be used concurrently in multiple engineering and business processes.

In addition, the solution offers a deep hindsight on the operational history of the asset, making it possible both to aggregate behaviour and performance over time, as well as going back in time for understanding root causes and patterns of behaviour. In principle, this can be done without an (extreme) big data approach – by storing only the defining sensor input stream, which typically amounts to one single stream per degree of freedom, we can replay the model on the input data providing the required state and behaviour for any previous point in time.

Along with the accumulation of insight into the relation between operating conditions and asset state behaviour, we can also hit the fast forward button in terms of predicting the asset's response to anticipated future scenarios. Combining this with the explicit modelling of the assets control system we can be better prepared for upcoming critical events, as well as having the ability to tune control system settings to optimize operational performance.

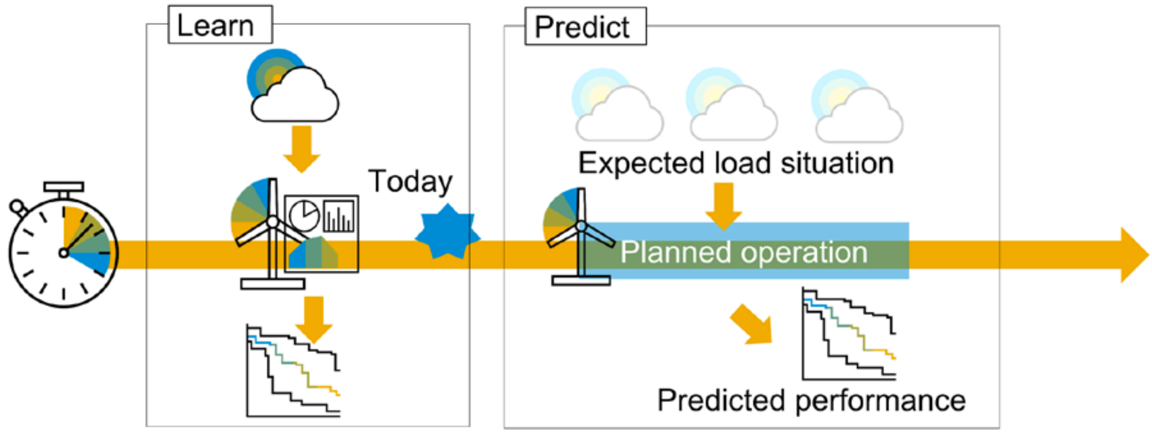

Fig.12: Extracting experience from operations for prediction and planning

3.6. Feedback to design

The classical engineering design process relies on creating load cases capturing at least the critical operating scenarios for the system to be designed. Typically, there is a significant uncertainty related to the accuracy of these load case models, as well their relevance in terms of representing the critical design conditions. Digital twin solutions are a leap forward in providing an opportunity to base design decisions on real load histories from deployed systems, thus influencing both the safety and the technical and commercial viability of new design solutions.

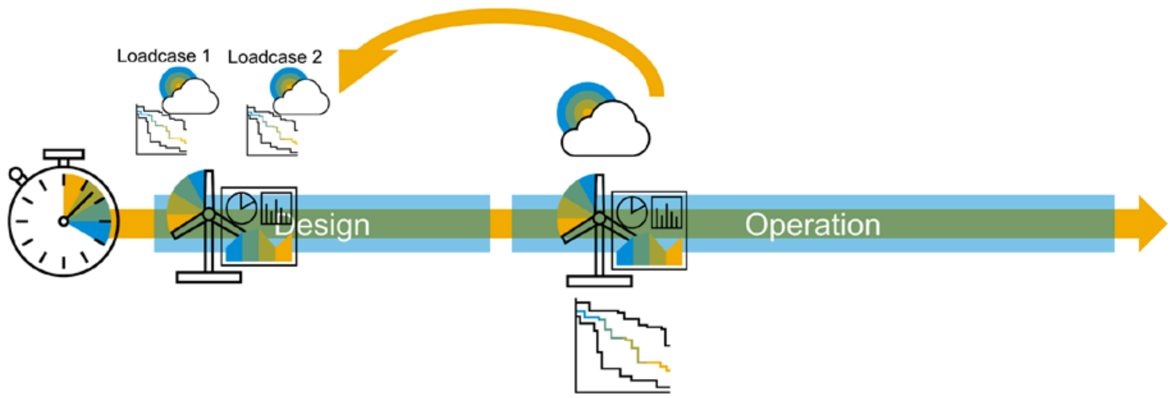

Fig.13: Digital twin load cases and corresponding structural response patterns reused in design

4. Summary

In this paper, we have presented the core principles underpinning digital twins, and discussed how they can be used within a larger IoT landscape. A digital twin solution is able to capture the intrinsic physical behaviour of an asset. This represents already today a unique opportunity for providing value into core business processes, such as inspection, maintenance and asset integrity management. At the same time, digital twin technologies are in the middle of a hype cycle as well as in their infancy on a conceptual level. We believe that we so far have seen just the first steps of a long journey towards comprehensive digital operations, in which the digital twin concept will continue to evolve.

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Improvement of Propulsive Performance of a Catamaran in Waves by a Biologically Inspired Hydrofoil

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Abstract

This paper provides the hydrodynamic data for developing a new catamaran with better propulsive performance in waves by attaching a hydrofoil. Tank tests were carried out in calm water and regular head wave conditions to capture ship motions and added resistance with changing wave-length ratios at 3 different ship speeds. Total resistance and effective power (EHP) of full-scale ships in long-crested irregular waves were predicted based on the tank tests results. The maximum EHP reduction ratio by the hydrofoil was about 15% for L_{pp}=28 m, about 10% for L_{pp}=56 m and about 15% for L_{pp}=84 m.

1. Introduction

Marine animals such as a dolphin and a whale swim forward in sea by vertically moving a horizontal tail fin. The thrust force generated by the vertical motion of the tail fin works as the leading edge thrust produced by an oscillating wing. A different way of looking at the situation is that the thrust is generated by the vertical movement of the water around the fixed tail fin. If the relative vertical movement of the water becomes larger by combination with vertical motion of the tail fin, larger thrust is expected. Such vertical movement of the water may be generated by sea waves.

Wave devouring propulsion using hydrofoils was studied by *Jakobsen (1981)*. In Japan, *Terao (1982)* studied the possibility of the wave devouring propulsion in model tests. *Isshiki et al. (1989)* substantiated the wave devouring propulsion by attaching a hydrofoil to the fore part of a ship with 15.7 m in the length in actual seas. In 2008, the wave devouring propulsor ship "Mermaid II" was designed and built as an experimental ship. It succeeded in sailing from Hawaii to Japan using only wave energy, *Terao (2008)*.

In this paper, we try to improve the propulsive performance of a catamaran in actual seas by attaching a hydrofoil. An improvement of the propulsive performance is expected due to leading edge thrust produced by the oscillating wing in waves and suppression of wave-making energy loss by reduction of the ship motion. The main purpose of this study is to obtain hydrodynamic data for developing a new catamaran with hydrofoils. For this purpose, tank tests were carried out in calm water and regular head wave conditions in Hiroshima University Towing Tank. In the regular wave tests, ship motions and added resistance were measured with changing wave-length ratio at 3 different ship speeds. Based on the tank tests results, total resistance and effective power of full-scale ships in long-crested irregular waves were predicted with changing the ship lengths such as 28 m, 56 m and 84 m to examine the effect of ship size. Through this study, finally, we make the effective range of the hydrofoil with respect to wave condition, ship speed and ship size clear.

2. Ship Model

Table I shows principal particulars of studied catamaran and hydrofoil. Fig.1 shows the tank test models of scale 1/13.75. In the table, d_w means depth from still water surface to chord line of the foil. The ship is a twin-propeller and twin rudder catamaran with asymmetrical demi-hull form, *Yasukawa et al. (2012)*. The hydrofoil model was equipped to the ship hull at Square Station 8-1/2 position. A plate spring was put inside the foil model to produce a restoring force for roughly keeping the initial angle of attack of the wing. The attack angle is smoothly changed according to the bow motions in waves. The spring stiffness was changed 3 kinds (we call the hard spring case sp1, the soft spring case sp3 and the intermediate spring case sp2) in the tests.

Table I: Principal particulars of ship and hydrofoil

Catamaran			Hydrofoil	
	Model	Full scale		
L_{pp}	2.036 m	28.0 m	Chord c	0.10 m
W	0.844 m	11.6 m	Span b	0.070 m
d	0.124 m	1.7 m	Asp. ratio $2b/c$	1.4
vol	0.0959 m^3	333.9 m^3	Depth d_w	0.070 m

Fig. 1: Models (left: catamaran, right: hydrofoil)

3. Tank Test

The tests in calm water and regular head waves were conducted at Hiroshima University Towing Tank (length: 100 m, width: 8 m, depth: 3.5 m). Table II shows parameters in regular wave tests. χ denotes the direction of waves, H_w the wave height, λ the wave-length, κ_{yy} the radius of pitch gyration and F_n the Froude number based on L_{pp}.

Table II: Parameters in regular wave tests

χ	180° (head waves)
H_w	30 mm
λ/L_{pp}	0.5~2.0
F_n	0.20, 0.35, 0.45
κ_{yy}/L_{pp}	0.30

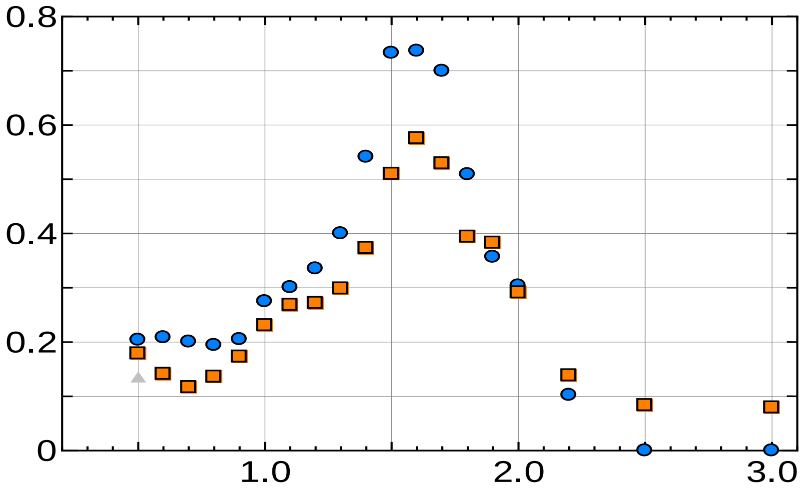
In the regular wave tests, ship motions and resistance were measured with changing wave-length tio λ/L_{pp} at 3 different ship speeds (respectively F_n) as shown in Table II. The added resistance in regular waves R_{AR} is obtained by Eq. (1), and is non-dimensionalized by Eq. (2),

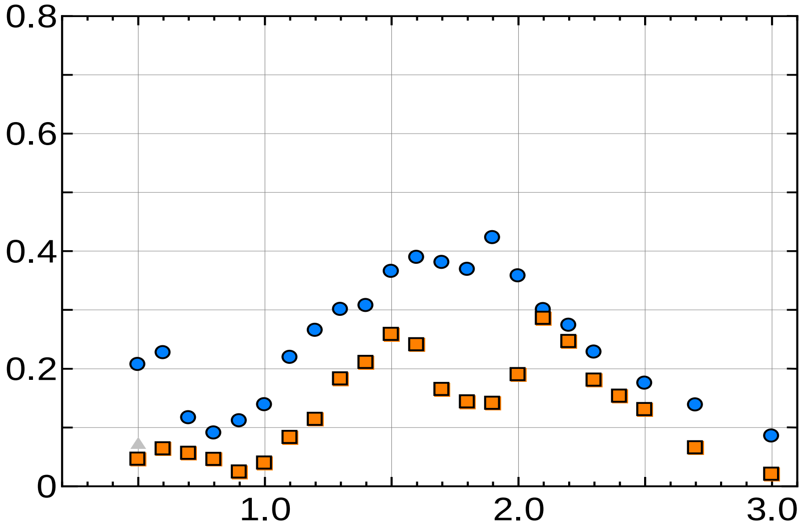
$$R_{AR} = R_w - R_0 \qquad (1)$$

$$C_{AR} = \frac{R_{AR}}{\rho g {h_a}^2 L_{pp}} \qquad (2)$$

where R_w is the mean resistance in regular waves and R_0 the resistance in calm water. C_{AR} is the added resistance coefficient, ρ the water density, g the gravitational acceleration and h_a the amplitude of the incident wave.

Fig.2 compares added resistance coefficients C_{AR} in regular head waves at F_n=0.2, 0.35 and 0.45. "W/O" means the condition without the hydrofoil. The added resistance is reduced by attaching the hydrofoil. The resistance reduction becomes more significant near $\lambda/L_{pp} = 1.7$ where the ship motions are relatively large. The different spring stiffness (sp1, sp2 and sp3) has an effect on the results.





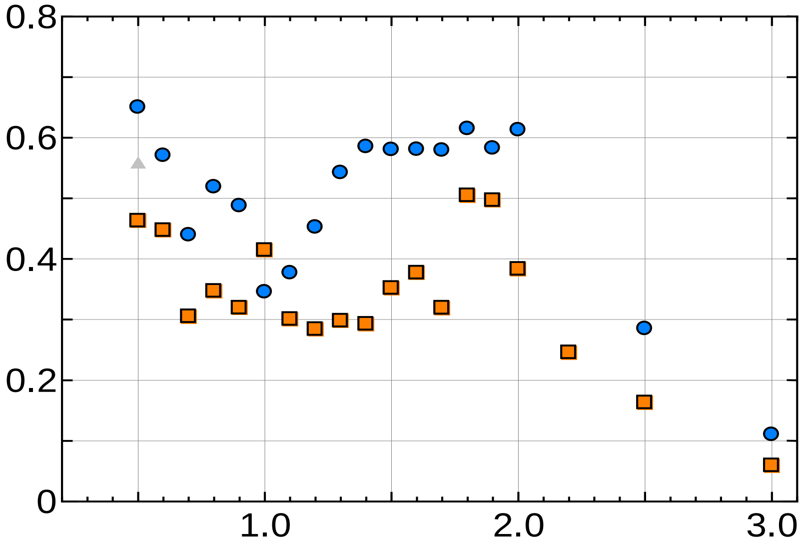


Fig.2: Added resistance coefficient curves in regular waves

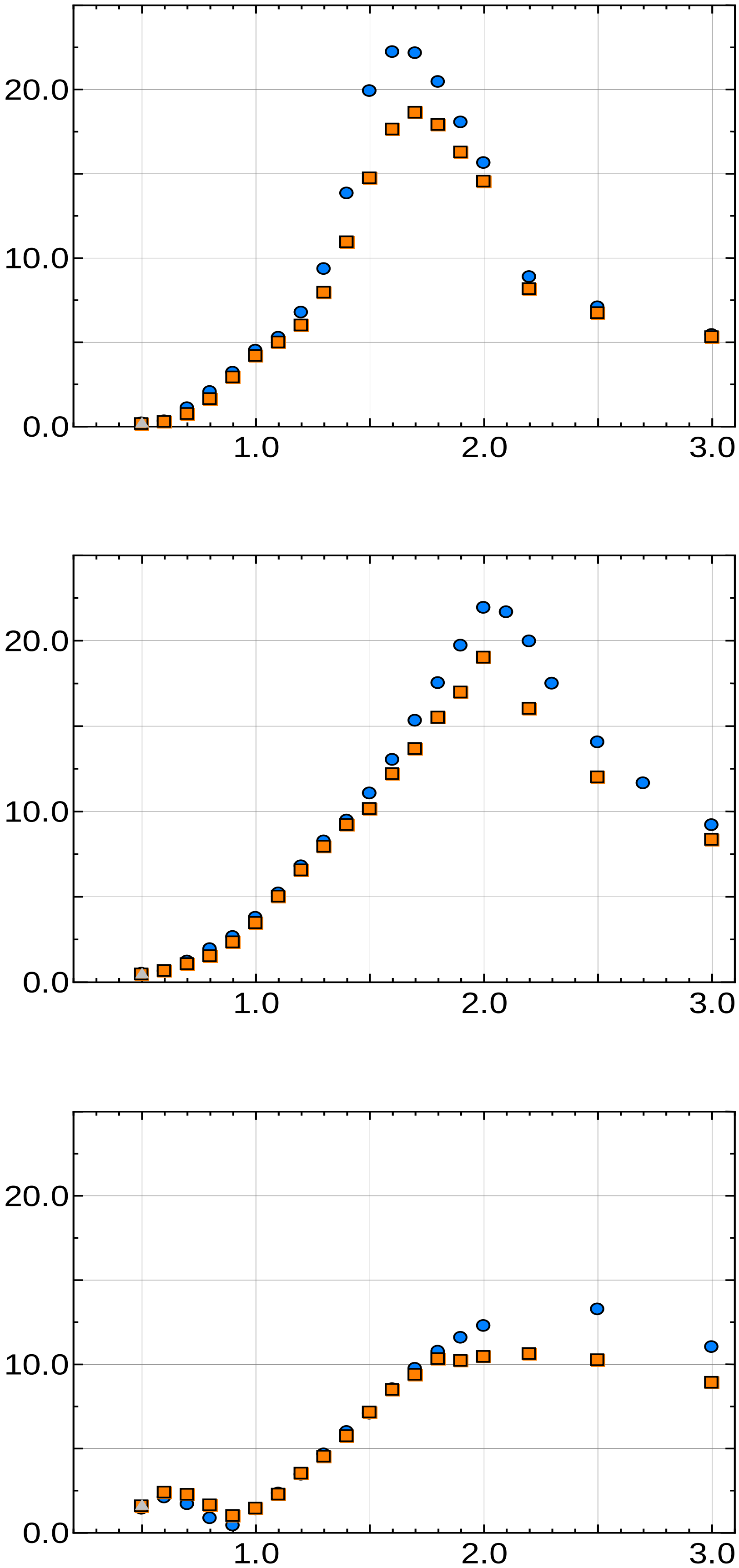


Fig.3: Amplitude of vertical acceleration at FP in regular waves

Fig.3 compares amplitude of vertical acceleration at FP in regular head waves at F_n = 0.2, 0.35 and 0.45. The acceleration amplitude is non-dimensionalized by Eq.(3).

$$a_z/(gKh_a) \qquad (3)$$

where a_z is amplitude of the vertical acceleration at FP and, K the wave number. By attaching the hydrofoil, the vertical acceleration amplitude is reduced by about 20% in relatively long waves. A clear difference in the amplitudes cannot be observed among sp1, sp2 and sp3. Thus the effect of spring stiffness on the acceleration is small.

4. Effective Power Prediction of Full-scale Ships in Irregular Waves

4. 1. Outline of effective power prediction

Effective power (EHP) of full-scale ships in actual seas was predicted based on the tank tests results. For the prediction of EHP, total resistance of the full-scale ships has to be predicted first. The prediction procedure is as follows:

- The total resistance in actual seas is predicted by sum of calm water resistance and the added resistance in irregular waves.
- The calm-water resistance is predicted by the two-dimensional extrapolation method based on Schoenherr's frictional resistance formula. Then, the residual resistance coefficient curve obtained in the tank tests was used.
- The added resistance in long-crested irregular head waves is calculated by the short-term prediction method based on RAO of the added resistance coefficients in regular waves. Note that the added resistance in irregular waves is proportional to square of significant wave height $H_{1/3}$. In the short-term prediction, ITTC wave-spectrum was used.

Eventually, the total resistance in irregular waves R_{TW} [kgf] and EHP [kW] are calculated by the following formulas.

$$R_{TW} = R_0 + R_{AW} \cdot {H_{1/3}}^2 \qquad (5)$$

$$\text{EHP} = \frac{R_{TW} \cdot V}{75} \times 0.7355 \qquad (6)$$

where V [m/s] is ship speed of full scale ship. In the predictions, the added resistance in irregular head waves was obtained with changing the ship lengths such as 28 m, 56 m and 84 m to examine the effect of ship size.

In this study, the wave condition was represented as the WMO sea state code (SS) 3-7 as shown in Table III. Navigation limits of the ships with different size are assumed to be shown in Table IV, where "O" shows that a ship can navigate and "X" shows that the ship cannot navigate.

Table III: Wave conditions

Sea State	Sig. wave height $H_{1/3}$ [m]	Average wave period T[sec]
SS3	1.25	4.32
SS4	2.50	6.10
SS5	4.00	7.72
SS6	6.00	9.46
SS7	9.00	11.6

Table IV: Navigation limits supposed in this study

L_{pp}	d	SS3	SS4	SS5	SS6	SS7
28 m	1.7 m	O	O	X	X	X
56 m	3.4 m	O	O	O	O	X
84 m	5.1 m	O	O	O	O	O

4. 2. Prediction results

Fig.4 compares EHP ratio of full-scale ship with different ship length of 28 m, 56 m and 84 m. The vertical axis of the figures means the ratio of EHP of the ship with/without hydrofoil to EHP of the ship without hydrofoil. Therefore, EHP ratio of "W/O" is always 100%. EHP ratio becomes smaller than 100% when the reduction of added resistance in waves is larger than the resistance increase in calm water by the hydrofoil.

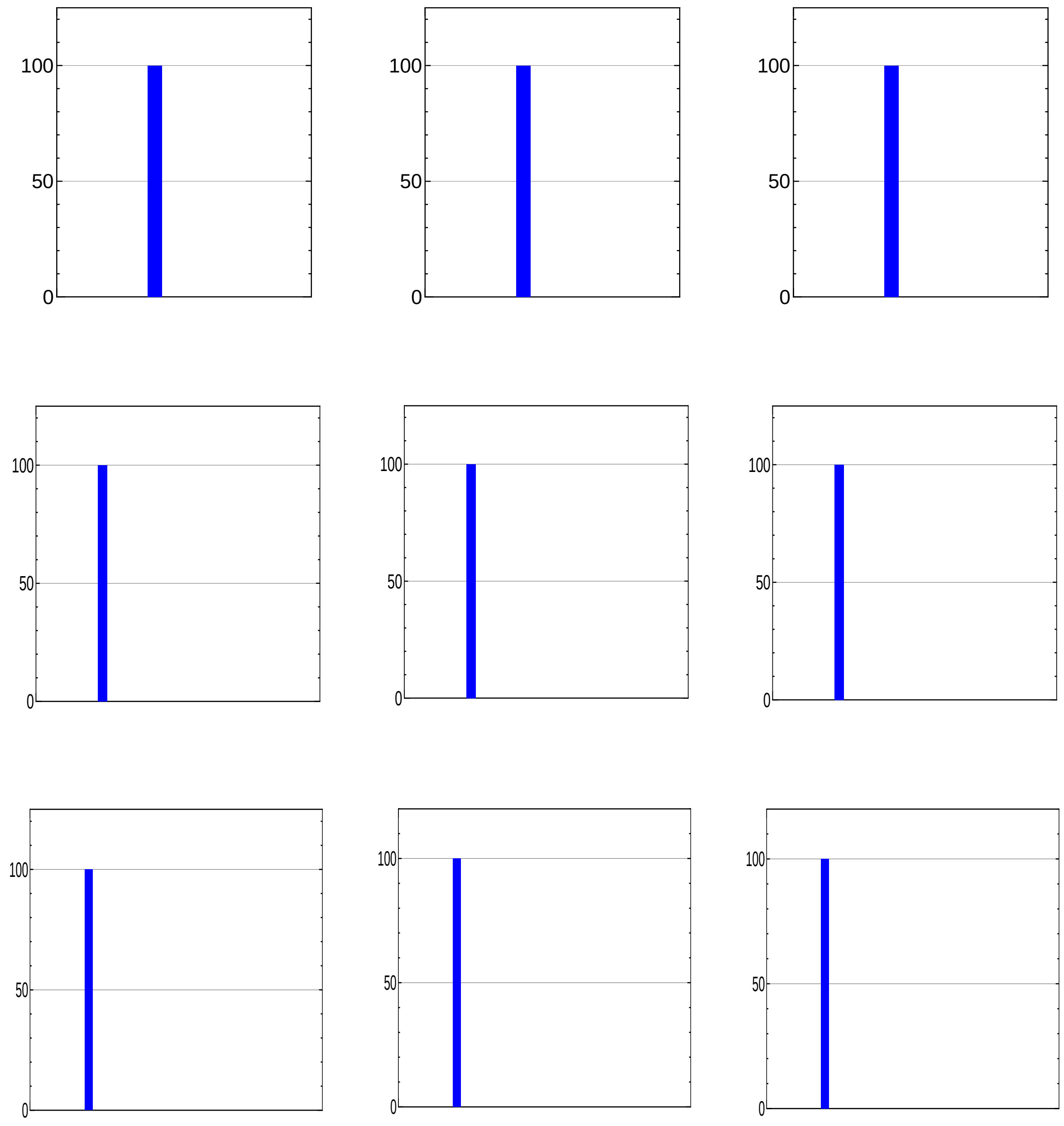


Fig.4: EHP ratio in calm water and irregular waves (L_{pp}= 28 m (top), 56 m (mid), 84 m (bottom))

In calm water, EHP ratio increases around 20% in F_n = 0.2, around 15% in F_n = 0.35, and around 10% in F_n=0.45 by attaching the hydrofoil. In irregular waves, EHP ratio decreases with increase of sea state compared to the calm water case due to the effect of reduction of added resistance by the hydrofoil. From the figures, the sea state where the gain appears can be obtained as shown in Table V. In F_n = 0.20 and 0.45, the sea state is SS3 for L_{pp}=28 m, SS4 for L_{pp}=56 m, and SS5 for L_{pp}=84 m. In F_n = 0.35, the sea state is SS4 for L_{pp}=28 m, SS5 for L_{pp}=56 m, and SS6 for L_{pp}=84 m. In the sea states lower than those mentioned in Table V, the gain by the hydrofoil cannot be expected, and it is desirable that the hydrofoil is put up to the air. Obviously, maximum gain is obtained at the most severe sea state such as SS4 for L_{pp}=28 m, SS6 for L_{pp}=56 m, and SS7 for L_{pp}=84 m, and there EHP is reduced about 15% for L_{pp}=28 m, about 10% for L_{pp}=56 m and about 15% for L_{pp}= 84 m in average. When attaching the hydrofoil to the present catamaran, F_n = 0.2 is the most effective for service Froude number since the resistance increasing in calm water by attaching the hydrofoil is relatively low. F_n = 0.45 is the 2nd effective Froude number, and F_n = 0.35 is the worst. The effect of the plate spring stiffness of the foil on the performance is not so significant, and only almost 2-5% difference appears. The soft spring sp3 is better for F_n = 0.20, and the hard spring sp1 is better for F_n = 0.45.

Table V: Sea state where the gain appears

L_{pp}	d	F_n=0.2	F_n=0.35	F_n=0.45
28 m	1.7 m	SS3	SS4	SS3
56 m	3.4 m	SS4	SS5	SS4
84 m	5.1 m	SS5	SS6	SS5

5. Ship Motion Reduction by Hydrofoil

Next, the short-term prediction of vertical acceleration at FP was conducted based on RAO of the acceleration in regular waves. The vertical acceleration is deeply related to comfortability for the ship in waves. Fig.5 compares of vertical acceleration ratio (ACC) at FP of full-scale ship with different ship length of 28 m, 56 m and 84 m. The vertical axis of the figures means the ratio of the acceleration of the ship with/without the hydrofoil in irregular waves to the acceleration of the ship without the hydrofoil. Therefore, the acceleration ratio of “W/O” is always 100% in any sea states. By attaching the hydrofoil, in F_n = 0.2 and 0.35, the acceleration ratio is reduced about 15% in average for any sea states. In F_n = 0.45, the acceleration ratio differs with sea states. The acceleration ratio increases in SS3, but the ratio decrease with increase of the sea state. The maximum reduction ratio is about 15%. As shown in Fig.3, the vertical acceleration increases at the short wave- length region by the hydrofoil. This is the reason for increasing the acceleration in SS3. The hard spring sp1 is better for all ship speeds.

6. Concluding Remarks

We tried to improve the propulsive performance of a catamaran in actual seas by attaching a hydrofoil to the fore part. To obtain the hydrodynamic data for developing a new catamaran with the hydrofoil, tank tests were carried out in calm water and regular head wave conditions. In the regular wave tests ship motions and added resistance were measured with changing wave-length ratio at 3 different Froude numbers (F_n = 0.20, 0.35 and 0.45). Based on the tank tests results, the effective power and vertical acceleration at FP of full-scale ships in long-crested irregular waves were predicted with changing the ship lengths such as 28 m, 56 m and 84 m to examine the effect of ship size. The results obtained in this study are summarized as follows:

- In F_n = 0.20 and 0.45, the sea state (SS) where the gain appears by attaching the hydrofoil is SS3 ($H_{1/3}$=1.25 m) for L_{pp}=28 m, SS4 ($H_{1/3}$=2.5 m) for L_{pp}=56 m, and SS5 ($H_{1/3}$=4 m) for L_{pp}=84 m.
- The maximum EHP reduction ratio is about 15% at SS4 ($H_{1/3}$=2.5 m) for L_{pp}=28 m, about 10% at SS6 ($H_{1/3}$=6 m) for L_{pp}=56 m and about 15% at SS7 ($H_{1/3}$=9 m) for L_{pp}=84 m. They are

obtained at the most severe sea state within the navigation limit for each.

- By the hydrofoil, the vertical acceleration at FP is reduced about 15% in average for any sea states and Froude numbers.
- The effect of the plate spring stiffness of the foil on the performance is not so significant, although there is a tendency that the soft spring sp3 is better for F_n = 0.20 and the hard spring sp1 is better for F_n = 0.45.

As continuous work, we will investigate the effect of hydrofoil size on performance.

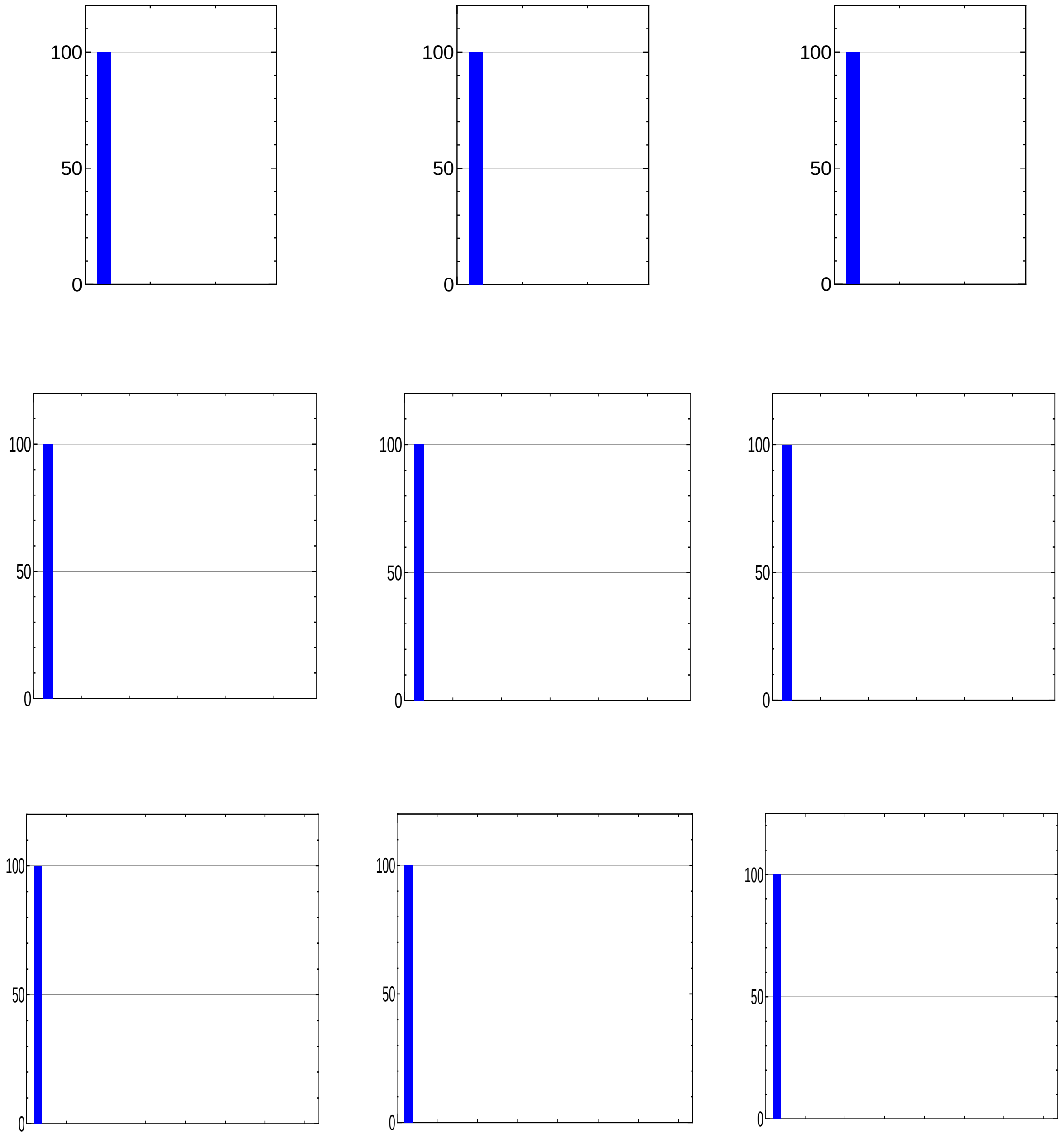


Fig.5: Vertical acceleration ratio at FP in irregular waves (L_{pp}=28 m (top), 56 m (mid), 84 m (bottom))

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Innovative Technologies for Maritime Industry & Future Scenario

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Abstract

A research project under the Japan Ship Technology Research Association (JSTRA) surveyed innovative technologies from various sectors and countries. The results of the research are described. First, innovative technologies expected to affect the maritime industry are introduced, looking at feasibility and magnitude of influence. Then we discuss some future scenarios for the maritime industry involving these technologies, e.g. future ship concept.

1. Introduction

We investigated new technologies adopted in other industries and examples of advanced technology implementation in the maritime industry worldwide. Considering the applicability of these technologies to the maritime industry was used as basis for discussing future ship technologies 30 years from now.

For our project, we surveyed literature and interviewed relevant parties (universities, research institutions, manufacturers, etc.) to extract technologies that could be applied to ships in the future. We also analysed individual technologies from the viewpoint of feasibility/maturity and magnitude of impact. This led to a technology roadmap to organize short-term and medium-term R&D projects (as described in Chapter 2). We extracted noteworthy technologies (6 fields, total 116 cases) for future ship and analysed them in Chapter 3. Finally, we conceived a future ship concept based on assorted innovative technologies.

2. An overview of the direction of future R&D

First, an overview on recent and future research and development (R&D) obtained from the survey is shown in this chapter. Note that the contents described here are not objectively verified with respect to their validity.

2.1. General overview

Advanced R&D seemingly focusses increasingly on a few specific areas: technology on the environment and energy, nanotechnology, information technology, and life sciences. The Japanese government has also focussed its funding on those fields. The research results from the technology on environment and energy, nanotechnology and information technology can become directly applicable to the maritime industry. But even some life sciences (e.g. brain science) may lead to applications in future maritime technology.

Overall, the current fields of science and technology are likely to communicate and cross-fertilize in the future. The future lies not in developing single technologies in depth, but to combine and integrate technologies from other fields and other industries. Many interesting developments in maritime technologies can be found in the USA. While developed for the US Navy, many technologies can be applied just as well in the civilian sector.

Likely "game changing" technologies include innovation of shipbuilding, ship operation and logistics by information & communication technology (ICT). The following should be the material applied by nanotechnology.

2.2. Materials

R&D efforts have been made for higher strength and more flexible steels. These achievements are sequentially incorporated into the shipbuilding industry. Meanwhile, there are R&D on smarter materials or functional materials in other industries.

Future ship materials will increasingly involve composites of various materials (steel, carbon, and organic material). We see already the practical use of CFRP (composite fibre reinforced plastics) in the aerospace and automotive industries. The application of new nanocarbon materials such as carbon nanotubes (CNT), Fig.1, and graphene should be game changing for the maritime industry. Ship structures have moved from wood to steel. Carbon may bring the next revolution.

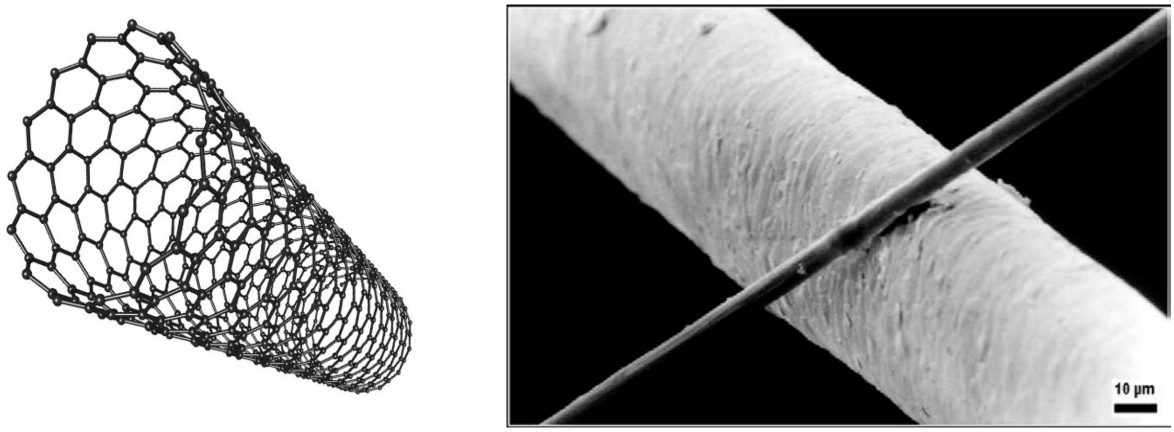

Fig.1: Carbon nanotube as game changing material – left: structure; right: black CNT and white hair

Nanocarbon material is not only a good structural material, but also a good functional material e.g. for built-in electronic circuitry, semiconductors or heat exchangers. Ship outfitting work may dramatically change (e.g. embedding electrical materials and printed circuit board directly into hull elements by printing). By realizing ultra-light ships, we may also see different hull forms and structural designs for volume carriers such as cruise ships, mega-yachts, ferries and navy vessels. Concept on LCA (life cycle assessment) including ship recycling would also be affected.

We may see increasingly high-performance materials with a variety of new features such as transparency (Fig.2), ability to reactively adjust shape or mechanical properties (biomimetic technology, Fig.3), self-healing, intelligence (with sensors embedded).

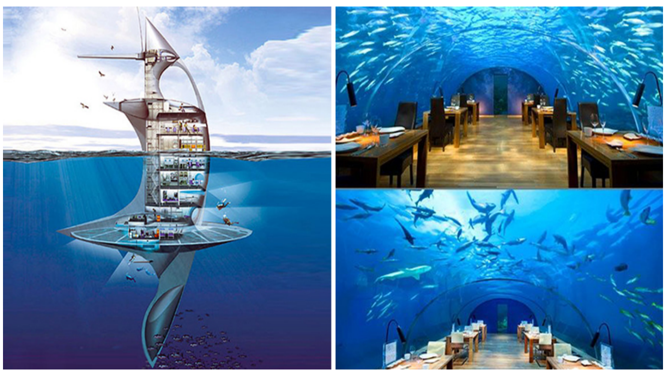

Fig.2: Conception of a ship composed of transparent structural members by Aluminium nitride, SeaOrbiter by Jacques Rougerie

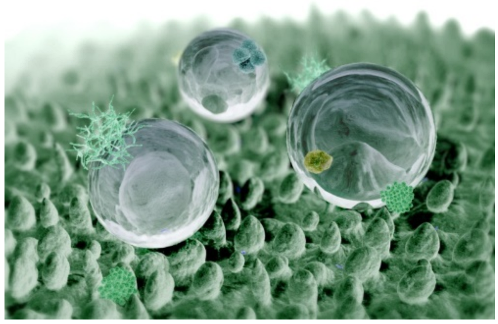

Fig.3 Examples of biomimetic materials. Lotus-Effect for hull coatings reduces frictional resistance and improves antifouling performance.

2.3. Simulation and Design

Along with increasingly available HPC (High Performance Computing), our capabilities in simulation have progressed, e.g. modelling directly complex turbulence or hydro-elastic fluid-structure interaction for ships, Fig.4. Simulation will proceed towards multi-scaled and/or multi-physics models, with high accuracy and high reliability. In the future, we can analyse and determine the behaviour of ships or systems by only simulation (simulation-based design or one-shot manufacturing). Tailored on-demand production will be taken for granted in the future society.

In addition, simulation will spread to include non-technical aspects, such as the human element in a system (behaviour model, human simulation, soft computing) or business models (Product-Service Systems, PSS). The focus will spread from the product itself to its service to maximize the product value. With respect to ship technology, various simulation technologies which are not only extensions of the classical applications (stability, hydrodynamics and structural behaviour) are expected to evolve and support design and operation.

Data science or statistical science is likely to become more important and widely used. The importance of "data science" is recognized as the fourth science (fourth paradigm). For example, physics-based simulation will be enhanced and/or supplemented by data mining, Big Data analyses and employing artificial intelligence (AI) techniques such as machine learning.

In the design field, design errors are minimized by visualization and advanced verification, using a wide range of techniques including 3D CAD and Virtual Reality / Augmented Reality (VR/AR) technology, Fig.5.

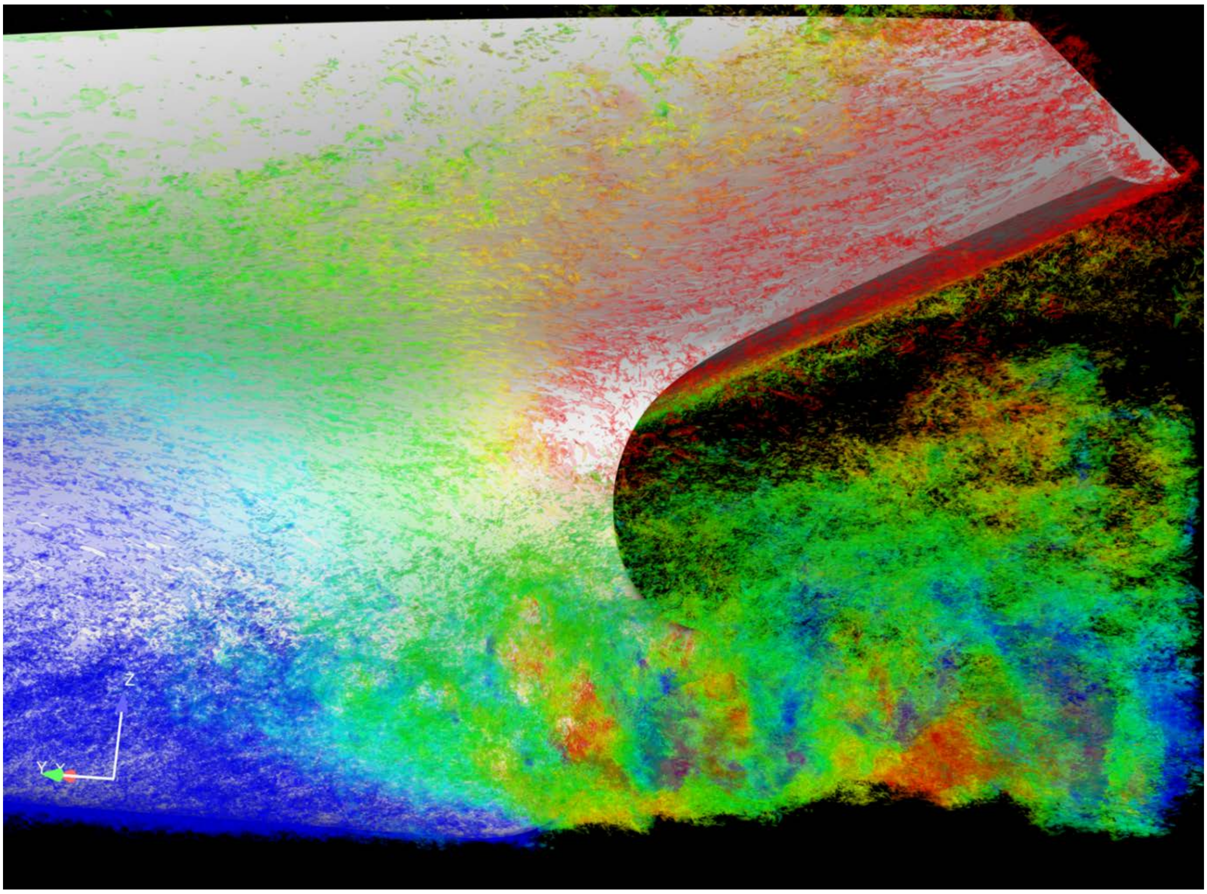

Fig.4: Large-eddy simulation of turbulence flow at ship stern, *Nishikawa (2015)*

Fig.5: Virtual Reality inspection of designs, source: SENER

2.4. Manufacturing and Construction

By introduction of the IoT (Internet of Things) in the production site, soon steel plates will be automatically conveyed by machines communicating with each other based on a predetermined construction plan from steel cut stage to the various assembly stages.

Further, it will be possible to record the complete building process through a spreading monitoring network of wearable devices all over the shipyard. These devices enable real-time traceability of the whole ship construction, allowing also quantification of a shipbuilding site's ability or work skill.

Current standard procedures may change by the introduction of ICT technology. Currently, the design department and the production site have different roles and are separated in the shipyard organization. It is also believed to be more efficient to divide work processes as much as possible. With ICT technology, especially with the spread of wearable devices or AR technology, Fig.6, information is integrated between the design department and the production site. Digitization of shipbuilding sites will not only lead to mutual understanding between design departments and production sites, but may also lead to new ideas of "on-site design" or design incorporation to the production department which ultimately draw or determine the specifications in the manufacturing site and not in the design room.

At present, 3D printing can only produce small parts and has limitation in strength and type of materials used, Fig.7. However, these issues should be fundamentally resolved soon and 3D printing is expected to spread rapidly also in shipbuilding. This will in turn advance the use of composite materials in ships. The ONR (Office of Naval Research) of the US Navy published a report to explore the possibility of producing the whole ship using 3D printing. Already, it is possible to build houses based on 3D printing.

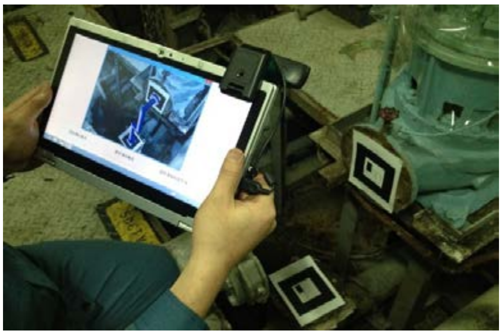

Fig.6: Wearable devices aid in production and record progress in real-time

Fig.7: 3D print of whole house by Italian DINITECH

Automation and robotics are also important, increasing productivity and quality. In the aerospace industry, automation of production is progressing by expanding the use of robots in the production line of large passenger aircraft. The same trend is likely for shipbuilding.

2.5. ICT technology

Computers are embedded everywhere around us, but we are often not aware of them (transparency of computer). One of the R&D directions in ICT is on the fusion of humans, things (ship, yard) and computers. The fusion of the real world (Physical System) and cyberspace (Cyber System) will combine the wealth of information from penetrated sensor networks in the real world with the powerful computing capability of cyberspace.

Noteworthy in this movement is an effort to discover entirely new knowledge from the vast amount of information (Big Data). Management or policy initiatives are starting to get based on analysing correlations from Tera-bytes of data. We will be able to handle enormous amounts of data as never before, such as oceanographic data, marine data from ship operation, construction data from ship-yards and personal data (e.g. health monitoring) from the crews and workers. This might lead to perspectives on ship design, construction and operation. We can make quantitative and rational decision, going beyond traditional intuition and experience.

Research looks into new ways of interacting with computers. New computer architectures mimic the human brain (neuro-synaptic computing). Future connection of the human brain and the computer may expand human capabilities; it may be possible to transmit one's intention by downloading from the brain to a computer. Inversely, it may be possible to upload knowledge and skills. The craftsmanship of workers may be transmitted directly to the brain (such as neuro-feedback technique) rather than through instructing words or texts. Our notion of training through a tedious process of nurtured may become history. When this comes to happen, it will have a major impact to our society, especially to education and training schemes.

In any case, ICT technology plays a key role for innovations in various fields. Advanced ICT skill will be required by our maritime workforce and this has implications also on education.

2.6. Transport and Logistics

A variety of players in the retail and logistics industries are competing to build new infrastructure and business models. We see the emergence of large, highly automated logistics facilities with the ultimate goal to deliver products at customers' specifications whenever and wherever they want it. It is inevitable that this trend will come to the field of shipping as well. Land-based and sea-based logistics will be tightly connected.

Various technology start to emerge to make shipping more competitive, such as the use of drones, unmanned operation of ships and ports, Fig.8, new ship concepts (such as cargo ships with changing hold arrangement changes for each voyage), or optimizing operations and logistics based on Big Data analysis. In addition to optimized transportation, we may also see new business models such as adding value to the cargo while transporting it, Fig.8.

IoT technology and Big Data analyses are already used for condition based maintenance schemes and performance monitoring of ships. In the future, we will see increasingly unmanned operation of ships.

Fig.8: Unmanned operation of ships and ports, source: DNV GL

Fig.9: New business models adding value to cargo while transporting it, source: Wärtsilä

2.7. Environment and Energy

Similar as for cars and planes, we will see shipping move towards low and eventually zero CO_2 emission scenarios. The vision of a future zero emission ship (ZES) combines various energy-saving technologies and sources of renewable energy, such as wind and solar power, bio-fuels, tapping into wave and tidal energy. Hydrogen technology will play a key role, as hydrogen allows efficient storage of energy generated offshore, such as wave and wind energy, solar power or even artificial photosynthesis using offshore algae farming.

Fig.10: Concept of offshore wind energy converted to hydrogen to fuel ZES, *Rohde and Sames (2014)*

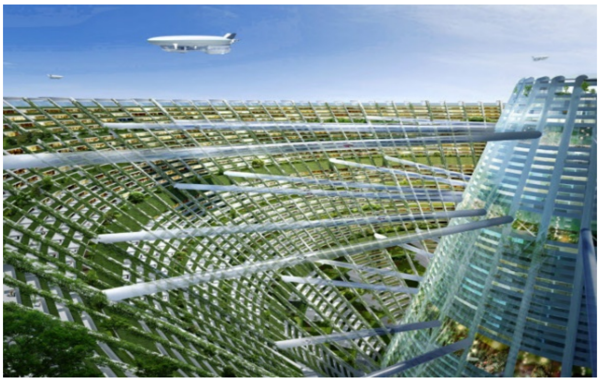

Fig.11: “GreenFloat” concept of a future city by Shimizu Corporation. Magnesium extracted from sea water is used to construct the floating city. Using solar and marine energy, vegetables are cultivated in a plant factory.

In general, sustainable shipping will play an increasing role. As we need to protect and preserve the habitat environment of our oceans, management of biological resources and water in a sustainable way will result in the demand for a “Non-negative Effect Ship” (NES). Design and operation of ships will then be aligned with this ultimate goal.

3. Survey on individual element technologies

Promising future ship technologies were evaluated from the viewpoint of technological feasibility and innovation. They were grouped in the following technical fields:

- Materials
- Design and construction of ships
- Ship operation and maintenance
- Transportation and logistics
- Propulsion and engines
- New types of ships (Other technologies)

Appendix 1 lists the 116 element technologies. Each technology was rated on a scale of 1 to 4 (1 = low, 4 = high). The average score was obtained from a questionnaire for the members of this investigation. Appendix 2 gives two-dimensional mapping of each element technology with the time span of R&D and the impact to maritime industry (The time span was defined as the product of "Difficulty of R & D for implementation to general use" and "Difficulty of R & D for implementation to maritime use" in the item of Appendix 1.). These maps indicate the R&D needed in short-term and medium-term. Element technologies with a high degree of reliability and good effectiveness are in the upper left areas of the maps. Among these, to be prioritized in R&D, are:

- CFRP material
- Self-healing material
- Virtual ship laboratory
- 3D printing (additive manufacturing)
- Laser technology (cutting, welding, bending, etc.)
- Autonomous or unmanned ship
- Robotics (manufacturing robot, drone, nano robots, etc.)
- Asset Visibility
- Big Data analysis of logistics data
- Superconducting technology
- Hydrogen energy

4. Future ship based on innovative technology (future scenario)

We outline possible future scenarios for the following five matters when future technologies are introduced, Figs.12 and 13.

4.1 Carbon ship

Future ships may be made of nano-carbon material, which is a similar game changer as moving from wooden ships to steel ships in the past. Carbon ships would be light-weight and high strength, resulting in overall completely changed hull and arrangement designs. For example, hull form and a hull structure may mimic the shape of a sea creature. Outfitting may be embedded in the material (sensor, power lines, data lines) and parts of the structure may be directly 3D-printed. Bulkheads may become transparent or contain displays. In any case, composites will be on the rise, combining metals, carbon and organic material.

3.2. Construction and Design

Through the IoT (Internet of Things) in the production site, soon steel plates will be conveyed automatically as machines communicate among each other. Robots will support at each stage, making ship assembly highly automatic. In the future, it may have become commonplace to deliver the ship in just a few days from its order. ICT networks will spread to every place in the shipyard allowing us to record the complete assembly process in real-time. This will ensure the quality of the vessel, but also help quantifying the performance of the shipyard. By recording data such as welding quality and fitting accuracy of the ship for every place, we can objectively show the quality of our shipbuilding. Design optimization will progress by numerical simulation, design automation and Virtual Reality. There will be no longer routine work in design, we will look for richer creativity and advanced engineering capabilities in the designer.

3.3. Ship operation

Future on-board systems will be operated with common operating systems such as Google's Android. This will allow connecting various types of equipment in the ship to one common system. The whole ship becomes a programmable entity. Ships may be operated after downloading and installing the optimum voyage plan from the Web for each voyage. Ships, cars, aircrafts and household appliances will run on the same operating system as smartphones. You can control the ship and your luggage by the smartphone app you use in everyday life. The data wealth from assorted ship systems is harvested in Big Data analytics, supporting e.g. real-time and true logistics. The real world is mirrored in Digital Twins in cyberspace. Vessels are connected ship-to-ship and ship-to-shore, e.g. to ports and hinterland logistics.

3.4. Transportation and logistics

The future of logistics goes toward bringing anything what people want anywhere at any time. There will be transparency and traceability of goods (raw materials, origin, processing method, distribution channels). Consumers and markets gets closer together and ships will play their role in this system. Small-size containers equipped with IoT devices may be used in door-to-door transportation between manufacturer and consumer. Containerships carry things in large quantities, possibly becoming moving warehouses on the sea. While operations and logistics are optimized, new services that add value to cargo during maritime transport may evolve.

3.5. Zero emission ship

The standard procedure of using fossil fuels to move ships may change. Instead, ships may have zero carbon footprint tapping into wind energy, solar energy, artificial photosynthesis, etc. Hydrogen will take a key role for this as widely used energy storage. Ships will run on hydrogen, but also transport it for land-based used in a future hydrogen society.

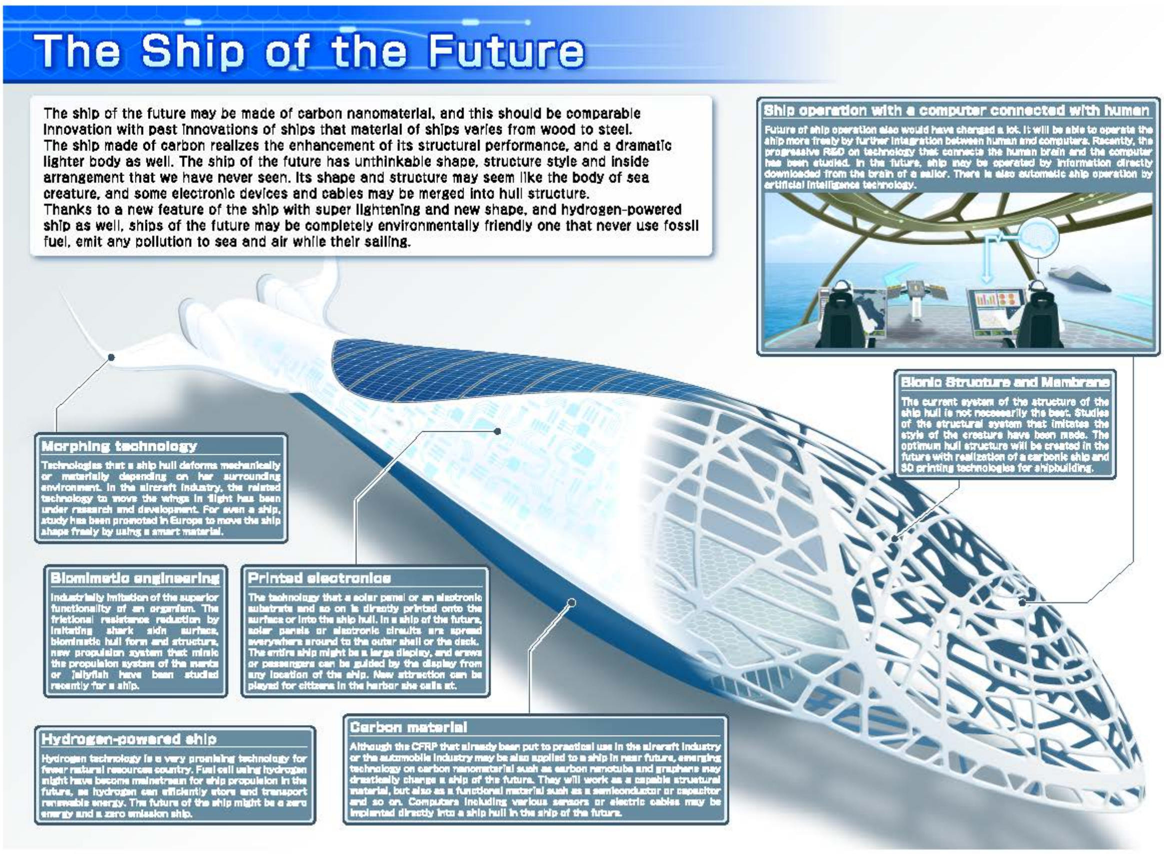

Fig.12: Ship of the future

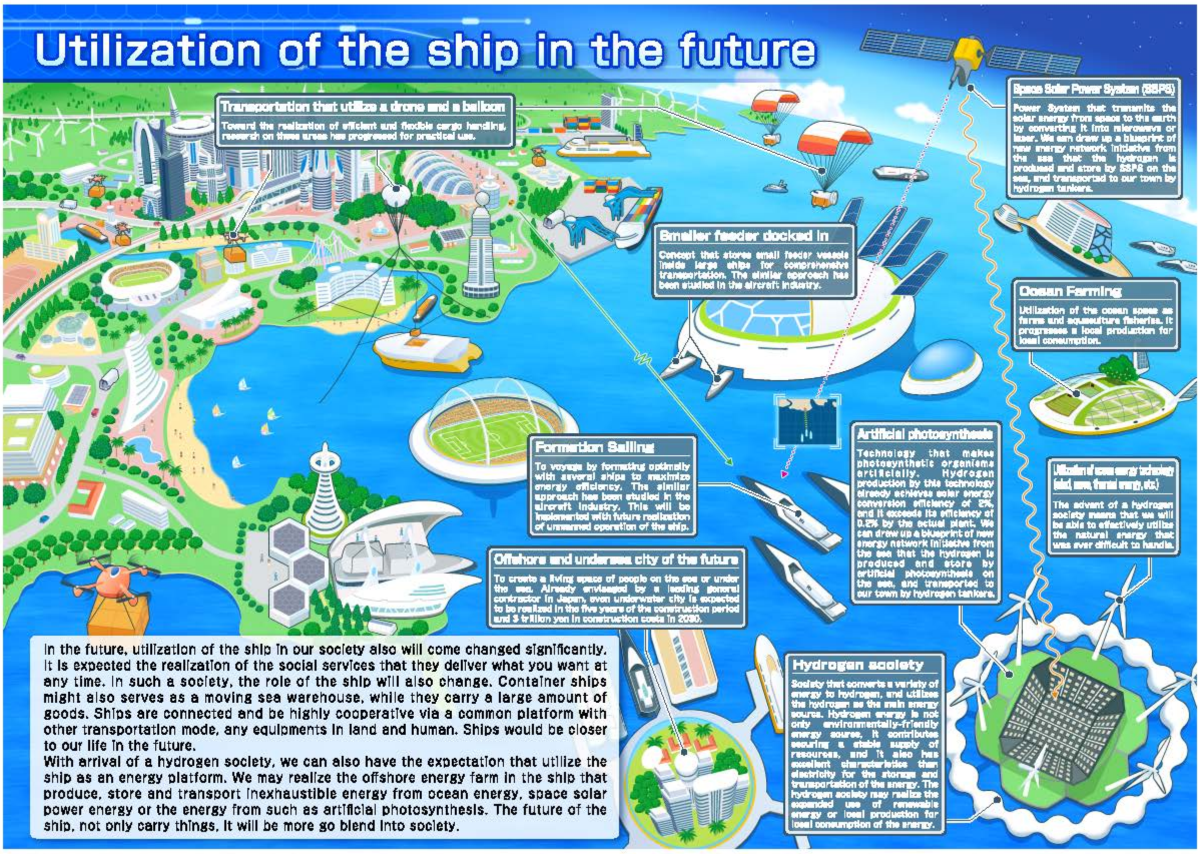

Fig.13 Utilization of ships in the future

Acknowledgements

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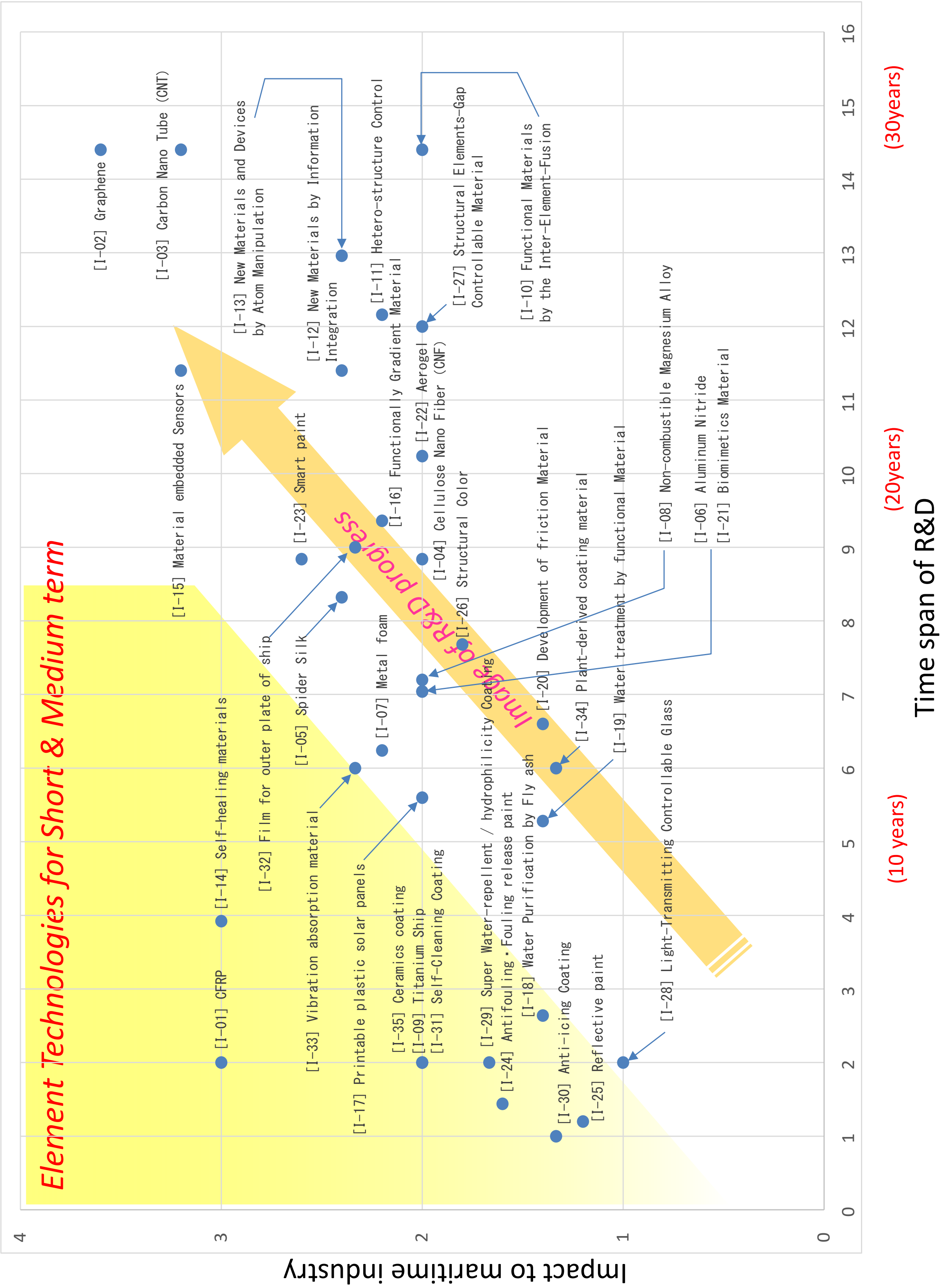
Appendix 1: 116 Element technologies and associated score (high = 4, low = 1)

Technical field		Element Technology	Score		
			Difficulty of R & D for implementation to general use	Difficulty of R & D for implementation to maritime use	Impact to maritime industry
I. Materials	Carbon materials	[I-01] CFRP	1	2	3
		[I-02] Graphene	3.6	4	3.6
		[I-03] Carbon Nano Tube (CNT)	3.6	4	3.2
	Other fiber materials	[I-04] Cellulose Nano Fiber（CNF）	2.6	3.4	2
		[I-05] Spider Silk	2.6	3.2	2.4
	New metal materials	[I-06] Aluminum Nitride	2.2	3.2	2
		[I-07] Metal foam	2.4	2.6	2.2
		[I-08] Non-combustible Magnesium Alloy	2.4	3	2
		[I-09] Titanium Ship	1	2	2
		[I-10] Functional Materials by the Inter-Element-Fusion	3.6	4	2
		[I-11] Hetero-structure Control	3.2	3.8	2.2
		[I-12] New Materials by Information Integration	3	3.8	2.4
		[I-13] New Materials and Devices by Atom Manipulation	3.6	3.6	2.4
	Functional materials	[I-14] Self-healing materials	1.4	2.8	3
		[I-15] Material embedded Sensors	3	3.8	3.2
		[I-16] Functionally Gradient Material	2.6	3.6	2.2
		[I-17] Printable plastic solar panels	2	2.8	2
		[I-18] Water Purification by Fly ash	1.2	2.2	1.4
		[I-19] Water treatment by functional Material	2.2	2.4	1.4
		[I-20] Development of friction Material	2.2	3	1.4
		[I-21] Biomimetics Material	2.2	3.2	2
		[I-22] Aerogel	3.2	3.2	2
	Paint	[I-23] Smart paint	2.6	3.4	2.6
		[I-24] Antifouling・Fouling release paint	1.2	1.2	1.6
		[I-25] Reflective paint	1	1.2	1.2
		[I-26] Structural Color	2.4	3.2	1.8
	Other technologies	[I-27] Structural Elements-Gap Controllable Material	3	4	2
		[I-28] Light-Transmitting Controllable Glass	1	2	1
		[I-29] Super Water-repellent / hydrophilicity Coating	1	2	1.7
		[I-30] Anti-icing Coating	1	1	1.3
		[I-31] Self-Cleaning Coating	1	2	2
		[I-32] Film for outer plate of ship	3	3	2.3
		[I-33] Vibration absorption material	2	3	2.3
		[I-34] Plant-derived coating material	2	3	1.3
		[I-35] Ceramics coating	1	2	2
II. Design and construction of ship	Design	[II-01] Virtual ship laboratory	2.8	3	3.2
		[II-02] Haptic technologies	3	3.4	2.4
		[II-03] Brain machine interface	3.2	4	2.8
		[II-04] CFD	1.2	1.4	1.8
		[II-05] Digital/Analogue hybrid simulation	2	2	1.8

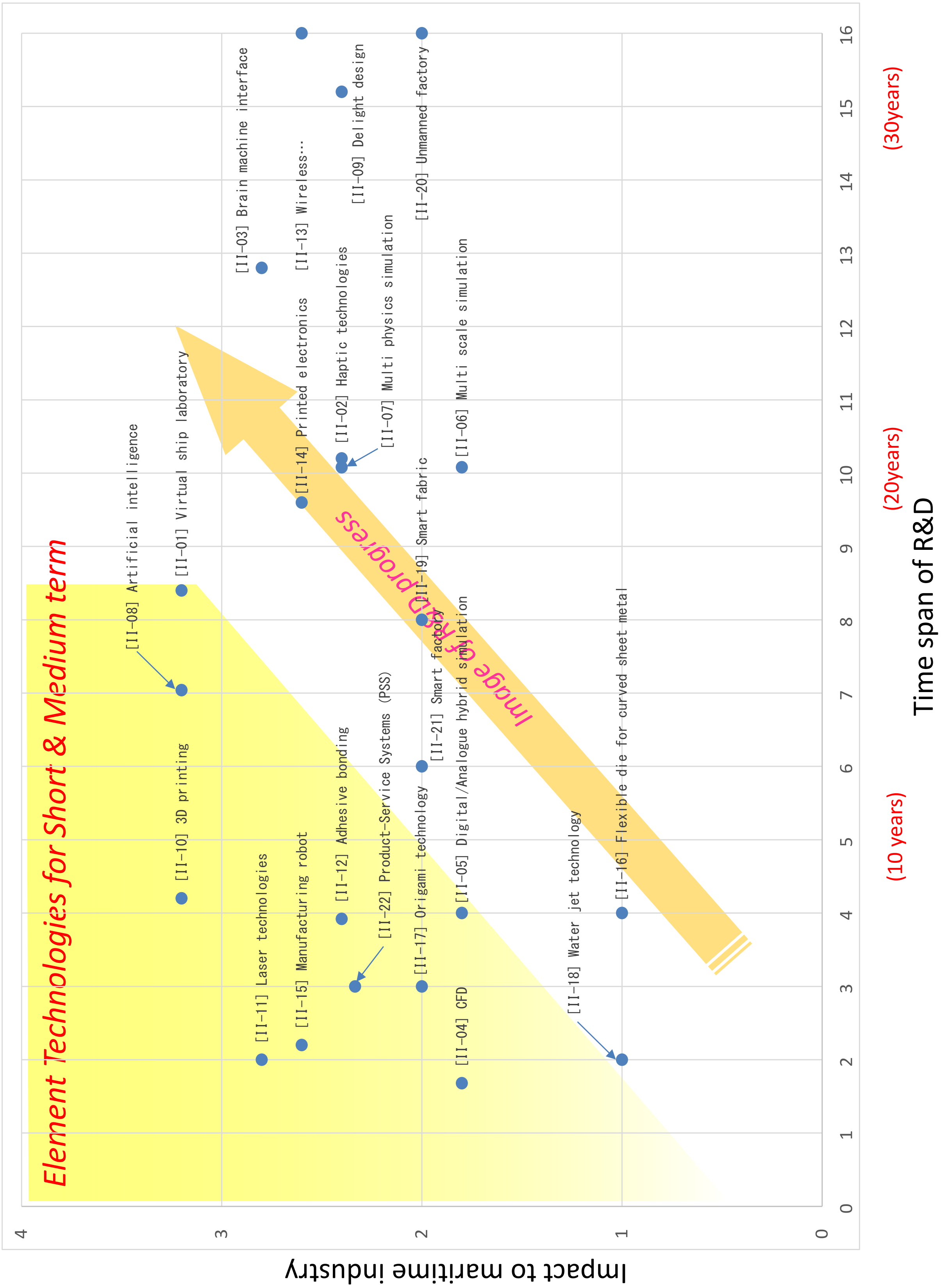
		[II-06] Multi scale simulation	2.8	3.6	1.8
		[II-07] Multi physics simulation	2.8	3.6	2.4
		[II-08] Artificial intelligence	2.2	3.2	3.2
		[II-09] Delight design	3.8	4	2.4
	Manufacturing	[II-10] 3D printing	1.4	3	3.2
		[II-11] Laser technologies	1	2	2.8
		[II-12] Adhesive bonding	1.4	2.8	2.4
		[II-13] Wireless transmission of electric energy	4	4	2.6
		[II-14] Printed electronics	3	3.2	2.6
		[II-15] Manufacturing robot	1	2.2	2.6
	Other technologies	[II-16] Flexible die for curved sheet metal	2	2	1
		[II-17] Origami technology	1	3	2
		[II-18] Water jet technology	1	2	1
		[II-19] Smart fabric	2	4	2
		[II-20] Unmanned factory	4	4	2
		[II-21] Smart factory	2	3	2
		[II-22] Product-Service Systems (PSS)	1	3	2.3
III. Ship operation and maintenance	Ship operation	[III-01] Autonomous or unmanned ship	2.8	2.8	3.2
		[III-02] Formation Sailing	3.2	3.2	2
		[III-03] Advanced bridge	2.2	2.4	2.2
		[III-04] Virtual Reality	1.2	2	2
		[III-05] Wearable device/electronic skin	1.4	2.8	2
		[III-06] Neurofeedback	2.4	3.8	2
		[III-07] Restoring Active Memory Replay	3.4	4	2.2
		[III-08] Augmentation of human ability	2.4	3.2	2.4
		[III-09] Autonomous Shipboard Humanoid	3	3.2	3
		[III-10] Airbag of ship	2	2	1.4
		[III-11] Intelligent wall	1.6	2.4	1.6
		[III-12] Satellite AIS	1.6	1.8	2
		[III-13] Online simulator	1	2	1.4
	Cyber Security	[III-14] Quantum cryptography	2.2	3	2
		[III-15] Cyber securities while sailing	2	2	2
	Ship maintenance	[III-16] 3D scanning/3D copy	1	1.4	2.4
		[III-17] Maintenance robot	1.2	2	2.2
		[III-18] MEMS sensor	1.6	2.4	2
		[III-19] Insect device	2.2	3	2
	Other technologies	[III-20] Eye glass for prevention of sea sickness	1	1	1
		[III-21] Diving suit without oxygen bottle	3	3	1
		[III-22] Photonic crystal	3	4	1
IV. Transportation and logistics	Transportation and logistics	[IV-01] Robot balloon crane	3	3.2	2.6
		[IV-02] Parafoil unmanned air-delivery system	2.8	3	2.6
		[IV-03] Drone	2	2.8	2.8
		[IV-04] Asset Visibility	1.4	2.2	2.8
		[IV-05] Adaptive ship	2.8	2.8	2.2
		[IV-06] Smaller feeder docked in	2.6	3.4	2
		[IV-07] Sensor-packed Shipping Container	1.4	2.2	1.6
		[IV-08] Vibration control	2.6	3.4	2.2
		[IV-09] Big data analysis of logistics data	1.8	2.6	2.8
V.	Propulsion	[V-01] Biomimetic propulsion	3.2	3.2	2.4

Propulsion and engines	and engines	[V-02] DC electric propulsion	1	1.2	2.2
		[V-03] Gas engine	1	1	2
		[V-04] Fuel cell	1	1.4	2.4
		[V-05] Solar panel	1	1.4	2.2
		[V-06] Bio-based fuel	1	1	1.8
		[V-07] Metal-air battery	2.4	2.4	2.4
		[V-08] Vibration power generation	2.2	3	2.6
		[V-09] Superconducting technology	1.4	2.6	3
		[V-10] Energy from sea water	4	4	3.4
		[V-11] Nuclear fusion engine	4	4	3.6
		[V-12] Black hole engine	4	4	3.6
	Other technologies	[V-13] Variable Diameter propeller	2	3	1
		[V-14] Automatic adjustment of bearing load	2	3	1.3
VI. New types of ships (Other technologies)	New ships	[VI-01] Non ballast ship	2.2	2.2	2.2
		[VI-02] Transformable ship (morphing technology)	3.2	2.8	2.6
		[VI-03] Bionic structure and membrane	3.4	4	3.2
		[VI-04] Ship surface heating	3.2	4	1.2
		[VI-05] Supercavitation	2	2	2.2
		[VI-06] Merchant submarine	2.8	2.8	2.2
	New utilization of Energy	[VI-07] Hydrogen energy	1	2.6	3.8
		[VI-08] MHD (Magneto-Hydro-Dynamics) generator	1.4	2.2	1.4
		[VI-09] Wind power generation	1.6	1.8	2
		[VI-10] Wave power generation Sea temperature power generation	1.6	1.6	2
		[VI-11] Artificial photosynthesis	3.2	4	2.8
		[VI-12] Space Solar Power System(SSPS)	4	4	2.8
	New utilization of sea	[VI-13] Offshore and undersea city	3	3.4	3.6
		[VI-14] Ocean Farming	2.6	2.8	2.6

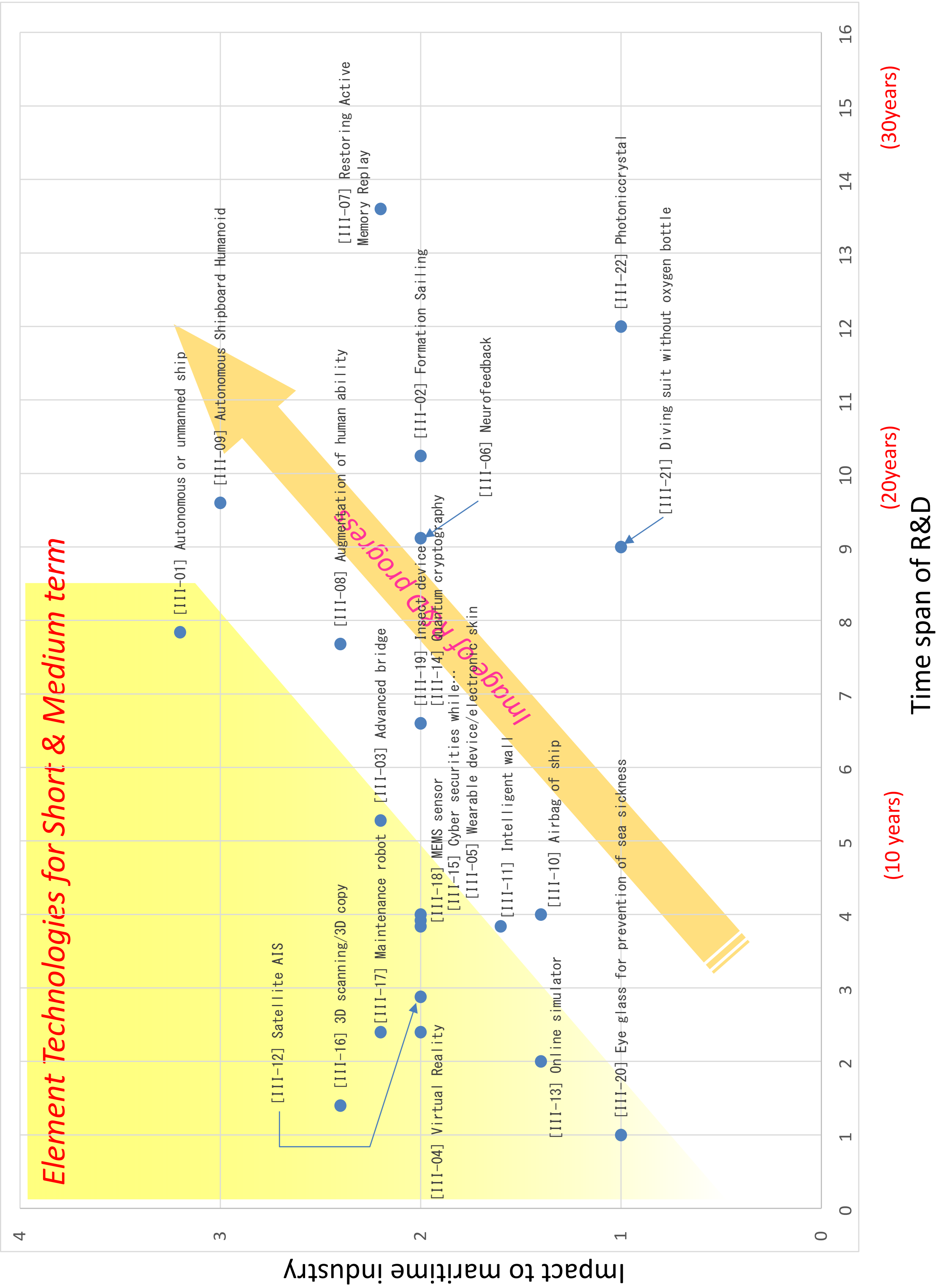
Appendix 2: Maps with the time span of R&D and the impact for each element technology



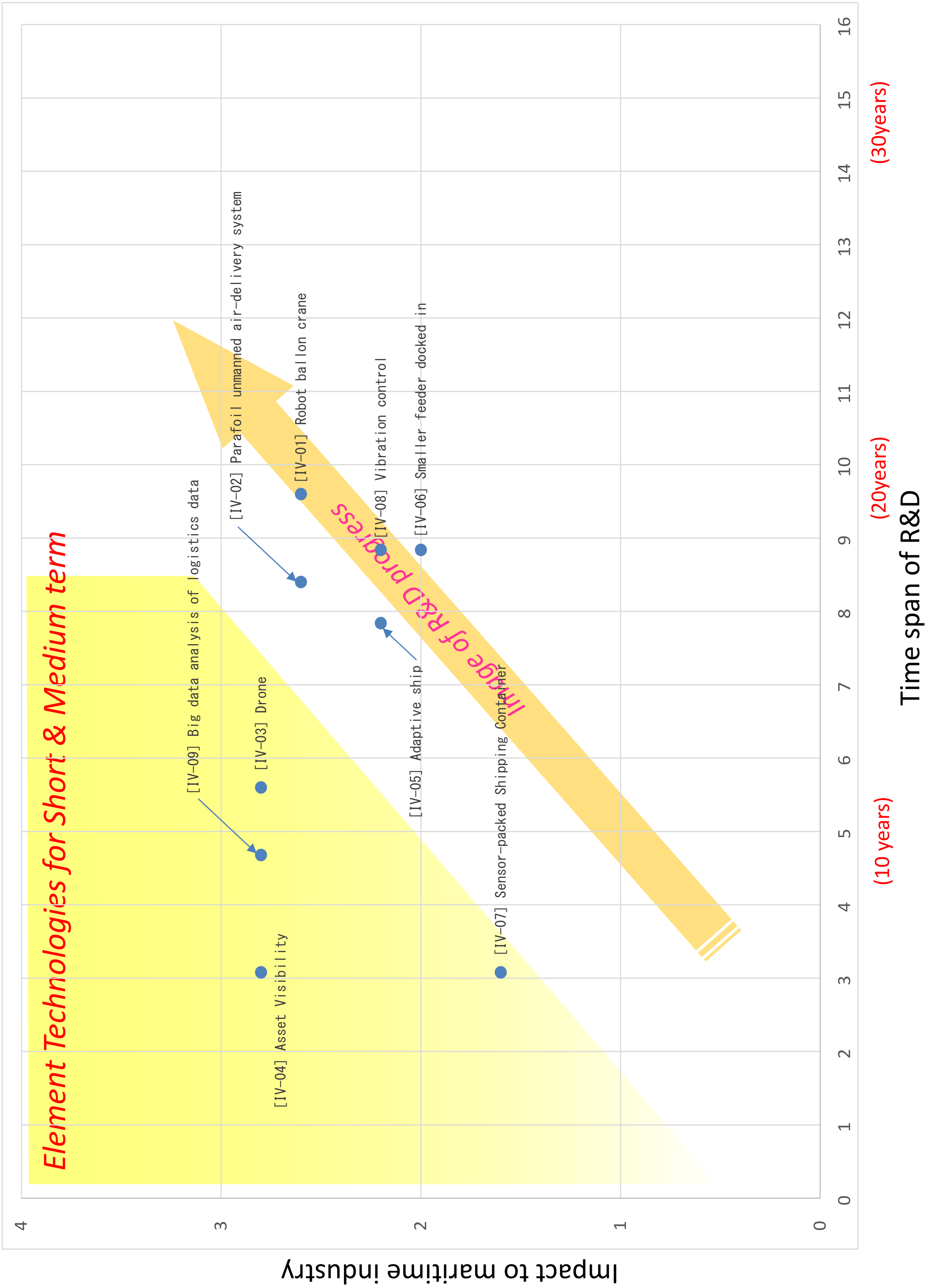
I. Materials



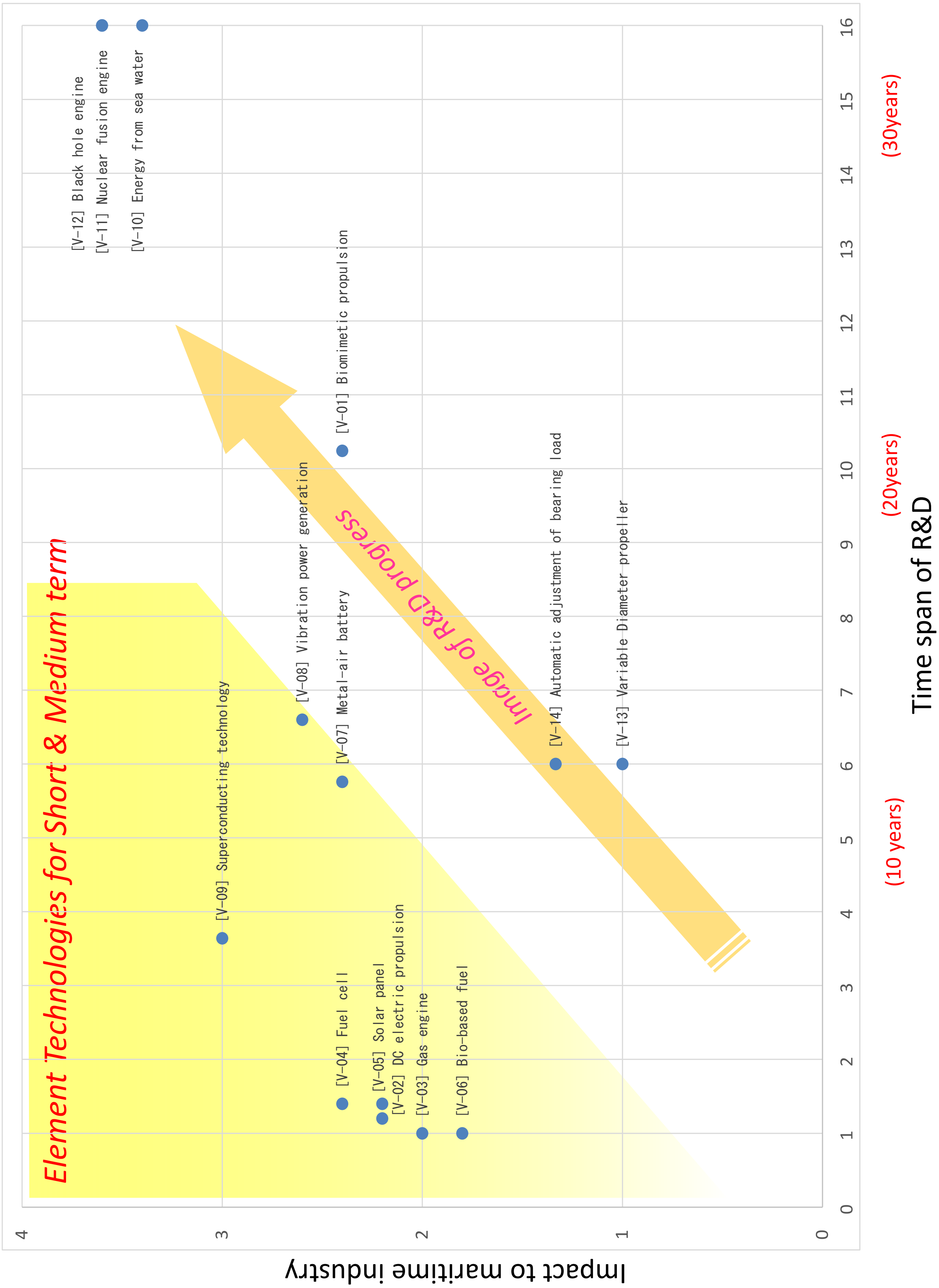
II. Design and construction of ship



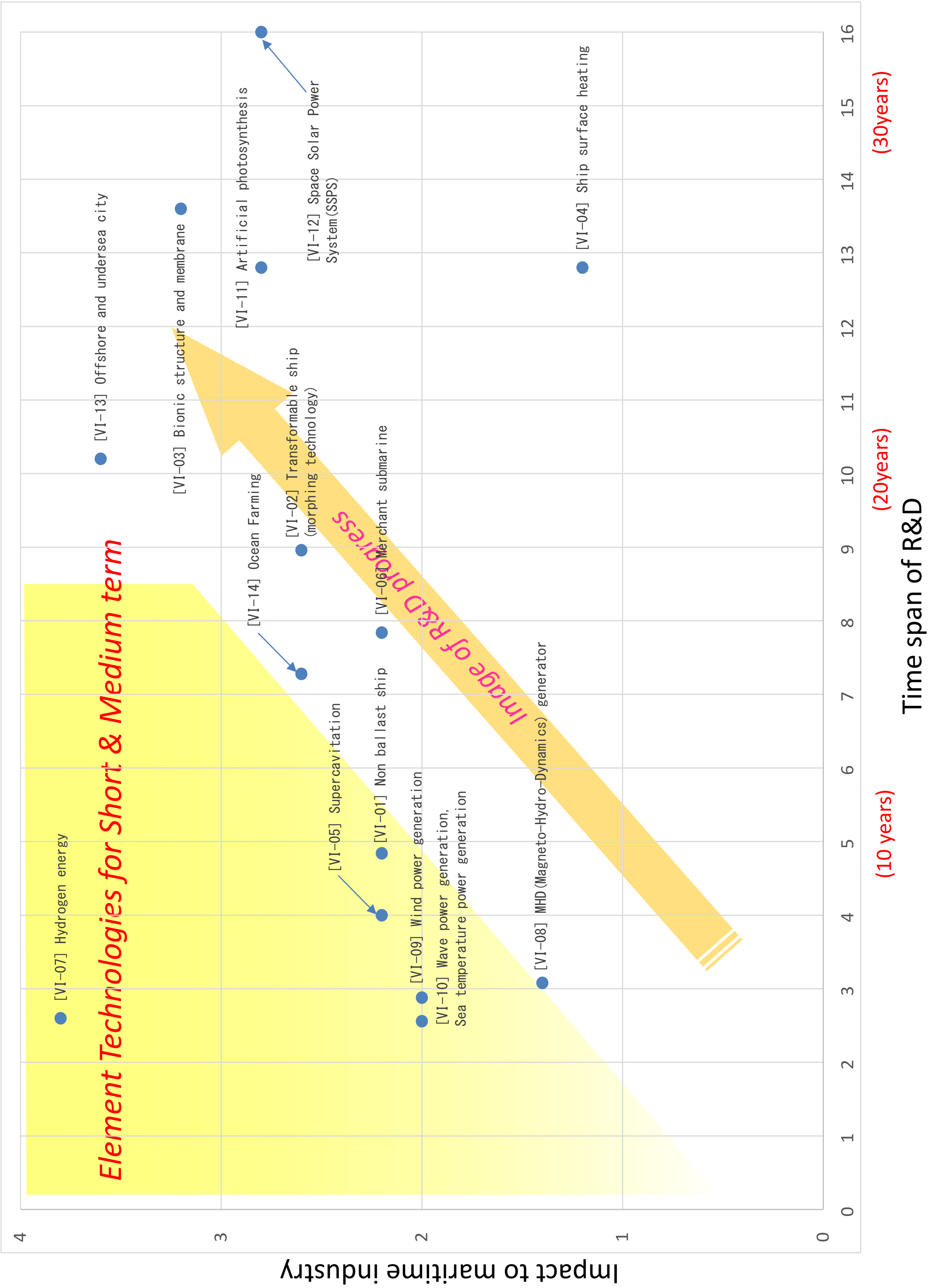
III. Ship operation and maintenance



IV. Transportation and logistics



V. Propulsion and engines



VI. New types of ships (Other technologies)

The Role of Standards for Future Adoption of Composites in Marine and Shipping

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Abstract

The use of lightweight high performance materials is dramatically increasing year-by-year in the maritime sector and there is a significant shift of focus in the sectors as well: as composite materials evolve they are considered more dominantly not just in the high-speed, military and leisure markets but also in the commercial and workboats as well. There are a number of factors that had been delaying widespread use of composites in those sectors: price of composites, lack of standardisation and fire safety issues. As governing bodies have a role to facilitate the adoption of innovations, including composites in the use of structural components, the next challenge for the marine industry is to understand how to design and work with composites without the need to be an expert. Relevant software which adopts multiple design guidelines aids this transition in the future of vessels and efficiency of designers.

1. Introduction

The adoption of composites in aerospace, automotive, renewable and rail industries has led to greater efficiencies in fuel and payload capacities, and decreased operational costs, leading to the question, why is it not used in commercial marine applications?

Many other marine sectors including leisure and military have been embracing the use of composites for over 30 years. The use of composites has led to increased performance in high shock resistance, low radar and magnetic signature, ballistics protection and increased speed as a result of reduced weight. It is often perceived that composites are difficult to design with, it can be hard to achieve a consistent quality and can be very difficult to certify, leading to higher initial costs compared to metallic design, however the operational costs are often overlooked, which can often reduce the overall vessel costs.

Statutory regulations define the minimum requirements for all classification societies, providing a solid baseline upon which, minimum requirements for design are set, however the costs and structural requirements for certification can change dramatically between regulatory bodies. The International Maritime Organisation (IMO) regulates the shipping industry, taking actions to improve safety, security and pollution prevention of worldwide shipping through universal application of standards.

The IMO delegates to the flag states and their recognised organisations (DNV GL, ISO, ABS, BV, LR, etc…) the responsibility to approach and provide certification taken from interpretation of the SOLAS regulations. This interpretation can often lead to excessively heavy vessels depending on the regulatory body. The release of new interim IMO guidelines allowing the use of composites in a limited range of structural elements is a big step for commercial shipping, and could lead to some great improvements in the industry; however fire performance is still a limiting factor for a broader adoption of composites.

Taking a look away from the classification bodies, push for the use of modern materials can be found in broader EU and CE regulations, forcing the global shipping fleets to innovate and develop the use of alternative materials from new regulations requiring a higher quality for fishing and shipping of goods.

2. Identifying variables linked with Design and Manufacturing for Composite Vessels

Vessels composed of composite vessels have three main interlinked elements for design and manufacture; Materials, Processing, Structural Design.

2.1. Composite Materials

Composite materials are made from two main elements: fibre and matrix. Fibres are the backbone of a composite, taking the majority of the load and are typically glass or carbon fibre. The role of the matrix is to distribute the load between the fibres, and is typically polyester, vinyl ester or epoxy. Combining these materials, along with an appropriate manufacturing process can provide a highly customisable range of mechanical and physical properties. Plies are stacked up together into a laminate, with the fibres orientated along the main load paths. Lightweight materials can be used to separate the two skins, increasing inertia of a sandwich panel; these materials are typically foam or wooden cores, PVC, PET and Balsa. Fire retardancy can be increased by adding ingredients to the matrix, causing a reaction under heat, emitting chemicals and gases to quench flames. Low technology, cheaper components are typically composed of woven /chopped strand glass fibre and a polyester matrix, whilst higher technology, higher performance components with low weight requirements are typically composed of unidirectional and stitched carbon fibre fabrics and epoxy matrix.

2.2. Processing

Processing of composite materials defines the physical and mechanical material properties, resulting in material that can be tailored with a wide range of strength and stiffness properties. Low technology components are typically made using hand laid up fabrics and mats in a mould, consolidated by hand, resulting in relatively heavy components with a lower fibre to matrix ratio. Higher technology components are laid up and consolidated by vacuum, giving a lower void content and higher fibre to matrix ratio (fibre volume fraction (FVF)). All composite components require mould tools upon which to form the shape and can be constructed from a variety of materials from MDF or plywood, carbon fibre composite through to high performance metals (e.g. INVAR), requiring thermal expansion properties similar to the product's properties. Typical low technology marine components are designed with ambient temperature curing, with post-curing at elevated temperatures (80-90° C), requiring cheaper moulds, whilst higher performance components are constructed with pre-impregnated fabrics to control weight and quality of laminate. These require curing at high temperatures (120° C), and tooling designed to withstand these temperatures.

2.3. Structural Design

As the materials choice and process has a large influence on the final material properties, efficient structural design has to account for all factors which could induce variability in the final product.

Certification bodies provide partial factors to account for this variability in material properties:

- Effects of Environmental Degradation (Ageing, temperature effects, UV Degradation, Humidity etc…)
- Static and fatigue modes of failure
- Type of use (Oil/Gas Carrier, Superyacht, Military Vessel)
- Material Type (Fibre/Matrix/Core/Paste Adhesives)
- Fabric Type (Woven, stitched, unidirectional etc…)
- Quality of Processing Method (wet layup, infusion, pre-preg etc...)
- Post processing of laminate (exothermic cure or post curing with different levels of control)
- Fire, Smoke and Toxicity Requirements
- Chemical Resistance

Pressures and loads are determined by three main elements; type of vessel, use of vessel and the vessel particulars. These elements all bring specific load cases and design pressures, derived from previous research and development of rules. These pressures are derived by governing bodies, and are more suited to specific segments, giving a different approach from each certification body.

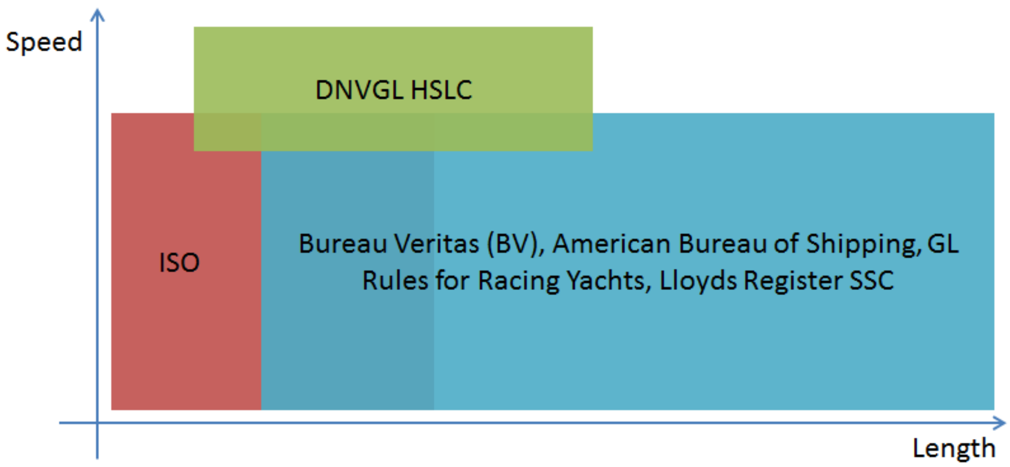

Fig.1: Governing Body Regulation Sectors by Vessel Particulars (non-exhaustive)

Even though the pressures and partial factors are generated for a specific sector, it can be seen that the solver is the same for each, giving opportunity for analysis and design software to span across multiple regulatory body guidelines. Multiple classification bodies have overlapping vessel particulars, Fig.1, allowing comparison and compliance with multiple rules and with suitable tools. Fig.2 shows the amount of control and inputs classification societies and standards have over design and manufacture, with generation of material properties, material partial factors, design pressures and thickness/fibre weight requirements.

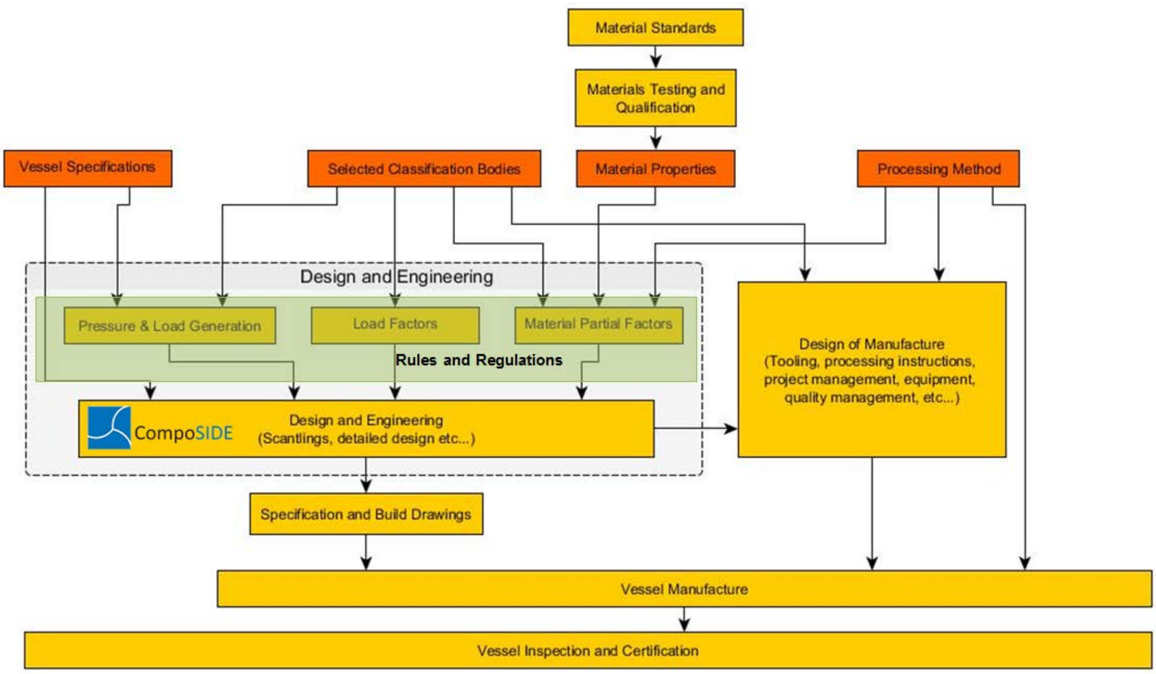

Fig.2: Composite Vessel Design Workflow

3. Current Barriers for Composite Adoption

There are many aspects to composites applications which could discourage adoption in the commercial marine industry. The first aspect is the accessibility of design; with a very large variability in composite material properties, and multiple failure modes for each material and laminate, prioritising the critical failure modes, in conjunction with the correct load partial factors, can quickly become time intensive and confusing. Composite design software's are available to aid with the design and analysis of composites, automatically applying correct material properties and material partial factors.

As mentioned in Section 2, the combination of processing and materials leading to a large range of mechanical and physical properties can lead to design choices which will affect the final product weight and performance – one of the key benefits of using composites! The lack of material standards within the composite industry, especially for carbon fibres, can lead to high costs when materials are sources from more than one manufacturer, where each material requires type approval, but is not produced to any standard. Certifying bodies give the option of two approaches to material properties used in design; using highly conservative minimum material properties, or using material testing to generate characteristic values. When the latter method is chosen, in an attempt to save weight and costs, changing materials can lead to very expensive re-qualification of properties. A typical test program for a single material (1 x fibre, 1 x matrix and 1 x processing method) can reach costs in the excess of multiple thousands of Euros.

As a comparison, the standardisation of material properties in the metals industry has brought many benefits to the end users; the main being reliability and consistency of material properties, directly leading to a reduction in material testing costs. Market access has also improved the option of multi-source supply, increased sales opportunities and client relations, which has directly influenced the time to market of a product and scalability issues for component manufacturers.

Fire resistance was a large challenge up until June 2017 when assessing highly regulated sector of mega power yachts, shipping and workboats. These are all regulated by IMO SOLAS (International Maritime Organisation for the Safety of Lives at Sea). Previous IMO SOLAS regulations previously specified according to Regulation II-2/11 that ship structures were to be constructed of steel or other equivalent material, where an equivalent material is non-combustible as specified in SOLAS Regulation II-2/3.43. This was a big challenge for lightweight materials such as composites and aluminium. Materials which can be proved as an equivalent to steel have a chance of being accepted, however with no clear performance parameters, this led to high cost and risk with no guarantee of approval. With the recent release of "*Guidelines for use of Fibre Reinforced Plastic (FRP) within Ship Structures*", released by the IMO, is a big step for the shipbuilding industry when guidance is required for composite components in ships. These guidelines, whilst currently interim, demonstrate a clear desire for the industry to adopt higher performance materials.

4. Adoption of Composite Design for Regulatory Bodies

As with any future development, feedback of results and research plays a key role in the future of any standards, as presented in Fig.3. Both require funding to develop composites vessels and execute research and development projects, something that is lacking in the marine industry. To take the aerospace industry as an example, light weighting of components is driven by fuel saving benefits, which has a clear effect on emissions and reducing costs, two main drivers from the industry.

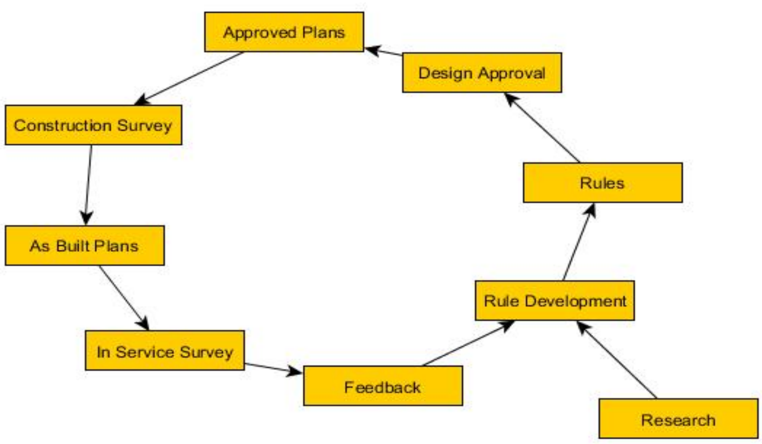

Fig.3: Rule Development Workflow

The lack of standards in the composite materials industry brings added barriers for adoption of composites, leaving the task to certification bodies to apply appropriate material partial factors for design, the requirement for material qualification and material testing. It can be seen in the industry that another large gap in some regulatory bodies is a lack of knowledge and understanding of composite materials, processes and design workflows, with most bodies providing software designed and optimised for large steel ships.

5. Composite Software Solutions

The first step, as mentioned earlier in the paper, is development of skills and knowledge of composite design and manufacture. This requires a set of tools that are easy and efficient to use, with a relevant set of design rules and guidelines implemented. Certification bodies often supply software for the design and verification of scantlings, or even just scantlings verification against individual rules. This requires engineers to learn new software, which can add to costs and time, in addition to software costs.

With these design tools, tested material data is very rarely given, with minimum, very conservative, mechanical properties published in guidelines, making it difficult to make a comparison between materials and processes, upon which a business case is generated, driven by weights and costs. CompoSIDE is one tool that fulfils these requirements, and is designed for easy design of composites for non-experts.

6. Summary

From the points discussed in the paper, the future of composites relies on the following main elements:

- Further Regulatory Progress - It is an encouraging step to see the IMO release of FRP guidelines, however the use of composites are still an exemption and requires individual certification, another barrier against the use of composite.
- Easier access to design tools – Removing pain points from engineers, increasing the ability of non-composite experts to engineer with composites.
- Material Standards – Introducing material standards similar to the metals industry removing large project costs.
- Consolidation of Existing Rules – reducing variation for engineers when using a range of guidelines and tools.
- Requires commitment from ship owners to have better solutions – Development requires a feedback loop, without a demand for the use of composites, development relies on research.

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An Alternative Approach for the Parametric Description of Hydrowing Blades in the Design Process

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Abstract

To lift the design of propeller and rudder blades to the next level a geometry description without the usual restrictions is needed. This paper presents a method for the free alignment of profiles with an inherent continuous surface description based on a parametric profile description with the parameters faired along the blade reference line.

1. Introduction

Traditionally the surface of wing-shaped appendages like rudders or propellers is described by offset tables containing pointwise data in a purpose adapted reference frame, which are transferred to the global reference frame when needed. This approach of describing the surface has several drawbacks when it comes to more complex surface shapes or if a finer resolution of the surface is needed downstream in the design process. From a design point of view propeller blades with a high rake and/or skew like tip-raked or Kappel propeller cannot be described, nor designed due to the coupling of degrees of freedom, in a satisfactory manner. In general, a high density of point data is necessary everywhere the curvature of the surface is high. For numerical applications like CFD, the surface description and the grid points of the numerical grid on the surface usually do not match. Hence interpolation becomes necessary, which leads to deviations between the CAD and the grid geometry.

To overcome these drawbacks, a new concept of parametric description of wings is shown in this paper. Therefore, the characteristic parameters (e.g. camber, thickness, etc.), which will be discussed later, to describe a profile are faired along the developed length of the reference line. Also, the rotation of the profile to the reference line is faired. This is comparable to the pitch for example. It is possible to represent any profile from a regular profile series at a specific section and calculate the profiles in between directly from the set of parameters. This procedure gives continuous parameters along the reference line and therefore also a continuous surface description. This enables the designer to get away from the classic profile description only on cylindrical surface in propeller design or normal to the shaft axis in rudder design. But it also gives the opportunity to define a specific section by a profile taken from a profile series, which is then transformed into the parameters. Therefore, the designer can apply his knowledge and experience to the design process the way he is used to it and combine this with the greater design space due to this new approach. Propeller designs like the one mentioned before are designed presently by a tricky combination of coupled factors. This approach turns this upside down and gives the designer the opportunity to directly adjust the value he likes to change. Also, the effort to interpolate the coordinates of the in between sections is cancelled out, because these are calculated directly.

2. Mathematical description of the surface

At first, a profile reference line is defined for the description of the surface. The profile reference line is defined by $n+1$ points (X_i, Y_i, Z_i) and the first derivative in each direction with respect to the parameter t at the beginning and end of the profile reference line. The coordinates between the given points are calculated with a three-dimensional cubic parametric spline with n sections. The coordinates of the i-th section is given by:

$$x_i(t_i) = a_{x,i}t^3 + b_{x,i}t^2 + c_{x,i}t + d_{x,i},$$
$$y_i(t_i) = a_{y,i}t^3 + b_{y,i}t^2 + c_{y,i}t + d_{y,i}$$
$$z_i(t_i) = a_{z,i}t^3 + b_{z,i}t^2 + c_{z,i}t + d_{z,i}$$

with $t_i \in [0; \Delta t_i]$,

$$\Delta t_i = \sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2 + (Z_{i+1} - Z_i)^2}.$$

The coefficients of a section of the spline are calculated from its boundary conditions. Two boundary conditions for each direction are the coordinates of the start and end points. Two more conditions yield from the connection of two neighbouring spline sections. At the connection, the first and second derivatives of the sections are equal. Furthermore, two more boundary conditions need to be provided at the beginning and end of the spline. Here, the first derivative at the beginning and end is used as a boundary condition. When solving the resulting tridiagonal linear equation system, the coefficients can be calculated.

Thereafter, the profile parameters, which are discussed in detail in section 2.1, are defined as two-dimensional cubic splines over the developed length of the profile reference line

$$L\big(x(t), y(t), z(t)\big) = \sum_i \int_0^{\Delta t_i} \left\| \left(\frac{dx_i}{dt}, \frac{dy_i}{dt}, \frac{dz_i}{dt} \right) \right\| dt\,.$$

As the profile parameters are now defined for every arbitrary point on the profile reference line, the surface of the wing can be calculated by building profiles from the parameters, as shown in section 2.2. Subsequently, the profiles are rotated in a way that they are normal to the profile reference line with their chord being parallel to the XZ-plane. Additionally, they can be rotated with three further parameters as shown in section 2.3.

2.1. Parameters for fairing

The four parameters needed for the description of the mean line are shown in Fig.1. The maximum camber is described by the parameter m and its position in X-direction by the parameter x_m. The parameters θ_{le} and θ_{te} depict the angles of the mean line to the X-axis at the leading and trailing edge, respectively. Additionally, the parameter x_{Off} describes the offset of the leading edge of the profile to the profile reference line. For the rotation of the profile exist three further parameters ϑ_x, ϑ_y and ϑ_z which describe the angle of rotation around all axes. From these three rotation angles is only the rotation angle around the Z-axis ϑ_z shown in Fig.1.

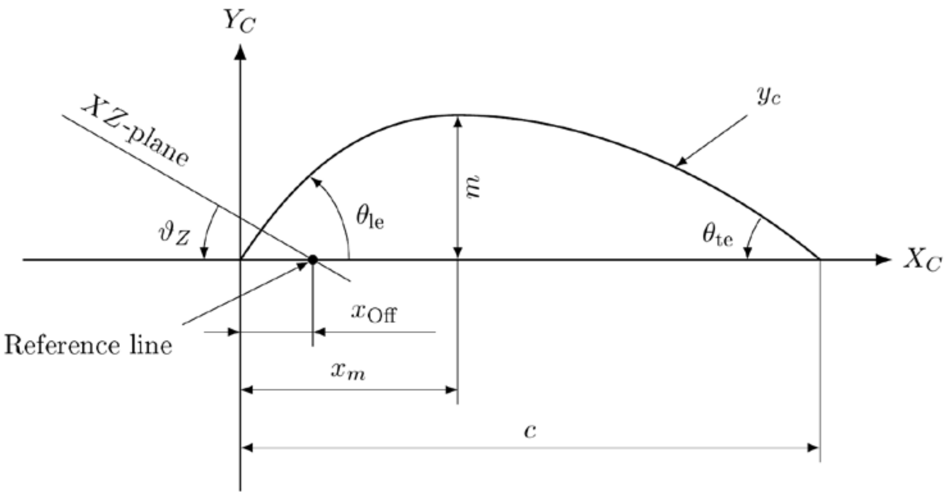

Fig.1: Parameters of the mean line

The thickness line is described by eight parameters, which are presented in Fig.2. The leading and trailing edge each have three parameters: a radius describing the curvature (R_{le} and R_{te}), a gap ($y_{\text{le, gap}}$ and $y_{\text{te, gap}}$) and a transition angle (α_{le} and α_{te}). At the leading and trailing edge, the thickness line follows a segment of a circle with the defined radius of curvature until the slope of the segment of the circle is equal to the slope defined by the transition angle. In addition, the parameter t represents the maximum thickness and the parameter x_d its position in X-direction.

All parameters have a direct meaning in the design process of hydrodynamic blades. The parameters can be defined at several points along the profile reference line. In between these points, the value of the parameters are calculated using a cubic spline:

$$y_i(x_i) = a_{y,i}x^3 + b_{y,i}x^2 + c_{y,i}x + d_{y,i}.$$

The boundary conditions for the calculation of the coefficients for the nonparametric cubic spline are similar as for the parametric spline discussed before.

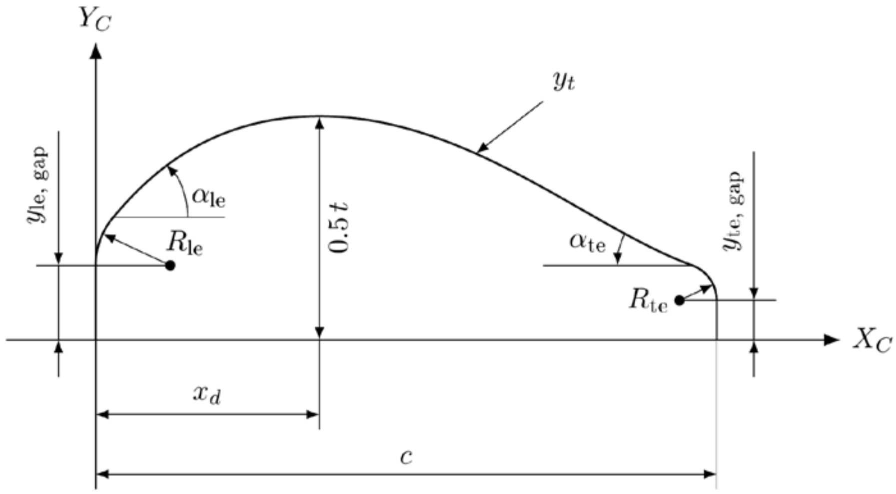

Fig.2: Parameters of the thickness line

2.2. Calculation of profiles from the parameters

As the parameters are defined along the profile reference line, profiles can be calculated from these parameters at every arbitrary point. The mean line can be calculated using separated two-dimensional parametric splines. The spline is separated at the point of maximum camber so that the slope can be set to zero to ensure that the point is a maximum. The boundary conditions for each half are the point of maximum camber, the first derivative of the parameter describing the angle at the leading or trailing edge and the first derivative at the maximum camber. The second derivative is not continuous for bad boundary conditions. Thus, only one angle can be set free while the other one results from the condition of a continuous second derivative.

In the following, two different approaches for the calculation of the thickness line of the profiles are discussed. One approach is based on the modified NACA four-digit series, *Stack and Doenhoff (1935)*. The other one uses quintic parametric Hermite splines. While the first one is more restricted, it is also more stable than the second one.

2.2.1. Modified NACA

The modified NACA four-digit series presented by *Stack and Doenhoff (1935)* is an expansion to the thickness line of the NACA four-digit series by *Jacobs et al. (1933)*. Besides the thickness, the position of the maximum thickness and the curvature of the leading edge are two further input parameters of the modified NACA profile. The thickness line is described by

$$y_t(x) = \begin{cases} \frac{t}{0.2}\left(a_0\sqrt{x} + a_1 x + a_2 x^2 + a_3 x^3\right) & x < x_{m,max} \\ \frac{t}{0.2}\left(d_0 + d_1(1-x) + d_2(1-x)^2 + d_3(1-x)^3\right) & x \geq x_{m,max} \end{cases}$$

The coefficients of the second section are determined before calculating the ones of the first section as the coefficients of the first section depend on the ones of the second section. The coefficients of the second section can be calculated from solving the approach for the following boundary conditions:

$$\begin{aligned} y(x_d) &= 0.5t, \\ \frac{dy}{dx}(x_d) &= 0, \\ y(1) &= y_{te,gap} \text{ and} \\ \frac{dy}{dx}(1) &= \tan\alpha_{te}. \end{aligned}$$

Here, two more input parameters are added to the formulation of the modified NACA series. In the third equation, the width of the gap is added, which is in the modified NACA series always 0.002. Additionally, the angle at the trailing edge is added in the fourth equation, where a function is used in the modified NACA series.

The coefficients of the first section are determined by solving the following equation system:

$$\begin{aligned} y(x_d) &= 0.5t, \\ \frac{dy}{dx}(x_d) &= 0, \\ a_0 &= \frac{0.2}{t}\sqrt{2R_{le}} \text{ and} \\ R(x_d) &= \frac{(1-x_d)^2}{2d_1(1-x_d) - 0.588}. \end{aligned}$$

2.2.2. Quintic parametric hermite spline

The challenge in designing a function for the description of a profile from parameters is to take care of all boundary conditions while still maintaining a smooth function without oscillations. Only a few points are fixed by the parameters (leading and trailing edge, maximum thickness and the point of transition from the radius to the rest of the thickness line at the leading and trailing edge), while there are several boundary conditions at these points. A polynomial over the complete chord length has a high polynomial degree and is vulnerable to oscillation. The degree of the polynomials decreases when using splines. Here, the lowest degree that can be used is a spline of fifth degree. Since this is still a high degree for a spline interpolation, oscillations may still occur. To overcome this problem, a similar approach, as already introduced by the NACA four-digit series by *Jacobs et al. (1933)*, is used. The profile is developed for a fixed relatively large thickness and scaled to the right thickness afterwards. In the case of the NACA four-digit series a thickness of $t/c = 0.2$ is used. For the approach using splines a thickness of $t/c = 0.3$ leads to satisfactory results where no oscillations occur. The boundary conditions need to be scaled accordingly. In the following, $\lambda = t/0.3$ denotes a scale factor with t being the desired thickness of the profile. The ordinates simply scale with the factor λ, the angles at the leading and trailing edge scale according to

$$\alpha_s = \arctan(\lambda \tan(\alpha))$$

and the radius of curvature scales with λ^2.

The spline of the profile is described by $n + 1$ triplets

$$P_i = \left(X_i; Y_i; \begin{pmatrix} dx_i \\ dy_i \end{pmatrix} \right),$$

where the first two values of a triplet are the abscissa and the ordinate of a point on the thickness line. As the first derivative is infinite at the leading edge, it cannot be used as an input parameter. Hence, the information on the first derivative at a point is given in the third value of the triplet as a unit tangent vector.

The triplets used in the spline for the description of the thickness line are the leading edge

$$P_1 = \left(0; \frac{y_{le,gap}}{\lambda}; \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right),$$

the transition from the radius to the rest of the thickness line with

$$P_2 = \left(\frac{R_{le}}{\lambda^2} - \frac{R_{le}}{\lambda^2} \sin \alpha_{s,le}; \frac{y_{le,gap}}{\lambda} + \frac{R_{le}}{\lambda^2} \cos \alpha_{s,le}; \begin{pmatrix} \cos \alpha_{s,le} \\ \sin \alpha_{s,le} \end{pmatrix} \right),$$

the point of maximum thickness

$$P_3 = \left(x_d; 0.3; \begin{pmatrix} 1 \\ 0 \end{pmatrix} \right),$$

the transition to the trailing edge radius (if present)

$$P_4 = \left(1 - \frac{1}{\lambda^2} (R_{te} + R_{te} \sin \alpha_{s,te}); \frac{y_{te,gap}}{\lambda} + \frac{R_{te}}{\lambda^2} \cos \alpha_{s,te}; \begin{pmatrix} \cos \alpha_{s,te} \\ \sin \alpha_{s,te} \end{pmatrix} \right)$$

and the trailing edge

$$P_5 = \left(1; \frac{y_{te,gap}}{\lambda}; \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right).$$

When the trailing edge radius is not present, the last two points merge into one:

$$P_4 = \left(1; \frac{y_{te,gap}}{\lambda}; \begin{pmatrix} \cos \alpha_{s,te} \\ \sin \alpha_{s,te} \end{pmatrix} \right).$$

Between these points, the thickness line is described by a spline with n sections. The values in the i-th section for the fixed thickness are expressed by following parametric approach:

$$x_{t,i}(t_i) = a_{x,i} t_i^5 + b_{x,i} t_i^4 + c_{x,i} t_i^3 + d_{x,i} t_i^2 + e_{x,i} t_i + f_{x,i},$$
$$y_{0.3,i}(t_i) = a_{y,i} t_i^5 + b_{y,i} t_i^4 + c_{y,i} t_i^3 + d_{y,i} t_i^2 + e_{y,i} t_i + f_{y,i},$$

$$\text{with } t_i = [0; \Delta t_i],$$

$$\Delta t_i = \sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2}.$$

The values of the triplets serve as boundary conditions for the calculation of the coefficients of the spline sections. Further boundary conditions are derived from the requirement that the second and third derivates are equal at inner points between two neighbouring splines. The last two missing boundary conditions yield from the curvature

$$\kappa_i = \frac{\lambda^2}{R_i} = \frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{(\dot{x}^2 + \dot{y}^2)^{3/2}}$$

at the beginning and end of the spline. In the above equation, the parameter R_i is the radius of curvature. These boundary conditions lead to a symmetrical tridiagonal linear equation system, which can be solved for the calculation of the coefficients.

Finally, the ordinate of the thickness line needs to be scaled to obtain the thickness line with the desired thickness:

$$y_{t,i}(t_i) = \lambda y_{0.3,i}(t).$$

The abscissa does not need to be scaled.

2.2.3. Combination of mean and thickness line

The mean and thickness line are combined to the upper and lower surface of the profile, *Jacobs et al. (1933)*. The points on the upper side are described by

$$x_U = x - y_t \sin\theta\,,$$
$$y_U = y_c + y_t\ \cos\theta$$

and the points on the lower side by

$$x_L = x + y_t \sin\theta\,,$$
$$y_L = y_c -\ y_t \cos\theta,$$

with $\tan\theta$ being the slope of the mean line at the position x, y_c the ordinate of the mean line and y_t the ordinate of the thickness line.

2.3. Rotation of the profile

The two-dimensional points of the profile are first rotated by the pitch angle parameters in the profile coordinate system. First, they are rotated by ϑ_x around the X-axis. Thereafter, the profile is rotated by ϑ_y around the Y-axis and finally by ϑ_z around the Z-axis.

After these rotations, the profile coordinate system is aligned with the profile reference line. The Z-axis of the coordinate system of the profile points, as already mentioned, into the direction of the profile reference line. The X-axis of the profile coordinate system is parallel to the global XZ-plane. Afterwards, the orientation of the Y-axis is fixed by the orientation of the other two axes.

The orientation of the profile reference line is described by the two angles of a spherical coordinate system. The angle Θ is between the profile reference line and the XY-plane and the angle φ is around the Z-axis between the reference line and the X-axis. With these two angles, the profile coordinate system is rotated by a $(z - y - z)$ Euler angle rotation. This means that the coordinate system is first rotated by Θ around the Z-axis, then by φ around the Y-axis and in a final step by $(-\Theta)$ around the Z-axis.

3. Application to hydrofoil blades

In the following, the application of the parametric approach on two different exemplary hydrofoil blades is shown. At first, a twisted rudder blade is presented and afterwards a tip rake propeller blade is shown. The geometric properties of the blades are purposely overdrawn since only the capabilities of the approach are shown here.

Fig.3 shows a rudder with a twisted leading edge. The profile reference line is designed with an S-shape and constant X-value. Thereafter, the pitch and the chord length are chosen in a way that the rudder has a straight trailing edge. The thickness line follows the NACA four-digit thickness line. The blade has a NACA XX30 at the top and a NACA XX10 at the lower end. The thickness properties in between are faired. The parameters describing the mean line are shown in Fig.4. At the lower edge of the rudder, the position of maximum camber x_m lays in the middle of the profile. The position of maximum camber moves further to the leading edge for positions nearer the upper edge of the rudder. The sign of the camber is depending on the position as the rudder is twisted in the upper half to one side and in the lower half to the other side. Afterwards, the parameters for the angle of the camber line at the leading and trailing edge are chosen in a way that the curvature of the camber line is smooth and does not change its sign.

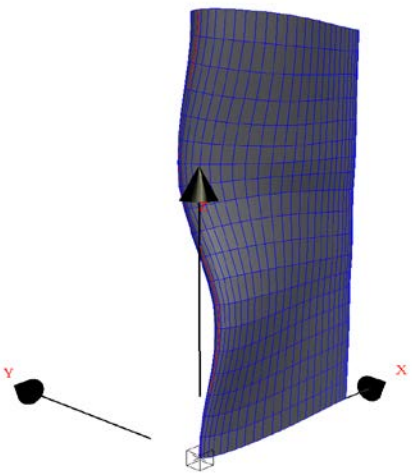

Fig.3: Exemplary twisted rudder blade

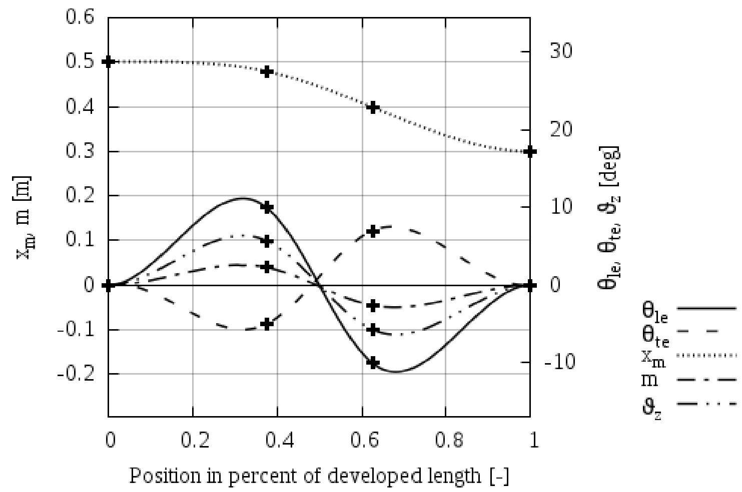

Fig.4: Faired parameters of the rudder blade. Points with explicitly given values are marked with a plus.

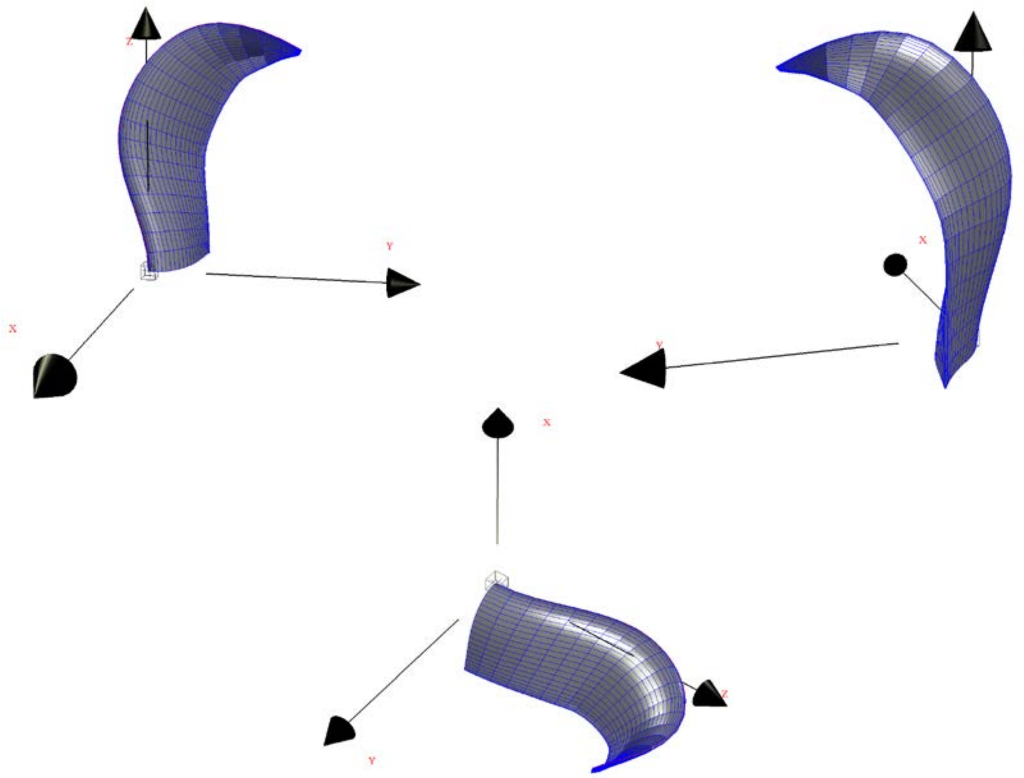

Fig.5: Exemplary propeller blade from different perspectives

In Fig.5, a single propeller blade with skew and tip rake is shown from different perspectives. Since the description of such a blade depends on the specific case, this is just an example here. Initially, the profile reference line is defined with the skew and a slight tip rake. The parameters of the thickness line are chosen in the same manner as for the rudder before. At the root of the blade, the thickness line is described by a NACA XX30 and at the tip by a NACA XX10. The angular parameters over the developed length of the blade are shown in Fig.6 and the parameters of the dimension of a length are shown in Fig.7. A certain camber is defined at the root of the blade and decreases to the tip (see m, θ_{le} and θ_{te}). The position of maximum camber x_m has a constant value over the developed length. The pitch around the Z-axis ϑ_z and the chord length are set in a way that the desired geometry is obtained. The pitch around the Y-axis ϑ_Y is introduced to overcome the problem that the profiles compress at the trailing edge due to the large curvature of the profile reference line.

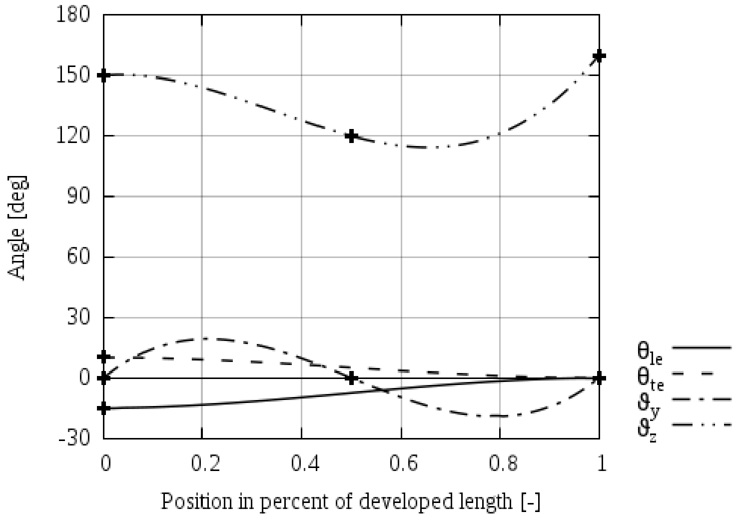

Fig.6: Faired angular parameters of the propeller blade. Points with explicitly given values are marked with a plus.

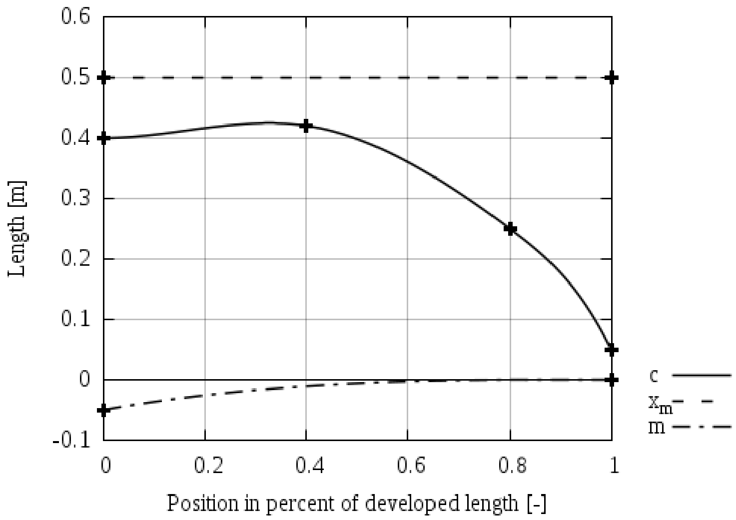

Fig.7: Faired parameters of the propeller blade with a dimension of a length. Points with explicitly given values are marked with a plus.

4. Conclusion and outlook

The presented procedure enables new designs, which were not possible before, or just with a great effort of factor coupling, caused by the data formats. The design process benefits from the new approach, due to a small amount of data that describes the complete hydro wing sufficiently. Therefore, also regular designs can benefit from this method. Furthermore, it is possible to align the profile exactly to the flow field and generate unconventional shapes. On the other hand errors due to interpolation are excluded and the refining of CFD grids is easily possible.

In the future, the ability of this method to map other profile families, rather than the NACA series, should be tested. Also, some design tools that handle a set of parameters at a time could be programmed. A possible example is to keep the projected area of a rudder constant while twisting it and therefore changing the chord length.

Although it is already possible to represent profiles from series at a specific section, it is desirable to read from different, established file formats and generate the set of parameters. The ability to write back to these file formats is necessary to exchange data between project partners, not using this approach.

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Local Results Verification of a 3D Non-Linear Lifting Line Method for Fluid-Structure Interactions Simulation on a Towing Kite for Vessels

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Abstract

This paper describes a 3D non-linear model based on the lifting line of Prandtl, expanded to address cases of wing with dihedral and sweep angles variable along the span, and with any flight kinematic including translation velocities and turning rates. This model has been checked by comparison with 3D RANSE simulations and shows good consistency with a relative gap of less than 10% for the global lift and drag coefficients on two different geometries. The local aerodynamic forces comparison gives also satisfying results on classical geometries even with various angle of incidence and sideslip.

1. Introduction

The "beyond the sea®" project aims to develop tethered kite systems as ships auxiliary propulsion to reduce fuel consumption with the use of renewable energy. Indeed, *Wellicome and Wilkinson (1984)* showed that kite wings are more effective for wind propulsion than other common systems. The fuel savings can be predicted by *Leloup et al. (2016)*. For the auxiliary propulsion of merchant ships, the common sport kites need a significant upscaling as they can be larger than 300 m². Therefore, it is not possible to experimentally test each new geometry. As the kite is a flexible structure, fluid-structure interaction (FSI) has to be taken into account to calculate the flying shape, *Bosch et al. (2014)*. Knowing the computational time necessary to carry out a fully coupled simulation using Finite Element and Computational Fluid Dynamics methods, it can be very useful in a design phase to use fast and reliable models to estimate rapidly the kite performances. Furthermore, fast simulations allow the studies of different trajectories and the determination of the critical load case, where more complex models can be used.

For the estimation of the kite performance, *Dadd et al. (2010)* use the zero-mass model, which neglects the weights of the kite and the tethers. This model allows the prediction of the kite velocity and the line tension but gives no information about the local loads, which are necessary to FSI simulations. *Gaunaa et al. (2011)* develop an iterative method which couples a Vortex Lattice Method with 2D airfoil data to consider the effects of airfoil thickness and of viscosity. The results are compared with RANSE simulations and show good agreement for cases without much sideslip. Nevertheless, as the kite can have complex trajectories with a non-null turn rate, the method has to be able to manage these different flight cases. The Prandtl lifting line is also a right method for wing performance prediction. As an example, *Graf et al. (2014)* use a non-linear iterative lifting line method to predict the lift and drag of a two-element straight wing for an AC72 catamaran. The comparison with Reynolds Averaged Navier-Stokes Equations (RANSE) simulations shows a good agreement for attached flow regime. A 3D non-linear lifting line model is already introduced in *Duport et al. (2016)* but the local forces estimation of the model has not been checked.

This study first details the 3D non-linear lifting line method which is implemented to manage wings with high dihedral and sweep angles. In section 3, the settings of the RANSE simulations are presented. The last part compiles the results of the simulations with swept or un-swept wings, purely in incidence or with an angle of sideslip.

2. 3D Non-Linear Lifting Line Method

The 3D non-linear lifting line method is based on an extension of the Prandtl's lifting line theory. This extension is intended to address cases of wings with variable dihedral and sweep angles, and take into account the non-linearity of the lift coefficient. The kite wind is supposed to fly in a given wind $\overrightarrow{V_{RW}}$. The kite velocity $\overrightarrow{V_K}$ or its turn rate $\vec{\Omega}$ can also be taken into account. The finite wing and its wake are represented by a set of horseshoe vortices of different strengths. The aim of the algorithm presented thereafter is to calculate the circulation Γ^i of each horseshoe vortex. Once these strengths are obtained, the local effective flow for each wing section allows local aerodynamic forces and torques calculation along the span of the wing. The numerical iterative solution is taken from *Anderson (2011)*, but the calculation of the local effective angles of incidence is adapted to the cases of wings which are non-straight and non-planar. The horseshoe vortices used for discretization, and calculation of their influences, are for their part derived from *Katz and Plotkin (2001)*.

The wing is divided in a finite number n of plane sections, each one represented by a horseshoe vortex, which consists of six vortex segments. The bound vortex is located at the local quarter chord length, perpendicularly to the plane of the considered section. An example of the discretized model is presented in Fig.1. This leads to a piecewise constant discretization of the lifting line, as it is theoretically required in order to have a correct match between the local lift calculated from the Kutta formula or from the polar of the section. Non-linear polar curves for the 2D section coefficients of lift, drag and moment about the quarter chord point are also supposed to be given with respect to the angle of incidence.

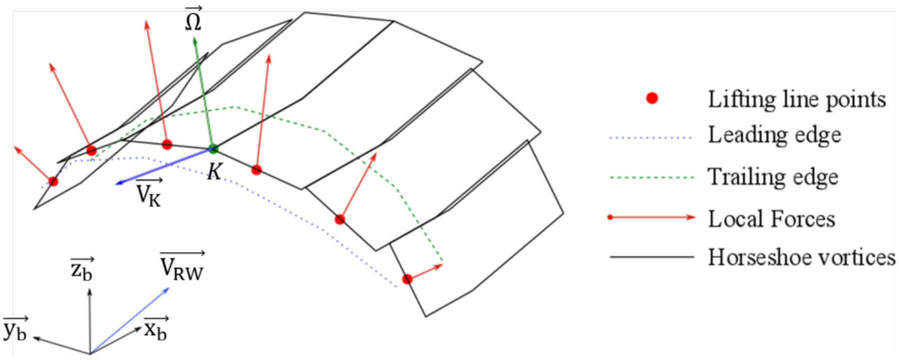

Fig.1: Low discretised lifting line model. Local torques are not reprensented to improve readability

The local circulation values are first initialized by an elliptical distribution along the wing span. Then for each point of the lifting line, the induced velocities by each vortex segment are calculated with the Biot-Savart law and then summed, leading to the induced velocity. The induced velocity combined with the given wind $\overrightarrow{V_{RW}}$, the kite velocity $\overrightarrow{V_K}$ and its turn rate $\vec{\Omega}$ gives the effective wind. This wind is projected in the plane of the section and set the section effective angle of incidence. Using the 2D lift polar curve of the section, the local lift in the section plane can be calculated:

$$L^i = 0.5\rho {V_{prj}^i}^2 c^i C_l^i(\alpha_{prj}^i) \tag{1}$$

With L^i the local lift per unit length, ρ the density of the air, V_{prj}^i the effective wind projected in the plane of the section, c^i the chord length of the section and $C_l^i(\alpha_{prj}^i)$ the 2D lift coefficient of the respective section at the effective angle of incidence α_{prj}^i. By construction, this local lift is orthogonal to the effective wind projected in the plane of the section. Therefore, the Kutta formula is equivalent:

$$\overrightarrow{L^i} = \rho \overrightarrow{V_{eff}^i} \times \Gamma^i \overrightarrow{t^i} \tag{2}$$

With $\overrightarrow{V_{eff}^i}$ the effective wind and $\overrightarrow{t^i}$ the normal to the plane section. The new circulation derives from Eq. (1) et (2):

$$\Gamma^i = 0.5 V_{prj}^i c^i C_l^i(\alpha_{prj}^i) \tag{3}$$

The circulation values are finally updated by weighing between the new circulation and the previous one with a damping factor. This iterative process is repeated until convergence of the circulation distribution.

Once convergence is reached the lift, drag and torque of each section of the wing are then post processed with the converged circulation, which leads to integrated local loads. Finally, these are vectorially summed, to obtain the global force and the global moment about the K point, which apply to the kite wing. The converged result is found to be independent of the initial solution.

Mesh convergence studies were performed. In the cases of straight wings in translation motion parallel to their symmetry plane, very good results versus analytical ones were obtained with at least 10 horseshoe vortices. Nevertheless, in the cases of 3D wings with variable dihedral and sweep, a larger mesh dependency of the converged results was observed, in particular for the total drag coefficient. The mesh having been varied from 10 to 200 sections, the confidence intervals at 95% were estimated using the standard deviations of the results. In the linear range, for angles of incidence typically lower than 10°, it was obtained: 1.0% for the lift, 1.3% for the drag and 1.6% for the moment about the K point. In the non-linear range, for angles of incidence typically greater than 10°, it was obtained: 4.0% for the lift, 15.3% for the drag and 14.1% for the moment about the K point.

3. RANSE simulations settings

The aim of this study is to validate the 3D non-linear lifting line method. For this purpose, 3D RANSE simulations have been performed with the generalist tool STAR-CCM+®. 2D simulations were first used for convergence studies and also to calculate the 2D polar curves of the section, needed in the lifting line model. The parameters of the simulations and the convergence studies are presented in this part.

All the RANSE simulations are incompressible, steady and fully turbulent. The retained turbulence model is the two-equation k-ε realizable model with a two-layer formulation for the wall treatment. The segregated flow solver is based on the SIMPLE algorithm, and a second-order discretization scheme. The kite section or the kite wing is set with respect to the computational domain, to avoid the creation of a new geometry for each calculation case. The direction of the inlet velocity is therefore changed to model the modification of the angle of incidence or the sideslip angle. The chord based Reynolds number is fixed at $3.1 * 10^6$. The turbulence intensity is set to 0.5% and the turbulent viscosity ratio is set to 1.

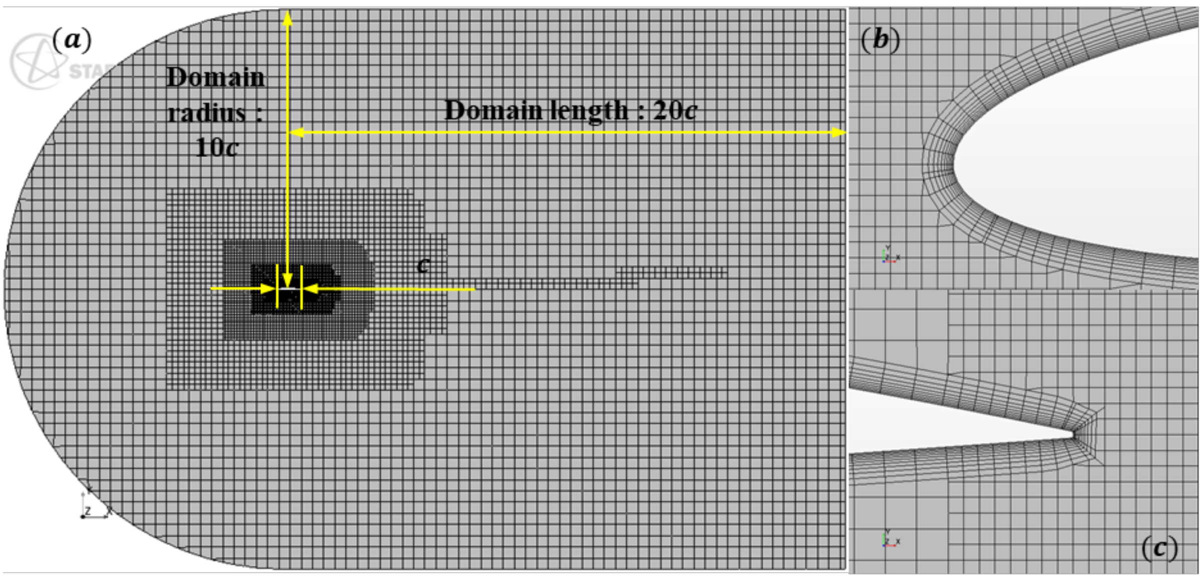

Fig.2: (a) 2D meshed computational domain. (b) Mesh around the profile section. Near wall mesh close to (c) leading edge, (d) trailing edge.

The 2D computational domain is presented Fig.2. The domain is meshed using the trimmed cell mesher, which led to predominantly hexahedral mesh. It is controlled by a cell base size ($0.1c$), with c the chord length of the section, and targeted cell sizes at some boundaries: inlet and outlet ($0.5c$), wing extrados and intrados ($0.025c$), wing leading and trailing edges (0.00625c). The cells size growth rate is very slow, which means at least 8 equal sized cell layer per transition. Around the wing a prism layer mesh is used in order to get orthogonal cells next to the wall. It is controlled by its thickness ($0.0125c$), a number of layer (10) and a growth rate between adjacent cells in the wall normal direction (1.2). Two anisotropic wake refinements are also used in the free stream direction from the trailing edge, one finely meshed (0.00625c) of one chord long and the other coarse ($0.2c$), extending over several chords ($15c$).

In 3D, the same settings are used in addition to a refinement ($0.00625c$) in a conical region at the wing tip, parallel to the mean free stream, in order to partially resolve the tip vortex. The wake refinements are based on the trailing edge and are also parallel to the mean free stream. For the wing with a sweep angle, the same conical refinement is also added at the symmetry plane (see Fig.3). The obtained 2D and 3D meshes are coarse, of about $16 * 10^3$ cells in 2D and $5 * 10^6$ in 3D, and they lead to a mean value of y^+ over the wing surface of about 35 in each simulated case. The stopping criteria of the simulations are based on the monitor of the lift and drag coefficients, specifying a $|max - \min|$ tolerance ever the 10 last calculated values. The tolerance is set to 10^{-6} for both coefficients, and it was found that it corresponds to the fall of the non-dimensional residuals over at least 4 or 5 decades.

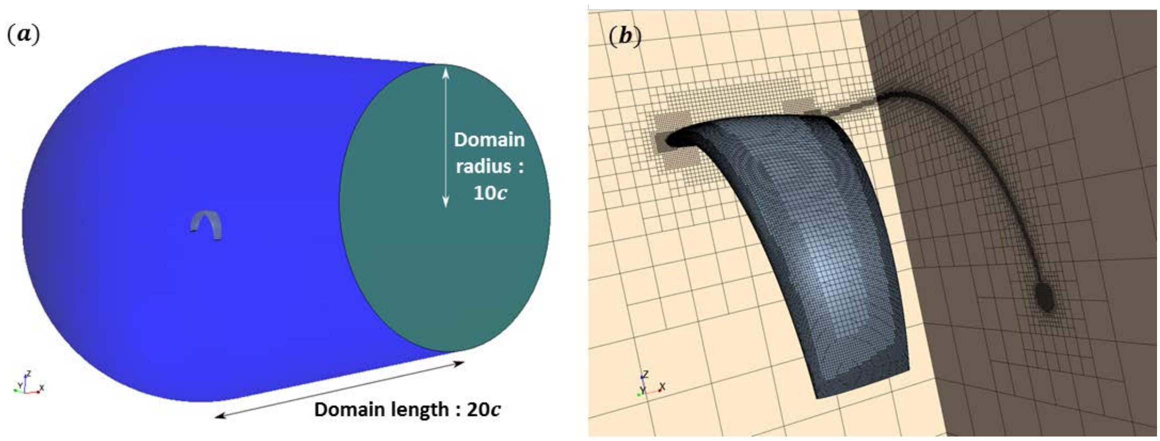

Fig.3: (a) 3D computational domain. (b) 3D mesh with refinements in the wake and near tip vortex

An attempt was done to estimate a numerical accuracy of the 2D and 3D RANSE results. It is supposed that results from 2D simulations are sufficient for that purpose and that they can be extrapolated to 3D cases. In addition, it is assumed sufficient to examine a single angle of incidence of 2° for the root kite section, to be representative.

Three elementary variations of the general numerical set up are considered. The results in term of lift coefficient are presented Fig.4. The obtained curves are similar for the coefficients of drag and moment. First (Fig.4 (a)) the size of the computational domain is varied (parameter N from 1 to 27, domain length=$2Nc$, domain radius=Nc), keeping constant the base size, the absolute targeted sizes at the section, the near wall mesh parameters and the growth rate. Second (Fig.4 (b)) the targeted sizes at each boundary being defined relatively to base size, the base size was varied (from 0.6c to 0.02c, leading to cell count from $6 * 10^3$ to $120 * 10^3$), keeping constant the near wall mesh parameters. Third (Fig.4 (c)) the number of layers of the near wall mesh was varied (from 4 to 32, leading to mean y^+ values from 156 to 0.5), keeping constant all the other mesh parameters. In this last case, two other turbulence models were also tested (k-ω SST and Spalart-Allmaras).

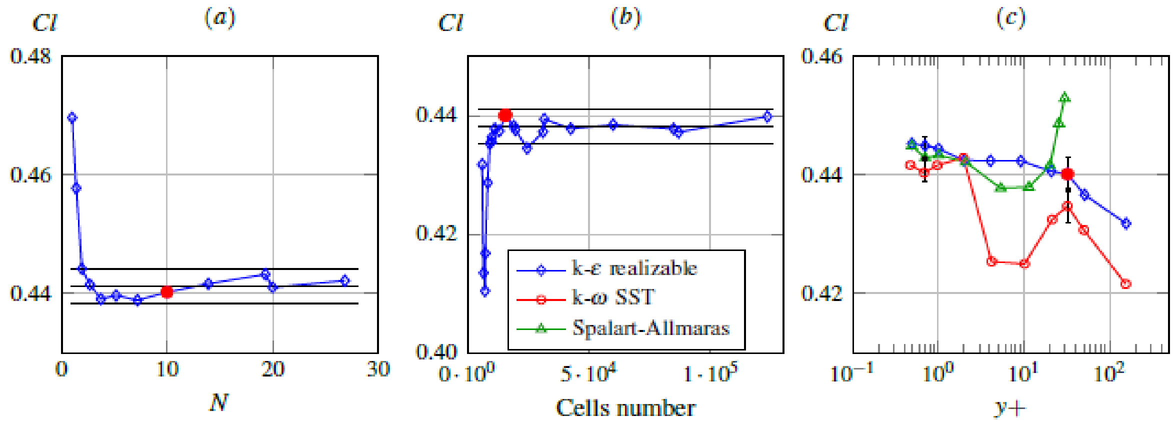

Fig. 4: Convergence history of the lift coefficient for variations (a) of the computational domain size, (b) of the number of cells in the mesh, (c) of the turbulence model and of the number of layers of the near wall mesh

For the variations of the domain size and of the number of cells, based on the limited number of computed points, for each aerodynamic coefficient, it is estimated a mean converged value and a standard deviation relative to this mean, and then a 95% confidence interval. For the variations of the near wall mesh and of the models, respectively around $y^+ \approx 1$ and $y^+ \approx 30$, it is estimated first the coefficients mean values and their standard deviations relative to these means due to model variations, and second the relative difference between coarse and fine mesh mean results. These confidence intervals are plotted in black Fig.4, and it is found that in each case the confidence interval encloses the red filled point corresponding to the general numerical set up presented previously. It can also be noticed Fig.4 (c), as expected, that intermediate meshes in the buffer layer, for y^+ in the range of [5;30], led to highly model dependent results, and that the Spalart-Allmaras model is valid only for fine meshes around y+ = 1.

It is finally estimated that the numerical results provided by the coarse meshed numerical set up presented previously are unconfined, mesh converged, and model independent, with the following relative accuracies: 3.7% for the lift, 7.7% for the drag and 7.1% for the moment.

With this chosen numerical set up, 2D RANSE simulations were carried out on the NACA2412 section for 14 angles of incidence within the range of [-8°;16°]. The numerical results are compared with experimental ones obtained in wind tunnel, *Abbott and von Doenhoff (1959)*, at the same Reynolds number. The parametric polar curves used for the lifting line method are established by approaching the RANSE results at best. All these results are presented Fig.5.

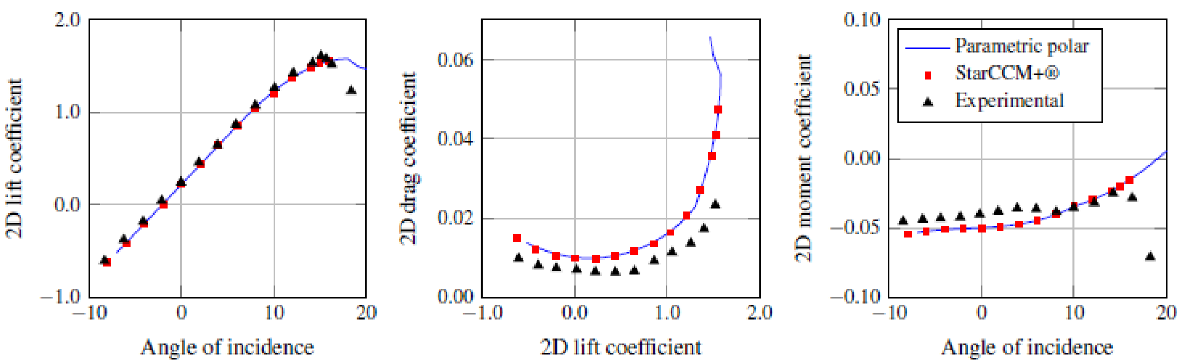

Fig.5: 2D polar curves obtained via StarCCM+®, compared with experimental data, and fitted with parametric polar curves used in the lifting line method

The agreement between experimental and numerical results is excellent for the lift coefficient and satisfactory for the coefficients of drag and of moment. For the last two, one of the explanations for the differences is that simulations are fully turbulent whereas the experiments were performed on a smooth section in a low residual turbulence wind tunnel.

4. RANSE simulations results

3D RANSE simulations have been performed on a large range of angles of incidence varying between -5° and 16° on two different geometries, one with a sweep angle of 30° and one without. The geometries have also been tested with different sideslip angles (from 0° to 17.5°).

4.1 Un-swept wing

First, the simulations have been carried out on a quite simple geometry. The kite is semi-circular of radius 1.5 m, un-twisted and un-swept. The kite section, defined by the NACA2412 points is kept constant along the span.

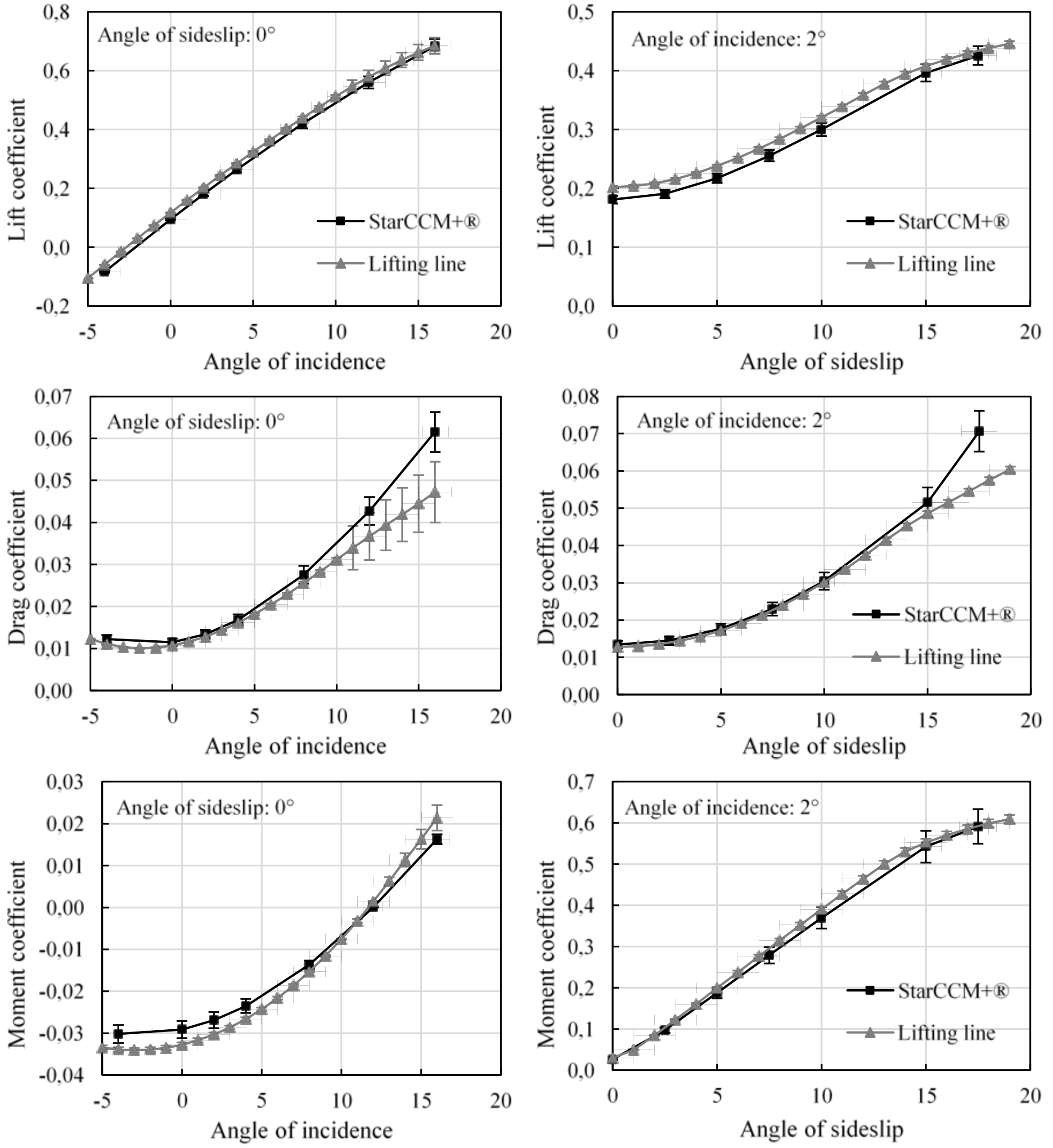

Fig.6: 3D aerodynamic coefficients with respect to the angle of incidence and the angle of sideslip, obtained via StarCCM+® and the lifting line method on a 3D kite.

The chord law varies linearly along the span from 1.0 m at root to 0.5 m at tips. Fig.6 shows the calculated 3D aerodynamic coefficients. The error bars represent the estimated confidence interval at 95% for the RANSE and the lifting line results.

The gap between the two methods purely in incidence is around 5% for the lift coefficient and 12% in average for the moment coefficient. For the drag coefficient, the difference is of 5% at low angle of incidence up to 20% for the higher angle of incidence.

A second set of simulations at 2° of incidence with various angles of sideslip was performed (see Fig.6). The lift coefficient is estimated from the aerodynamic resultant orthogonal to the wind direction. For the lift coefficient, the gap is approximately the same between the kite purely in incidence at 2° and the kite with any sideslip angle included in [0°, 15°] meaning less than 10%. For the drag and moment coefficients, the difference is only of a few percent until 15° of sideslip. With more than 15°, the results for the drag coefficient start to differ significantly.

For the use of the lifting line model in a Fluid-Structure interaction, the local aerodynamic load shall also be validated. On the same geometry without sweep, small slices ($0.025c$) have been added to the RANSE simulations to get the local efforts on the wing. In Fig.7, the magnitude of the local efforts per unit length are presented, nondimensionalized by the maximum local effort of the RANSE simulation. Four simulations have been carried out, three at 2° of incidence with 0°, 7.5° and 15° of sideslip (Fig.7 (a), (b) and (c) respectively), another one at 12° of incidence only (Fig.7 (d)).

The lifting line results are satisfying and follow the same trend than the RANSE simulations, in incidence or in sideslip. The gap is maximum at the center of the kite in incidence and on the most loaded side in sideslip, and always inferior to 15%.

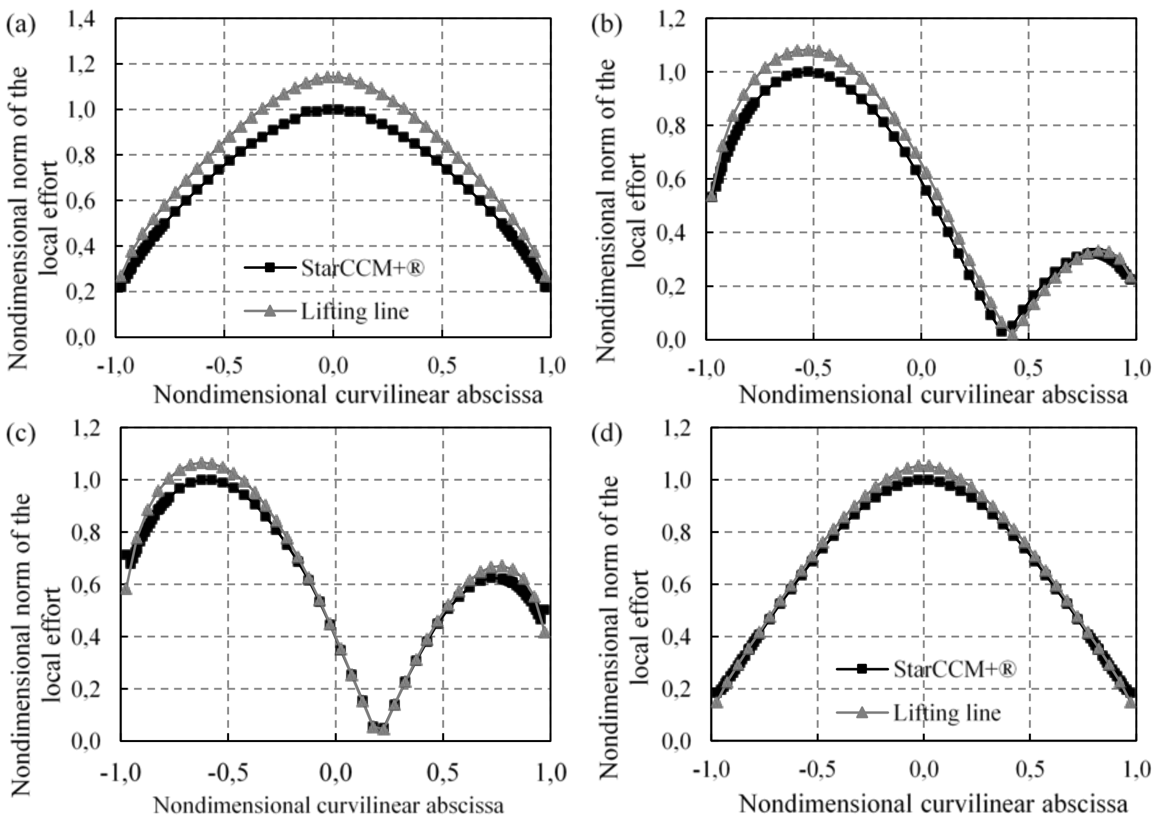

Fig. 7: Nondimensional local aerodynamic force per unit length on a kite wing obtained via StarCCM+® and the lifting line method at 2° of incidence and (a) 0° of sideslip, (b) 7.5° of sideslip, (c) 15° of sideslip, (d) 12° of incidence only.

4.2 High swept wing

To further validate the lifting line model, simulations have been carried out on a swept wing. The geometry is the same than previously described except a linear sweep law of 30° depending on the curvilinear abscissa of the wing. This creates a quite sharp angle at the center of the wing, thus a conical mesh refinement was added to better describe the flow around the center of the kite (see Fig.8).

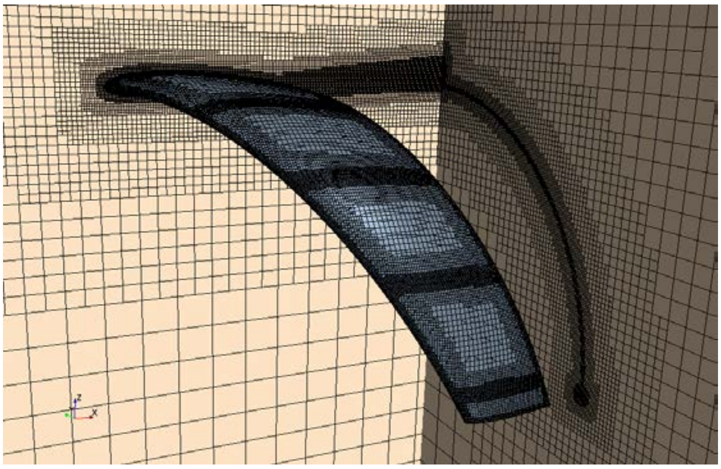

Fig.8: 3D mesh sections with the wake and the two conical refinements. The slices on the wing are also finely meshed.

Fig.9 shows the lift, drag and moment coefficient for the kite purely in incidence. The relative difference between the RANSE results and the lifting line model are around a few percent for the drag coefficient and 9% for the moment coefficient. For the lift coefficient, the relative gap is around 7% with a difference between the two slope coefficients of 10%.

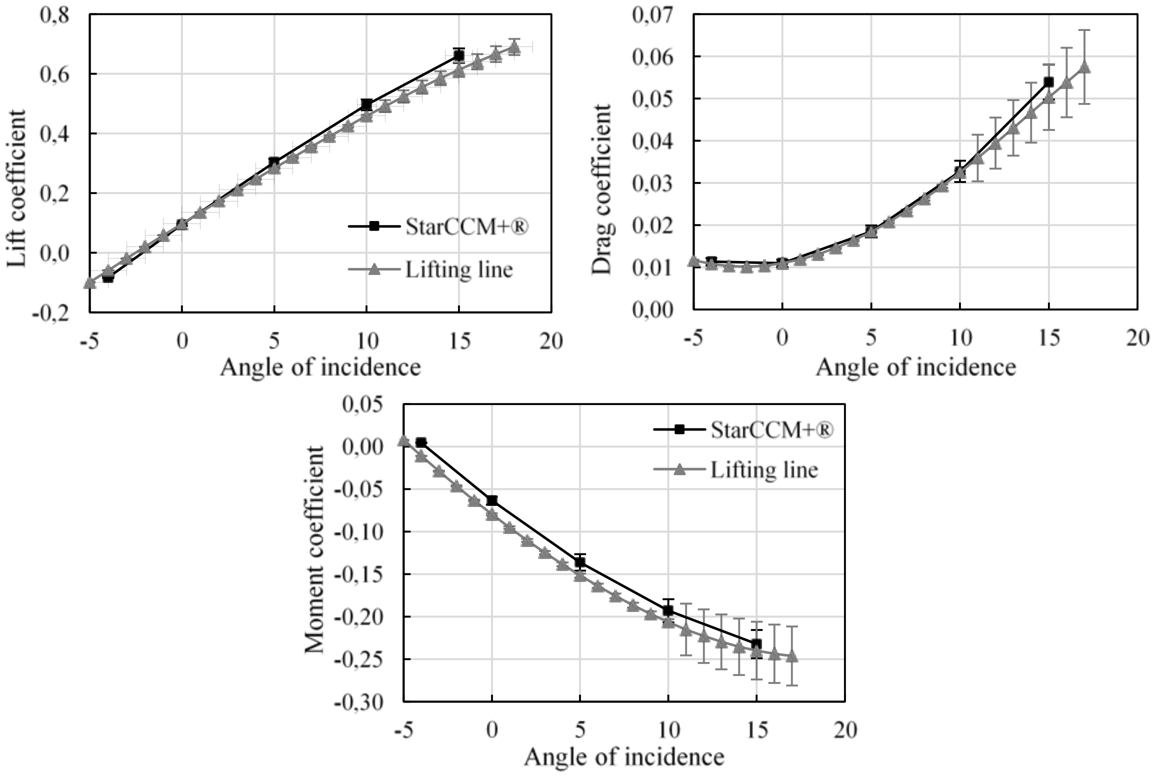

Fig.9: 3D aerodynamic coefficients with respect to the angle of incidence, obtained via StarCCM+® and the lifting line method on a 3D swept kite.

The local aerodynamic efforts have also been computed at -4°, 5° and 15° of incidence. Fig.10 shows as previously the magnitude of the local efforts per unit length nondimensionalized by the maximum local result of the RANSE simulation. The curves show a good consistency at the sides of the kite in contrast with the center of the wing, where the local efforts can differ of almost 60%. These results have to be put in perspective with the fact that the sweep angle is high (30°), therefore the angle in the middle of the wing is sharp. Furthermore, the mesh is coarse ($y^+ = 35$), the RANSE simulations stay diffusive even with the mesh refinement at the center of the kite.

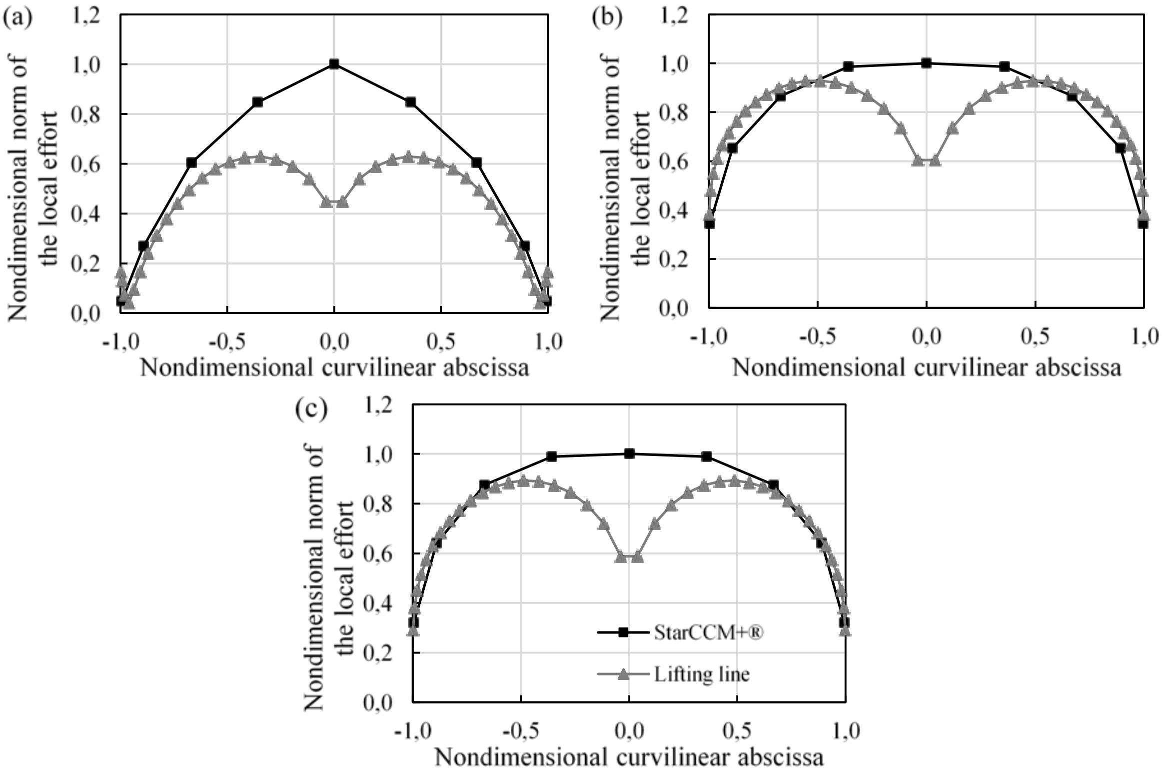

Fig.10: Nondimensional local aerodynamic force per unit length on a swept wing obtained via StarCCM+® and the lifting line at (a) -4°, (b) 5°, (c) 15° incidence angle.

One simulation on the swept wing with a sideslip angle has been carried out. The kite is at 5° of incidence with a sideslip angle of 7.5°. For the global estimation, the gap between the RANSE simulations and the lifting line is of 19% for the lift coefficient and less than 6% for the drag coefficient. The local loads have also been calculated on this swept wing. As can be seen in Fig.11, the two curves follow the same trend with a maximal difference of 10%, except as previously at the center of the wing where the gap reaches 40%.

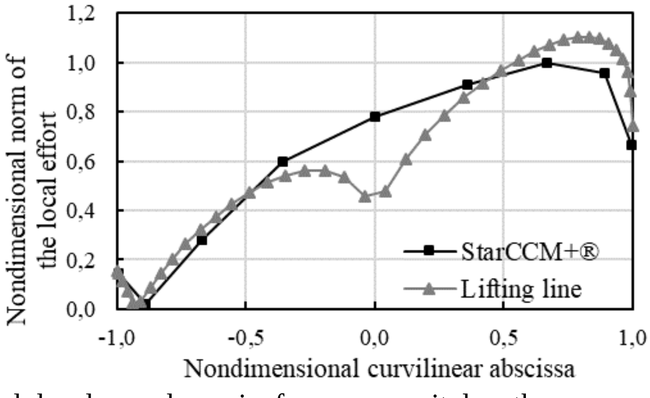

Fig.11: Nondimensional local aerodynamic force per unit length on a swept wing obtained via StarCCM+® and the lifting line method at 5° of incidence and 7.5° of sideslip.

5. Conclusion

A 3D non-linear lifting line model has been described. This iterative model is able to deal with wings, which are non-straight and non-planar, and with high dihedral and sweep angles for any kinematic conditions including kite velocities and turning rates. The method shows a small mesh dependency at low angles of incidence (less than 10°). The results have been checked with 3D RANSE simulations on two different geometries, one un-swept and the other with a high sweep angle of 30°. The global aerodynamic coefficients show good consistency, the lift coefficient estimation is very satisfying in most of the simulation cases with less than 10% of difference between the two methods. The gap for the drag coefficient is only of a few percent at the low angles of incidence and sideslip, up to 20% for the higher angle of incidence. The estimation of the local loads shows also good consistency for the un-swept wing, with the two methods following the same trend even in sideslip. For the swept wing, the local results have to be put in perspective since the mesh of the RANSE simulations is possibly not fine enough to account for the sharp angle of the geometry. Furthermore, the computational efficiency of the lifting line method is indisputable with only a few seconds of computation time.

Acknowledgements

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Totally Integrated Automation for Ships: A Step Closer to Industry 4.0 Realization

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Abstract

In the sphere of shipping, larger, safer and smarter vessels that require smaller crews are becoming the norm thanks to the wide-scale implementation of Integrated Automation Systems. Yet more can be done to improve the vertical integration between a ship's technological layers and so enhance its data collection capabilities. Shipbuilders are thus seeing the benefits of a Totally Integrated Automation approach that promises superior operational efficiency and hence lower overall life-cycle costs. A requirement for the implementation and maintenance of such systems are highly skilled personnel that are adequately prepared to meet the challenges introduced with the technology. In this paper, the forefront ship automation concepts are reviewed in light of the sector's shift towards Industry 4.0. The paper also showcases an effective - online based - educational platform that may be used to prepare students or technical staff to face real-world automation & control problems with confidence.

1. Introduction

In order to effectively serve the rapidly growing demands that globalization brings, the maritime industry has had to transform its technologies and labour resources in order to remain productive and cost efficient, *Corbet and Winerbrake (2008).* This is interpreted as a demand for bigger, smarter and more efficient vessels that have minimal crewing requirements. The technological advancements that have taken place in recent years have enabled shipbuilders to meet some of these demands through the implementation of system wide control and monitoring solutions that provide continuous information on the operational state of the vessels in real-time, *Thompson et al. (2003).* Although automation technology is already widely used in the maritime world, there remains need for much faster processes that are more flexible, more accessible, more efficient and above all, more cost effective. A Totally Integrated Automation (TIA) approach unlike earlier automation concepts promises exactly these benefits and ultimately seeks to yield lower overall lifecycle costs. Such an approach also sets the stage for the next major industrial revolution - Industry 4.0, a concept that is quickly catching on in the manufacturing and process industries.

This paper reviews current trends in automation systems employed on-board modern ships and then looks at future trends with emphasis on the TIA approach and its influence on the direction of the sector towards total vertical integration and hence Industry 4.0 realization. Furthermore, given the rapidly changing technological landscape, the paper also highlights the educational challenges portrayed by the new technology and presents an online approach to practical engineering education and training within the fields of control systems, process control and instrumentation. A novel e-learning system that has been developed, implemented and tested as an undergraduate control system and process control laboratory makes use of actual industrial hardware and software components to control a selection of virtual, model-based plants that can be re-configured and expanded upon without having to purchase additional components.

2. Connectivity for the future - Industry 4.0

Advances in the manufacturing and process industry have paved the way for Cyber-Physical-Systems (CPS) that envision the integration of computational algorithms, controllers, networks and physical processes to bring virtual and physical worlds together. Such systems have vast social and economic potential and are thus gaining widespread international attention, http://cyberphysicalsystems.org/. CPS forms the basis of IoT which makes smart services and products possible by interconnecting and promoting interaction of everyday objects with one another and with humans via the internet, *Xia et* *al. (2012).* Industry is gradually also moving towards fully integrated and connected systems in what has been named the fourth industrial revolution or Industry 4.0. It is a collective term consisting of different technologies used in the 21st century (e.g. contemporary automation, data exchange and manufacturing technologies). As shown in Fig.1, it includes the operation, monitoring and modification of plants, processes and machines through the Internet (remote access). The rise of Industry 4.0 will undoubtedly be accompanied by a corresponding change in human activity and involvement with machines, *Gorecky et al. (2014).*

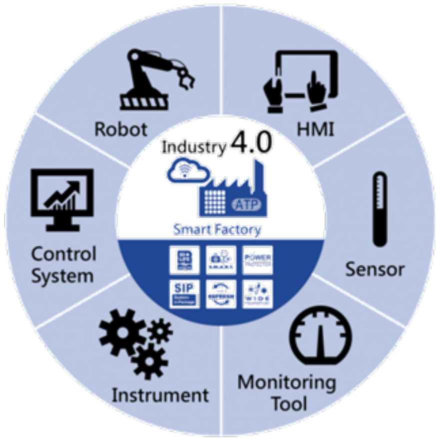


Fig.1: Industry 4.0 for total connectivity

3. Automation Systems on ships

Industries around the world have reached new heights in terms of their ability to meet the ever growing consumer demand, *NN (2012).* To maintain their competitive advantage, industries have had to continually find innovative ways to reduce their manufacturing costs, while continuing to maintain production outputs. Automation technology has thus evolved to make processes faster, more flexible, efficient and cost effective, *NN (2015).*

Ship automation systems are not dissimilar to their land based counterparts in that there are many similar parameters to be controlled or monitored including: pressure, temperature, viscosity, level, position, flow, torque, speed, control, voltage, current, and the operational status of machinery, http://www.emi-marine.com/vessel-automation, *Zaghloul (2014).* Often, the only difference is found in the fact that marine based automation systems and products have been designed, tested and certified to withstand the usually harsh marine environments that they must operate in. In this regard, standards such as ISO 17894:2005 provide mandatory principles, recommended criteria and associated guidance for the development and use of dependable marine programmable electronic systems for shipboard use. It applies to any shipboard equipment containing programmable elements which may affect the safe or efficient operation of the ship. It contains information for all parties involved in the specification, operation, maintenance and assessment of such systems, *ISO (2014).* Historically, ship systems were only semi-automated and permitted individual machines or processes such as fresh water, fuel, seawater cooling and HVAC systems to be automated and controlled with hard-wired controls spanning a few meters or by means of rudimentary fieldbus systems running to and from control centres such as the bridge or engine room. Non-critical systems usually remained locally controlled and were operated only on demand. While lower than the previous non-automated ships, the crewing requirements for these newer vessels of the time still remained quite high, *Krčum et al. (1997).*

3.1 Integrated Automation Systems (IAS)

Modern automation systems predominantly make use of Programmable Logic Controllers (PLCs) or similar industrial grade computational platforms such as process stations, while Personal Computers

(PCs) or Human Machine Interfaces (HMIs) provide the graphical user interfaces which often also include capability for data logging, alarming and trending. The number and configuration/topology of the automation depends on a combination of the vessel size and customer requirements, *Zaghloul (2014)*. Fig.2 shows the typical components within an automation system.

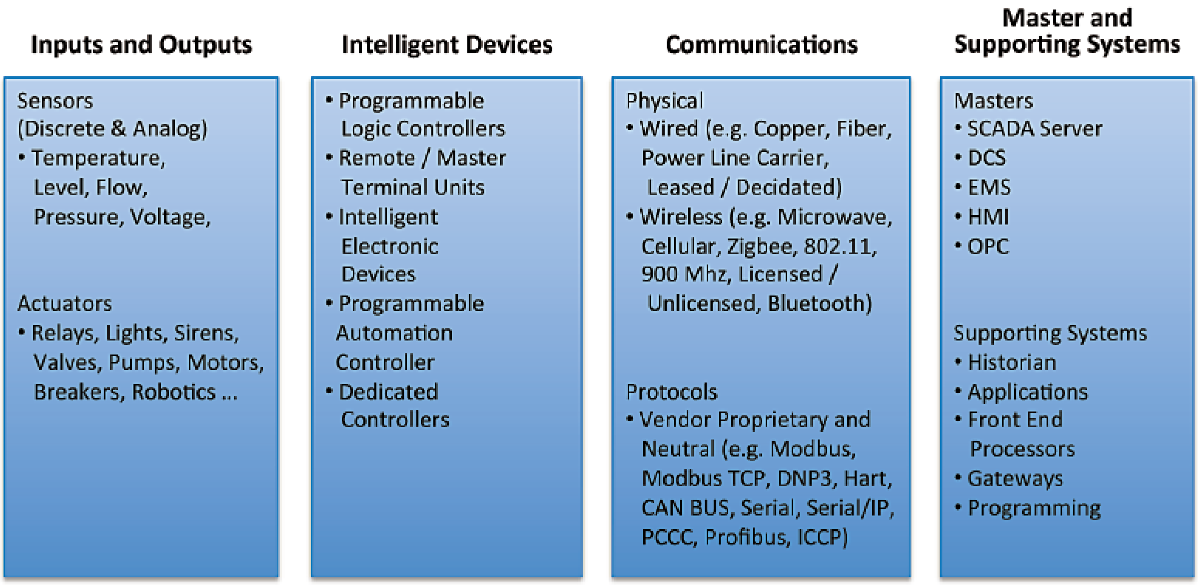


Fig.2: Typical components within an automation system, *Luallen (2011)*

Integrated Automation Systems are based on modular Distributed Control Systems (DCSs), *Valkeejärvi (2014)*, and allow numerous geographically diverse components to be linked into a complex hierarchy, Fig.3, that may span the entire vessel and that can be monitored and controlled easily from numerous locations (including, in some cases, remote onshore locations) by means of flexible communication systems such as PROFIBUS or PROFINET. Networks such as these permit interfacing to higher-level control systems, *NN (2010)*. Electrical signal coupling by means of digital or analog interfaces is also possible, *Valkeejärvi (2014)*.

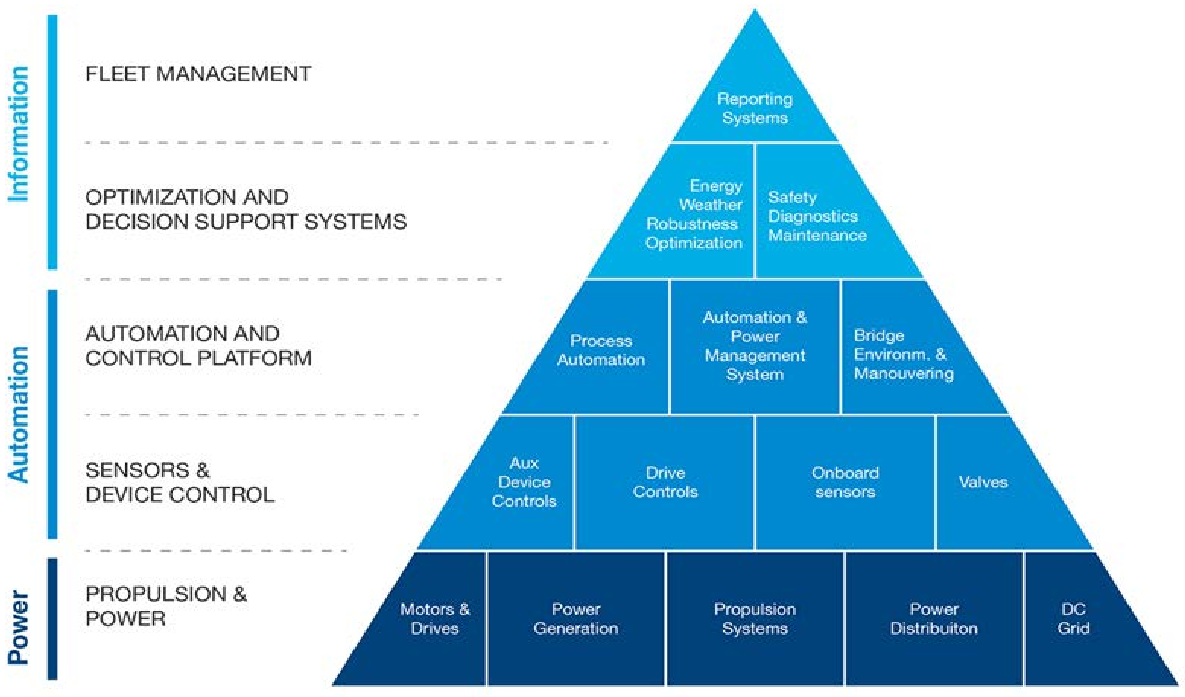


Fig.3: Hierarchy of ship systems, *ABB (2017)*

An integrated-systems approach offers numerous benefits including increased operational efficiency, space saving, reduced cabling and improved situational awareness without at the same time compromising vessel integrity or individual system functionality. Improved situational awareness is achieved through enhanced single-screen access that provides the crew with a "Full Picture", *NN (2010)*, of all connected systems including monitoring, diagnostics and alarming features. It also minimizes the consequences of emergency situations by helping to avoid damage to the environment, loss of human life and/or loss of equipment through the implementation of a safety system that meets stringent requirements of standards such as IEC 61508 and IEC 61511, *ABB (2017)*. For integrated automation systems to work reliably, both the design of the integrated system as well as the management of its use must support the safe and effective performance of the crew as a critical component of the total system. This human-centred approach must be based on a thorough knowledge of the particular skills, working environment and tasks of the crew using the integrated automation system, *ISO (2014)*.

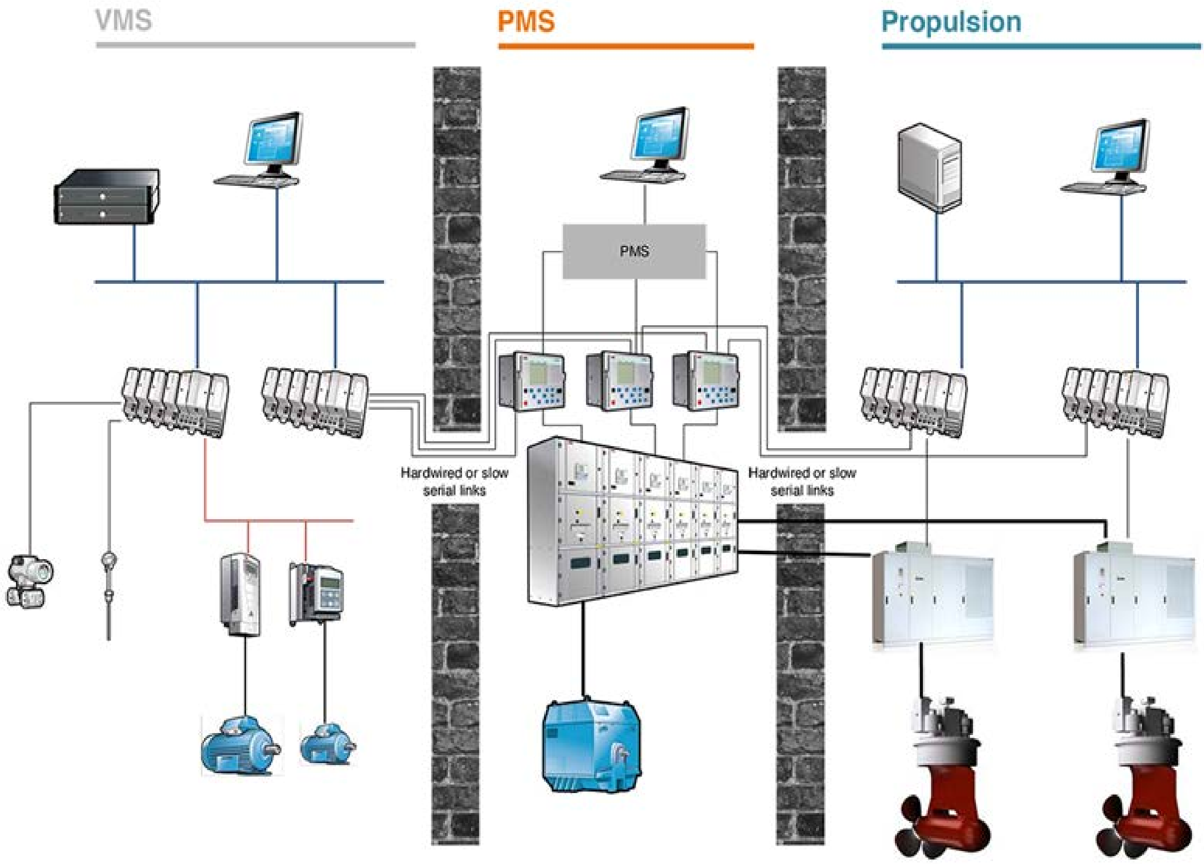


Fig.4: Traditional approach to system integration on-board, *ABB (2017)*

Integrated Automation Systems allow moderate to complete horizontal integration between devices and/or machines found within the automation and control layers represented in Fig.2. Conversely, vertical integration - which is rarely possible within IASs - allows seamless connectivity from the sensor to management layers regardless of vendor. Also, within IASs, fundamental technical differences between devices and/or machines in the different layers as well as differences in their communication protocols, fieldbuses or speed requirements create complex barriers that in practice are too difficult or costly to cross. A further limitation with IASs is that embedded intelligence is limited to the automation layer. Fig.4 shows a typical IAS with a blend of communication networks and limited horizontal integration taking place through hard wired connections or through slow serial lines, *ABB (2017), Werr (2014)*.

3.2 Totally Integrated Automation (TIA)

A Totally Integrated Automation (TIA) approach is characterized by its unique level of vertical and horizontal integration at all levels of a vessel's system hierarchy. This implies a literal "one-stop shop" with consistent data management, global standards and common interfaces for both hardware and software. As depicted in Fig.5, the TIA approach offers an open-system architecture with embedded intelligence at every level of connectivity which permits the seamless interconnection of machines, sensors, controllers and Human Machine Interfaces (HMI's) through the use of a single standardized communication system.

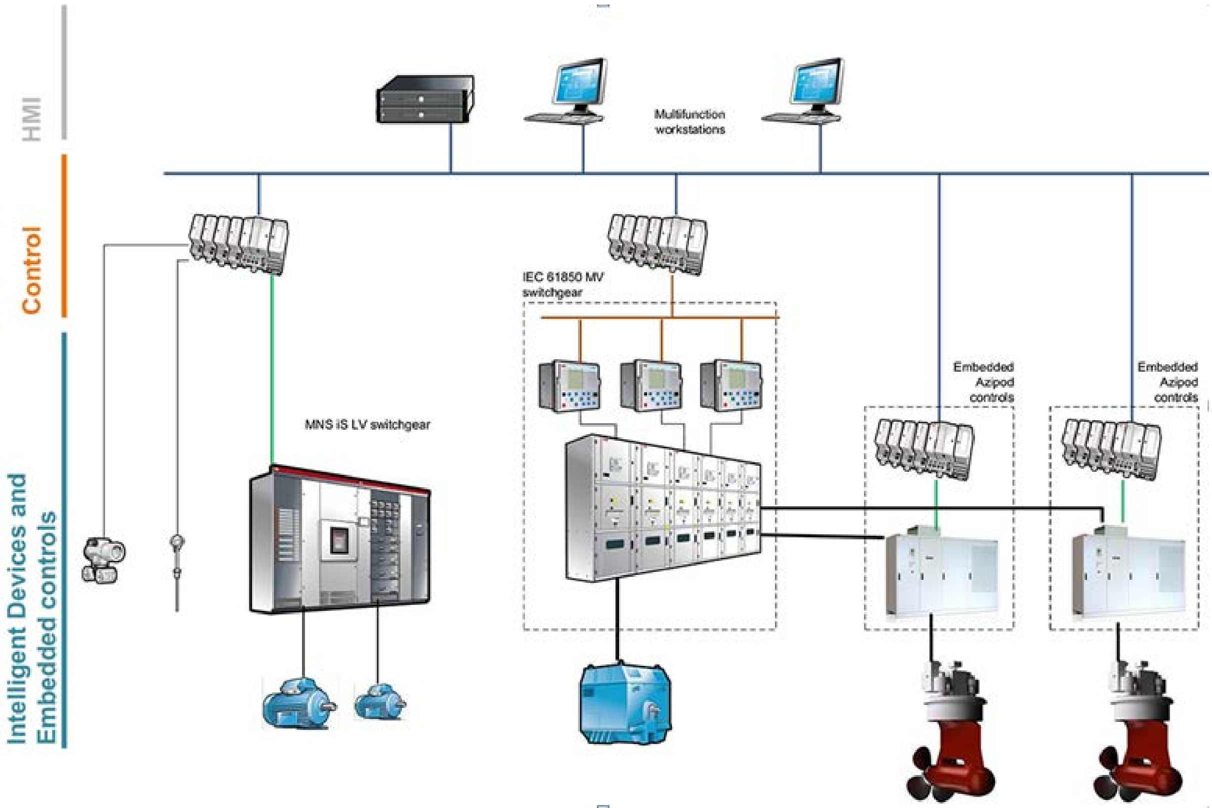


Fig.5: Totally Integrated Automation approach, *ABB (2017)*

The cost of expansion, modification and maintenance are thus significantly reduced. Interfacing to existing or older systems or networks still remains possible with the addition of special coupling modules. All these advantages serve to produce higher productivity and lower lifecycle costs. Information is also transparently transferred between all system layers, and the system interfaces at all levels are well defined to ensure compatibility, efficient engineering and optimal utilization of information, *ABB (2017), NN (2010b), Werr (2014).*

Redundancy within the automation system and its critical interconnections ensures that they remain available even in the event of a serious malfunction or accident, *Valkeejärvi (2014)*. Network solutions within the TIA concept are predominantly based upon Ethernet technology because of its global acceptance and openness as well as its high transfer rate and low costs. PROFINET is one such open Industrial Ethernet standard which offers safe, reliable and high-speed data exchange at all levels, making it the basis for stable processes. For a communication system to be safe, it must be proven and certified according to domain-specific safety standards. PROFIsafe for example is an IEC 61508-compliant integrated safety technology developed under PROFIBUS and PROFINET International, *NN (2014b)*. This level of openness brings with it all the vulnerabilities that other sectors have experienced and developed protections against; yet the notion of protecting control systems with these tools is relatively new, *Luallen (2011)*.

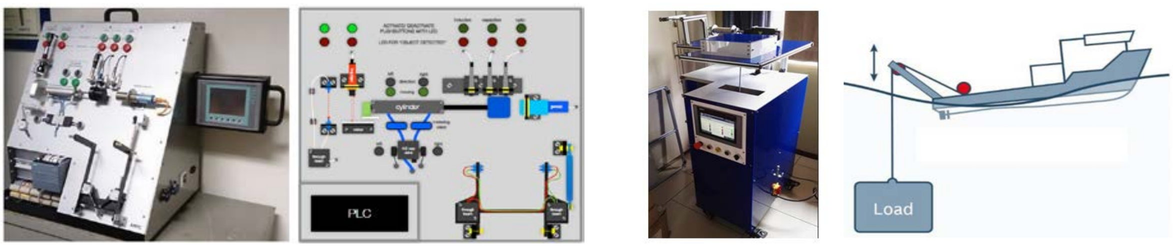
In TIA, safety functionality is integrated in to standard automation system to form a uniform complete system that meets relevant international standards (IEC 61508, EN 954-1), *NN (2014a)*.

4. TIA – A step closer to Industry 4.0 and Smarter Ships

TIA enables the complete digitalization of a ship's hierarchy using integrated technologies and communication capabilities. It will provide the infrastructure required for Industry 4.0 realization on ships and hence enable smarter and more efficient shipping. Although "totally" autonomous shipping is still a concept for the future, one facet of Industry 4.0 that is already within reach is predictive maintenance where with growing numbers of sensors utilized on ships, vast amounts of data can be gathered from ship processes and systems, allowing further analysis and optimization, *ABB (2017)*. This data can be transmitted back to manufacturers who can improve their products, make recommendations or match customer requirements based on real data or it can be monitored and processed by on-board computers to predict equipment failure or make suggestions to improve operational efficiency and vessel uptime. Accurate predictions made in this way will also enable the industry to switch from calendar-based planned maintenance to condition-based maintenance, saving significant maintenance expenditures and reducing lifecycle costs, *NN (2016)*. A further benefit of complete vertical integration is connectivity to advanced performance management and fleet management systems increases vessel efficiency and profitability.

5. An Educational Perspective: Preparing students and employees for the ships of the future

As marine vessels move towards totally integrated and connected system architectures, marine engineers, electro-technical officers and students of these disciplines will need to be equipped to handle a broader range of digital systems, control and IT related problems, *Jensen (2009)*. Owing to the growing implementation of sensors, actuators and computing technologies found within these integrated systems as well as a growing need for access, connectivity and human-machine interaction, it is important for educators in technical fields to aim for a holistic, industry based and interdisciplinary approach to teaching and learning, *Wikander et al. (2001), Dym et al. (2005).* Curriculums that are highly technical should be problem-based, product design oriented, and project-team organized and should include as many real-life situations as possible, *Wikander et al. (2001)*. However, in a time of soaring costs and increasing student numbers, the reality is that it is often impractical for institutions to provide an all-round engineering education. A less burdensome approach is therefore required that mitigates the mentioned challenges by harnessing the power of a more connected world.



(a) (b)

Fig.6: (a) Industrial sensor station, (b) Model heave compensation system

Within the Department of Mechatronics at the Nelson Mandela Metropolitan University (NMMU), an initial approach to address this problem within automation and control systems courses at the third-year and fourth-year level was to develop student learning laboratory systems in-house. This was achieved by allocating these systems as final-year student projects placed under industry mentors. For most of these systems, standard industrial equipment such as PLCs, drives and HMIs were used. These often capital intensive systems came predominantly through special partnerships between the university and major technology players such as Siemens and Festo. A total of nine such systems were built within a period of 5 years. Three are shown in this paper including an industrial sensor station (Fig.6 (a)) developed in 2014, a marine based heave control system (Fig.6 (b)) developed in 2016 and a process system (Fig.7) also developed in 2016.

Fig.7: Industrial process system

Because the products used within these systems fully support TIA, with the addition of web cameras they are in the process of being converted into remotely accessible systems that allow students to perform laboratory work through a web page that features session scheduling. This reduces the burden on lecturing and lab staff and gives students a self-paced learning environment. One limitation with using physical lab equipment is that it can be difficult and costly to maintain, upgrade or reconfigure. A second novel approach taken at NMMU is through the implementation and use of simulated real-world systems that employ real industry standard automation products (software and hardware) interfaced to easily reconfigurable software plant models instead of physical models as in the first approach, Fig.8.

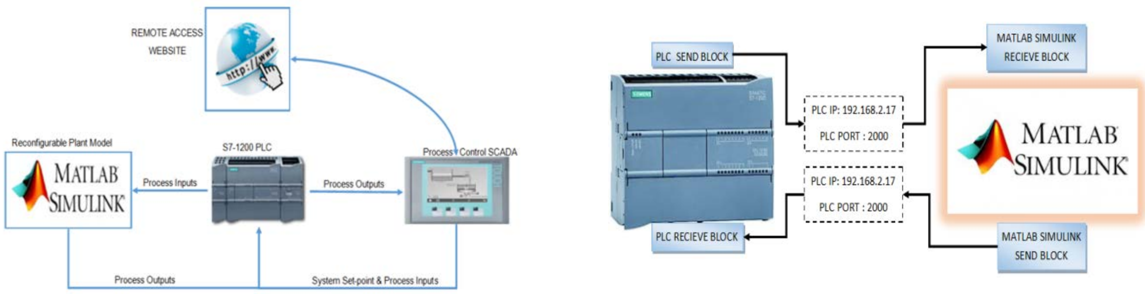


Fig.8: Simulated real-world system

The following requirements are met through this approach:

1. Possibility of multiple reconfigurable and multi-disciplinary simulions based on real models running in Matlab/ Simulink (no additional hardware or software needed to implement a new model)
2. Scalability and flexibility, i.e. it is easy to scale up the number of PLCs and plant models to accommodate more students simultaneously.
3. Use of industry standard hardware and software (e.g. PLC's, HMI's, diagnostic tools etc.) so students still get exposed to modern industrial techniques and technologies.
4. Remote access (via internet) for students and staff
5. Retrieve plant data remotely in real-time for statistical analysis and reporting
6. All necessary study material and practical guides easily available within the online platform for students to access at any time
7. Online option for students to comment, ask questions and give feedback

One of the developed simulated models was based on a submarine’s ballast depth control system, Fig.9.

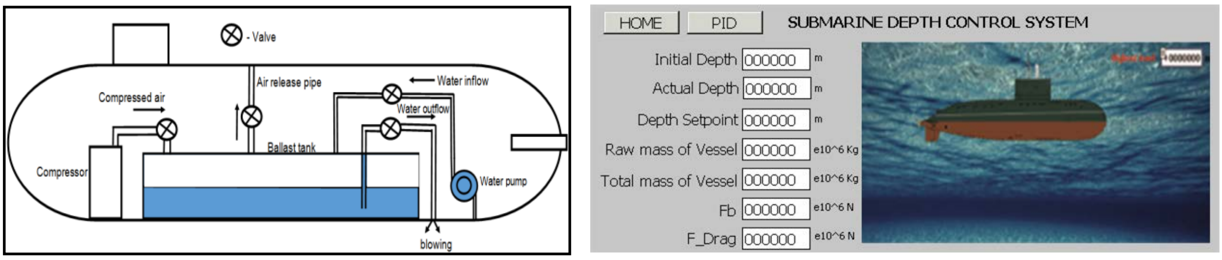


Fig.9: Submarine depth control system

Learning tasks within a third-year Controls System class include:

1. Determining the time constants of the systems
2. Determining (and plotting) the systems response parameters
3. Deriving system differential equations
4. Designing and implementing a variety of controllers (e.g. PD, PI, PID, Intelligent controllers)
5. Using suitable tuning methods
6. Performing statistical analysis
7. Drawing conclusions from gathered results

The system had an overall positive response from the group of students that used it. Feedback from third-year Control System’s students who used the simulation platform for the first time in 2017 to complete a compulsory practical section of their curriculum showed that most students who engaged with the system (Fig.10 (a) -92%) found the web interface interesting and stimulating as it gave them a sense of operating a real system. 48% of students (Fig.10(b) -92%) felt that system could be improved by adding more functions and activities, while 44% had a neutral feeling. Most students (Fig.10 (c) 82%) found the developed platform’s data logging procedure functional and easy to use.

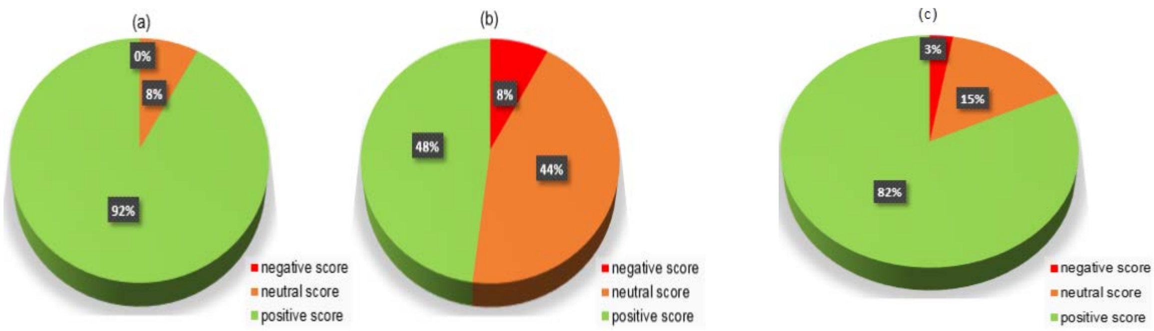


Fig.10: Student feedback on Simulation, visualization and improvement of platform

6. Conclusion

In this paper, current integrated automation systems employed on-board ships were compared with a newer automation concept called Totally Integrated Automation. TIA offers complete horizontal and vertical integration and provides the infrastructure required for Industry 4.0 realization. The next industrial revolution will usher in, with it the autonomous age, an era of supreme data transparency and management. These facets should be harnessed within the marine transportation sector to ensure stable growth through greater efficiency. Consequently, as vessels become smarter and more connected, they will also require highly skilled crews who have a thorough understanding of the technology together with its benefits and risks. Forward thinking within education is therefore key! Smarter ways of transferring knowledge are required that adequately prepare students or trainees to face the real world without placing unrealistic burdens on institutions of learning. In this paper, a simulation based process control system was presented that utilizes real automation hardware and software components integrated with virtual plant models. The system offers remote yet real-time engagement and has a definite cost saving benefit when compared to the same automation products interfaced to physical plants. Through the use of the internet, systems such as these could be used to offer specialized short course training to personnel in the field, including those deployed on-board marine vessels.

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From (Big) Data to Insight – A Roadmap for the "SA Agulhas II"

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Abstract

Full-scale measurements on polar research vessels present an opportunity to advance the state-of-the-art in ship design through high-quality long-term measurements of environmental conditions and ship responses. Real-time data analysis of such data towards monitoring and decision aiding could benefit the insightful operation and management of these expensive assets. This paper presents the conceptual design of such a monitoring and decision aiding system for the SAA II – a modern polar supply and research vessel. This system will focus on human factors, vessel response monitoring of the hull and propulsion systems and the monitoring of wave state and ice conditions in the operational environment. Results indicate that significant potential beckons in the integrated acquisition, analysis and utilization of full-scale ship-borne measurements.

1. Introduction

Polar supply and research vessels operate in some of the harshest dynamic environments on earth. Knowledge of sea ice, its properties and resultant loading on vessels is far from complete and as such the safety of ships operating in these environments is based on the extrapolation of engineering data with reasonable assumptions from scale model tests in ice tanks and simulation models. Paramount to this, understanding of operational ice and wave loading on ships in the Southern hemisphere is particularly sparse.

The SA Agulhas II (SAA II) is a polar supply and research vessel owned by the South African Department of Environmental Affairs, Fig.1. She was manufactured by STX Finland in Rauma shipyard and measures 121.30 m between perpendiculars and is 21.70 m wide. She is propelled by four Wärtsilä 3 MW diesel generators that power two Conver Team electric motors which are each connected to two shafts, each with a four-bladed variable pitch propeller. Accommodations are available for 44 crew and 100 passengers on annual research and re-supply voyages to Antarctica, Gough Island and Marion Island. Amongst these passengers are scientists who are not regularly sea-borne who work in laboratories on-board during oceanographic research expeditions. She is the first vessel in her class to be built to the SOLAS 2009 Passenger Ship Rules and as such, her design could provide valuable operational experience towards the commissioning of other polar supply and research vessels by several countries.

Fig.1: SAA II vessel during the 2015/2016 relief voyage Antarctica

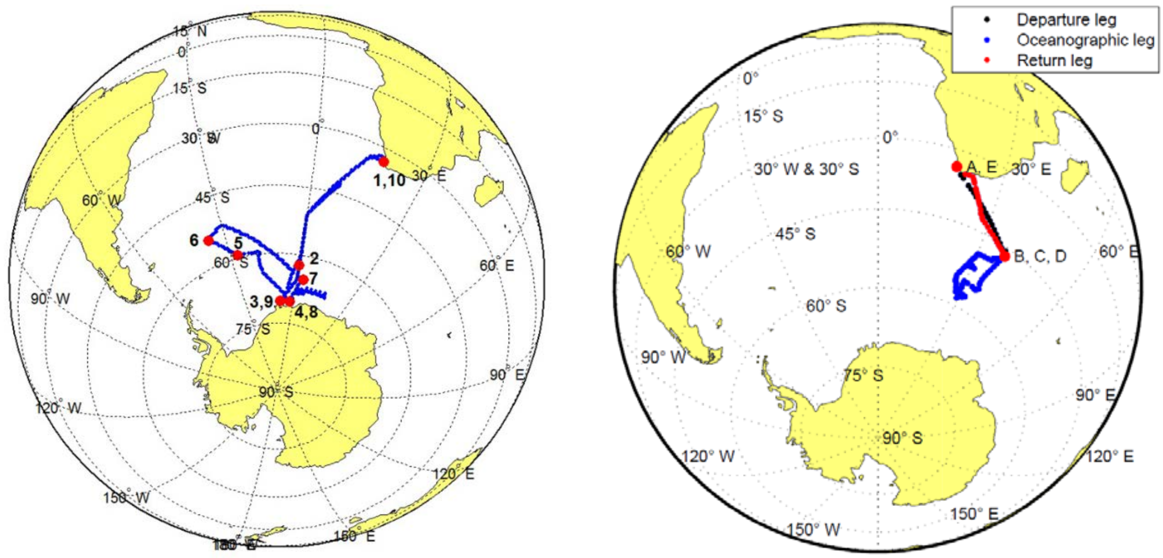
In a world where climatic changes are probable, and where the prediction of such changes relies greatly on knowledge and understanding of the ocean, *Ansorge et al. (2017)*, the SAA II will play a key strategic role as a world class research platform. The recent Belém statement, *Moedas et al.*

(2017), mandates collaboration between the European Union, South Africa and Brazil in the South Tropical Atlantic, and Southern Ocean. The SAA II is therefore likely to be funded towards increasing utilization beyond her current operations which require 120 days per year.

An international research consortium comprising the University Stellenbosch, Aalto University, Aker Arctic, DNV GL, Rolls-Royce, STX Finland, University of Oulu, Wärtsilä and the Department of Environmental Affairs South Africa initiated a full-scale measurement program on the SAA II for her ice-trails in the Baltic Sea in March 2012, *Suominen et al. (2013)*. These measurements included:

1. ice loads on the ship hull and propulsion system,
2. ice-induced structural vibrations and noise,
3. whole-body vibration comfort,
4. ship dynamics in ice,
5. global ice loads,
6. underwater noise and
7. mechanical and physical sea ice properties.

Subsequently, Stellenbosch University and Aalto University have maintained this effort, resulting in a one-of-a-kind full-scale measurement campaign which, to date, includes five Antarctic relief voyages and two voyages to Marion Island with typical GPS tracks shown in Fig.1. This work aims to contribute to the scientific basis for the design of ice-going ships and shed light on the inter-relationships between sea ice, structural loading and vibration on ice-going vessels.



(a) (b)

Fig.2: GPS tracks for an (a) Antarctic relief voyage and a (b) Marion Island voyage of the SAA II

This article outlines the motivation and proposed strategies to consolidate the expertise, data and analysis algorithms, developed from five years of full-scale measurements into a real-time multi-sensor monitoring and decision-aiding system. The motivations include:

1. Challenging ice conditions and rough open water are the factors that most degrade operational efficiency. Can the real-time processing of operational ship data assist in aiding tactical judgments in ship handling to improve safe navigation and cost savings? This could result in direct economic benefits through fuel savings and improved more efficient ship operations for the same ship time.
2. The vast majority of marine casualties have their origins in human-related errors, where human errors are still one of the major causes of maritime accidents. Can navigators be assisted through vessel monitoring and decision support systems, to contribute to increased safety?

3. Insight into the accrual of fatigue loading (progressive damage as a result of repeated bending and twisting) on the SAA II through a decision aiding system will assist in the development of long-term strategies to answer how ships can be operated and navigated to achieve a prolonged service life. What is the impact of Southern hemisphere storms and Antarctic ice on the structural health and propulsion system of the SAA II? How does the vessel actually operate in relation to her design limits and how should her lifecycle be managed to maximize her use and useful life? The answers are not explicitly known as she was designed from a Northern hemisphere knowledge base, which further relies heavily on simulation models and model scale tests for a lack of operational data of ice-going ships in the southern hemisphere. Therefore, her maintenance strategy and useful operational lifecycle are estimations based on the best engineering logic available.
4. The imperfections in engineering practice for ice-going vessels in the Southern hemisphere is emphasized by the fact that the SAA II is pre-disposed to prevalent stern slamming in even mild following sea states with 1 m swells, *Omer and Bekker (2016)*. The pursuit of mitigating measures for slamming is governed by the underlying question: Will slamming vibration crucially reduce the operational lifecycle of the vessel? Public literature is largely devoid of recommendations to eliminate wave slamming through navigational strategies and full-scale measurements that elude to possible loading conditions and risks. The reason for this is the unpredictable and non-linear nature of slamming on full-scale ships, which implies that measurement campaigns can run for years without successfully capturing a slamming event.
5. In a more general sense, this pursuit is motivated by the industrial drive towards the reduction of ship crew and new technologies for the remote sensing and control of ships. Can machine algorithms be trained to predict structural damage and guide navigational decisions on ships? The development of the “ship as a sensor related technology” will have crucial importance in future as automation and remote control is adopted in practise also on the maritime sector. This cannot be accomplished without sufficient high quality operational data to train and condition machine learning algorithms. The autonomous operation of ships with harsh voyage profiles, will likely prove a significant engineering challenge. As such, the study of the voyages of the SAA II in harsh waves and ice could contribute to the training data required for autonomous operation algorithms.

Against this backdrop, it is argued that research on full-scale measurements of the SAA II have already prepared the vessel for permanent monitoring where data could now be further analysed and used in real time to provide insight into the operational safety instructions and decisions towards ship navigation and operations.

The first aim, being monitoring, requires the measurement of ship responses and real-time data analysis algorithms which calculate monitoring parameters. Such parameters can then be evaluated against criteria to lend interpretation to the significance of such data. The longer-term analysis of monitoring data is envisioned to lead to decision aiding whereby benefits can be derived from concurrent experience and analysis. To this end, the measurement parameters and sensor layout is discussed, along with analysis and monitoring strategies and finally, the envisioned framework for decision aiding, Fig.3.

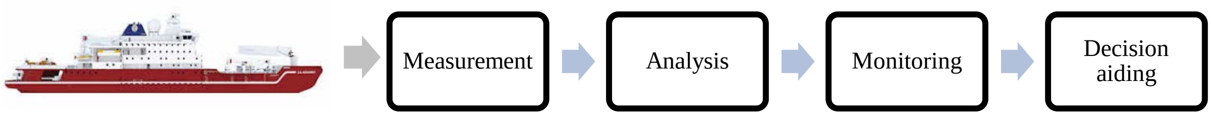


Fig.3: Data flow from ship response measurements to decision aiding

2. Measurement setup

The scope of full-scale measurements on the SAA II comprises measurements of ship operational parameters, hull-loading (starboard side), shaft-loading (port-side), global vibration responses and subjective observations of ice conditions and wave height. These measurement systems have been utilized in variable states of maturity during ice trails in the Baltic Sea, five Antarctic relief voyages and two voyages since 2012, Fig.2(a).

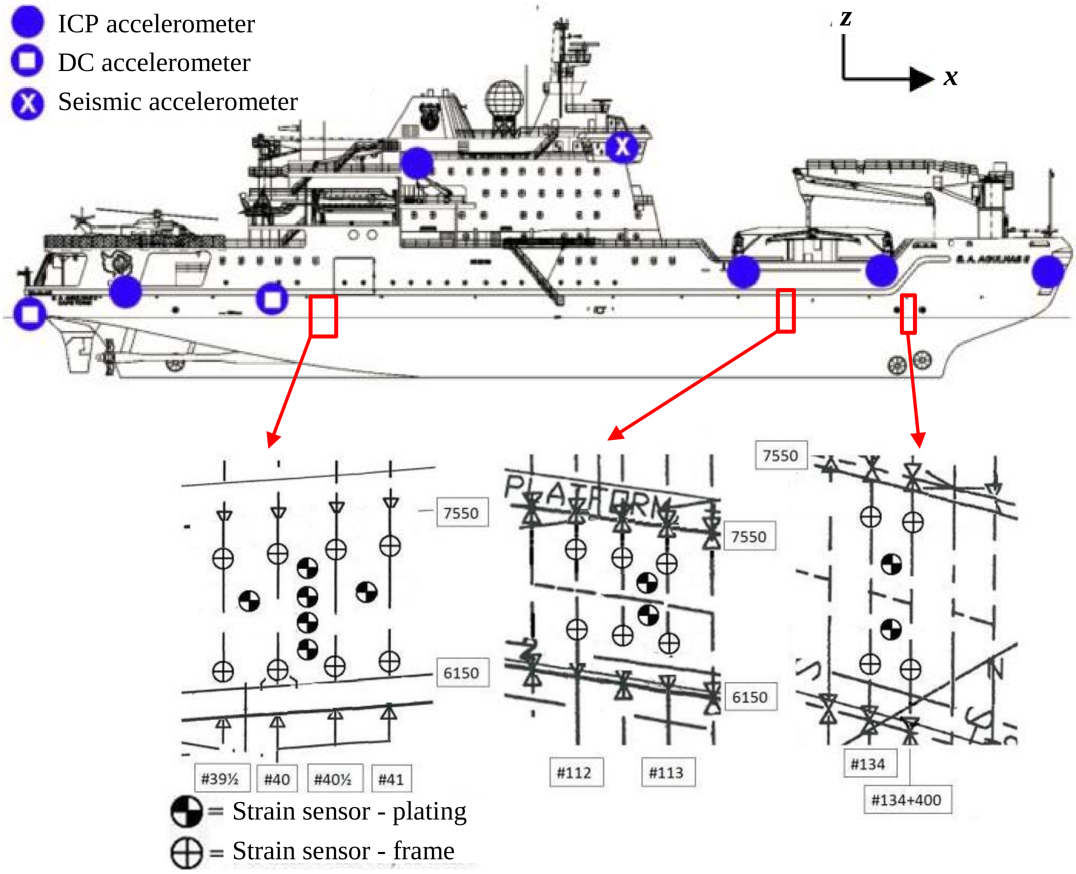


Fig.4: Network of accelerometers and strain gauge instrumentation on the ship hull at bow, bow shoulder and aft shoulder, *Kotilainen et al. (2017)*

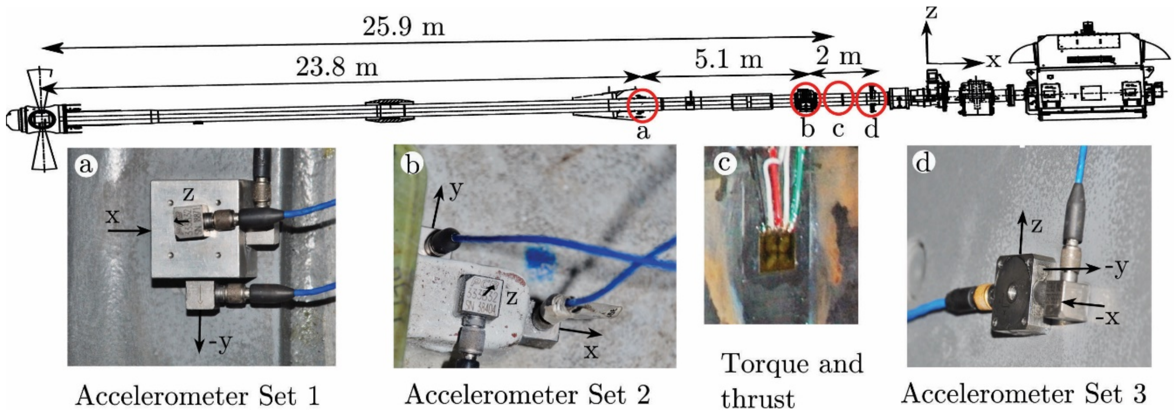


Fig.5: Accelerometers and strain gauges mounted along the shaft line for the SAA II (Adapted from technical ship drawings, source: STX Finland

2.1 Hull measurements

Hull measurements involve the instrumentation of the starboard side of the hull of the SAA II which was instrumented with strain sensors in three areas to measure ice loads, Fig.4. Two frames were instrumented in the bow, three in the bow shoulder and four on the aft shoulder. In addition to the hull structures, the hull plating was instrumented with strain sensors in each area. Strain measurements are performed at a sample rate of 200 Hz. The ice loads on the ship hull are measured with V-shaped strain gauges which are mounted to the frame structures. The strain gauges measure the shear strain on the upper and lower part of the frame and the ice load (shear force) is determined through algorithms as outlined by *Kotilainen et al. (2017)* and *Bekker et al. (2014)*.

2.2 Vibration measurements

Vibration measurements are performed with a network of accelerometer sensors (sample rate 2048 Hz) as shown in Fig.4. From these measurements the rigid body motion of the vessel can be determined as well as the global flexure and bending of the ship in real time, *Soal et al. (2015a), Omer and Bekker (2016)*. This allows the structural dynamic analysis of the vessel structure and estimations of the global force resistance through novel analytical techniques, *Soal et al. (2015a,b)*. These sensors further serve to provide a measure of motion sickness and whole-body vibration, *(Bekker at al. (2017),* for vessel occupants in relevant areas.

2.3 Shaft-line measurements

Shaft-line measurements entail the installation of strain gauges on the port side shaft line of each of the SAA II to determine the shear and axial strain as described in *De Waal et al. (2017)*. This allows for the determination of the instantaneous torque and thrust at the measurement locations on the shaft line. Measurements on the shaft-line have a three-fold purpose: firstly, to obtain an indication of the transient torque and thrust in the shaft and secondly, to provide a means through which propeller loads can be estimated by inverse methods, *Ikonen et al. (2014)*. Finally, the potential exists to provide estimates of global resistance forces through concurrent analysis of the shaft thrust and ship speed, *Su et al. (2011)*.

2.4 Operational ship parameters

Operational ship parameters are recorded through the onboard Central Measurement Unit (CMU). The CMU captures several operational paraeters, most prominent of which includes the GPS track of the vessel, propulsion parameters such as propeller pitch, rotational speed and motor power. The progress of the vessel is also reported through parameters such as the vessel speed over ground and heading.

2.5 Environmental parameters

To date, environmental parameters have been determined mainly through visual observations from the bridge. Wave height is typically observed in four-hourly intervals by navigational officers on the Bridge and noted in the ship logbook. The recorded swell heights were based on the measured wind speed and the Beaufort scale. Ice thickness is also determined from visual observations on the Bridge in round-the-clock surveillance shifts when the vessel engages in ice-passage. A yardstick with 20 cm long black and white markings is suspended over the edge of the ship. As the ice rotates upwards alongside the hull the observer is tasked to judge for how many minutes in a 10 minute interval a certain ice thickness was experienced, *Bekker et al. (2017), Suominen et al. (2013,2017)*.

Expensive assets such as ice and wave radar are not yet part of routine measurements on the SAA II. For the estimation of the wave state and wave spectra, the combined use of strip theory and rigid body motion is being investigated as proposed by *Pascoal and Guedes Soares (2009)*. The most promising automated ice property estimators involve carefully trained image processing algorithms whereby footage from stereographic ice cameras is to be analyzed, *Kulovesi and Lehtiranta (2014)*.

3. Monitoring – Parameters, methods and insight

The envisioned monitoring project on the SAA II will focus on the acquisition of parameters that pertain to human factors, ship responses and environmental conditions. The envisioned parameters, the proposed real-time analysis methodologies and potential insights to be gained are summarized in Fig.6. Most of the parameters, their analysis methodologies and preliminary insights have been the subject of separate studies. As such, the following paragraphs briefly outline the rationale behind the selected analysis methodologies and preliminary insights.

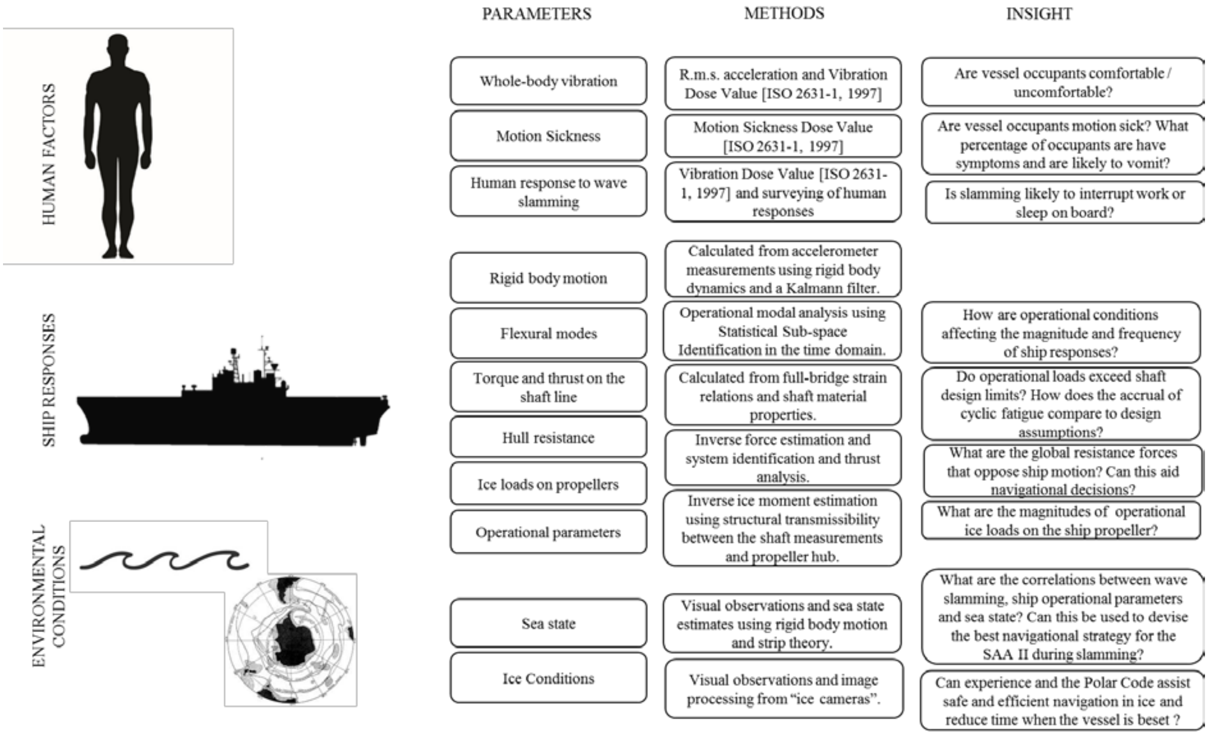


Fig.6: Real-time measurement parameters, analysis methods and anticipated insights for the SAA II

3.1 Human factors

The Requirements for Polar Ships specify the requisites by International Association of Classification Societies (IACS) to ensure a safe journey for crew travelling on steel ships that navigate in ice-infested polar waters. Whole-body vibration comfort and motion sickness on polar supply and research vessels was deemed to be of interest as these requirements is that they do not yet contain guidelines to direct shipbuilders as to the allowable vibration limits for human vibration exposure. This is attributed to the absence of scientifically reported field research on vibration conditions in human environments gathered when ships break through ice. To this end whole-body vibration exposure associated with open water and ice passage was investigated, *Suominen et al. (2013), Bekker et al. (2014), Bekker et al. (2017)*, using the methodologies outlined in ISO 2631-1, *ISO (1997)*. During an Antarctic relief voyage it was found that occupants are exposed to perceivable vibration for most of the voyage and are likely to experience vibration at levels considered "not uncomfortable". As a result of high crest factors, r.m.s. metrics do not offer a robust means of quantifying in-service ship-borne vibration. In comparison with sailing in calm water, whole-body vibration exposure increased by 21 times in rough open water and up to eleven-fold during ice-passage. As a result of vessel pitching in rough open water, vibration on the Bridge mostly exceeds that of the accommodation decks.

On the SAA II, the main reasons for the vibration discomfort of vessel occupants is attributed to motion sickness as well as wave slamming, of which the latter is prevalent on the SAA II. Investigations into wave slamming have shown that the flat, extended, transom design of SAA II pre-disposes the vessel to stern slamming, *Omer and Bekker (2016)*. The impulsive vibration of slamming impact and the oscillatory whipping response that follows, has caused complaints among crew and researchers regarding interference with sleep, equipment use and research activities.

Passenger claims of sleep interference disturbed motor tasks and equipment damage as a result of wave slamming was surveyed during normal operations of the vessel. The hypothesis was investigated that whole-body vibration metrics from ISO 2631-1 are potentially suitable for the prediction of human slamming complaints. Full-scale acceleration measurements were performed and wave slamming events were subsequently identified from the human weighted acceleration time histories, *Omer and Bekker (2016)*. The vibration caused by wave slamming was found to be strongly correlated with sleep disturbance and activity interference. Sleep and equipment use were found to be the most affected parameters by slamming. There was a marked increase in the reports of respondents considering a slamming event to be 'severe' when the cumulative vibration dose value, *ISO (2004)*, exceeded 6.0 $m/s^{1.75}$ at the stern of the vessel, *Omer and Bekker (2016)*. It remains to evaluate the structural impacts of wave slamming and the oscillating whipping response that rings through the structure for up to 50 s after wave impact.

3.2 Ship responses

Global structural responses of the SAA II were investigated through Operational Modal Analysis, *Soal et al. (2015b)*. Commercial software packages were used to investigate the structural dynamic characteristics of the vessel as a result of response-only measurements. The LMS Operational PolyMAX frequency domain and ARTeMIS CCSSI time domain OMA techniques were used to estimate the modal parameters, *Soal (2014), Soal et al. (2015b)*. Three stable modes are identified and show agreement to within 1.2 % by both Operational PolyMAX and CCSSI, whereas the damping estimates show less agreement. The three modes are identified as the 2-node (first), 3-node (second) and 4-node (third) normal bending modes. Difficulties with the batch-processing of data have prompted the development of in-house algorithms to enable the real-time monitoring of ship modes and natural frequencies. These methods rely on operational modal analysis in the time domain using a statistical subspace identification approach, *Peeters and De Roeck (1999)*. An example of such results from the in-house algorithm is presented in Fig.7 which shows the migration and intermittent excitation of the first lateral and vertical bending modes from full-scale measurements on the German research vessel, FS Polarstern. The normal bounds of modal migration can be identified from real-time monitoring data and used to devise operational strategies to extend the useful lifecycle of the SAA II.

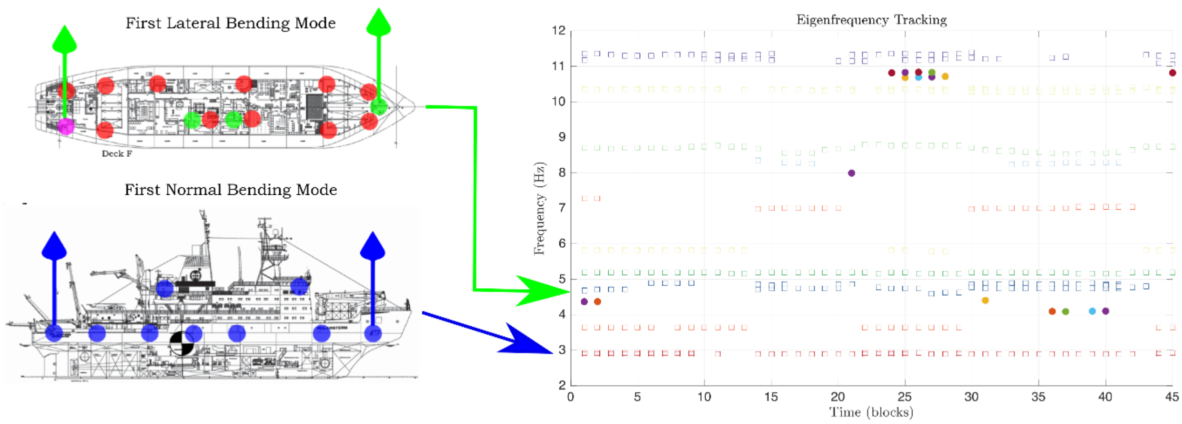


Fig.7: Migration and intermittent excitation of first lateral and vertical bending modes from full-scale measurements on the German research vessel, FS Polarstern

The analysis of shaft-line data provides potentials such as the rainflow counting of the transient torque and thrust cycles in order to gain insight into the respective demands of different operational environments. As an example, the SAA II the vessel spent 16% of the 2015/2016 Antarctic relief voyage in ice and a further 54% in open water navigation. Fig.8 compares relative distributions of the peak torque and thrust cycles for ice passage, open-water navigation and stationary operations on an Antarctic relief voyage. The operational loading of the SAA II shaft line could be evaluated against the Maximum Continuous Rating specified in the ICE Class Rules, *De Waal (2017)*.

In order to estimate the forces exerted on ship propellers during ice navigation, the rotational dynamics of the propulsion system need to be accurately modelled. The direct measurement of ship propeller loads during ice navigation is challenged by the harsh operating environment. Indirect measurements are therefore performed on the dynamic model of the shaft line of such ships to estimate propeller loads through an inverse problem.

An inverse moment analysis of operational data showed that the highest ice-induced external moment was only marginally less (6.8%) than the maximum allowed ice induced torque on the propeller and depended on the selection of the regularization method used, Fig.9. It remains to develop an inverse algorithm with the potential to process continuously recorded shaft loading histories although maximum ice-load load cases can be successfully investigated, *De Waal (2017)*. Such an algorithm would continuously monitor shaft loads and alert the vessel operator of navigation which exceeds operational design limits in real time. Continued use of this algorithm would again point to navigation situations which do likely over-stress the mechanics of the propulsion system. Such trends could assist in navigational and operational decision making during ship operations.

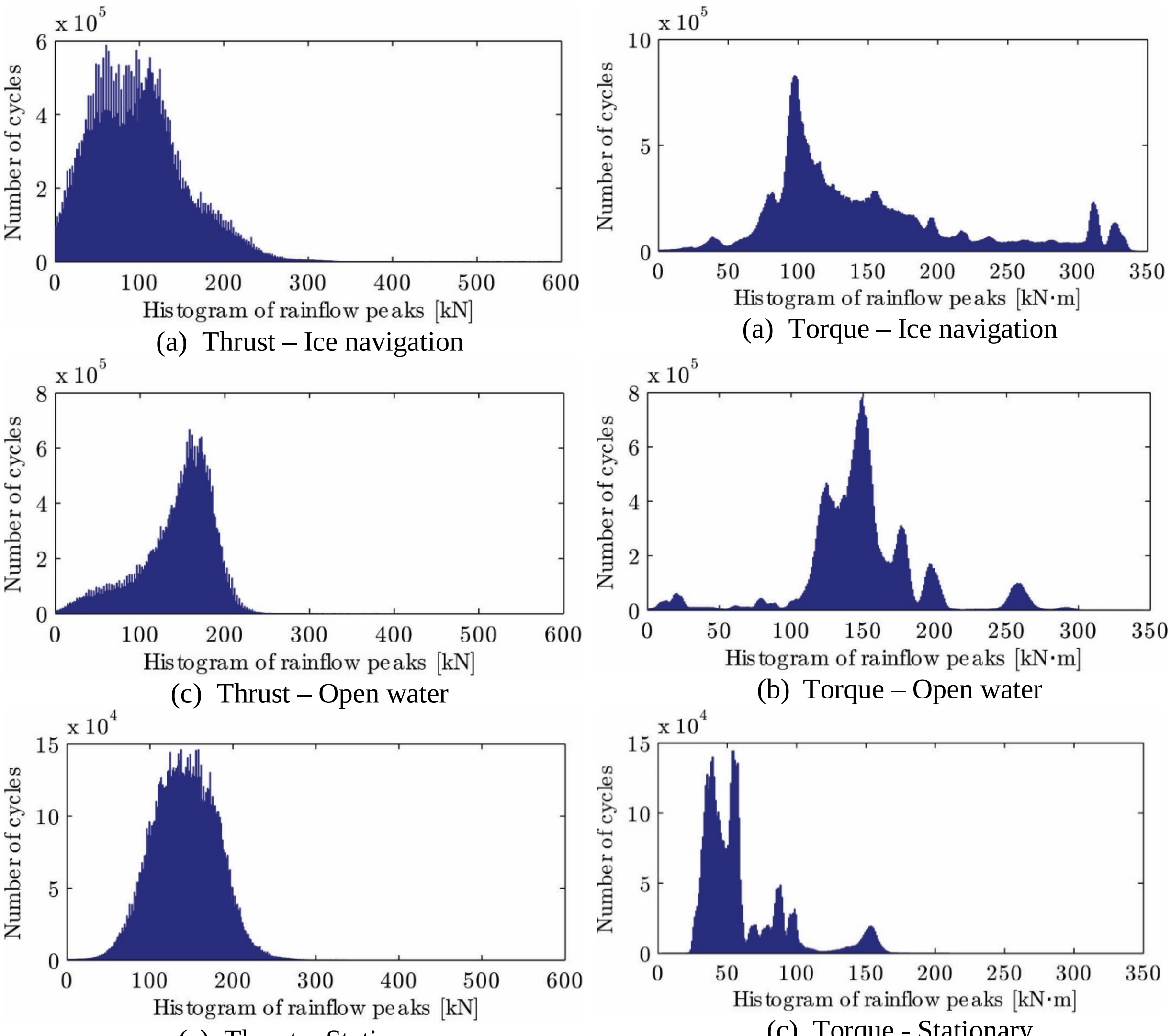
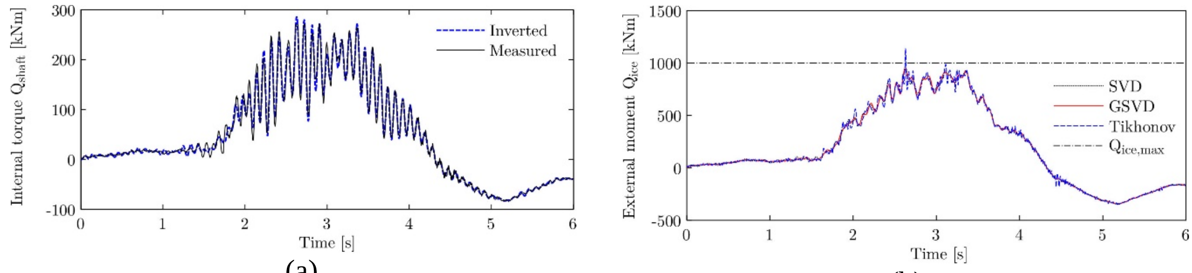


Fig.8: Thrust and torque peak rainflow cycles for the SAA II during the 2015/2016 Antarctic relief voyage, *De Waal et al. (2017)*

Multivariate statistical analyses were performed to investigate the relationships between multiple environmental and operational parameters and vibration response variables, *Soal (2014)*. During open water navigation wind speed relative, wave height and vibration response group together in a factor identified as forced structural dynamic excitation and response. The propulsion power and heading relative to the wave direction are seen to group in orthogonal factors and are therefore considered to have less influence on vibration response. The envisioned uses of the developed prediction models are the mitigation of undesirable vibration responses and the prediction of vibration response for vessel monitoring applications.



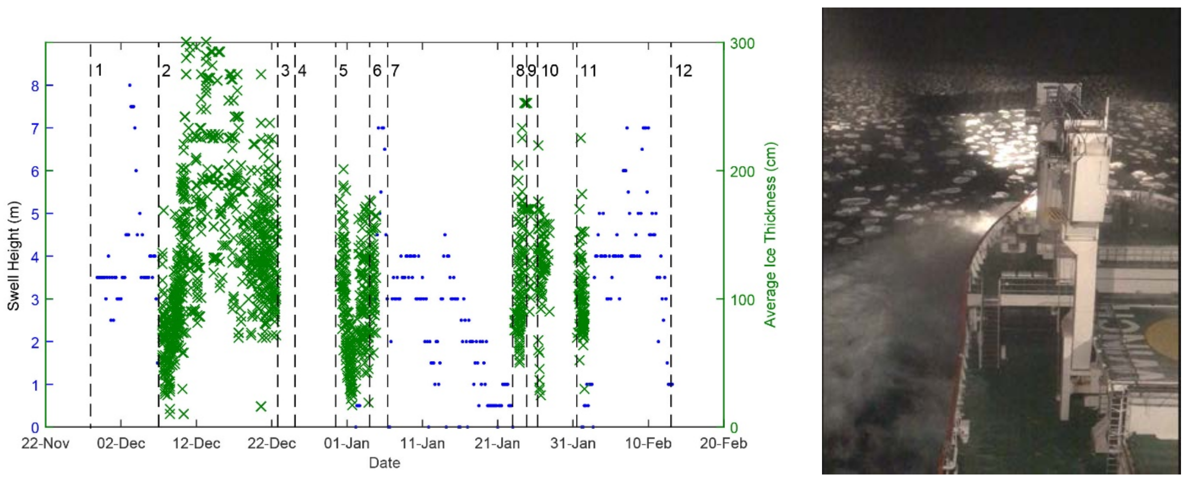
(a) (b)

Fig.9: External propeller moment determined from measured shaft line internal torque on the SAA II through inverse methods, De Waal (2017), using Singular Value Decomposition, Generalized Singular Value Decomposition and Tikhonov regularization as proposed by *Ikonen et al. (2015)*

3.3 Environmental conditions

Fig.10(a) shows an example of environmental conditions observed on an Antarctic relief voyage. On this voyage the most challenging conditions included wave heights of up to 9 m and a maximum ice thickness of 3 m. The vessel sailed in four storms where the wave height exceeded 7 m and encountered a maximum ice thickness of 3 m upon entering the ice-field en-route to Akta Bukta (between 9 and 12 December). Estimates indicate that the thickest ice on the return journey was at least 0.5 m thinner than that encountered on the outbound voyage. This explains the comparatively shorter return journey of 13 days compared to the outbound voyage of 24 days. Overall the operational profile of the voyage comprised 37% of ship time in ice navigation, 43% open water and for 19% stationary ship operations.

With increasing research in the marginal ice zone, wave slamming was experienced in icy waters, where ice debris is even flung onto the deck as a result of the displacement of water and ice when sections of the vessel hull emerge from the water and re-immersed with great force and impact. Fig.10(b) presents a photograph where the SAA II is slamming into 7 m swells with ice in the marginal ice zone.



(a) (b)

Fig.10: (a) Example of observed wave height and ice thickness on an Antarctic relief voyage. (b) Wave slamming in 7 m swells as experienced in a marginal ice zone.

3. Decision-aiding concept

The full-scale measurement system on the SAA II should be updated to enable the concurrent acquisition of all desired parameters. Monitoring could be achieved through sufficient computing power and efficient real-time analysis algorithms. Machine learning and multivariate statistical analyses will likely play a key role in the development of efficient methods to provide real-time information. The use of monitoring data for active decision aiding of the crew on the bridge will be investigated as suggested in a concept implementation by *Perera et al. (2012)*. It is envisioned that officers will view real time information on the bridge regarding the measured ice thickness, ice forces, wave height and dangerous changes in the structural dynamic response of the ship hull and propulsion systems. It is further proposed that real-time calculations of the POLARIS risk indexing system, *Kujala et al. (2015),* assists with decision aiding for safe ice navigation from automated ice thickness measurements.

4. Conclusions

Results indicate that significant potential remains to be exploited through the acquisition, analysis and utilization of full-scale ship-borne measurements. It is envisioned that such data will be used for the monitoring of ship responses in relation to design values or the provision of supplementary information on current environmental conditions. It is proposed that the analysis of monitoring and response data be utilized to create a framework for active decision aiding though the display of relevant data to the crew on the bridge. Such real-time information could include ice thickness, resistance forces, wave height and dangerous changes in the structural dynamic response of the ship hull and propulsion systems or condition of the passengers and crew on board. Such decision aiding could provide tangible benefits to operate and manage the SAA II with increased safety and efficiency. Such insightful operation and management of the SAA II would maximize this platform to support research in Antarctica and the Southern Ocean.

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Marine Bees: Robotic Ocean Exploration Inspired by Nature

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Abstract

Mapping and exploring the depths of the ocean is a challenging technical task. Our answer is a fleet of micro robotic autonomous submarines providing a robust and scalable solution. The key is how to coordinate and control hundreds of AUVs to map an unexplored region. We have taken our inspiration from nature and specifically bees. Their exploration and search for nectar is analogous to our submarines search for data and images. This paper describes the techniques used to recreate the behaviour of a bee hive and its application as part of the Shell Ocean Discovery Challenge XPRIZE, an international competition to drive innovation in ocean exploration.

1. Introduction

In 2016, the XPRIZE organization launched the Shell Ocean Discovery XPRIZE competition, http://oceandiscovery.xprize.org/. Like their other competitions such as the Google Lunar XPRIZE and the Ansari Space XPRIZE, this competition is designed to drive global innovation and technology development. For this challenge however, they are not looking to the stars, but heading to the deep.

The goal of the Shell Ocean Discovery XPRIZE is to encourage innovation in automated ocean exploration and bathymetric mapping. The world does not have a map of its own oceans and with current ship-based technology the cost and time to produce a detailed map of the sea floor would take decades and cost billions. An automated robotic solution can break-down these barriers and unlock the mysteries of the deep oceans.

The targets for the first round of the competition are:

- create a bathymetric map of a 500 km^2 target area up to 2000 m deep
- the map must have 5 m horizontal accuracy and 0.5 m depth accuracy
- find and image a target object at the 2000 m depth
- complete above tasks within 16 h using an automated solution with only shore based control

The targets are easy to describe but, from a technical viewpoint, extremely difficult to achieve. There are no existing solutions in the market today that can fulfil all these requirements. A new solution has to be found. It will need to be bold, innovative and different to what exists today.

This global competition has attracted teams from around the world from both industry and academia. We are one of the teams.

This paper describes how our engineers have taken inspiration from nature to develop a fleet of miniature robotic submarines that we named Marine Bees. They take their design from real bees, not just for the way they look, but also because they mimic the behaviour of real bees and the operation of a hive to explore and image the ocean floor.

2. Distributed Robotics

A key aspect of ocean exploration and bathymetric mapping is that it is a scalable problem. If there is a device that can map 100 m^2 of the ocean floor then using the same device in series, over time, it can be used to map 1 km^2, then 10 km^2 and so on. Likewise, multiple copies of the device can be used in parallel, so 100 of them together could map 10 km^2 at the same time. This is a scalable problem which allows large and complex tasks to be completed using multiple devices each performing part of the task. In robotics a scalable problem can be solved using swarm or distributed robotic techniques.

The primary difference between distributed robotics and standard robotics is that in distributed robotics there are multiple, low-cost, simple robots instead of a single, custom-built, complex robot.

The advantages of distributed robotics are:

- Robustness: operation continues even if single robots are lost or malfunction.
- Scalable: time or area constraints can be overcome by adding more robots.
- Flexibility: each robot follows simple rules yet the emergent complex group behaviour is adaptable to changing environments.
- Design Optimization: each robot is designed to do one and only one task. The design of each robot can be optimized with respect to that task.
- Lower cost: it can be cheaper to develop hundreds of simpler robots compared to one complex robot, due to economies of scale and mass production techniques.

Overall a distributed robotic solution is well suited to ocean exploration but what should this solution look like?

2. Bees for Inspiration

The closest analogy for distributed robotics is found in nature, specifically in insect populations. The organisation of ant colonies, termite mounds, and bee hives all display key features that distributed robots can emulate.

For our ocean exploration technology we have chosen a distributed robotic solution that mimics the behaviour of bees and the operation of a bee hive. Bees were chosen because they closely match what we are trying to achieve.

Just as the real bees leave their hive and fly into the fields and woods looking for flowers, returning to tell the other bees what they have found, our Marine Bee submarines do exactly the same. They dive down to the bottom of the ocean floor, spreading out to explore and map an area. They bring back their nectar, which for us is the data and images. Returning to the surface they share the data with the other Marine Bees so they can decide where to explore next. Each bee is exploring on its own, but there are lots of bees all doing that simultaneously to cover a large area.

Our solution is inspired by nature but how far can we model real hive behaviour and will it be suitable for ocean mapping?

3. Marine Bees – Miniature Robotic Submarines

The basic building block for our solution is the Marine Bee, Fig.1. This is our realization of a single bee in the hive. Each Marine Bee has many features of a full sized Autonomous Underwater Vehicle but they are smaller and cheaper. Their limitation is that due to their size and power, they can only explore a small area on their own.

The main body of the bee is the manoeuvring system consisting of multiple props to drive the unit underwater and a guidance system to manage its position and attitude.

The head of the bee is the payload and is interchangeable to provide different features. One of the key aspects of distributed robotics is that each robot has one and only one specific task. This is achieved using different payloads.

The standard head, or payload, is a visual system that includes cameras and range finders which enable the bee to measure distances in its environment, for mapping, and also for collision avoidance.

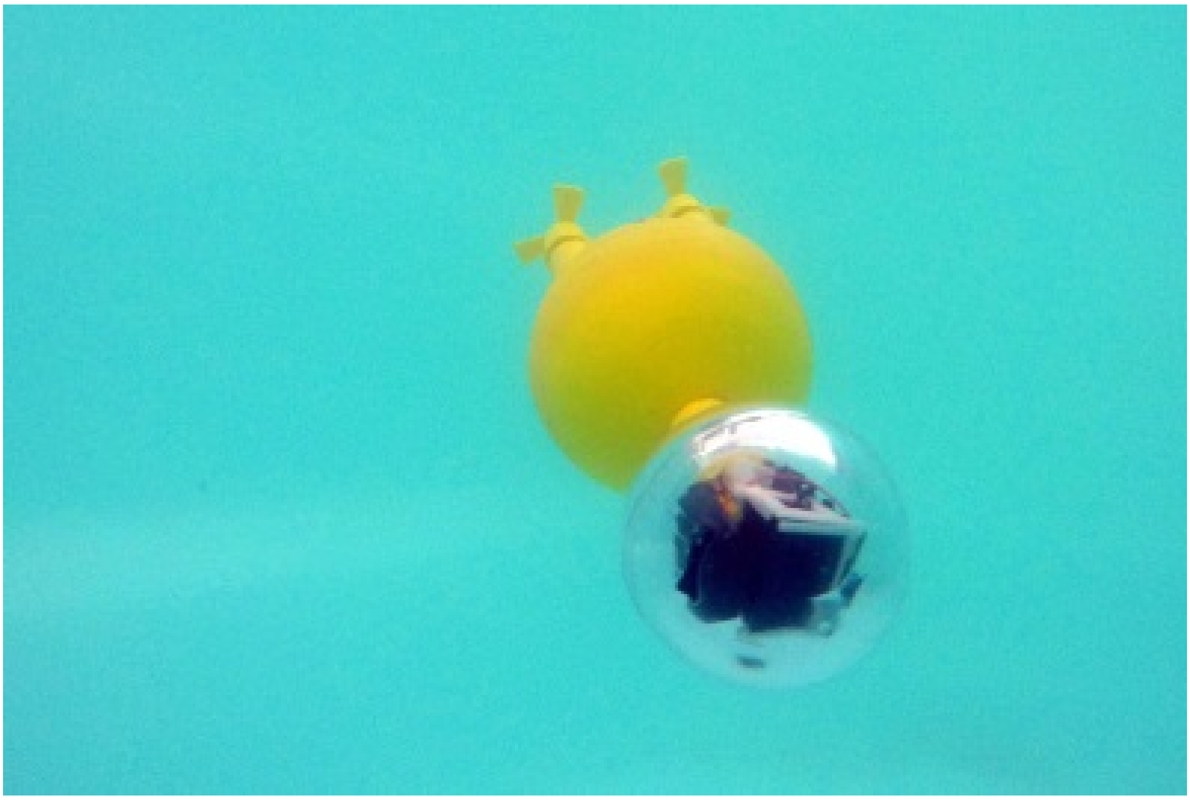

Fig.1: Eauligo Marine Bee

4. Bee Exploration Algorithms

Fig.2 shows typical exploration patterns that a robotic submarine could follow. To explore an area, the submarine can follow a course, either over a grid or along a spiral, taking measurements at regular intervals. This is brute-force exploration, the goal is to visit each point within the region.

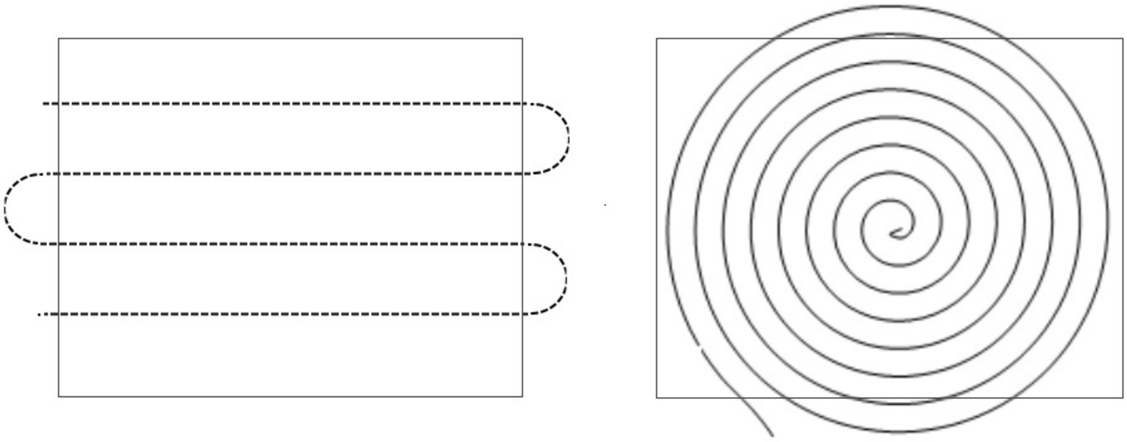

Fig.2: Brute-force exploration

However, if we look at the foraging patterns of real bees they do not take a brute-force approach. A bee does not fly in a regular pattern to explore each area. Studies of bee foraging behaviour have shown that bees tend to follow simple heuristic rules, with evidence of spatial memory only when a bee has spent a lot of time in a particular area. The bees try to enhance energy returns by minimizing flight costs, resulting in highly directional flights with minimal variation in direction, combined with short flights in areas of flowers with high potential and longer flights in areas of low reward.

The difference with brute-force exploration and bee foraging is that in brute-force exploration all points are considered the same, to create the map each point must be visited. In bee foraging the goal is for the bee to find nectar or pollen, they are visiting specific flowers using strategies to maximize the return. Not every point for them in a garden is important, only the flowers that give the most reward are targeted.

To mimic the behaviour of real bees with our Marine Bees we need to introduce a concept of nectar, or value, during the exploration process. For us the value is in the measurements and images that the Marine Bees take of the ocean floor. Our nectar is data. Unlike brute-force exploration we cannot consider all data as equal, we need to take into account the qualitative aspect of the data, not just its quantity. Just as bees optimize their strategy to find flowers that maximise the amount of nectar returned for energy expended, the Marine Bees need to maximise the quality (not quantity) of data collected against battery consumption.

For a bathymetric map the data is just a measurement of depth, what does quality of data mean in this case? When we talk about quality of data, we actually mean the ability to collect the data. The ocean floor is unpredictable and the Marine Bees can only be programmed with basic heuristic rules and very limited Artificial Intelligence algorithms. There will be many situations where it will be difficult to collect data, or the data will be inaccurate. Some examples are:

- Areas with poor sensor readings, such as terrain that can cause confusing sonar echoes or areas with high silt content that block visual images.
- Areas with strong sea currents that limit the robot's speed or result in excessive battery consumption to make progress.
- Areas with many obstructions or difficult terrain, that again results in high power usage to navigate.

As stated, the goal for each Marine Bee is to collect the best data versus power use. Therefore in areas where conditions are good, and data can be collected with low power consumption, a Marine Bee should maximize its time in these regions. These are the gardens with flowers full of nectar. In areas where conditions are bad these areas should be passed quickly, just as real bees fly rapidly across areas bereft of flowers. Our overall algorithm for exploring the ocean floor looks like Fig.3, a bee foraging pattern.

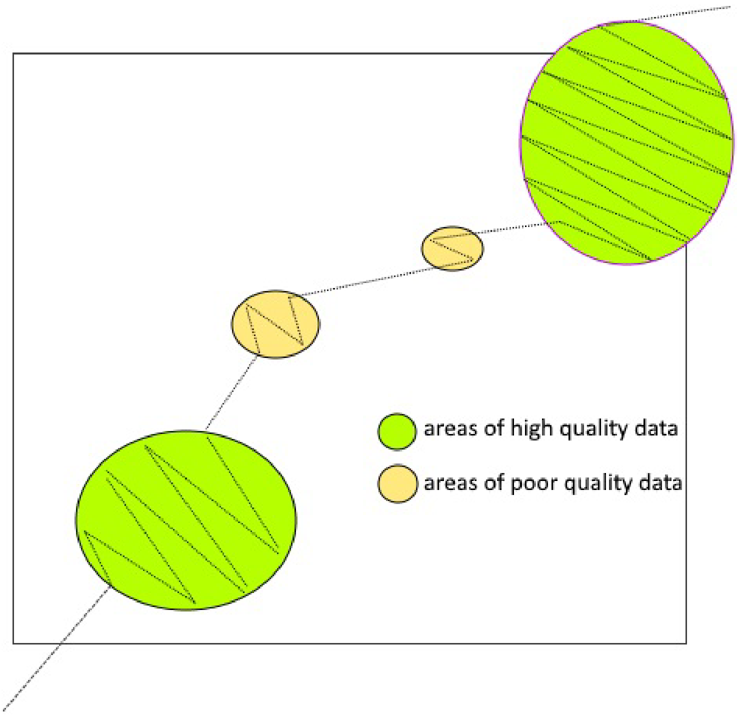

Fig.3: Bee exploration

3. Floating Hives – Autonomous Surface Vessels

Each Marine Bee is able to explore a small part of the ocean floor and by using many bees together we can map large areas. However, we need a way of getting the bees to their target location and a way of sending data back to shore. Continuing the analogy, the surface part of our solution is a floating hive.

The hive is an autonomous surface vessel that manages a cell of 50 bees, Fig.4. Initially the bees are stacked inside the hive. The hive drives out to the target location and drops the bees at spaced intervals. The hive also acts as a communication hub, when the bees return to the surface they transmit their data to the hive which then relays the data back to land. Finally, the hive will recapture each bee as it returns ready for the return voyage.

The hives also provide the spatial memory for the bees. In a real bee hive the bees dance to communicate what they have found and where to explore next. The Marine Bees are too simplistic to store representations of areas that have been explored and where best to go next. This functionality is provided by processors in the hives which store copies of the data returned by the bees and build the overall spatial map of the area. Using this map the next cell of bees is sent out to explore new areas.

The hives are essentially floating HQs, they provide communication to the shore and they manage a group of bees.

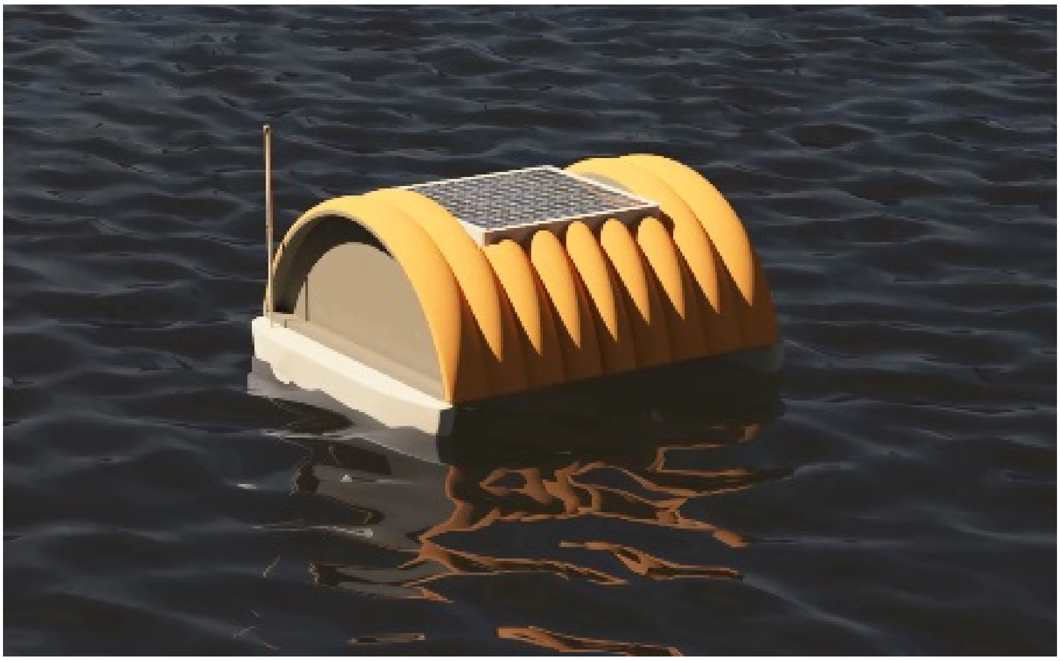

Fig.4: Floating Hive

4. Conclusion

In this paper we have presented a solution for ocean exploration based on distributed robotics inspired by the behaviour of bees and the operation of a bee hive. The key elements are a simple, low cost miniature robotic submarine, an exploration algorithm based on bee foraging, and autonomous surface vessels which act as floating hives to manage a group of bees.

Testing and optimization of our solution is still ongoing but based on the current performance we will need around 200 to 300 Marine Bees working together to complete the challenge set by the Shell Ocean Discovery XPRIZE. An impressive number of robots that will be deployed to depths up to 2000 m, we hope we will get them back.

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Effect of Keel Pads and Fillets on the Performance of a Planing Hull

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Abstract

This paper describes an empirical investigation of the effects of keel pads and keel fillets on the performance of a planing hull. The standard, V- shape keel, planing hull is analysed using the Savitsky method. Bottom geometries with various keel pads and keel fillets are investigated in model tests. Based on the results, guidelines for the size and location of keel pads and keel fillets are given.

1. Introduction

So far, in boat design, the design of hull and appendages is based mainly on experience and not experimentally proven model tests or numerical simulations. This is suspected to result in sub-optimal designs.

Theoretically, keel pads, Fig.1, increase lift and reduce resistance. However, larger lift does not always lead to lower resistance. The effect of keel pads, depending on their actual design parameters, is investigated here by means of model tests. The purpose of a keel fillet, Fig.2, is to generate slight suction toward the stern to increase trim. This can be used to change trim to improve hull performance.

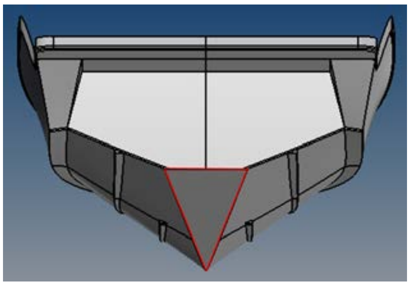

Fig.1: Keel pad

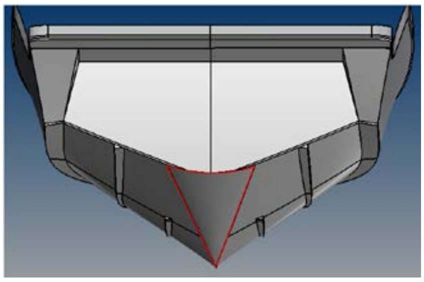

Fig.2: Keel fillet

The theoretical lift increase of a keel pad, Fig.1, can be motivated by two equations from *Savitsky (1964)*: the lift coefficient of a flat planing surface, Eq.(1), and a deadrise hull, Eq.(2). The lift coefficient for a deadrise hull will be lower. Thus, theoretically a keel pad, Fig.1, should increase lift.

$$C_{Lo} = \tau^{1.1}[0.0120\lambda^{\frac{1}{2}} + \frac{0.0055\lambda^{2.5}}{{C_v}^2}] \qquad (1)$$

C_{Lo} is the lift coefficient for a hull with zero deadrise, τ the trim angle of the planing area (in deg), λ the mean wetted length-beam ratio (in ft), and C_v the speed coefficient.

$$C_{L\beta} = C_{Lo} - 0.0065\beta {C_{Lo}}^{0.60} \qquad (2)$$

$C_{L\beta}$ is the lift coefficient for a hull with deadrise angle β (in deg).

Savitsky's method cannot be used to predict the effects of keel pads and keel fillets on the performance of a planing hull. Instead, these are to be determined experimentally.

Planing hulls are designed to rise up and glide on top of the water surface at high speeds. However, at low speeds, they are in displacement mode, where trim increases with speed. In a transition zone ("hump region"), very high trim angles occur and resistance is relatively high, before the boat reaches the planing phase for which it is designed. In the planning phase the trim angles, draft and resistance coefficients are low. Speed limits are often determined by the seakeeping characteristics of the boat, specifically the accelerations passengers and crew can tolerate, *Savitsky and Koelbel (1993)*. For this study, human comfort is not considered and will thus not be discussed further.

Previous studies at Stellenbosch University found that keel pads and fillets increased the resistance of planing hulls, but only a few LCG (longitudinal centre of gravity) positions and hull geometries was tested. The scaling method is also known to be sensitive. Therefore, the results were considered to be inconclusive, motivating the study presented here, *Brand (2015)*.

2. Savitsky's method

We used Savitsky's method in this study as a simple, semi-empirical planing hull performance prediction method. The method is user-friendly, not patented and requires relatively few input data. The disadvantages of the method are:

a. It only considers the maximum chine beam, a single characteristic value for the deadrise angle, the hull mass and the *LCG* position, *Barry et al. (2002)*.
b. It neglects the wave resistance and viscous resistance of the wetted surface of the sides of the hull and it neglects the spray resistance.
c. It does not consider the change in deadrise angle in longitudinal or transverse direction.
d. It is quasi-static and thus does not accurately predict transient behaviour.
e. It is not possible to predict the point and panel hydrodynamic loads on the hull because the method lumps all the forces into a series of empirical relationships, *Akers (1999)*.
f. The spray resistance component of some of the areas of the wetted surface are neglected.

Savitsky's (1964) method was coded in Matlab and used here to determine the resistance *D*, running trim τ and the submergence of the transom in the water, of a planing hull, operating at a range of speeds. For the purpose of these calculations we assume smooth-water operation and that the hull has a constant deadrise, beam and running trim for the entire wetted surface.

2.1. Planing phase

The lift on a planing hull combines buoyancy and dynamic lift. The empirical planing lift equation (1) for a flat planing hull is applicable in the following conditions: $0.6 \leq C_v \leq 13$, $2° \leq \tau \leq 15°$, $\lambda \leq 4$. The speed coefficient is:

$$C_v = \frac{V}{\sqrt{gb}} \quad (3)$$

V is the horizontal velocity of the planing surface (in ft/s), g the acceleration constant due to gravity (in ft/s^2), and b the beam of the planing surface (in ft).

The total hydrodynamic drag follows from pressure drag D_p and frictional drag D_f along the bottom (both in lb) neglecting side wetting of the hull:

$$D_f = \frac{(C_f+\Delta C_f)\rho {V_1}^2(\lambda b^2)}{2cos\beta} \quad (4)$$

$$D_p = \Delta tan\tau \quad (5)$$

C_f is the Schoenherr friction coefficient, ΔC_f= 0.0004 [ATTC Standard Roughness], ρ the mass density of water (in lb/ft^3), V_1 the mean velocity over the bottom of the planing surface (in ft/s) and Δ is the mass of the boat (in lb). The total drag *D* (in lb) acting on the hull is then:

$$D = D_p + \frac{D_f}{cos\tau} \quad (6)$$

Neglecting viscous effects and elevation variation effects, the average bottom velocity for specific deadrise angles V_1 (in ft/s) is, *Savitsky and Ross (1952)*:

$$V_1 = V(1 - \frac{C_{L\beta}}{\lambda cos\tau})^{1/2} \quad (7)$$

The Reynolds number *Re* is calculated as follows, *Savitsky and Ross (1952)*:

$$Re = V_1 \lambda b / \nu \quad (8)$$

ν is the kinematic viscosity (in ft^2/s). The Schoenherr friction coefficient follows from, *Taylor (1942)*:

$$\frac{0.242}{\sqrt{C_f}} = log_{10}(ReC_f) \quad (9)$$

The centre of pressure C_p (in ft forward of the transom) is calculated as follows, *Savitsky (1964)*:

$$\boldsymbol{C_p = 0.75 - \frac{1}{5.21\frac{C_v^2}{\lambda^2} + 2.39}} \quad (10)$$

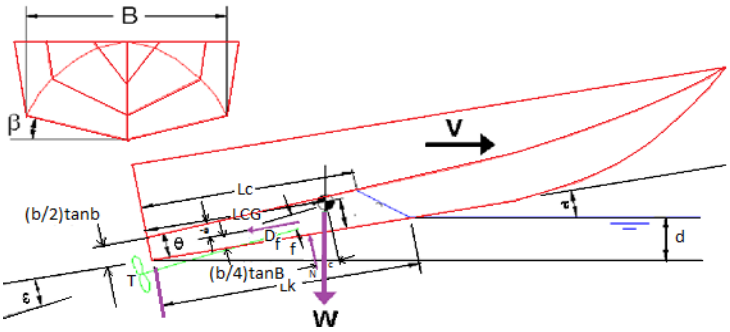

Fig.3: Force diagram

The distance *c* (in ft) between the resultant of pressure forces acting normal to bottom *N* (in lb) and the centre of gravity measured along the keel from the transom *CG* (in ft, measured normal to *N*) as per Fig.3:

$$c = LCG - C_p \lambda b \quad (11)$$

LCG is the longitudinal centre of gravity (measured along the keel from the transom) (in ft). The distance between D_f and *CG* is, as per Fig.3:

$$a = VCG - \frac{btan\beta}{4} \quad (12)$$

a is the normal distance between D_f and CG (in ft). The viscous drag component, Eq.(4), is used to balance the equilibrium:

vertical equilibrium: $\Delta = Ncos\tau + Tsin(\tau + \epsilon) - D_f \sin\tau$ (13)
horizontal equilibrium: $Tcos(\tau + \epsilon) = D_f cos\tau + Nsin\tau$ (14)
trim equilibrium: $Nc + D_f a - Tf = 0$ (15)

T is the propeller thrust (in lb), ϵ the inclination of the thrust line relative to the keel line (in deg). f is the normal distance between *T* and *CG* (in ft). Combining Eqs.(13)-(15) yields:

$$\Delta\left\{\frac{[1-\sin\tau\sin(\tau+\epsilon)]c}{\cos\tau} - f\sin\tau\right\} + D_f(a-f) = 0 \tag{16}$$

If we also consider air resistance R_{air}, the combined equilibrium condition becomes, *Brand (2015)*:

$$\left\{D_f\cos(\tau) + \left(\frac{\Delta}{\cos(\tau)} + \frac{D_f\sin(\tau)}{\cos(\tau)}\right)\sin(\tau) + R_{air}\right\} f + D_f a - R_{air} h - \left(\frac{\Delta}{\cos(\tau)} + \frac{D_f\sin(\tau)}{\cos(\tau)}\right)c = 0 \tag{17}$$

h follows from Fig.4.

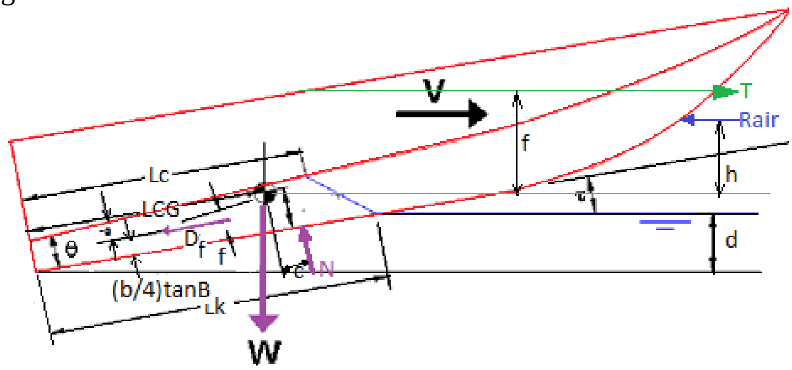

Fig.4: Icarus Marine experimental model force diagram

2.2 Non-planing correction

Savitsky's method for hull resistance prediction is accurate for the planing phase, but not the displacement and transition phases. It is necessary to apply a correction factor to Savitsky's method, *Blount and Fox (1976)*:

$$M = 0.98 + 2\left(\frac{LCG}{B_{PX}}\right)^{1.45} e^{-2(F_\nabla - 0.85)} - 3\left(\frac{LCG}{B_{PX}}\right) e^{-3(F_\nabla - 0.85)} \tag{18}$$

M is the multiplying resistance correction factor to the Savitsky's predicted resistance, B_{PX} the maximum chine beam, $F_\nabla = V/\sqrt{g\nabla^{1/3}}$ the volumetric Froude number and ∇ the displacement volume. The M-factor should only be used when $F_\nabla \geq 1.0$ and $LCG/L_P \leq 0.46$.

The improved correction factor is calculated as follows, *Blount and Bartee (1997)*:

$$M' = K(M-1) + 1 \tag{19}$$

M' is the improved multiplying resistance correction factor and $K = 0.5$ is the correlation factor used to refine the hump-region resistance prediction. Eq.(19) is applicable for $0 \leq K \leq 1$.

2.3 Scaling

The volumetric Froude number for a model and a full-scale hull is the same. For the model-test drag is scaled using the equations below. The subscript M indicates model and the subscript FS indicates full-scale. Following ITTC recommendations for high-speed craft, no form factor is used in the scaling. The frictional resistance coefficient is, *ITTC (1957)*:

$$C_F = \frac{0.075}{(\log_{10}(Re) - 2)^2} \tag{20}$$

The mean wetted length to beam ratio used to calculate the Reynolds number is the same for the model and the full-scale hull. The air resistance coefficient C_{AA} is, *ITTC (2008)*:

$$C_{AA} = \frac{\rho_A {V_A}^2 A_V C_D}{\rho V^2 S} \tag{21}$$

ρ_A = 1.225 kg/m is the air density (in kg/m^3), ρ the water density (in kg/m^3), C_D = 1.4, *ITTC (2002)*, V_A the air speed (in m/s), A_V the transverse air resistance section area (in m^2) and S the running wetted surface area (in m^2). If no wind is present the air speed is equal to the hull speed.

The total resistance coefficient for the model is, *ITTC (2008)*:

$$C_{TM} = \frac{D_M}{1/2(\rho_M S_M {V_M}^2)} \tag{22}$$

C_{TM} is the total resistance coefficient for the model and D_M its total resistance (in N). The residual resistance coefficient is, *ITTC (2008)*:

$$C_R = C_{TM} - C_{FM} - C_{AA} \tag{23}$$

C_R is the residual resistance coefficient and C_{FM} is the frictional drag coefficient of the model. The total resistance coefficient for the full-scale hull is:

$$C_{TFS} = C_R + C_{FFS} + C_A \tag{24}$$

C_{TFS} is the total resistance coefficient of the full-scale hull, $C_A = 0.0004$ and C_{FFS} the frictional drag coefficient of the full-scale hull. The total resistance for the full-scale hull is:

$$R_{TFS} = \frac{1}{2} \rho_{FS} {V_{FS}}^2 S_{FS} C_{TFS} \tag{25}$$

R_{TFS} is the total resistance of the full-scale hull (in N), ρ_{FS} the density of the water in which the full-scale hull is operating (in kg/m^3), V_{FS} the speed of the full-scale hull (in m/s), and S_{FS} the running wetted surface area of the full-scale hull (in m^2). The lengths given by the experimental data is scaled using a scale factor of 7.5, *Taunton et al. (2010)*.

2.4 Implementation

The procedure outlined above was coded in Matlab. This approach acted as a baseline so that the model test results could be evaluated. The process followed to obtain the resistance *D*, running trim τ and the submergence of the transom is iterative, ensuring dynamic equilibrium. For further details, see *Brand (2015)*. The Matlab code of the outlined Savitsky's method was verified against numerical examples in *Savitsky (1964)*. The Matlab code predicted trim and drag values very similarly as another Savitsky prediction software, www.boatdesign.net, further verifying our implementation.

The Matlab code was again validated against experimental results of *Taunton et al. (2010)* with satisfactory agreement. The average difference and the maximum difference between the experimental drag and the predicted drag is 4.8% and 8.1%, respectively. This is a very reasonable error, since there are many factors that influence the accuracy of both the experimental drag values and the Savitsky predicted values. Note that the Savitsky's method is a tool for quick assessment of planing hulls and is known to deliver inexact results.

3. Model tests

3.1. Model

The base model, Fig.5, Table I, was a hull design from Icarus Marine, http://www.icarusmarine.com/. The model scale was 1:18. The high-speed planing hull has a steep deadrise angle which gives the boat the ability to cut through waves resulting in a smoother ride. The hull features a reverse chine with a chine to generate additional lift and to improve the stability and control of the boat. The disadvantage of the chine design is that more slamming can be experienced in rough waters. Spray rails aid the reverse chines in redirecting rising water. The same model was used in previous investigations, allowing comparisons with previous tests and reducing time and costs for this study.

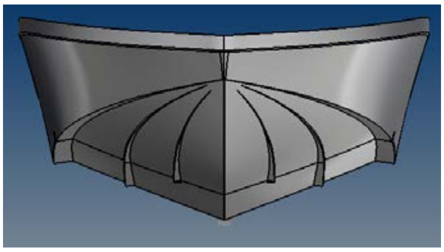

Fig.5: Icarus Marine hull

Table I: Icarus Marine design

Mass	21.2. t
Length	16.976 m
Waterline length	13.298 m
Draft	1.158 m
b	4.887 m
β	21°

The base model was modified to incorporate keel pads and keel fillets of four sizes, each with two different centre of gravity positions for each keel pad and keel fillet. Two *LCG* positions were investigated: 210 mm and 228 mm (3.78 m and 4.11 m in full scale) forward along the keel from the transom for the model hull.

The Volumetric Froude number for the model tests was kept the same as for the full scale hull to ensure dynamic similarity between the full-scale hull and model. The chosen model scale of 1:18 ensured that the model was suitable for the Stellenbosch University towing tank (90 m × 4.5 m × 2.7 m with maximum trolley speed 8.2 m/s), meeting the recommendations of *Lewis (1998)*: model length must be less than tank depth and half tank width.

3.1.1 Weight redistribution system

The weight redistribution system, indicated by number 1,2 and 3 in Fig.6, designed by Mr. A. L. Janssens was used to position the LCG as desired. The steel plate masses were sized so that the model weight corresponds to the scale factor. This system allows for a wide range of LCG positions to be tested, but in this paper the focus is limited to two LCG positions.

3.1.2 Weight balance calculations

The individual parts show in Table II were weighed and logged in an Excel spreadsheet in order to determine the adjustable weight positions. The weights and positions of the steel masses are determined by an iteration method where the steel masses are altered until the desired model weight and LCG position is achieved. The weight balance was done with moment balance equations in Microsoft Excel. A sample Excel calculation is shown in Table II. The Excel sheet shown in Table II includes the VCG position calculation, since it is required for the Savitsky's method. The formulas used are described by Eqs.(26) to (28).

$$\sum_{i=1}^{i=n} Moments = (Mass_1 \cdot LCG_1 \cdot 9.81) + (Mass_2 \cdot LCG_2 \cdot 9.81) + \ldots + (Mass_n \cdot LCG_n \cdot 9.81) \quad (26)$$

$$\sum_{i=1}^{i=n} Mass = Mass_1 + Mass_2 + \ldots + Mass_n \quad (27)$$

$$Model\ overall\ LCG = \frac{\sum_{i=1}^{i=n} Moments}{9.81 * \sum_{i=1}^{i=n} Mass} \quad (28)$$

Where n is the number of mass components

Table II: Weight balance for the standard keel with 210 mm LCG

Component	Weight [kg]	LCG [mm]	LCG mom	VCG [mm]	VCG mom
Upper hull with bolts	1.979	275	5333.405	71.7	1391.983
Hall attached foam	0.58	238.5	1355.634	23.05	131.1499
Weight	1	68	666.4	85.81	841.7961
Washers	0.014478	68	9.648092	95.81	13.60775
	3.573478	210.096	7365.087	67.84999	2378.537

3.2 Keel fillet and keel pad

The 4 hull shapes that were tested were designed in Rhino Modeller and the line drawings were made with the help of the Orca 3D line drawings function. Three keel fillets were evaluated, including one keel fillet that was also evaluated by Mr A.L. Janssens in 2014 (for verification purposes). The test models were tested at two different LCG positions each. The full-scale LCG positions that were evaluated are 4.11 m and 3.78 m from the transom. The Long keel fillet hull has a full-scale keel fillet width of 2.125 m and a full-scale keel fillet length of 5.753 m. The Short keel fillet hull has a full-scale keel fillet width of 2.125 m and a full-scale keel fillet length of 2.125 m. The 2014 Keel fillet hull has a full-scale keel fillet width of 1.08 m and a full-scale keel fillet length of 11.44 m.

The keel pad that was evaluated was one of the keel pads evaluated by Mr A.L. Janssens in 2014. The test model was tested at two different LCG positions. The full-scale LCG positions that were evaluated are 4.11 m and 3.78 m from the transom. The 2014 Keel pad hull has a full-scale keel pad width of 1.08 m and a full-scale keel pad length of 11.44 m.

3.3 Model design features

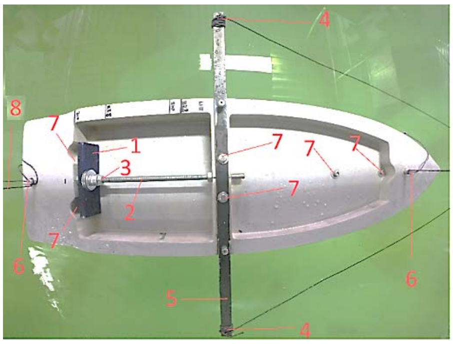

Fig.6: Model features

Each design feature of the experimental model is given a numbered label, indicated in Fig.6 to provide a description of the model design. Each feature is described in Table III.

Table III: Model Features

1	Steel plates	To achieve the desired model mass and LCG position.
2	Threaded rod	The steel plate slides on the threaded rod to the desired location.
3	Positioning nuts	Tighten the threaded rod and steel plates into position.
4	Towing points	A single towing point at the bow of the hull would have had adverse effects on the trim of the hull. The model therefore has two towing points.
5	Towing bar	The position of the towing bar aids in the directional stability of the hull and has minimal effect on the hull trim during experimental testing
6	Loops	To attach the trim sensors.
7	Keel attachment bolts	To pull the keel attachments flush against the upper hull by tightening the bolts in the threaded inserts.
8	Safety line	Stops the model when the towing tank trolley stops to prevent sensor damage.

4. Testing of model

4.1 Testing facility and equipment

The University of Stellenbosch towing tank was used to conduct the experiments. The towing tank is fitted with a self-propelled trolley used to tow the model hulls. The maximum speed of the trolley allows for planing hulls testing. The maximum trolley operating speed at which the measurements are considered reliable is taken as 7.5 m/s. The trolley will not reach steady state at higher speeds, which is required to gather useable readings. The sensors that were used for capturing the data are an analogue thermometer, two Coil displacement sensors, a load cell and a tachometer. The sensors were calibrated before the experimental test was conducted. The sensors are connected to a data acquisition (DAQ) system. The signal conditioning box reads the signals sent by the sensors. A laptop is used to collect the data and to do the calibration conversions.

4.2 Experimental set-up

The set-up for the model hulls that were tested is shown in Fig.7. The load cell is responsible for measuring the resistance of the hull and is connected to the towing points by a towing line that is fed around a pulley. The pulley height is constant, but the height of the towing points on the model is dependent on the trim and draft of the hull. The influence of the towing angle on the trim of the hull is negligible, since the towing angle remains very small. The trim sensors are connected to the stern and bow trim loops by a thin rope. Extra weights were attached to the trim sensor rope to counter the force pulling up from the sensors. This ensures that no other external force acts on the model hull at the trim sensor attachment points. The speed of the trolley and thus the model hull is measured by a counter which measures the rotating rate of the trolley wheels.

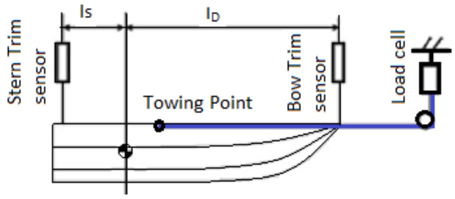

Fig.7: Model set- up

The ITTC recommends that the experimental test should take place under turbulent water conditions, but turbulent water conditions could not be reached at the lower speeds without adjusting the surface roughness of the hull. Turbulent flow over the model hull is needed to represent the operating conditions of the full-scale hull accurately. Turbulent flow conditions were reached by attaching a thin piece of 400 grit sandpaper at 5% of the stationary wetted keel length to the rear from the bow, *Lewis (1998)*, and another piece of 400 grit sandpaper midway towards the transom as shown in Fig.8.


Fig.8: Turbulence stimulators

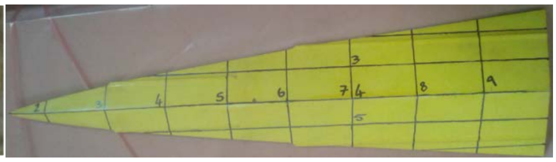
Fig.9: Sectioned standard keel

4.3 Experimental procedure

All towing tank experiments were followed the International Towing Tank Convention (ITTC) guidelines, ITTC-Recommended Procedures, High Speed Marine Vehicles. Resistance, trim, speed and wetted surface tests were done on each hull shape at two different LCG positions. The resistance, speed and trim tests were done at a minimum of seven different speeds, with a speed range of 0 to 7.5 m/s. The wetted surface tests were done at four different speeds, including one test in the stationary position, one test in the transition mode and two tests in the planing mode. Onley the steady state sensor readings were used. The steady state readings for each run were averaged. The steady state results plots are shown in section 6. During the wetted surface test, vertical and horizontal lines were drawn on the model hull and each line was numbered as shown in Fig.9. The hull was towed at minimum of four different speeds for each hull shape and LCG position. Underwater footage was taken to measure the wetted area on the model.

4.4 Limitations and constraints

The following limitations and constraints were present during testing:

- The temperature of the water in the towing tank cannot be regulated.
- The size of the test model is limited due to the towing tank size.
- The experimental speed range is limited due to the maximum steady state speed of the trolley.

5. Savitsky Prediction

A mathematical model and corresponding computer programme were developed, *Brand (2015)*, to predict the resistance and trim for the Standard Icarus Marine hull. The experimental model's propelling force, shown in Fig.4, was positioned differently from the propelling force of the models in *Savitsky (1964)*. Air resistance was present during the experimental testing of the model. The programme thus takes into account the effect air resistance as well as the positioning of the propelling force.

The method described in section 2 is again used here for predicting the performance of the Icarus Marine hull, but with a few changes. The programmed calculation method used for the Savitsky's method trim and drag prediction is explained in detail by *Brand (2015)*. The equation used in the *Savitsky (1964)* example for the calculation of the equilibrium trim is different for the case where the propelling force T is located as indicated in Fig.4 and the air resistance force R_{air} is taken into account. The new equilibrium equations are derived from Fig.4 by calculating force and momentum equilibrium calculation, *Brand (2015)*. Savitsky's method was adapted by applying the K, *Blount and Bartee (1997)*, and M, *Blount and Fox (1976)*, factor. The correction factor was applied as described in section 2.2. The water properties and constants that are used in the Savitsky prediction of the performance of the models are g = 9.81 m/s^2, ρ = 999,1026 kg/m^3, and $\nu = 10^{-6}$ m^2/s.

5.1 Scaling of experimental results

The same drag force and speed scaling methods were used for the experimental results of the Icarus Marine hull as the method shown in section 2.3. The experimental speed and drag measurement scaling were done in Excel, *Brand (2015)*.

5.2 Savitsky vs. Experimental data

The Savitsky's method could only be used to predict the resistance and trim for the standard Icarus Marine hull design. There is no provision made in Savitsky (1964) for keel pads and keel fillets. The predicted full-scale results for the drag of the standard Icarus Marine hull, with an LCG of 4.11m, are shown in Fig.10. The predicted full-scale results for the trim of the standard Icarus Marine hull, with an LCG of 4.11m, are shown in Fig.11. Fig.10 and Fig.11 compare the Savitsky predicted results to the full-scale experimental results gathered in 2015 and in 2014.

The Savitsky method produces a predicted trim and drag that differs from the 2015 scaled-up experimental results. The predicted Savitsky error in Fig.10 is 23.68% at a speed of 6.15 m/s in the displacement mode. At a speed of 13.47 m/s in the transition mode the error is 2.04% and 16.95% at a speed of 20.3 m/s in the planing mode. The error in Fig.11 is 2.497° at a speed of 6.15 m/s in the displacement mode, 0.447° at a speed of 13.47 m/s in the transition mode and 0.354° at a speed of 20.3 m/s in the planing mode.

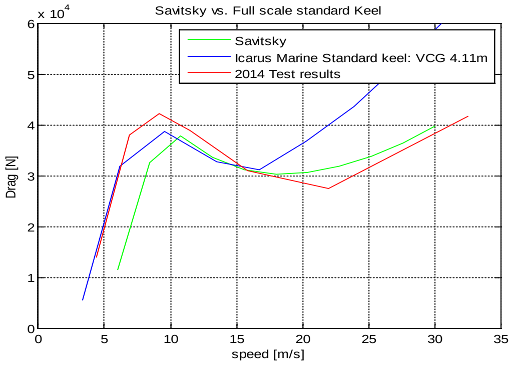

Fig.10: Savitsky drag vs. Experimental drag (LCG=4.11m)

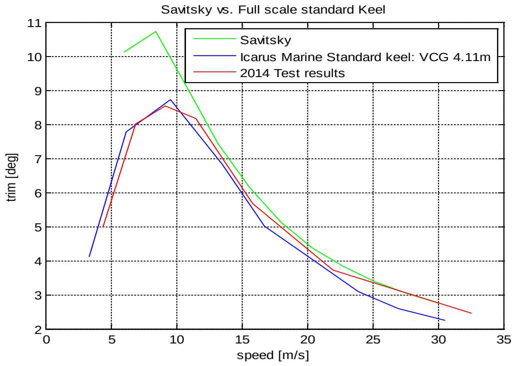

Fig.11: Savitsky trim vs. Experimental trim (LCG=4.11m)

Fig.12 and Fig.13 compare full-scale experimental results and the Savitsky's predicted results for an LCG of 3.78 m. The error in Fig.12 is 28.15% at a speed of 6.71 m/s in the displacement mode, 2.05% at a speed of 13.32 m/s in the transition mode and 9.97% at a speed of 20.31 m/s in the planing mode. The error in Fig.13 is 3.256° at a speed of 6.15 m/s in the displacement mode, 0.133° at a speed of 13.47 m/s in the transition mode and 0.604° at a speed of 20.3 m/s in the planing mode. At low speeds, when the hull is operating in the displacement and transition mode, higher levels of error in the Savitsky's predicted data is to be expected. Savitsky's method was constructed for performance prediction of a hull operating specifically in the planing mode. The M-factor (described in section 2.2) was thus implemented in the Savitsky's method to improve the predicted results for the transition mode, reducing the error considerably.

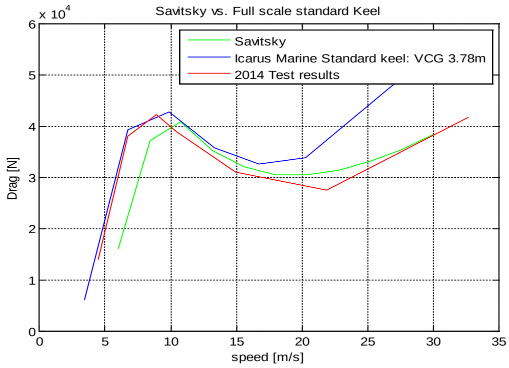

Fig.12: Savitsky drag vs. Experimental drag (LCG=3.78 m)

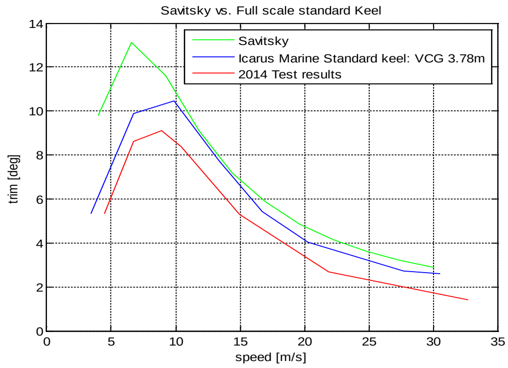

Fig.13: Savitsky trim vs. Experimental trim (LCG=3.78 m)

It was also observed that the stern of the hull dips deep into the water between approximately 4 m/s to 9 m/s. The bow drops, lifting the stern, as speed exceeds 9 m/s. This is not accounted for in the Savitsky's method, which explains the increase in resistance between 4 m/s to 9 m/s in the displacement mode for the experimental results. This phenomenon is not investigated in this paper since the paper only focuses on steady state data. The study of the transient response of the keel shapes in the future could be very beneficial.

The difference between the Savitsky predicted results and the scaled-up experimental results can be attributed to several influences. One of the influences include the shape of the Icarus Marine hull. Savitsky's method does not account for the effect of the spray rails and the reverse chine that is present on the Icarus Marine hull. The hull considered in the Savitsky's method is a smooth prismatic hull. Other possible influences could be the highly sensitive nature of the scaling method (described in section 2.3), the slight ridge present at the keel shape attachment surface of the model hull, possible slight human error in the manufacturing process and the simplicity of the Savitsky's method. The difference in results for the Savitsky's method data and the scaled up experimental data is undesirable, but is as expected.

6. Experimental data analysis

It was observed during experimental testing that planing commences at approximately 4 m/s for the model scale hulls. Porpoising is an unwanted effect where the hull bounces on the water. Porpoising results in a very uncomfortable, dangerous and unstable boat ride. It was observed that porpoising took place at the speeds listed in Table V. Since the effect of porpoising is outside the scope of this paper, the speeds listed below only include the speeds at which the wetted area tests were conducted.

Table V: Porpoising during wetted area tests

Keel Shape	LCG [mm]	Speeds [m/s]
Standard keel	210	4.5
2014 Keel fillet	210	4 ; 4.5
2014 Keel pad	210	4.8 ; 5.1
Long fillet	210	4.2 ; 5.4 ; 6.2
	228	4 ; 5.3
Short fillet	210	3.6 ; 3.9 ; 5 ; 5.8 ; 7.07
	228	4.3 ; 5.4 ; 6.3 ; 7.03 ; 6.3 ; 7.03 ; 7.09

The speed range at which porpoising was observed is the largest for the Short fillet. Porpoising was observed in the entire high speed range for the Short fillet. It is therefore recommended that the Short keel fillet hull should not be operated in the high-speed range. It was also observed that porpoising was more prominent for an LCG position of 210 mm than for an LCG position of 228 mm. It can thus be anticipated that a better balanced boat is more stable and will exhibit less porpoising.

The moments of inertia for the model hull were not accurately scaled to the full scale Icarus Marine hull, since it was outside the scope of this project. It is therefore not possible to say with certainty to what level porpoising will take place at the speeds mentioned in Table V. However, porpoising is likely to take place at the speeds mentioned, since the hull shape appears to be unstable at the specified speeds. Porpoising results in unreliable data for the speed range at which it is observed. It is therefore not possible to accurately evaluate the keel shape in that speed range.

The experimental data for the different LCG positions and keel shapes are evaluated at model scale to eliminate the possible error effect of the sensitive scaling method.

6.1 Wetted area

The wetted surface experimental measurements were read into an Excel spreadsheet and plotted on the model for each hull shape. The experimental points were used to calculate the wetted surface. The transom area was removed from the wetted surface area calculations as recommended by the ITTC.

6.2 Data: 2014 vs data from 2015

During the experimental testing of the keel shapes in 2014, the effect of wind was eliminated by making use of a wind screen that was attached to the towing trolley. In the experimental testing in 2015 the effect of wind resistance was taken into account and no wind screen was used. The towing forces and air resistance forces resulted in a bow down moment. This is illustrated in Fig.14. The reduced trim due to the bow down moment results in a larger wetted area, which could result in larger resistance values. However, the effect of the air resistance is so small that it is negligible. This is clear from the similarities in the 2014 and 2015 experimental results in Fig.15 to Fig.18.

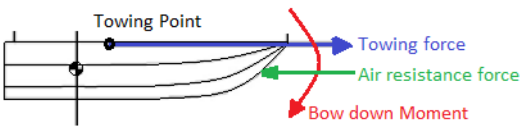

Fig.14: Bow down moment

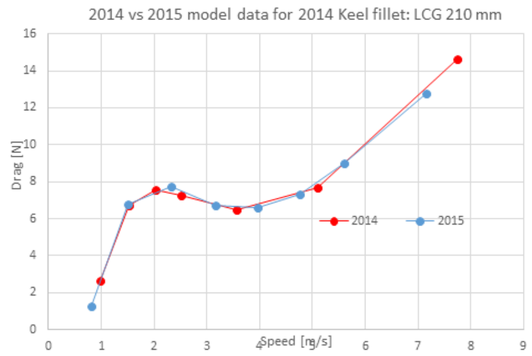

Fig.15: 2014 vs 2015 for 2014 Keel fillet drag (LCG = 210 mm)

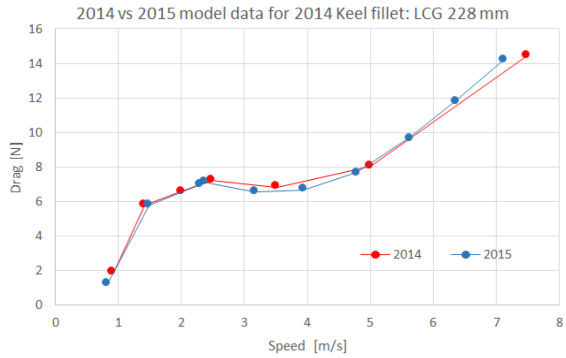

Fig.16: 2014 vs 2015 for 2014 Keel fillet drag (LCG=228 mm)

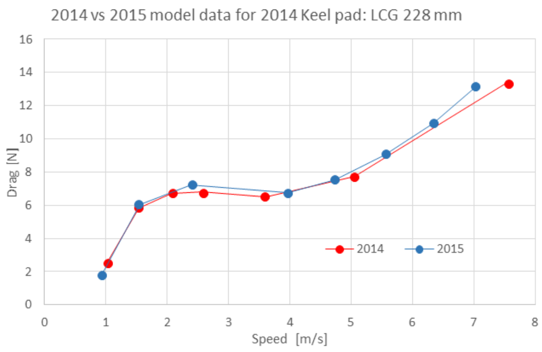

Fig.17: 2014 vs 2015 for 2014 Keel pad drag (LCG=228 mm)

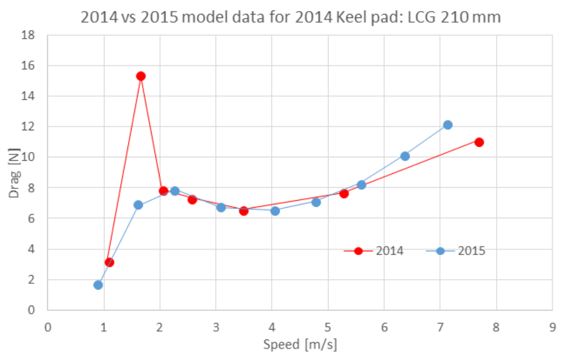

Fig.18: 2014 vs 2015 for 2014 Keel pad drag (LCG=210 mm)

The 2014 Keel fillet (LCG of 210 mm) experimental data from 2015 closely resemble the experimental data from 2014 as shown in Fig.15. The 2014 Keel pad's and 2014 Keel fillet's (LCG of 228 mm) experimental data from 2015 closely resemble the experimental data from 2014 as shown in Fig.16 and Fig.17. This validates the experimental results for these shape and LCG combinations. The 2014 Keel pad (LCG of 210 mm) experimental data from 2015 does not resemble the experimental data from 2014, as shown in Fig.18. The 2014 curve does not resemble the general shape for the drag force curves. Mr. A.L. Janssens attributed the spike in resistance at 1.66 m/s to a phenomenon where the upper deck generated a suction effect between the deck and transom. This suctions effect was said by Mr. A.L. Janssens to trap water, which caused a high increase in resistance. This phenomenon was not observed during the experimental testing of the 2014 Keel pad in 2015.

6.3 Effect of LCG on hull performance

In displacement and transition mode the resistance is higher for the 210mm LCG position compared to the 228mm LCG position. The further back the LCG position is on the boat the larger the resultant trim will be in the lower speed range, as shown in Fig.19. The high trim values result in the transom sitting deeper in the water, resulting in a larger horizontal force at the centre of pressure. The increased trim causes increased difficulty for the hull to move into planing mode. Higher drag forces have to be overcome by a hull, with a LCG closer to the transom, in order to reach planing. This explains the increased drag forces in the hump region. The model hull reaches planing mode at approximately 4m/s. In planing mode the resistance is lower for the 210mm LCG position compared to the 228mm LCG position. The hull is better balanced with an LCG of 228mm, the stern lifts out of the water more easily, reducing the wetted area. This results in lower drag forces for a hull with a LCG closer to the transom when the hull is operating in the high speed range. This effect is clearly illustrated in Fig.20 to Fig.22.

Fig.19: Standard keel trim

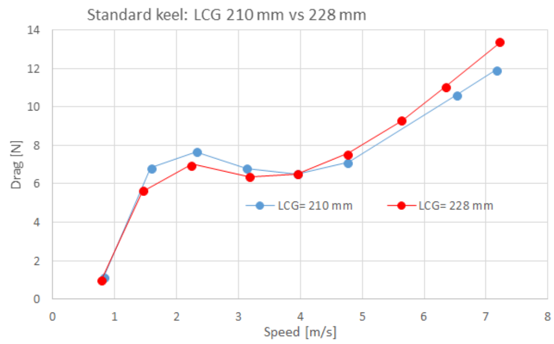

Fig.20: LCG effect for Standard keel

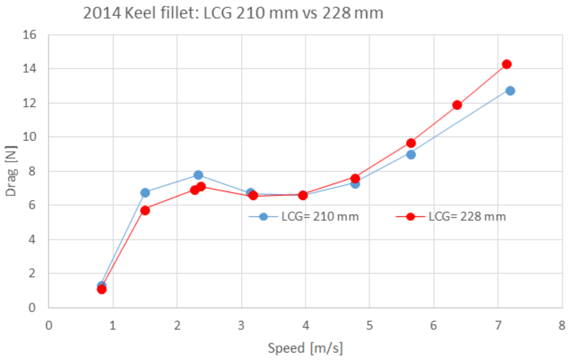

Fig.21: LCG effect for 2014 Keel fillet

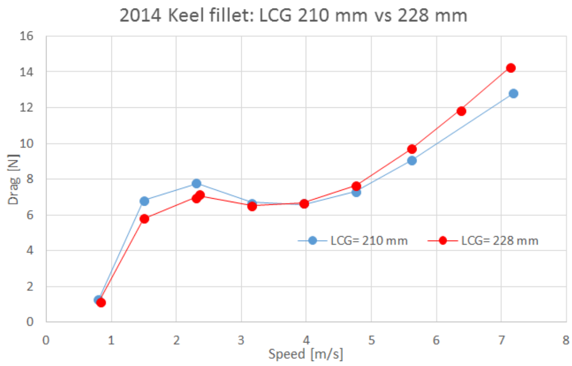

Fig.22: LCG effect for 2014 Keel pad

The effect of the LCG position on the drag force for the Long keel fillet and Short keel fillet is shown in Fig.23 and Fig.24. The LCG position has a lesser effect on the Long and Short keel fillets compared to the 2014 Keel fillet and 2014 Keel pad, especially at high speeds. The experimental data suggest that the 228 mm model LCG position delivers better results than the 210 mm model LCG position. The 228 mm LCG position delivers a more balanced hull, with fewer occurrences of porpoising.

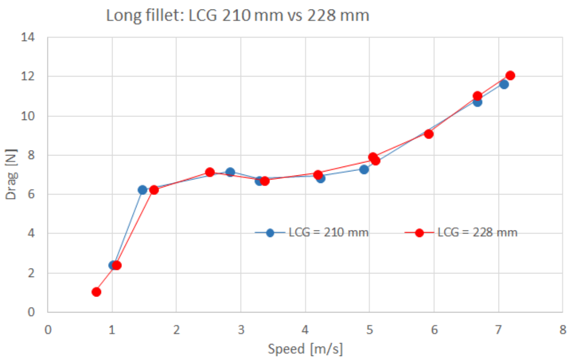

Fig.23: LCG effect for Long fillet

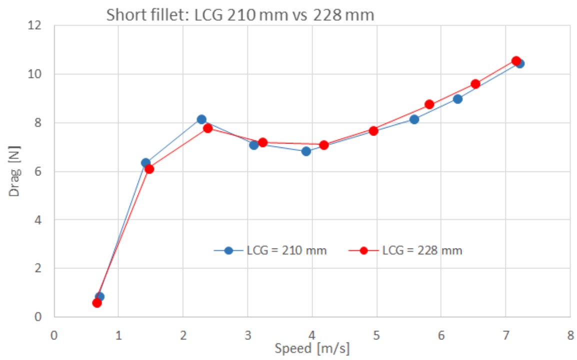

Fig.24: LCG effect for Short fillet

6.4 Keel shape evaluation

Fig.25 and Fig.26 show the drag force comparison for the different keel shapes at two LCG positions. The hull shape considered in this paper is designed to operate in planing mode. Low drag force on a hull is desirable and the keel shape that delivers the lowest drag forces in planing mode is considered to deliver the best performance.

The effect of the keel shape on the drag of a planing hull is not very prominent at an LCG of 210mm as shown in Fig.25. However, it is clear from the graph that the 2014 keel fillet shape has higher resistance values than the other shapes in the planing mode as shown in Fig.25.

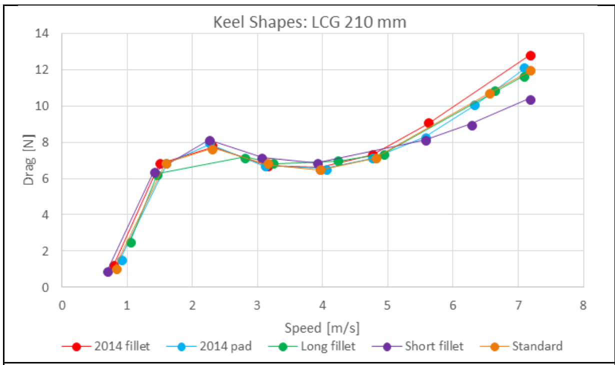

Fig.25: Keel shapes (LCG=210 mm)

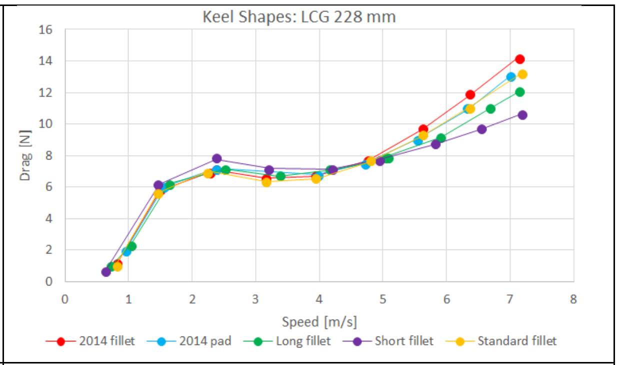

Fig.26: Keel shapes (LCG: 228 mm)

The effect of the keel shape on the drag is much more prominent at an LCG of 228 mm as shown in Fig.26. From both Fig.25 and Fig.26 it is visible that the 2014 Keel pad does not perform much better or worse compared to the standard Icarus Marine keel. Fig.25 and Fig.26 also show that the resistance of the hull is least for the Short keel fillet and the Long keel fillet in the planing mode. However, the experimental results for the Short keel fillet in the higher speed range are not reliable, since porpoising is observed in that speed range. The experimental data only reflect the average response at a specific speed and do not account for porpoising. The performance effect of the Short fillet keel shape is thus inconclusive at high speeds. It can, however, be predicted from Fig.25 and Fig.26 that the Long fillet keel shape delivers a better performance and the 2014 Keel fillet shape delivers a weaker performance compared to the Standard keel shape in planing mode.

The Short keel fillet is ignored due to the porpoising effect. The only competitive keel shape that is left after disregarding the Short keel fillet is the Long keel fillet. The Long keel fillet outperforms the Standard keel fillet by 1.07% in Fig.25 and by 8.27% in Fig.26 in the planing mode at 7m/s. The results verified some of the findings of Mr. A.L. Janssens. The 2014 Keel pad and 2014 Keel fillet shapes have a negative effect on the performance of a planing hull in the planing mode under the specified conditions.

7. Conclusion

The objective of this project was to measure the effects of keel pads and keel fillets on the performance of a planing hull under specific operating conditions. This enabled the project to provide guidelines in the design of a planing hull. The objective of the project was achieved through experimentally testing five different keel shapes at two LCG positions each.

The experimental data gathered suggest that 2014 Keel pad and the 2014 Keel fillet shapes should not be implemented in the design of planing hulls, because they have higher hull resistances than the standard keel. The Short fillet keel shapes should also not be implemented in the design of planing hulls, because the keel shape exhibits unstable characteristics. The Long fillet keel shape, however, is a viable option in the design of an improvement on the Standard Icarus Marine planing hull, because the keel shape has lower hull resistance than the standard keel. The experimental data also highlighted the importance of a well-balanced hull. It was found that a well-balanced hull reduces hull resistance and the occurrence of porpoising.

The experimental testing of only two LCG positions and five variations on the keel shape is not enough to adequately construct helpful guidelines in the design of a planing hull. However, it does give insight into which types of keel shapes improve the performance of a planing hull. The experimental results for the Long fillet keel look very promising for a relatively well-balanced hull.

Further experimental testing of a larger variety of LCG positions and keel shapes will prove to be invaluable as an accurate and objective method to quantify the effects of keel pads and keel fillets on the performance of a planing hull. Continued research to determine the optimum design for the keel shape of a planing hull will be invaluable.

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SchIBZ:
Large Fuel Cell Systems for Eco-friendly Diesel Propelled Seagoing Vessels

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Abstract

Thyssenkrupp Marine Systems and 6 partners from industry and science developed a fuel cell system for seagoing vessels. The unique feature of this system is the use of low sulphur diesel oil as fuel. The system is based on solid oxide fuel cells coupled with a unique reforming unit for the diesel fuel and connected with an energy buffer. The advantages of the system are an electrical efficiency around 50%, very low gaseous emissions without exhaust gas treatment, low noise, very low maintenance, possibility for heat recovery for further energy efficiency and the potential to reduce the power installed on board. Additionally, the availability of energy supply can be increased by decentralized installation of the units on board of oceangoing ships.

Abbreviations

APU	Auxiliary Power Unit
HTPEM	high temperature polymer electrolyte membrane (fuel cell)
Li-Ion	Lithium-Ion (battery)
LCC	Life Cycle Costs
LNG	Liquefied Natural Gas
ORC	Organic Rankine Cycle
PEMFC	polymer electrolyte membrane fuel cell
SOFC	solid oxide fuel cell
SuperCap	super capacitor
ULSD	ultra low sulphur diesel oil

1. Introduction

The global shipping is faced with ever more stringent emission regulations. While short sea shipping is evaluating battery electric solutions, ocean going vessels have, from today's perspective, further to use hydrocarbon based fuels, to be able to store the necessary energy content in an acceptable volume.

Still a favourite fuel is diesel oil, since the handling is very well known and the intrinsic safety is high. To reduce emissions from the usage in internal combustion engines, the engines have to be equipped with a number of auxiliary systems. These add not only space and weight, but also complexity and maintenance requirements. An elegant alternative solution would be a fuel cell system, if able to use diesel oil. Therefore, thyssenkrupp Marine Systems decided to investigate the possibilities and develop a system, if it seems feasible.

After rating the features of several configurations, the combination of low-sulphur diesel oil and high temperature fuel cells promised to be the best solution, although one with considerable development needs. To execute this development thyssenkrupp Marine Systems sought for partners with the respective know how. Finally, the consortium consists of thyssenkrupp Marine Systems, DNVGL, sunfire, Oel-Waerme-Institut, Motion Control & Power Electronics, Leibniz-University Hannover and the ship owner Braren. Additionally, funding by the German government was applied for under the NIP. The project is part of a so-called lighthouse initiative, named e4ships. Finally, a 50 kWe demonstrator is in test operation and shall be set to work on board a merchant ship later this year.

2. Development Approach

For the development of the system, a number of boundary conditions were chosen:

- use of proven components as far as possible
- modular design for a scaling from 100 to 500 kW approx.
- ~50 % electrical efficiency
- wide operating range
- exhaust gas energy recovery
- preparation for the external forces on board a seagoing ship
- matching to consumer network
- fully automated operation
- comparable costs to an emission reduced diesel engine driven genset

The exhaust gas must be of a composition that it can be released not only via the typical funnel. The operating range also should permit to follow the load changes as close as possible. The system must have a high reliability and availability. To achieve this the number of moving components should be kept very low.

The development was structured in certain phases:

- Selection of the process design
- Experimental prove of the reforming process
- System test in a small scale around 10 kWe
- Construction of a large demonstrator for seaborne tests

2.1. What are fuel cells?

2.1.1. Build-up of fuel cells

Fuel cells are electrochemical energy converters. They are not an energy source like a battery or a means of propulsion like a diesel engine. A fuel cell converts chemical energy from a fuel to electrical energy.

Fuel cells need a fuel gas with high hydrogen content, pure or as chemical compound, and oxygen, most likely from air. These substances interact with each other along the membrane of the fuel cell. This is not a combustion but an oxidation. This process releases electrons, which generate the electrical current.

A single fuel cell is an assembly of

- a µm thin layer of a membrane (electrolyte), which is permeable for certain atoms or ions,
- anode and cathode layers, which are catalysts and support the chemical reactions,
- gas diffusion layers, which distribute the fuel gas and the air over the membrane area and
- interconnectors, which mainly have the function to transfer the current to the exterior.

Such assemblies have typically sizes of 10x10 up to 30x30 cm^2, in a few cases larger. They produce a power of several Watt at ~1 Volt. To gain a useful power output some hundreds or thousands of the fuel cells are mounted in stacks and connected together. The direct current provided by the fuel cells must be inverted into a suitable alternating current, matching the board network.

The exhaust of fuel cells consists mainly of water vapour. Depending on the type of fuel cell it contains also carbon dioxide. Due to the oxidation process without an open flame at temperatures far below 1000° C (the combustion in a diesel engine takes places at around 2000° C) no carbon monoxide, nitrogen oxides or soot are present. That is why the exhaust is also called “exhaust air”, although the CO_2 content is it comparably high. It can be lead outside the vessel nearly everywhere, where air conditioning outlets can be arranged.

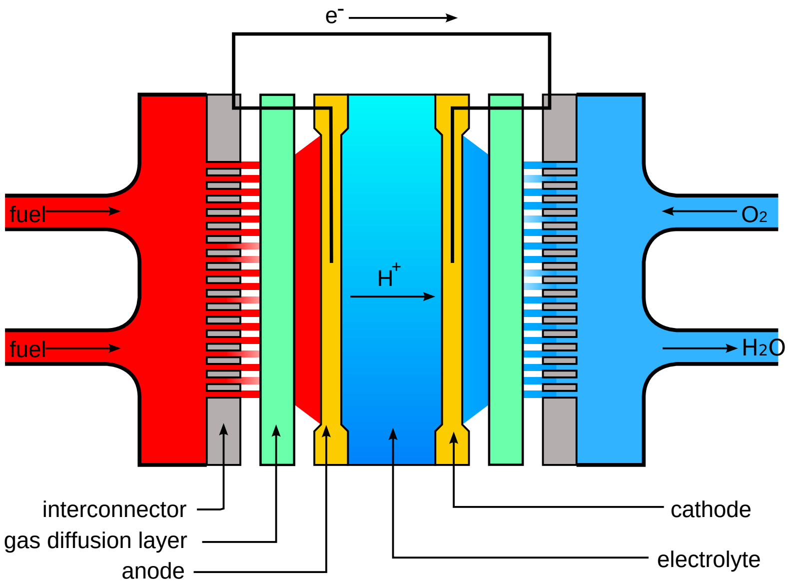

Fig.1: Principle assembly of fuel cells

2.1.2. Benefits of fuel cells

Fuel cells have a high efficiency in converting the energy. Depending on the actual type the electrical efficiency is in the range of 40% to 60%. These values are superior to standard generating sets as used today. Energy recuperation from the exhaust air is possible with high temperature fuel cells. The temperature level is sufficient for hot water or steam production and the heat exchangers will keep clean since no soot is contained.

Another advantage is the absence of oscillating components. A fuel cell system contains just a small number of pumps and blowers, which have a low inherent noise level and can be silenced easily. Thus, structure borne noise is not an issue and remaining air borne noise is subject to well-known dampening measures.

From the above-mentioned follows that fuel cells can also be installed decentralised, next to living areas. Such a configuration enhances the redundancy of the power supply to a vessel significantly.

Depending on size and type of the fuel cell installation and the character of the consumer network an energy buffer may become necessary. Fuel cells have a limited load dynamic and even “quick” types like low-temperature PEMFC benefit from constant loads with a longer lifetime. For this reason, load changes must be buffered towards the fuel cells, either at the consumer side or at the generation side. A feasible method seems to be the application of Li-Ion-batteries or SuperCaps.

2.2 Design of the fuel process

To apply fuel cells for seagoing vessels first a suitable fuel must be chosen. Basically, hydrogen is the best fuel. However, this is not widely obtainable and hardly storable on board in sufficient quantities.

To overcome this, several options are explored:

- methane (natural gas, bio gas)
- alcohols (methanol, ethanol)
- gas oil
- synthetic diesel (XtL)

The fuels are different in price, properties and processing. The processing of natural gas is the least complex. A disadvantage is the low volumetric energy content, even in liquid phase. LNG has a 1.6x lower volumetric energy content. Additionally, the tank needs an insulation of at least 100 mm thickness and it has to be placed as loose tank inside the vessel, so that it needs further space for the installation, Fig.2. Although the handling is becoming more usual in marine business, it requires extensive safety measures. LNG has a temperature of -162°C and evaporates by the factor 600 instantly if released to normal temperatures.

Alcohols have a higher volumetric energy content than gases and need no special tank arrangement. The processing is not difficult and the handling needs comparably few special safety measures due to the toxicity of their vapours. Especially spills must be avoided, since they are soluble and toxic in water and cannot be separated and collected from it.

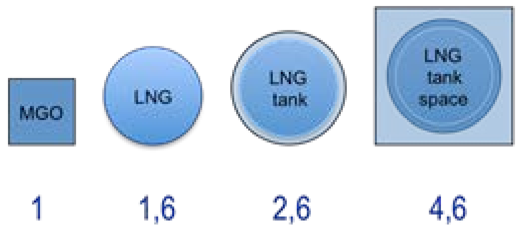

Fig.2: Bunker space needed for the same energy content with gas oil and LNG

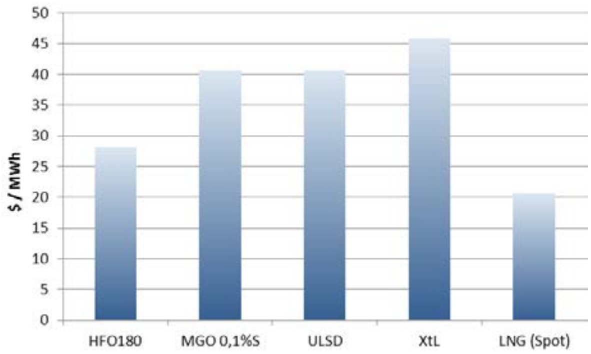

Fig.3: Prices of suitable fuel oils (25.8.2017) www.bunkerworld.com

Gas/diesel oils have the highest volumetric energy content and are well known in handling. A concern is the sulphur content. Sulphur levels of typical marine fuels are not acceptable. Fuel cell systems can be designed to stand a sulphur content of up to 15ppm. This corresponds to the qualities of truck diesel (ultra-low sulphur diesel oil), bio diesel of second generation and synthetic diesels. The last one is very well suited for fuel cells, due to the absence of sulphur and other cell toxic substances. But the availability will be poor for the next years. Due to the upcoming regulations for the sulphur levels in marine fuels the hurdle to bunker road diesel gets lower. There is no relevant price difference between MGO0.1% and ULSD anymore, Fig.3, because low sulphur marine fuels will be more and more produced together with truck diesel.

Since fuel cells cannot convert liquid fuels directly, these must be converted into a suitable fuel gas, by means of a reforming unit. The so-called reformate gas from hydrocarbon fuels contains not only H_2 but also CH_4, CO/CO_2 and H_20. Depending on the fuel cell type different mixtures of these can be facilitated. The composition of the reformate gas can be adjusted by certain process parameters and steps, which will not be described in detail in this paper. The energy for the evaporation of the liquid and the conversion in the reforming should be taken from the exhaust gas energy of the fuel cell for best efficiency. The reformate gas is lead to the fuel cells and further converted to H_20, CO_2 and electrical energy.

From the variety of fuel cell types currently on the market the most suitable for ship borne use were selected for a comparison of process designs. The fuel cell types in question are:

- PEMFC – polymer electrolyte membrane fuel cell
- HTPEM – high temperature PEM
- SOFC – solid oxide fuel cell

With these fuel cell types a study was performed, to design the necessary processes for an operation on diesel fuel. A straight forward system can be achieved by using solid oxide fuel cells. Due to the high internal temperature of SOFC of around 800°C there is enough excess heat to promote a reforming process with a high level of hydrogen production. Although the anode material is less sensitive to sulphur as in a PEMFC, desulphurisation enhances performance and lifetime. This is realised with a nickel based reformer material, which serves as sulphur trap, *Nehter et al, (2014)*

To make best use of the thermal energy content of the off-gas it is used to pre-heat the process gas and then finally oxidised in a catalytic burner for other pre-heating purposes. The advantage, that no surplus fuel is needed for the reforming process, allows high rates of system efficiency. Values of more than 50% have been measured. Variations are possible, e.g. the use of the off-gas burner to heat the reformer by fuel injection in the start-up phase will be investigated. The process air is heated by the cathode off-gas to keep thermal energy inside the process.

In comparison to PEMFC, MEAs of SOFCs are small with a stack size limited to around 5 kWe as of today. This requires an advanced design and thermal integration of the numerous stacks to attain a useful output, however SOFC offer better possibilities for varying the power output and an inherently higher system efficiency than the other types.

The system shown in Fig.4 is a basis for further improvements, especially in the areas of reformer and stack configuration potential to gain up to 10% more efficiency is expected. The adaption to other hydrocarbon fuels is possible with acceptable efforts.

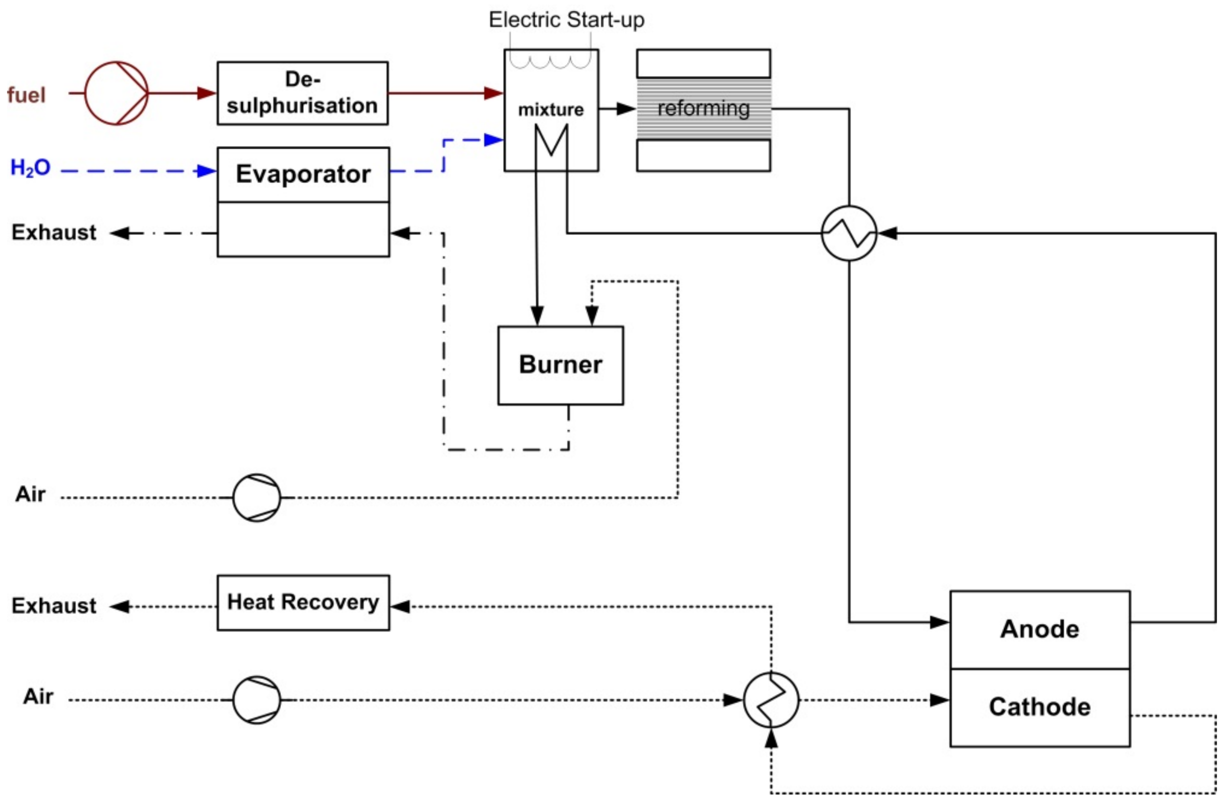

Fig.4: SOFC fuelled by road diesel, *Leites et al. (2013)*

2.3 Design of the electrical process

Since SOFC are not capable of rapid load changes, energy buffers are needed to cope with the transient load requirements in small, isolated networks. Based on the knowledge about the possible load change rates from small scale tests, a calculation method was developed to size energy buffers such that they suit the actual network load profile. The idea behind this concept is that the fuel cell provides an average current over some time and the energy buffer takes care of higher or lower power requests by additionally feeding the network or receiving the surplus power from the fuel cell, as shown in Fig.5. The size of the fuel cell is selected according to the maximum condition in the load balance. For the selection of an energy buffer two values must be determined:

- the amount of energy which is contained in the integral between the load curves of the network and the fuel cells
- the maximum short term peak currents of consumers like pumps or compressors or short circuit failures

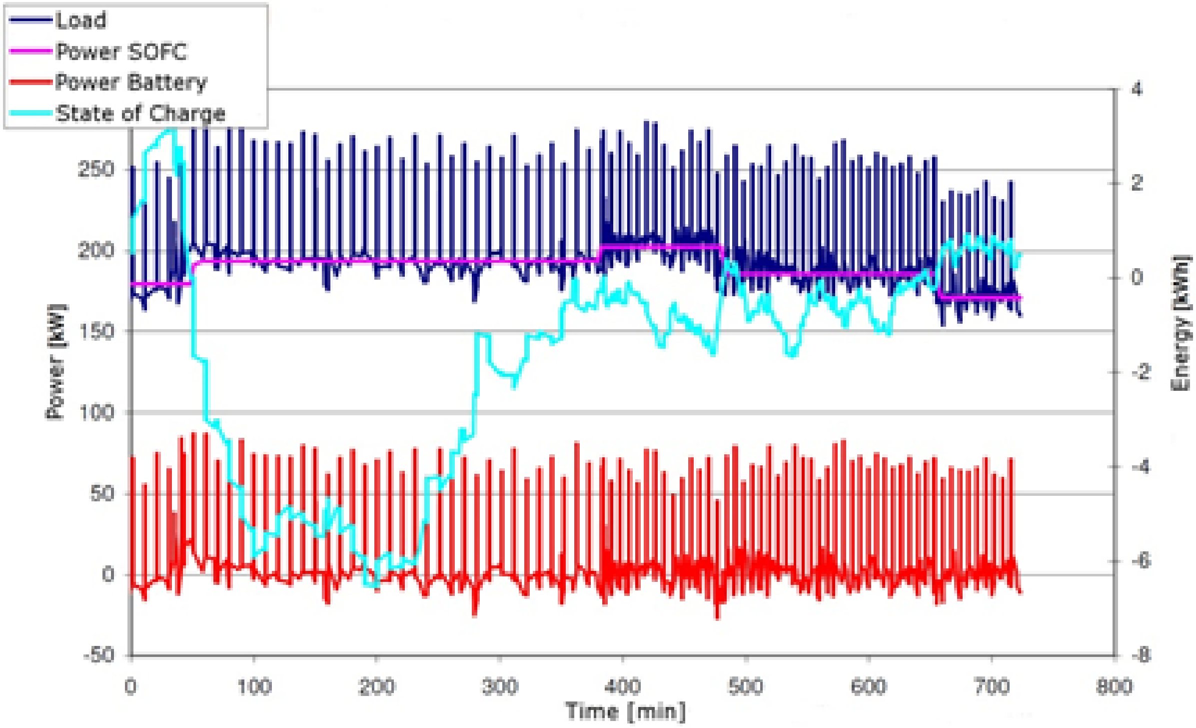

Fig.5: Detail from the load graph of the test vessel MS Forester

The size of the fuel cell can be reduced, if the energy buffer is large enough to power large consumers, which are in operation for short times, like thrusters. Available technologies are Li-Ion batteries and Super-Capacitors. The configuration of large batteries is well demonstrated today in several marine applications. One of the first was the research boot Planet Solar, equipped by thyssenkrupp Marine Systems.

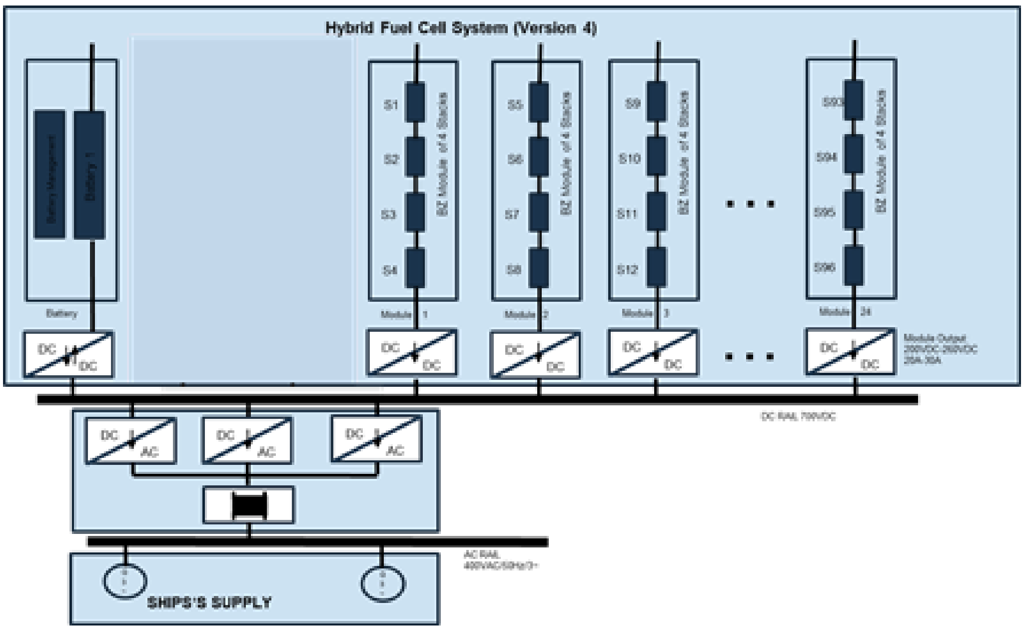

Fig.6: Basic concept of electric coupling of fuel cells and energy buffers

The choice for either energy storage depends on the actual characteristics of the fuel cells and the shipboard network. The slower the fuel cells can follow load changes and the higher the load changes are, the larger the storage capacity must be. Most likely Li-Ion batteries will fulfil these requirements. If short but steep load steps must be covered, the application of super-caps should be evaluated. There is no general relation between fuel cell power and energy buffer size. In principle, the energy buffer can be smaller the larger the network of a vessel is, because a large number of consumers and generators averages each other somewhat statistically.

Fuel cells as well as the most energy buffers are DC sources. It is useful to connect them via a DC rail and then convert the total current to AC for the board network, Fig.6. For this concept, every power source is coupled with a DC/DC converter to provide a fixed voltage level at the DC rail.

2.4 Design of Fuel Cell Systems for Ships

To use fuel cells in maritime applications some additional aspects must be respected:

- the air is contaminated with salt
- a ship is constantly in motion
- equipment for ships must stand continuous vibrations

The process air must be desalinated to avoid molecular effects at the membranes due to the ions. Previous tests have shown that an air filtration as for gas turbines is sufficient to protect the fuel cell. Therefore, a combination of demister, coarse and fine filter is applied.

Special aspects of the marine application of fuel cells are the motions and vibrations of ships. Particularly high temperature fuel cells are potentially sensitive against permanent list and vibrations. To assure the suitability of the fuel cell assemblies dedicated tests were performed. First, a long-term test with a list of 22.5° was executed, Fig.7, to assure that the single fuel cells do not slide out of the stack. After that the stacks were mounted on a shaker and exposed to vibration profiles according to class rules, Fig.8. During both tests the fuel cell stacks were hot and fuelled with a small amount of hydrogen, to simulate operating conditions.

Fig.7: Test of operation at a permanent list of 22.5°, ©sunfire

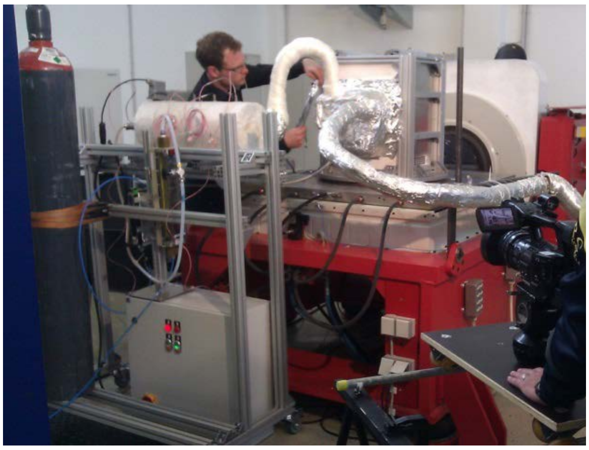

Fig.8: Vibration test at a shaker, ©sunfire

In both tests, no deviations in operation parameters and no damages were found. But another important action point was discovered: the fixation of the insulation needed to be modified, to avoid that the single plates rub against each other and get damaged.

In addition to the technical requirements, the strive for better fuel efficiency requires to reuse exhaust heat. The advantage of fuel cell exhaust is, that it is free of soot or sulphur oxides which may damage recuperation units. The exhaust of a SOFC system has a temperature level of about 350-400°C which can be used for onboard heating services or steam production. An alternative may also be ORC systems, which are meanwhile also available for lower thermal energy amounts around 200 kW. Since the exhaust heat energy is roughly the same as the electrical output, expected systems of 200+ kW_e would fit.

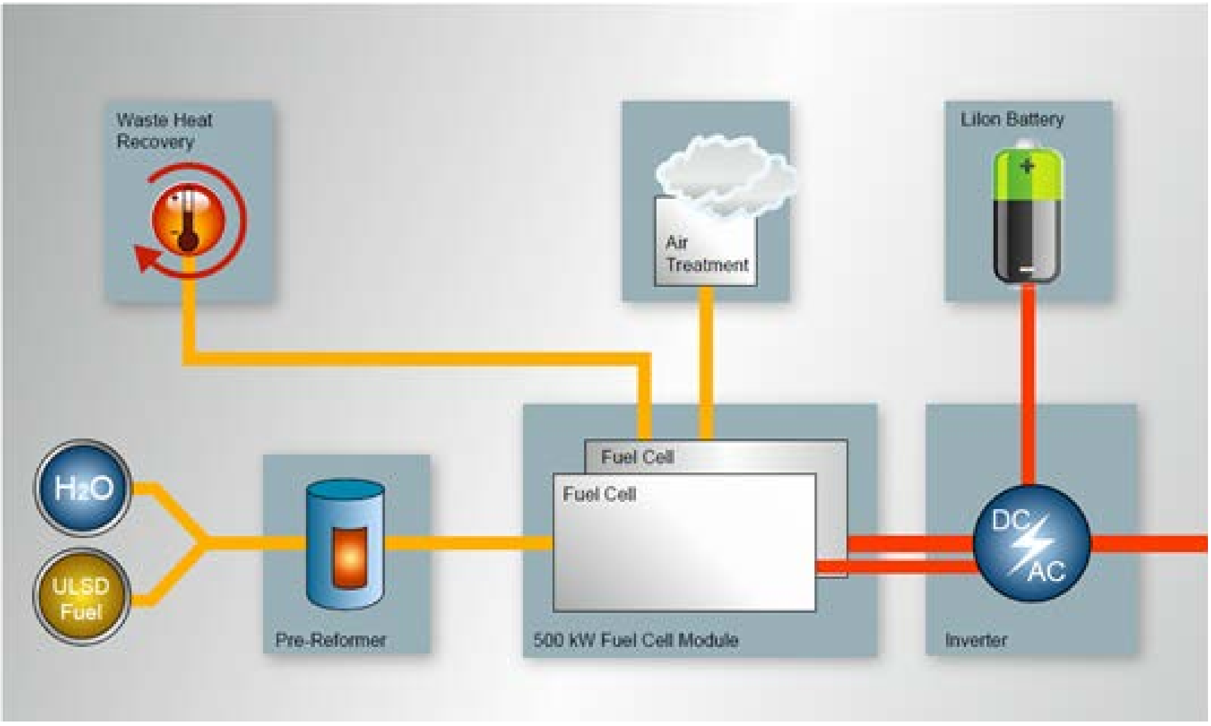

Fig.9: Simplified schematic of the proposed fuel cell system as APU

2.5 Integration into ships

To use fuel cells for larger ship applications a concept for the integration has to be developed. The use of all advantages allows and requires a significant redesign of the ships.

Two main features of fuel cells enable the build-up of a highly redundant energy supply: low noise and clean exhaust. Such systems can be placed throughout the vessel since the noise emissions are very low and easy to handle. Beneficial for this is the fact that the exhaust air is of such consistence that it can be exhausted along with air conditioning exhausts.

A redundant energy supply with decentralised generators like shown in Fig.10 is build up by connecting the generators via a bus type power network. If this network is in itself redundant, damages in one ship section on one side cannot cut the energy supply for large areas of the vessel.

The system developed in the project SchIBZ is modular scalable, so each APU can be selected according to the actual energy demand in that section or other considerations. An area of special consideration is the fuel supply. Due to the liquid phase of diesel a distribution is not lavish but it must be ensured, that the pipes are installed in enclosures and adequately monitored for leakages. Sufficient ventilation prevents the fuel cell installation spaces of accumulating explosive gases if small leakages are present. Larger leakages must be detected by a dedicated gas alarm system. Due to the small amounts of gases inside the system an automatic fire Fighting can be applied, e.g. NOVEC 1230 as in several LNG installations.

Roughly it can be said that it is feasible to substitute the generating sets with fuel cells. Even slow speed propulsion can be realised by means of PTI motors. Full propulsion by fuel cells will is from today's perspective only possible with great compromises in range, speed and available space on board.

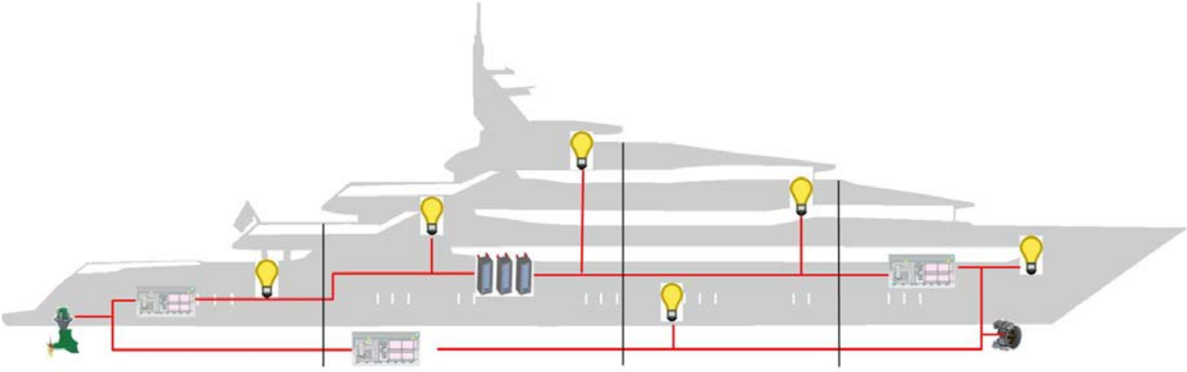

Fig.10: Concept for a distributed installation of FC systems in seagoing vessels

3. The demonstration plant

To verify the seaworthiness of the power supply system a 50 kWe demonstrator was designed and will be commissioned this summer. A failure mode and effect analysis (FMEA) was performed to ensure that it fulfils the class requirements of DNV GL for main power supplies on merchant ships. Based on this the approval process is started to gain an approval for experimental use. This will be the basis for a type approval for commercial applications later. Accompanying work is done to support the development of fuel cell safety regulations (part of the IGF code) at the International Maritime Organisation. Especially the safety analyses are provided for the discussion in the respective working group, *IMO (2015)*.

The fuel cell power system consists of one reforming unit connected to several fuel cell modules, Fig.11. To improve the availability of fuel cell power valves are installed in the fuel gas supply lines at the fuel cell modules. These valves allow cutting off one module from the system in case of a failure. Therefore, only the power of one basic module is lost instead of several 100 kW. This feature is hardly possible with combustion engines.

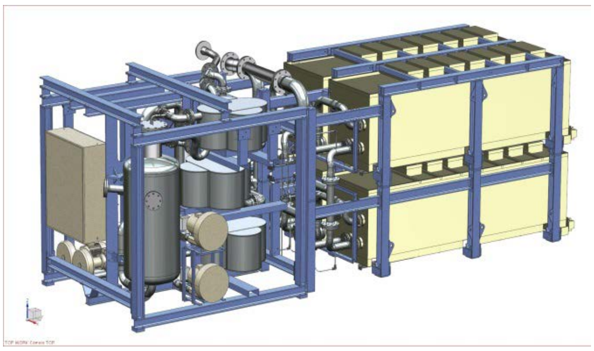

Fig.11: 200 kW_e SOFC aggregate for operation on ULSD, ©thyssenkrupp Marine Systems GmbH

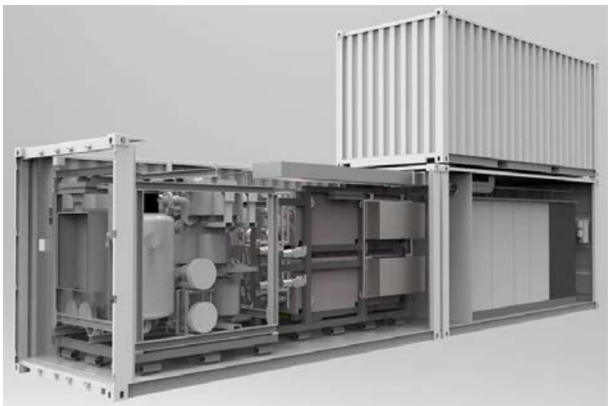

Fig.12: 50 kW_e SOFC demonstration system incl. energy storage and auxiliary systems

The core of the demonstration plant is a 40” container, carrying in two spaces the process components (fuel cell modules, reformer module) and the electronic components (cabinets with power electronics, automation and monitoring systems, the energy buffer and the generator switchboard for the connection to the board network), Fig.12. The container is necessary to mount the test system on deck of MS Forester as additional power supply to the network. The container is regarded as fuel cell installation space according to the IGF code. The volume of the container could accommodate up to 200 kW SOFC power plus the necessary electronic systems.

The complete test set up is shown in Fig.13, the location on board MS FORESTER of Reederei Braren in Fig.14. The demonstration plant is a complete power station which can operate as standalone unit. For this reason, it has additionally to the power supply system an auxiliary container with ventilation, air filtration and safety systems like firefighting and a separate tank container. The ventilation is dimensioned according to the requirements from the IMO IGF code for spaces containing gas fuelled machinery. These spaces must either be inherently safe or equipped with sufficient ventilation to prevent an explosive atmosphere under any circumstances (ESD concept) with underpressure against surrounding spaces. These facilities are normally part of the vessels infrastructure.

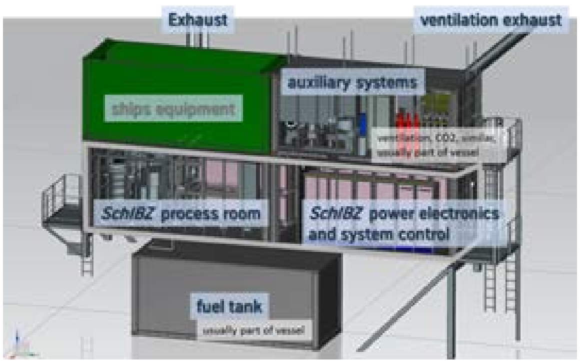

Fig.13: Standalone power supply system for technology demonstration on board


Fig.14: Installation of the demonstration plant at MS FORESTER

The test vessel MS Forester has a power consumption between 100 and 200 kW. The supply is shared between the on-board generator and the fuel cell system such, that the short-term load variations are covered by the energy buffers and the base load according to Fig.5 is shared between the two aggregates proportionally. In this configuration, the fuel cell supplies between 25 and 50% of the power consumption, which has not been demonstrated before.

The control and monitoring system is designed for a fully automatic operation of the plant with just an observation monitor and restricted user interface for the crew inside the machinery control room. For this first installation, the crew is not trained to operate or service the fuel cell but the standard auxiliary systems like ventilation, alarm and reverse osmosis. In case of failures can the system be controlled via remote access, in case of major defects experts must travel to the ship.

4. Results

During the commissioning of the test installation a number of experiences were made and operation parameters gathered. Some of the important experiences relate to the fluid dynamic design of vessels and pipes. In certain areas, the flow of the gases must be redesigned with respect to differential pressures and temperature behaviour. On the other hand, the fuel/fuel cell process proved its functionality and robustness. It is expected that the lifetime of the cells will be in the range of 20.000 h as demonstrated in smaller assemblies.

The system showed the expected efficiency around 50% and the cleanliness of the exhaust, Fig.15. The effect of the energy storage system could not be validated up to now, since the connection to the shore based power network inhibits the usage of them. However, values are not completely corrected by the parasitic losses. They will reduce the part load efficiency a little bit.

A substantial drawback is for time being the cost situation. A fuel cell system as described has investment costs of more than 10000 €/kW. A full equipped diesel genset with exhaust gas cleaning and noise and vibration dampening has investment costs of approximately 1500 €/kW. Even under consideration of maintenance and fuel costs a diesel genset has lower LCC. But under the assumption that the production volumes will get larger, the fuel cell system is expected to get investment costs down 2000 €/kW. In this range, it is competitive to engine based solutions.

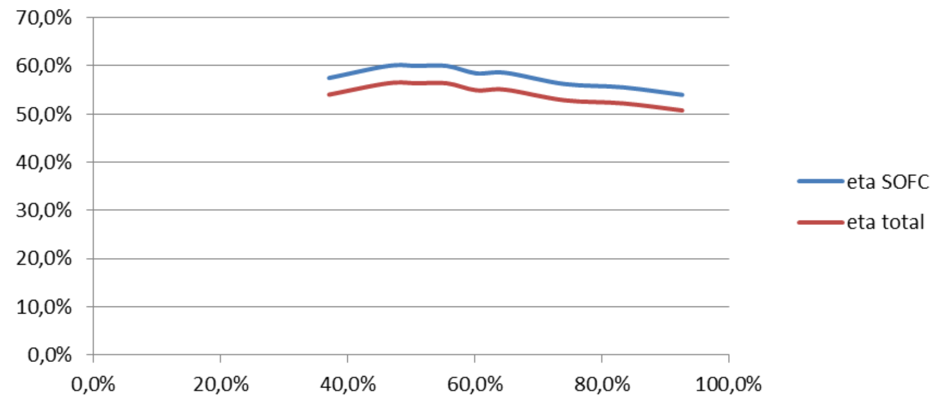

Fig.15: Efficiency curve of SchIBZ test plant (at SOFC level and including power converters)

5. Conclusion

The application of fuel cell systems like presented is in several aspects beneficial for seagoing vessels. First of all, it is the only technology that can significantly improve the efficiency of onboard power production. An electrical efficiency of more than 50% plus the possibility of easy exhaust heat recovery is far better than a modern diesel generator set. So, the higher costs for the fuel are compensated, since 10 kWh electrical power consumes just 20 l of fuel instead of 25 l as a modern diesel engine (-20%). So, fuel cell systems will also make shore power connections obsolete, since they are free of toxic emissions and even allow vessels to sail clean in coastal areas. Furthermore, a distributed installation is increasing the safety of such ships, since damage in one compartment cannot disable the full power generation. There is need for further improvement and especially cost reductions, but the potential is worth the efforts.

Acknowledgements

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Technologies and Attributes of Future Yards

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Abstract

Tense customer budgets in line with increasing requirements and system complexity, delayed or cancelled projects have put pressure on naval yards around the globe to evolve and to adapt to the shifting environment. The outcome of this change process at thyssenkrupp Marine Systems is an integrated and collaborative lifecycle management process which is applicable to many yards delivering and supporting complex marine systems. The article addresses particularly the needs and benefits of architectural frameworks, the introduction of model-based systems engineering and virtual prototyping techniques in order to provide reliable and most beneficial solutions to the customers.

1. Introduction

The production systems of the shipbuilding industry as well as its products are strongly influenced by Industry 4.0, also known as the industrial internet-of-things (IoT). Although shipbuilding engineering and constructions processes are not yet to be performed by self-controlled and self-configuring spatially dispersed networks of autonomous manufacturing resources, *Kagermann et al. (2013),* many implications of the IoT are already effective today. The products, i.e. ships and other manifold marine systems, by themselves appear to have mutated to highly connected mobile industrial plants which have to be designed, constructed, and maintained throughout the lifecycle.

Therefore, the classical role of shipyards to provide infrastructure, engineering, construction, and project management expertise to facilitate the manufacturing process as a systems integrator may change to a life-time partnership with their products and their operators. This opportunity, however, will force traditional yards to transform and to develop new capabilities in order to provide the desired services.

Particularly naval yards are facing increasingly high risk awareness by governmental contractors – for good cause – leading to more complex project setups and to the fall-back to proven design solutions slowing down innovation on the long run. Further, due to the nature of military systems, naval ships are especially vulnerable to cyber physical threats in a world of IoT, *U.S. Department of Defense (2016)*. Not least, naval yards have to comply with the need of foreign customers – again for good cause – to increase the local content in the procurement programmes and to facilitate the transfer of technology leading to global sourcing networks for hard- and software as well as for engineering and construction services.

In consequence, shipyards of the future must be capable to integrate a growing number of heterogeneous stakeholders into increasingly complex processes. Secondly, the yards have to find ways to provide specific, secure, and efficient access to their product data world for all parties involved. Thirdly, appropriate tools have to be introduced to assess and control innovations risks from the very beginning. In the following, some desirable technologies and attributes are presented which are believed to be healthy ingredients for a profitable and sustainable evolution of future yards.

2. Integrated Lifecycle Management

Starting point of the transformation is the awareness, that the yard could play the crucial role throughout the whole lifecycle: During conception and design all necessary structure and information is conceived to support a ship's or naval system's lifecycle – one potential benefit which is often disregarded by yards after commissioning. Another fact is that requirements on data representation and data abstraction over the whole lifecycle are not met by many current product data management systems. Integrated lifecycle management is understood as a collaborative process of systems engineering, logistic support, and project management backed by a continuous product information management as shown in Fig.1. The challenge to capture, manage and deploy data and information over the whole lifecycle in the desired condition is supported by the use of architectural frameworks.

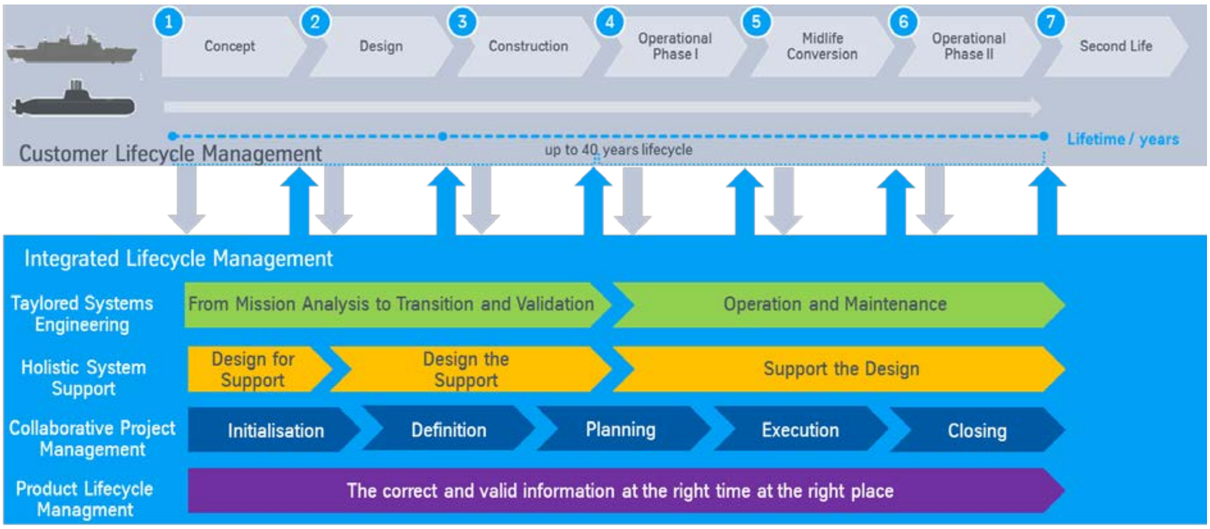

Fig.1: Integrated life cycle management comprises various aspects backed by a continuous information management

3. Architectural Frameworks

Architectural frameworks are employed to provide different and distinct views on one product. Framework architectures do not only support the description of the system solution, but also the description of capability, organizational, operational, security, and many other aspects of one product, Fig.2. The modelling of such frameworks enables traceability of relationships between different views and viewpoints which cannot be achieved in an isolated product structure.

Today, architectural frameworks like the NATO Architecture Framework (http://nafdocs.org) are widely used in defence programmes for procurement, design, deployment, support, and information systems. Next generation architecture frameworks are intended to support also commercial and industrial domains as well.

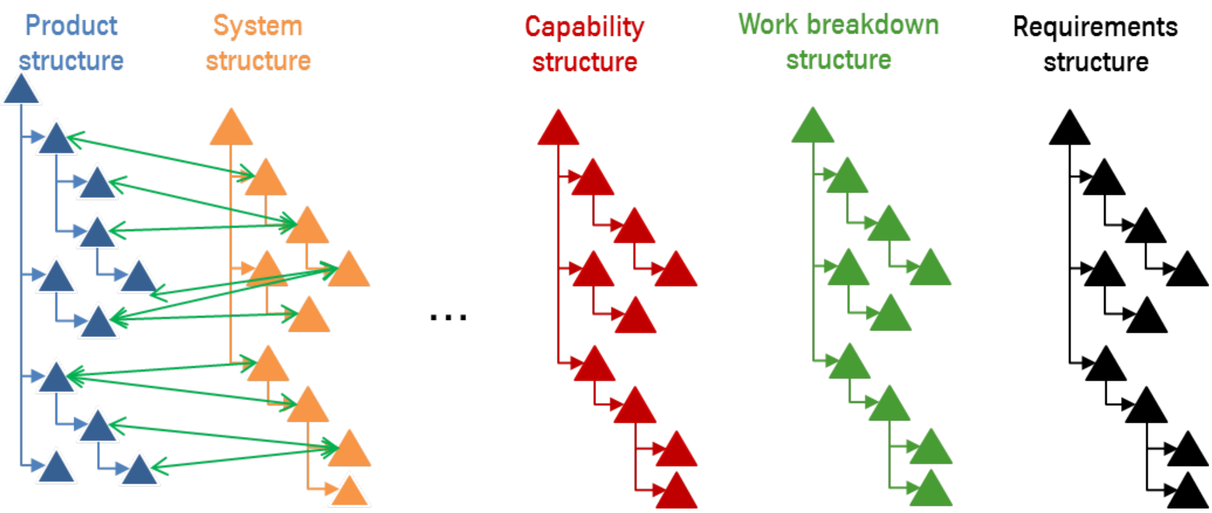

Fig.2: Architectural frameworks enable manifold purpose-oriented views on one product

4. Model-based Systems Engineering

In traditional, document-based approaches, engineering and product data is maintained in separate, stand-alone, documents, spreadsheets, diagrams and drawings or independent databases. As a result, the information distributed over different sources is difficult to assess for completeness, consistency, and timeliness. The introduction of an architectural framework offers the opportunity to organize and maintain all relevant data in one single model repository. The capability to define and navigate different views enables provision and retrieval of specific information via a collaboration platform and establishment of customized working environments for the systems engineers in the so-called active workspace, Fig.3.

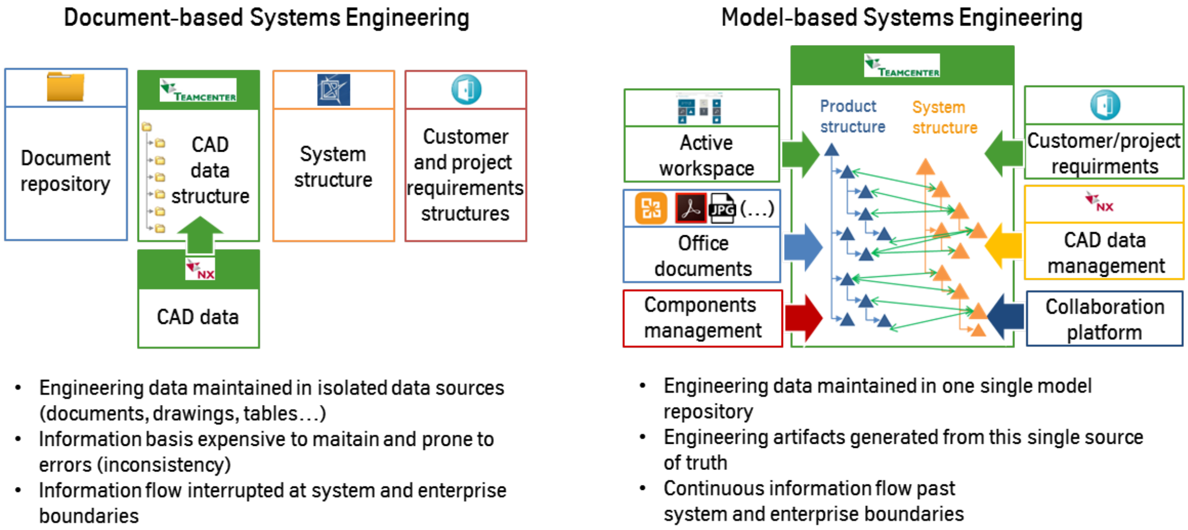

Fig.3: Document-based versus model-based systems engineering

5. Total System Simulation and Virtual Prototyping

Today, numerical simulations of various kinds are employed to support different purposes during the phases of the product lifecycle, Fig.4. Computational fluid dynamics (CFD) have been used for a long time in naval engineering for design and analysis of components and systems as well as for the optimization e.g. of ship hulls and propellers with respect to the propulsion power demand.

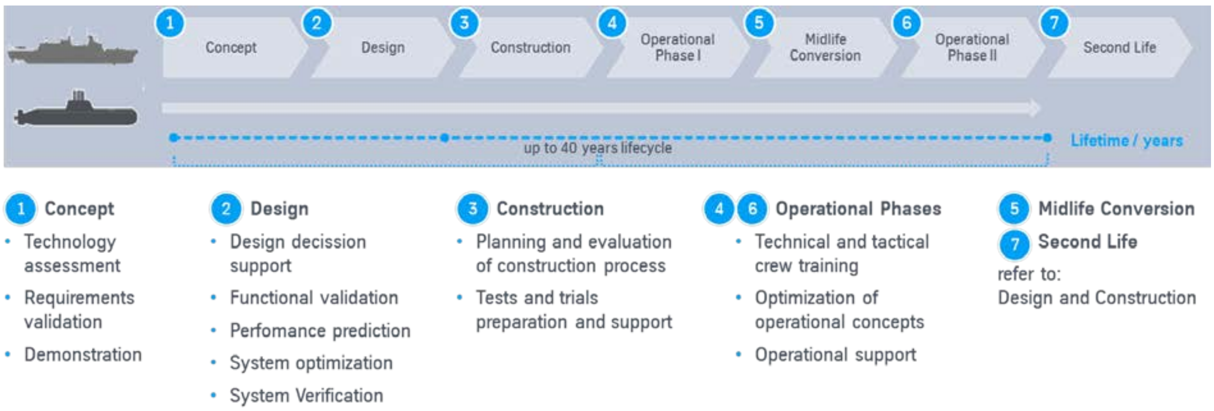

Fig.4: Purpose of simulation applications during lifecycle

Up to now, these tasks were solved by division into sub problems in a sequential manner, like determination of ship resistance, assessment of propulsion efficiency, power prediction, and layout of the propulsion train. Today's simulation capabilities and computing performances allow addressing and solving such tasks in one total system analysis where various disciplines, like fluid dynamics and mechatronics are integrated into one comprehensive simulation model and supplemented by a graphical user interface so that the operator obtains a true impression of the system's behaviour under consideration, an effective virtual prototype.

The additional effort associated with this integration approach appears justified in those cases, where the total system behaviour is dominated by the dynamic characteristics and interactions of individual components in a complex system configuration, like a naval hybrid energy and propulsion system. Total system simulation provides the possibility of in-depth analysis of system dynamics and the opportunity to investigate critical operating conditions and load cases already during the early design phase. The insights gained from the simulations provide a valuable basis for design decisions regarding system configurations as well as system control strategies.

In the following, the approach of total system simulation is illustrated for a combined diesel-electric and gas turbine (CODLAG) propulsion system configuration described by *Sichermann et al. (2014)*. In order to predict accurately the acceleration, crash-stop, and manoeuvring behaviour of vessel under consideration, detailed information on the hydrodynamic characteristics have to be retrieved, Fig.5.

The results for the CFD analysis are transferred to a Matlab SIMULINK environment with the mechatronic model of the propulsion system, Fig.6, where the propulsion analysis is performed. The simulation is controlled by the user interface, Fig.7, where different ship operation modes and environmental conditions can be selected. The ship's track can be displayed either on geometric grid as well as on loaded sea charts as shown in Fig.8.

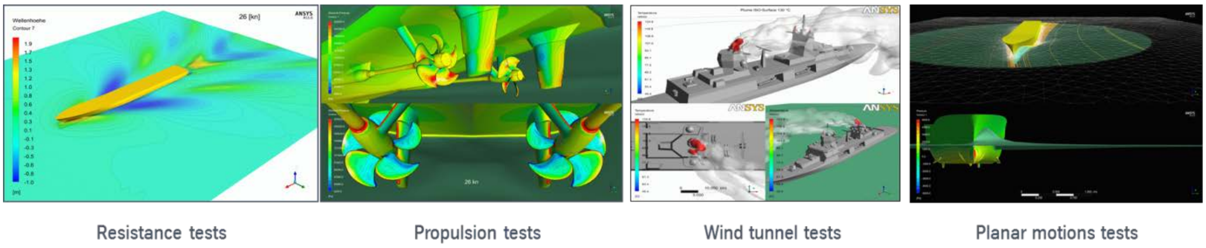

Fig.5: Preparative CFD simulations for the total system analysis

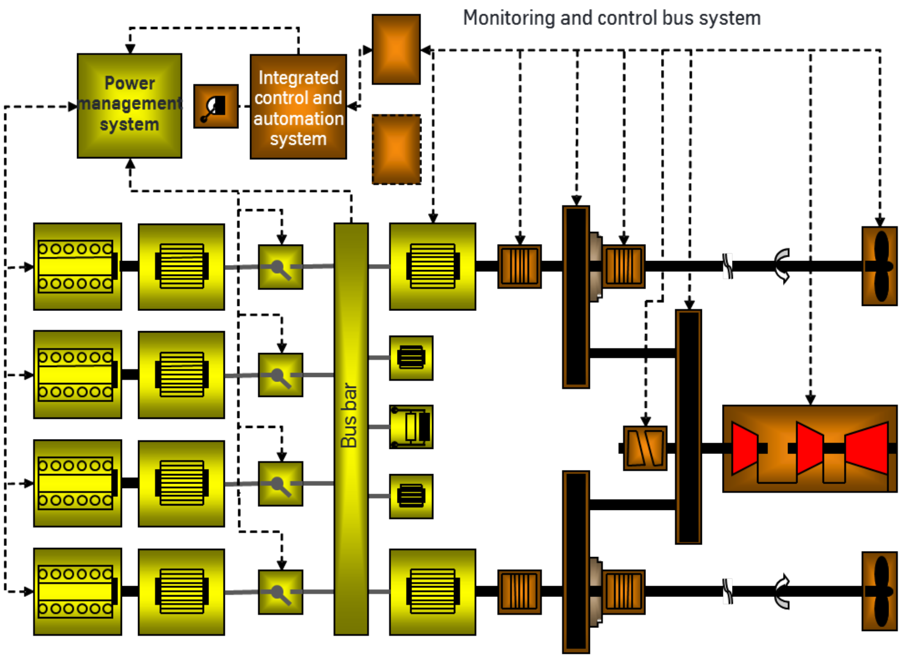

Fig.6: Mechatronic propulsion model: electric power generation and drive system (yellow) and mechanical components of propulsion train (brown)

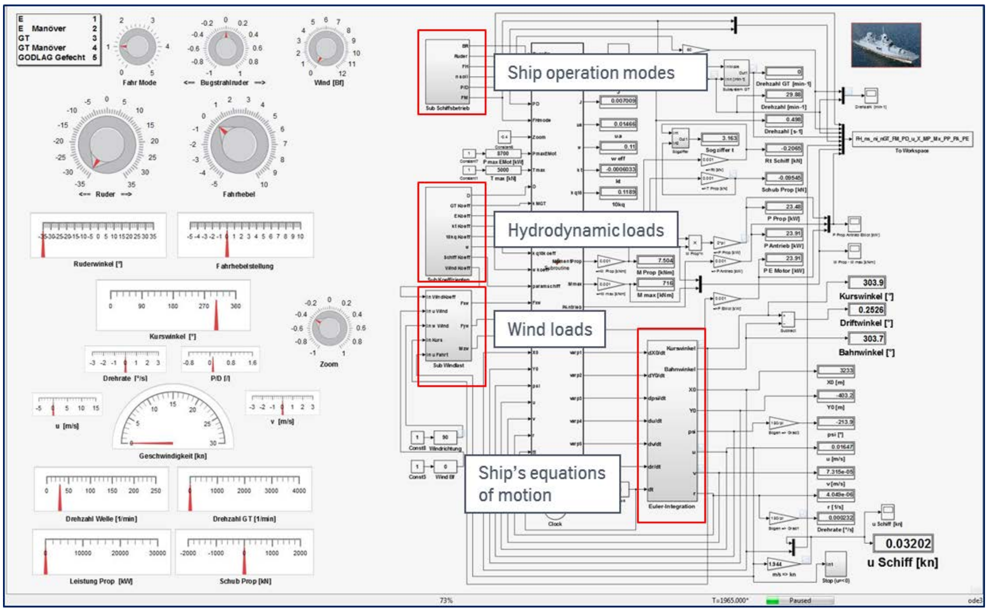

Fig.7: Matlab SIMULINK user and control interface of propulsion simulation

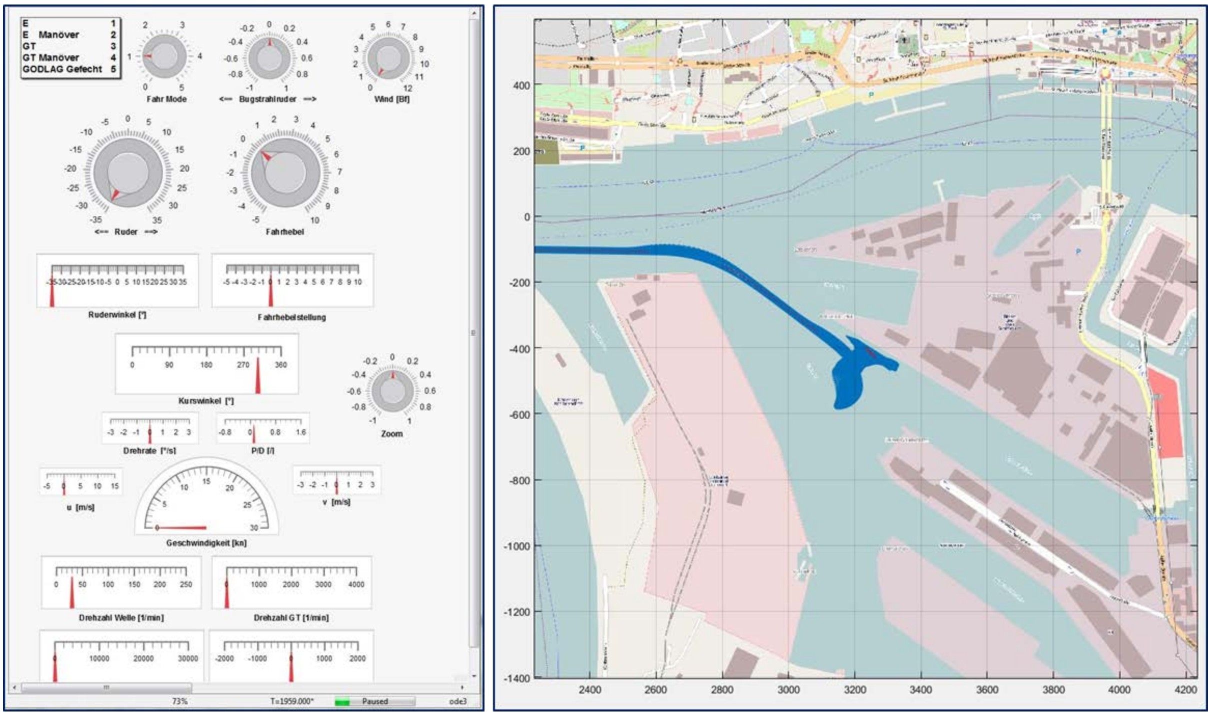

Fig.8: Ship's track during berthing manoeuvre in the port of Hamburg

6. Conclusion

The shift in the naval and marine industry and the increasing speed of digitalization provides new opportunities for yards to find their right to exist in a world of IoT.

Acknowledgements

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Index by Authors