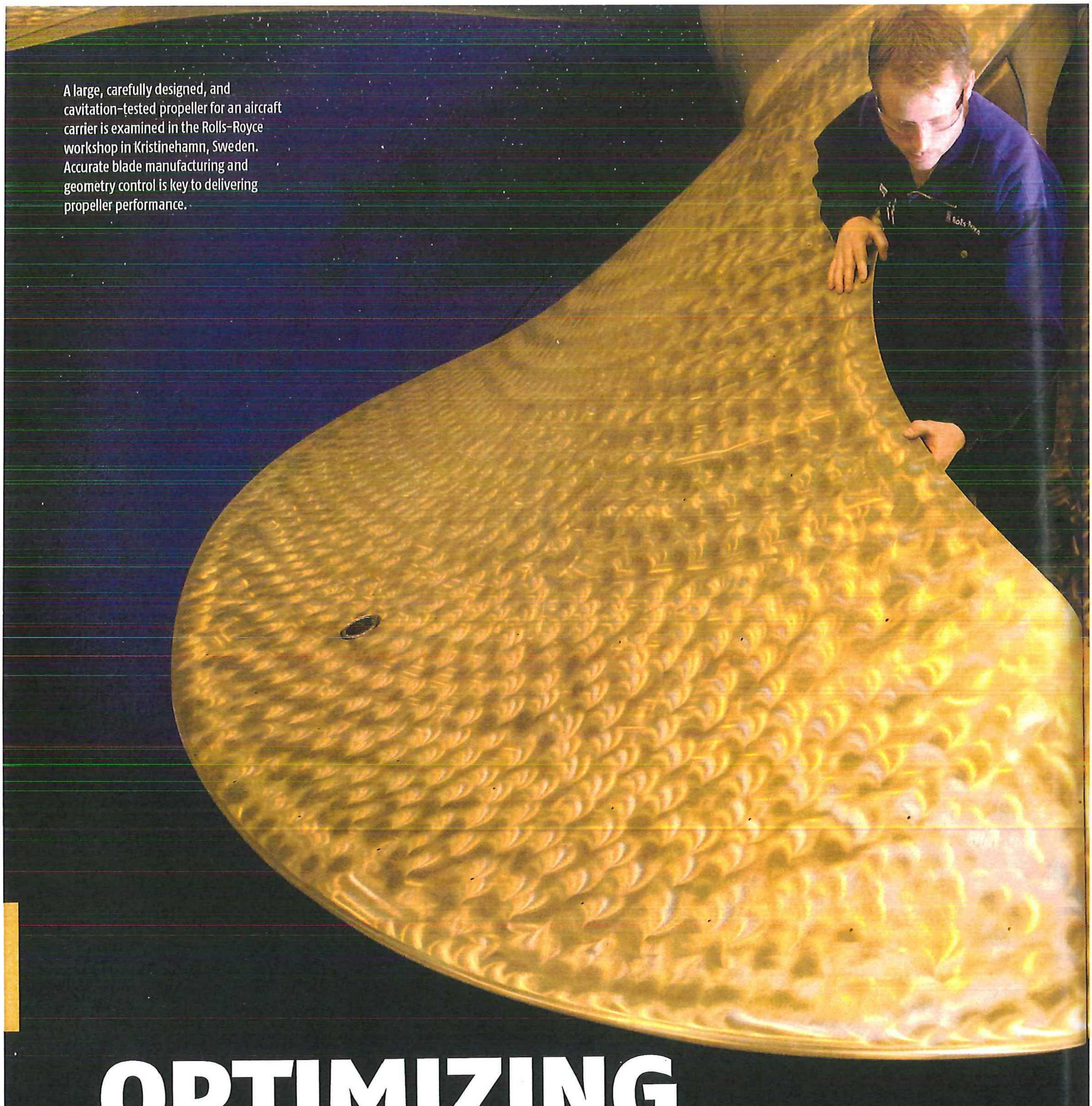


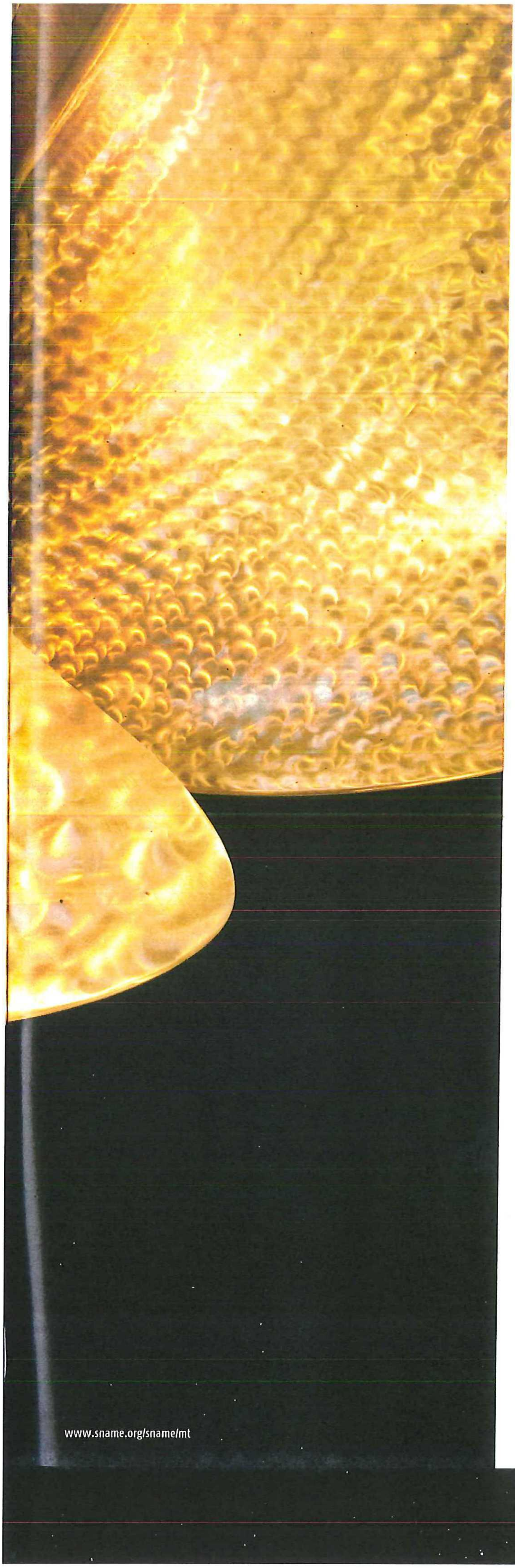
A large, carefully designed, and cavitation-tested propeller for an aircraft carrier is examined in the Rolls-Royce workshop in Kristinehamn, Sweden. Accurate blade manufacturing and geometry control is key to delivering propeller performance.

# OPTIMIZING

## PROPELLER AND PROPULSION

The quest for reduced fuel consumption, emissions, and noise levels

*By Göran Grunditz*



As a system supplier for the merchant, naval, and offshore markets, Rolls-Royce is part of a competitive market providing propellers and propulsion equipment to new and upgraded ships. Company representatives often attend comparative performance races, where several suppliers are competing for an order. The supplier with the best performance normally wins the contract to deliver propulsion equipment to the vessel in question. These races are done at model scale in a towing tank, normally at a respected testing institute.

Comparison of power consumption over a speed range is done in a self-propulsion test, in which a self-driven hull model is run in a towing tank while thrust, torque, and shaft speed of the propeller(s) are measured. The power consumption is scaled to full-scale conditions according to ITTC's proposed procedures, and is compared between tested suppliers. The supplier with the lowest power consumption, and hence the lowest fuel consumption, becomes the winner and has a chance to get the contract to deliver the requested equipment. The competitive situation, especially in the merchant market, has changed over the last 4 to 5 years from being a question only about investment cost to a situation where efficiency and fuel consumption play a more important role in the selection of a supplier. This is a better situation than just the price of the equipment being the competing parameter and of courses comes with increasing bunker prices, environmental awareness, and emissions regulations.

The current trend is that radiated noise levels are increasing in importance. This is due to the rise in shipping on the seas and operations increasing in environmentally sensitive areas. Operators (offshore and cruise) now request documentation of hydro-acoustic noise emissions from ships/propellers when they operate in ocean areas with a high population of certain marine mammals, such as whales, seals, dolphins, walruses, and so forth. In 2010, DNV published the first class notations on underwater-radiated noise as a response to environmental concerns on underwater noise pollution.

However, to be the winner in efficiency model test races, the target is to achieve the lowest possible power consumption in the towing tank test at model scale. Other factors often are suppressed to a large extent—factors such as vibrations onboard, radiated noise levels, risk of erosive cavitation, and fuel consumption at full scale where the vessel actually will operate at different drafts, trim angles, and exposure to wind and waves.

Vibration and noise levels onboard today's normal cargo vessels are normally not critical and these are often given little focus, sometimes because the time available for propulsion design is limited. A worrying trend is that these model test races between suppliers lead to sub-optimization. In this type of scenario, there is a risk that the only focus is to achieve the lowest possible power consumption, at model scale in the testing, without taking into account other performance criteria that normally are of a contradictory type. This could lead to problems at later stages, such as when the cavitation performance, pressure pulses, and vibrations

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are to be validated, or even worse, when the vessel is in operation. Cavitation performance and noise level normally are contradictory to high efficiency. High propeller efficiency often also results in high pressure pulses and a lot of cavitation with a high risk for erosion and high noise levels as a result. Over time, this could lead to increased noise emissions into the seas. Propeller design is the art of compromises between efficiency, pressure pulses, and noise levels; it is important that a propeller also is fit for purpose in the real world, where vibrations and erosive cavitation might risk the availability of a vessel. The target is to find the right balance of the propeller design that fulfills a shipowner's expectations and needs on all levels.

### A better way

Comparisons are a good way of finding the best alternative and the best performance, provided the total picture is taken into consideration. In this context, the total picture is the performance requested by the end user, normally the shipowner. No shipowner wants a propeller that initially has very good efficiency, but after a couple of months experiences cavitation erosion, or a propeller that gives high vibration so that the vessel is uncomfortable or the hull structure suffers fatigue damage. If comparative model testing is the only way to select a supplier, it is recommended, as a minimum, to perform two tests before a supplier of a propeller or a whole propulsion system is finally selected. The first is a towing tank test (resistance and self-propulsion), where power consumption is measured, and the second, a cavitation test, where cavitation performance and pressure pulses are validated. This will ensure that the comparison is based on the total performance picture and that problems with cavitation or noise later in the design process are avoided.

*The time available for design iteration is often a limiting factor and a delivered propeller design isn't necessary the same as the optimum design.*

Different ship types will have different potential, and a better way of optimizing propulsion and reducing fuel consumption of a new vessel is to involve a supplier of a propulsion system and drive train at a much earlier stage of the project. A supplier should have propulsion expertise and the ability to perform optimization of the aft ship, interaction effects, propeller, and drive train; a supplier also should strive for an iterative development of the propulsion system with a lifecycle perspective.

### Propeller blade optimization

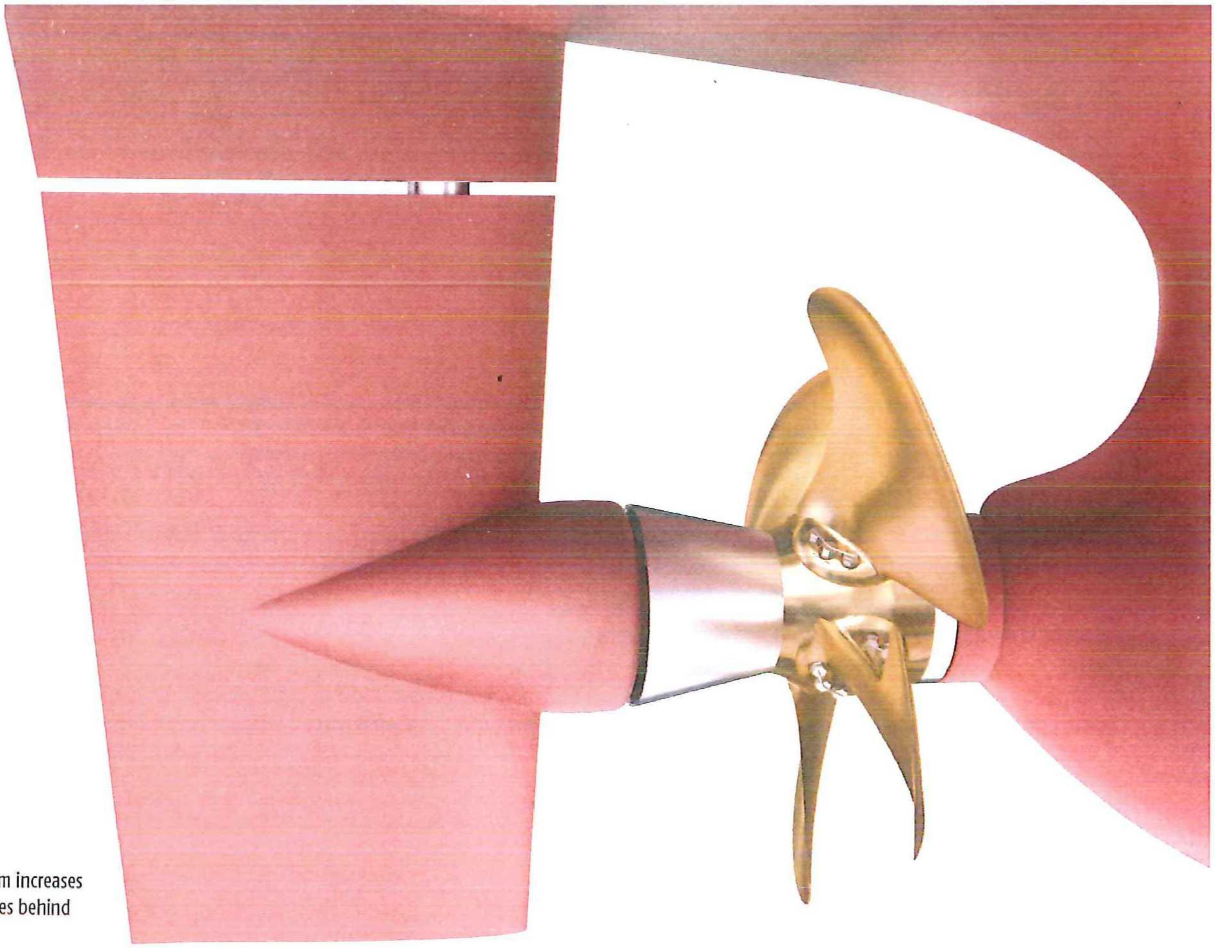
Propeller design is an art that has developed significantly since the 1950s and 1960s, when designs were made with pen and paper, to today's use of computational fluid dynamics (CFD). The challenge for today's propeller designers is to design a propeller that fulfills the customer's high expectations of efficiency, cavitation, and noise levels in the short time frame available before manufacturing of either a model scale or full-scale propeller. Design of propellers is a complicated process, in which a large number of analyses and assessments are made; in combination with the designer's experience, the geometry of the propeller blade is developed toward what is believed to be an optimum design.

With sufficient time, more design alternatives can be analyzed and more advanced analysis methods can be included in the design process. But the time available for design iteration is often a limiting factor and a delivered propeller design isn't necessary the same as the optimum design. The analysis methods used to calculate propeller efficiency, cavitation extension, pressure fluctuations, and blade strength have to be used very quickly. Faster analysis methods allow for more design iterations, but they also normally mean less accurate results. The challenge in this context is therefore to free up time in the design process to enable more advanced and accurate analysis methods, which can guide the design toward better performance.

What is good performance in the context of a propeller design? Most people would say good efficiency and low fuel consumption. In most cases, that's correct. But for operation of an icebreaker, reliability and blade strength for ice milling might be more important; for a cruise vessel, a yacht, or a seismic low noise levels normally are the most important factor. Naval vessels often need a high cavitation inception speed; that is, the speed at which the vessels can operate before the propeller starts to cavitate.

### Automatic optimization

Automatic optimization of propeller design (the propeller blade geometry) is being seen more frequently, in research projects and at model institutes. The developments are great, but there is a general problem with these propeller optimizations. They tend to be very academic, with a focus on demonstration of the optimization techniques rather than generating a better, more



The Rolls-Royce Promas system increases efficiency by regaining of losses behind propeller and hull.

optimum propeller design. There are a large number of practical limitations that must be taken into account before these optimized designs can actually be built and put on a vessel. It isn't only the hydrodynamic performance, in terms of efficiency and cavitation, which has to be optimized. There are a number of practical parameters, as follows.

1. The static strength of the propeller blade and the effects of ice loads are critical considerations. The three-dimensional shape of today's propeller blades requires finite element calculations to determine the maximum static stress level.
2. Dynamic strength has to be calculated based on the maximum stress level and the operational lifetime of the propeller.
3. Classification rule requirements on propeller blade thickness have to be fulfilled.
4. The strength of the controllable pitch propeller hub is dependent on the size and shape of the propeller blade, the blade area, the weight, and the spindle torque necessary to change pitch of the blade.
5. The clearance between the individual blades of a propeller and the hub during pitch changes of a controllable pitch propeller (CPP) has to be maintained. This limits the blade area and the chord length that can be used at different radii of the propeller blade.
6. The risk of having erosive cavitation has to be controlled. The amount of cavitation and its extension normally can be predicted as part of the manual propeller design process. However, to do it in an automatic optimization routine requires fast analysis methods with an automatic interpretation of the results, as many design alternatives are to be calculated. This normally is the most challenging part and the weak link of an automatic optimization routine.

All of these parameters and practical limitations to the propeller design have to be dealt with during the optimization procedure, or the optimized propeller design will only be academic and not possible to build. The large number of design alternatives being studied puts restrictions on the lead time of performance analysis, so viscous CFD methods are today not possible to run as part of the optimization routine. Instead, they are used at a later stage for fine tuning when the design is closer to optimum. When automating the design process and putting it into an optimization algorithm, the various judgments an experienced propeller designer is making during the development of the propeller design must be automatically processed; additionally, decisions must be made by the computer itself. This is much more challenging than finding an optimization algorithm that is able to find a global optimum of the objective function. A further complicating factor, which comes on top of the balance between efficiency and cavitation mentioned earlier, is that several operating conditions of the propeller must be considered. Very few vessels of today have only a single design condition; it is increasingly common that a wider range of ship speeds and drafts are to be considered when a propeller is designed.

At Rolls-Royce Hydrodynamic Research Centre, we work continuously to build propeller optimization algorithms into the software system that is used for propeller design. This means that the optimization algorithms will have access to, and will run in sequence, all of the analysis methods that are part of the normal manual design process. Geometry handling is accessible; propeller hub strength and clearance between blades as well as strength and performance analysis are all run in a sequence similar to that used during the manual design process.

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The propeller designer's interpretations also are automated. This gives several benefits. First, the number of design iterations this affords becomes much larger than any propeller designer ever will be able to do. Secondly, the outcome—the optimized propeller design—has passed exactly the same analysis and assessments as a manual design. Lastly, the optimization process can be run in parallel to the manual design process and can be used as a complementary design process. There will be a long development process before we can program the computers to interpret analysis results and apply the same experience and tweaks to the design as our most experienced designers. The dependency on the designers' skill is reduced and the lead time for delivery of a well optimized propeller design is shortened.

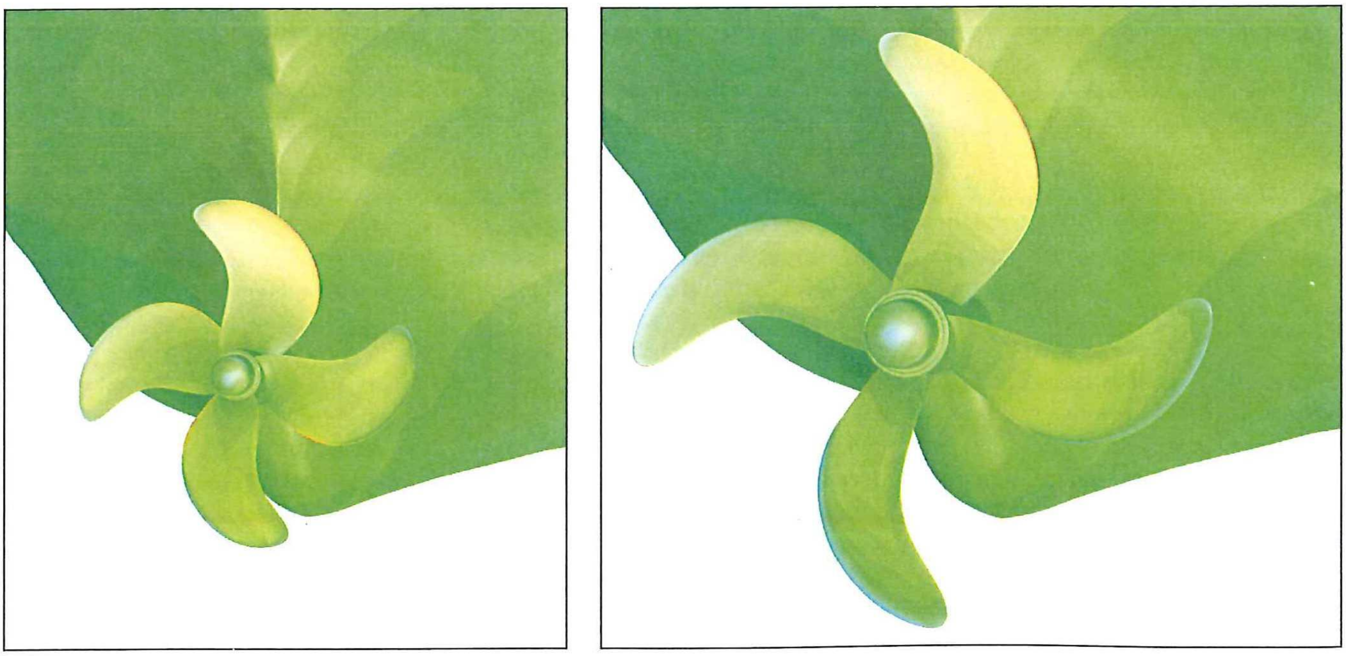
*A CPP has the possibility to always operate at optimum shaft speed independent of operational environment and ship resistance.*

### Propulsion system optimization

For a typical propeller, considering that diameter and shaft speed are kept fixed (as well as position of propeller and rudder), the efficiency improvement that can be achieved by optimizing the shape of the propeller blades is in the range of 2 to 3% for constant levels of pressure pulses, vibration, and noise. This also means the same amount of reduction in fuel consumption. If we look beyond the propeller design and consider the aft ship with the whole outboard propulsion system, we find that the potential for improvements is even larger. With this view, we can look at losses behind the hull and propeller as well as the interaction between the propeller, the rudder, and the hull. This view shows that the potential for improvements can be in the range of 5 to 10%, or even larger.

Benchmarking between different propulsion system concepts is normally made at a concept level where estimations of hull resistance, interaction effects, and propulsor efficiency are used to build up a comparison of power consumption at different ship speeds. Most of the focus normally is on design draft, design ship speed, and maneuverability to find the most optimum propulsion concept; sometimes, an operational profile is used to balance the comparison. At this stage, a large number of parameters are considered: type of propulsion, maneuverability, fuel consumption, payload, main dimensions, passenger/crew comfort, effects on the maritime environment, initial investment cost, and so forth. Possible alternatives could be single or twin screw, open twin shafts or twin skegs, podded propulsion, mechanical thrusters or even a combination of different types such as wing thrusters with a center propeller, or propellers in combination with waterjets. Often, the initial investment cost becomes the major decision factor, while factors such as the lifecycle perspective,

FIGURE 1: The original (left) and 30% larger (right) propeller.



the total fuel bill, and the total environmental impact over the ship's lifetime are given less attention.

As all of these different propulsion concepts will have different hull lines, and thus different interaction effects between propulsors and hull, a fair comparison is difficult to achieve. In the past, we have seen some comparisons of podded propulsion to conventional open shafts, in which model tests have been made to determine differences in hull resistance, interaction effects, propulsor efficiency, and so forth. These comparisons are made as fairly as possible.

As indicated earlier, the potential improvement by optimization of losses and interaction effects for one concept could be in the range of 5 to 10%. An alternative found to be optimum at the concept level benchmarking might prove inferior to others when further optimization of the alternatives is undertaken.

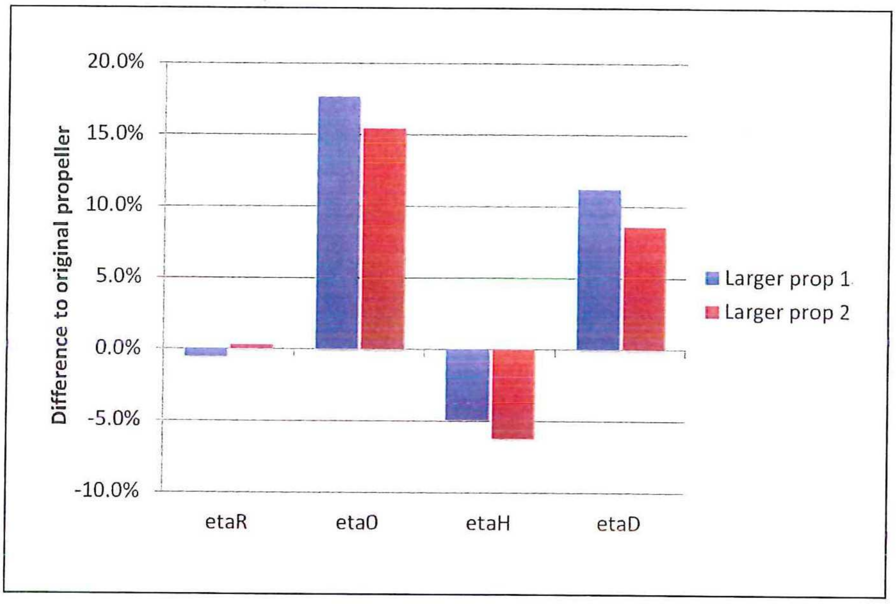
Today's CFD techniques are developing quickly, computers are getting faster, and clusters are getting bigger; however, computing and comparing propulsive efficiency and power consumption on a concept level require accurate simulations that still are very time consuming. Seldom is this affordable at the concept stage of a ship design project. When one or two propulsion concepts are selected, CFD is a more useful tool to actually look at the power consumption at different speeds and drafts. Optimization of interaction effects and quantification of losses behind propeller and hull can take place and it is possible to move from a concept level toward a design and optimization level.

## Supplier engagement

Once the propulsion system concept is selected, a more thorough optimization can take place. At this still early stage of the project, it is beneficial to work with a supplier of propulsion equipment that has the ability to outline the propulsion system; to find the optimum propeller diameter, shaft speed, and position of propeller and rudder; and to perform optimization of the aft ship.

Figure 2

The effect of a 30% larger propeller diameter and two different propeller designs demonstrates the effect on interaction, propeller efficiency, and total propulsive efficiency. (The difference is shown relative to the original propeller.)




The effect of optimizing interaction effects—something as simple as looking at the optimum position of the rudder relative to the propeller and the propellers position—can be larger than what can be achieved with optimization of the propeller blade itself (as in the model test races mentioned earlier). Energy saving devices, such as the Rolls-Royce Promas system, which increases efficiency by regaining of losses behind propeller and hull, should be considered at this stage and incorporated in the optimization. As the interaction to the hull is a key parameter, and the inflow to the propeller(s) to a large extent determines the performance of same, it is beneficial to allow for modification to the hull lines. Optimizations can be made at different levels depending on the time available for the particular project. From looking only at the propeller blade geometry, to positioning and size of propulsors, to more complete optimizations where hull lines are allowed to change, losses are quantified as a base for selection of energy saving devices and interaction effects are taken into account.

As CFD techniques develop, and it's known that scale effects are present if studies are made at model scale, investigations tend to move toward full-scale simulations, in which vessel performance in waves and operational profile also are taken into account. This offers great opportunities for further reduction of fuel consumption, and making time available for such simulations is becoming a critical factor for success. Engagement of a propulsion equipment supplier that has the ability to do this type of analysis, early in the design process, enables a focus on total system performance and a lifecycle perspective that normally results in lower fuel consumption in the end.

## Propulsion drive train

So far, we have explored optimization of propeller design, propeller blade geometry, and hydrodynamic optimization of the aft ship where a reduction in power consumption at a certain ship speed has been set equal to a reduction of fuel consumption. A third level of propulsion optimization is the optimization of the propulsion drive

*Normally, propeller combinator curve is very static and doesn't change with ship resistance, which means the propeller only operates at its optimum at one single point.*

train—that is, the propeller shaft line, gear boxes, and engines. Especially in the case of a controllable pitch propeller (CPP), this offers further possible reductions in fuel consumption, as the specific fuel consumption of an engine varies with power and shaft speed. A CPP has the possibility to always operate at optimum shaft speed independent of operational environment and ship resistance.

At this third level, an engagement with the supplier of the propulsion system becomes important as the hydrodynamic performance and control of the propeller needs to be linked to the fuel consumption characteristics of the engine. The propeller diameter has to be matched to the propeller shaft speed, which should to be matched to an available size of gear box and gear box ratio. This can become an optimization problem, both when selecting equipment sizes where initial cost has to be balanced against operational performance and when the control system of the propeller is being designed. A larger propeller diameter is always more efficient than a smaller diameter if the propeller shaft speed can be sufficiently adapted to the diameter. A larger, more efficient propeller needs a lower shaft speed, which leads to a higher shaft torque, giving a larger shaft diameter and a larger, more expensive gear box. The gear box ratio needs to be matched to the engine. The initial cost of the whole shaft line becomes higher and needs to be recovered by the fuel saved by the better hydrodynamic efficiency.

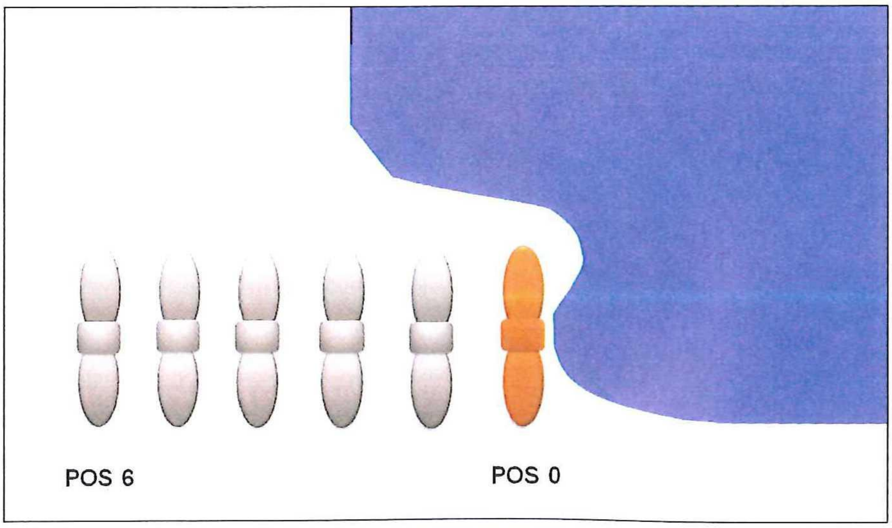
At this stage, the optimization should be focused on fuel consumption, taking the operational speed profile of the vessel into account and balanced to the initial investment cost. The efficiency of the propulsors at each operational condition is used to calculate the power consumption as a function of ship speed, propeller pitch, and shaft speed, what is normally called the PD-n diagram. The specific fuel consumption of the engine should be linked to these calculations so that the fuel consumption as a function of ship speed, propeller pitch, and shaft speed is given instead. At this level, it is possible to actually make sure that the engine is running at its optimum, independent of ship speed and resistance. The benefit of a controllable pitch propeller is that the relation between shaft speed and delivered power (the propeller pitch) can be controlled. The combinator curve can be selected so that the propeller, at any ship speed and at any draft, is operating at the optimum combination of pitch and shaft speed. Normally, propeller combinator curve is very static and doesn't change with ship resistance, which means the propeller only operates at its optimum at one single point.

An operational profile of a vessel, in which the vessel total operational time is broken down into time fractions at different speeds and drafts, can be linked to the combinator curve of the propeller and combined so that the fuel consumption in a lifetime perspective is reduced.

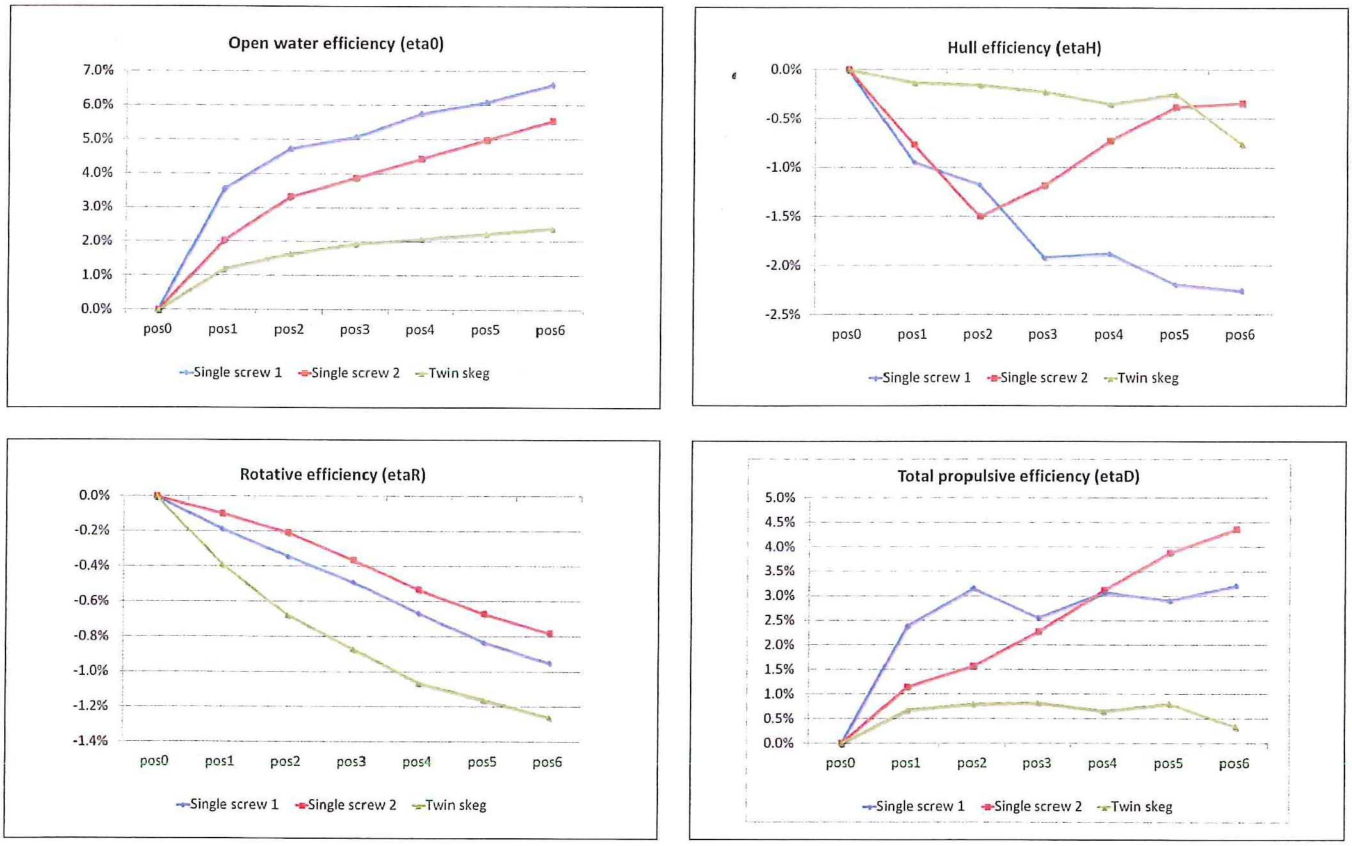
This third level optimization, which is concentrated on the propulsion drive train, can be separated from the two earlier optimizations and also made in a shorter time frame than time-consuming CFD analysis. The key here is the knowledge about the complete drive train, which enables the propeller efficiency to be linked to the fuel consumption of the engine. Comparisons of different propellers, engines, gear boxes, and shaft speeds can more easily be compared and an optimum solution in terms of cost and/or performance in a lifecycle perspective can be found.

## Larger diameter effect

A larger propeller diameter is the most effective way to improve propulsive efficiency. Provided the shaft speed is adapted to the diameter, the efficiency will increase with increasing diameter. A larger propeller needs a lower shaft speed, otherwise the efficiency won't be better; a smaller diameter needs a higher shaft speed.




Theoretical propeller positions simulated to investigate the effect of the propeller position.




The effect of the propeller longitudinal position on propeller efficiency (etao), hull efficiency (etaH), rotative efficiency (etaR), and total efficiency (etaD).

Considering a larger propeller on a single-screw ship with a normally sized propeller as a starting point (see Figure 1) demonstrates this effect and what happens to the interaction with the hull. Even though the open water efficiency of the propeller itself is increasing, the interaction effects are reducing the impact of it. CFD simulations of two alternative propeller designs with different tip loading—both with 30% larger diameter—were compared to the original propeller. The increased diameter and corresponding lower shaft speed resulted in more than 15% higher propeller (eta0) efficiency (see Figure 2). The interaction effects, however, become worse: the wake fraction is dropping and the hull efficiency (etaH) is being reduced by more than 5%, limiting the improvement achieved with the larger diameter. The total propulsive efficiency (etaD) is improved by 8.6 to 11.2%. Notable is that one of the propellers gives less open water efficiency but also less hull efficiency, that is, worse interaction effects. This indicates that details of the propeller design itself affect interaction and the propulsive efficiency by 3.5%.

## Effect of propeller position

If propeller diameter, shaft speed, and design are kept constant and the propeller position is moved longitudinally, the interaction as well as the efficiency of the propeller (open water), and the total propulsive efficiency, are affected. This highlights the importance of the propeller position and the effect it has on total propulsive efficiency. To demonstrate this, the propeller has been moved backward from its original position in six steps for three different vessels, two single screws and one twin skeg. As this study was made purely on a theoretical basis, the rudder and its effects have been neglected, which also simplifies the CFD simulations a lot.

The propeller efficiency (eta0) is increased when the propeller is moved backward, due to the reduced loading when the propeller comes out of the wake field of the hull. This is compensated for by reduced interaction effects. Hull efficiency and rotative efficiency are reduced due to the same reason, and the propeller comes out of the wake field and doesn't recover losses behind the hull as efficiently as in its original position. The combined effect is an increased total propulsive efficiency, for the single screws in the range of 3 to 5%, while the twin skeg is less sensitive to the propeller position. As mentioned earlier, this study is purely theoretical and a propeller position as far aft as "pos6" wouldn't be possible in reality. However, it demonstrates the importance of not only the propeller design but also the interaction with hull and rudder. **MT**

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