Technology guidelines for efficient design and operation of ship propulsors

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Introduction

The number of vessels equipped with controllable pitch propellers (CPP) has steadily grown in recent decades. Today fixed pitch propellers (FPP) are used for vessels where simplicity and operation at sea are dominant. This includes tankers, bulk carriers and containerships.

These vessels are normally equipped with 2-stroke diesel engines. There are also a number of vessels where the application of fixed pitch propellers in combination with a 4-stroke engine and a gearbox has become the standard. Examples of such vessels are container feeders, offshore vessels, dredgers and ferries.

Market requirements include the need to use maximum engine power in all operating conditions, along with good manoeuvring capability and fully automatic control systems. There is also a continuing demand for increased power and ship speeds.

Building reliable and efficient machinery, including fixed and controllable pitch propellers, has always been the prime target for Wärtsilä which has long recognized these trends and we are continuously updating our propulsion systems to meet these demands.

Developments in our product line include:

- The most powerful CPP in the world
- The heaviest FPP in the world
- Advanced hydrodynamic designs
- Compact hub designs
- Integrated control systems with field bus technology
- High-efficiency waterjets.

This article reviews the main design criteria of FPP and CPP installations for various applications, focusing on the common design criteria for both concepts and the special considerations concerning controllable pitch propellers.

We also address typical developments on the hydrodynamic side as well as the benefit of combining the engine propeller and gearbox. In addition we describe the special application of the Efficiency Rudders as well as typical cases for the application of nozzles.

Trends in propeller design

The ship speed of vessels has been increased in recent years. This development applies to large container vessels (container carrying capacity has risen to 8000 TEU), large dredgers (hopper capacity has increased to 22,000 m^3) and large RoPax vessels (ship speeds and power have gone up to 30 knots and 15 MW).

Concurrent with this trend the design of propellers for these vessels has become more difficult and more stringent requirements have been forwarded to the supplier of the propulsion installation.

The shipbuilding contract reviews requirements concerning the ship speed, the level of vibration on board, the level of noise given the vessel's load carrying capacity (deadweight or number of containers or passengers) and the ship speed. In general the requirements placed on the propulsion installation can be translated into direct requirements for the propulsion installation. The link is as follows:

Ship building contract:	**Propulsion installation:**
Ship speed for a given power	Propulsive efficiency
Vibration limit	Propeller induced pressure pulses on the hull
Inboard noise levels	Type and extent of cavitation on the propeller

Balancing boundary conditions

It is a general rule when designing propellers to aim for the highest possible level of propeller efficiency while keeping vibration and noise and hence cavitation at the lowest possible level. This leads to conflicting boundary conditions. Less cavitation, for example, results in a large blade area ratio, whereas trying to obtain a high propeller efficiency requires the reverse.

Each ship has its own dedicated design propulsion system which guarantees the best operational performance. Its propeller, therefore, must keep a subtle balance between several extremes, resulting in a compromise that depends on the experience of the propeller designer and the correct use of the design tools at his disposal.

Fig. 1 Propulsion installation for a typical Ropax ferry.

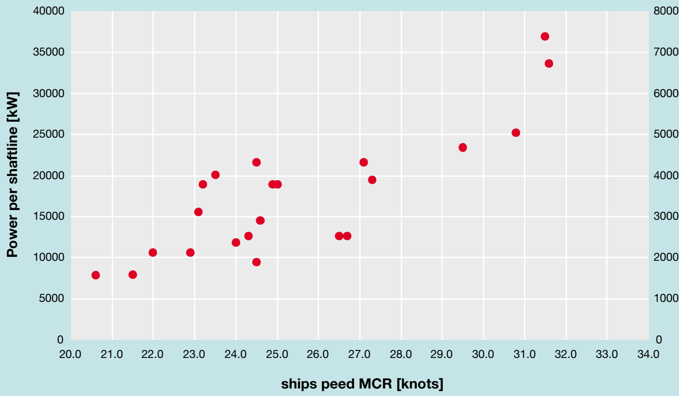

Fig. 2 Power per shaft versus ship speed for RoPax vessels.

To reduce the boundary limitations as much as possible Wärtsilä has developed blade sections that combine large cavitation-free operation with good structural characteristics and low drag properties. The result is an optimized design with higher efficiency. In addition the propeller design system used and developed by Wärtsilä consists of interactive design and analysis modules as shown in the graph.

A propeller design can only be initiated after the design criteria have been selected. The design criteria used in our propeller design system consist of information on the type of ship, its mission profile, and possible limitations regarding propeller diameter, efficiency, ship speed, cavitation behaviour and propeller-generated pressure pulses on the ship's hull.

These criteria are to be considered as the boundary conditions or constraints for any propeller design. They normally have their greatest impact on the balance between the design and off-design properties of the propeller.

Shaft speed and propeller diameter are closely related. For a given diameter, a low shaft speed is beneficial from the efficiency point of view but it also leads to a relatively high shaft torque and subsequently large shafts, hubs and gearboxes. A balance must be found between hydrodynamic performance and the total cost of the propeller system.

Figures 2 and 3 show the relation between propeller power and ship speed, and alternatively the power density (the power divided by the propeller disc area) versus ship speed. These diagrams show a clear trend typical for most vessels. When the ship speed increases, so does the power density on the propeller and therefore the difficulty in designing a propulsion installation increases.

Making a first estimate

Generally speaking, the largest propeller diameter gives the highest propulsive efficiency. However, the diameter behind the ship is normally limited by the draught of the vessel and the tip clearance.

For a first estimate the propeller diameter based on the power and revolution rate can be selected using the following formula. This formula is based on a series of propellers and the optimum selection of diameter and number of revolutions given the best propeller efficiency:

$$N_{opt} = 101 \cdot \sqrt[3]{\frac{P}{D^5}}$$

where

N_{opt} = optimum revolution rate (rpm)
P = propulsion power (kW)
D = propeller diameter (m)

This simple but reliable formula also makes it possible to check the tip speed of the propeller:

$$V_{tip} = \pi \cdot \frac{N_{opt}}{60} \cdot D = 5.29 \cdot \sqrt[3]{\frac{P}{D^2}}$$

Fig. 3 Power density versus ship speed for vessels.

Finally the tip speed is related to the power density of the propeller.

Comparing the results for various applications shows that, given the power density, the tip speed normally falls within +/- 20% of the calculated figure. The tip speed together with the inflow to the propeller is a dominant factor in the design of propellers, especially with respect to cavitation performance (described in more detail below).

The propeller efficiency is mainly determined by the given propeller diameter and required thrust. Based on momentum theory a relation can be derived to obtain the ideal propeller efficiency:

$$\eta_{prop} = \eta_{ideal} - 0.175 = \frac{2}{1 + \sqrt{1 + C_T}} - 0.175$$

where

$$C_T = \frac{T}{\frac{1}{2} \cdot \rho \cdot V^2 \cdot \frac{\pi}{4} \cdot D^2}$$

and

T = propeller thrust [N]
ρ = water density [kg/m^3]
V = the advance velocity [m/s] of the propeller, i.e. V = V_S.(1-w),
where V_S is the ship speed [m/s] and w is the wake fraction.

This formula is a first estimate of the propulsive efficiency. Without the deduction of 0.175 the formula would assume a propeller with an infinite number of blade and no frictional or rotational losses. In practice the blade number reduces the efficiency and friction of the blades as they are drawn through the water and also the finite blade number. In total this adds up to about 0.175.

For a propeller with a larger wetted surface this effect is larger. The formula clearly shows the positive effect of selecting a large propeller diameter for a given required thrust. Normally this thrust is based on the thrust required to drive a certain size of vessel at the ship speed required by the owner.

Similar simplified relations can be derived for vibration. Depending on the tip speed and the tip clearance, i.e. the distance between the propeller blade tip and the hull, the propeller vibration is felt every time a blade passes the hull.

The presence of cavitation on the propeller blade tip strongly amplifies the pressure pulse on the hull. In general the pressure pulses on the hull:

- are inversely proportional to the tip clearance
- increase with increased power density
- increase with increased inflow disturbance from the ship.

The inflow at the propeller blade tip is much less then the ship speed; for single-screw vessels the inflow is as low as 50% of the ship speed. This implies that the blade profile of the propeller varies strongly in the angle of attack during one revolution.

Propeller design

Many vessels today are equipped with controllable pitch propellers, especially vessels with an installed power of less than 10,000 kW. The engines driving these propellers cannot be reversed. The application of shaft-driven generators for the efficient generation of electricity or for heavy manoeuvring requirements favours the application of CP propellers.

Fixed pitch propellers are applied when the vessel mainly operates at sea. Simplicity counts. However, there are limits to the operation of fixed pitch propellers. For instance the 2-stroke engine cannot operate below a certain number of revolutions, which will restrict the low-speed operation of the vessel. Controllable pitch propellers also make it possible for the diesel engines to absorb the full power in both bollard and free-running conditions.

In the pre-design stage, the main parameters are determined in close co-operation with the yard and the owner. Diameter, shaft speed and hub size are selected. In most cases a preliminary propeller design is made and

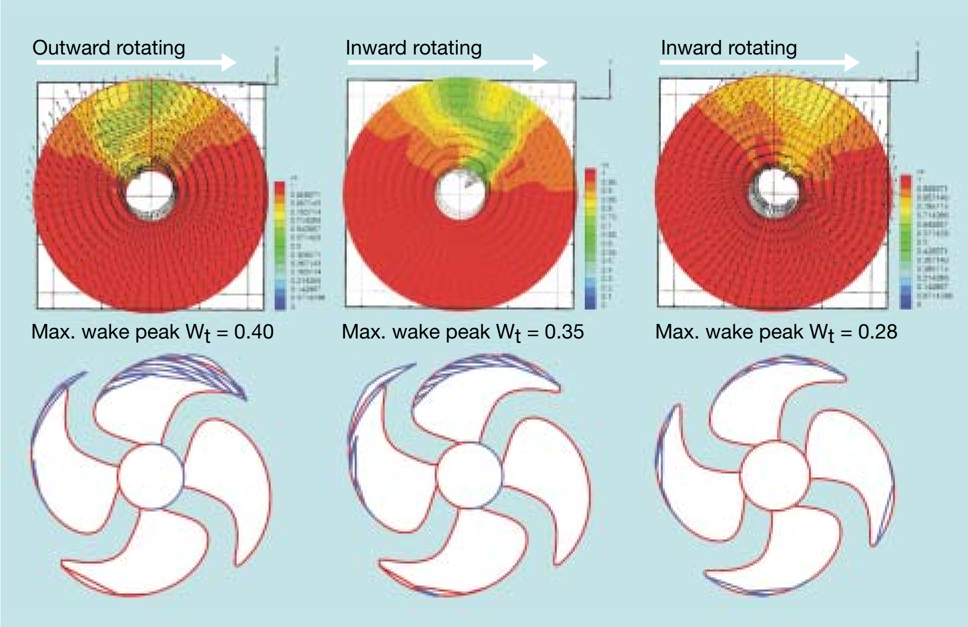

Fig. 4 Effect of wake fields on direction of rotation and calculated cavitation extent for fast RoPax vessel.

Fig. 5 Modern blade outlines.

discussed with the yard and the owner. The design conditions and off-design modes are carefully agreed and registered. This is especially important for dredgers, passenger and RoPax vessels.

Inputs from model tests for the propeller design are:

- Self-propulsion test with stock propeller (and nozzle if applicable)
- Open-water test with stock propeller (and nozzle if applicable)
- Wake field measurements.

Figure 4 shows the effect of the wake distribution and the direction of rotation on the cavitation performance of highly loaded controllable pitch propellers. Depending on the wake peak and thus the quality of the wake, significant differences exist in the cavitation pattern.

The propeller geometry is based on the following parameters, which we discuss in detail below:

- Chord length
- Pitch and camber
- Skew and rake
- Profile thickness.

Tip unloading

The propeller design has an unloaded tip. Unloading is accomplished by the pitch and chord length distribution. The larger the power density, the more tip unloading is required to reduce noise and vibration hindrance. The tip unloading in free-sailing conditions has evolved from a loaded tip to an unloading of the tip by about 50% following a specially developed circulation distribution in the tip area.

Camber

Fine-tuning of the cavitation patterns is carried out by means of the camber distribution. The selection of camber is based on minimizing the cavitation extent in free-sailing modes, while face cavitation has to be avoided for part-load conditions such as operation on one engine.

Skew

The skew distribution has an effect on several items. The higher the skew, the smoother a propeller blade will enter the wake peak and thus will generate less variation in thrust. In addition, tip skew has a beneficial effect on the unloading of the tip.

Unfortunately an increase in skew will not always improve the propeller design! Excessive skew can result in leading edge vortices, which can be erosive or generate noise. The aim should be a good balance and combination with loading at the tip, and finding the optimum solution requires considerable skill. A high skew at the tip can also lead to high blade stresses. Finally, skew is one of the determining parameters for the actuating forces of the hub.

To summarize, a moderate to high skew is preferred from a hydrodynamic point of view and the skew distribution has to be balanced for strength reasons and actuating forces.

Blade thickness

The blade thickness is the result of a fatigue and static strength assessment using the Finite Element Method. Each propeller design is analysed regarding fatigue and peak loading. The mean and maximum stresses in the free-sailing conditions are determined.

Those figures are compared by Wärtsilä with the corrosion fatigue data of the material used. Peak stresses, exceeding a certain maximum, can cause (micro-) cracks in the blade. These (micro-) cracks can grow rapidly due to fatigue and cause blade failure.

An example of a peak load is the crash stop. The internal criterion for peak stresses adopted for Lips propellers is more stringent than the rules from Classification Societies. Thanks to the well-balanced design, this does not result in greater blade thickness than the Classification Societies require.

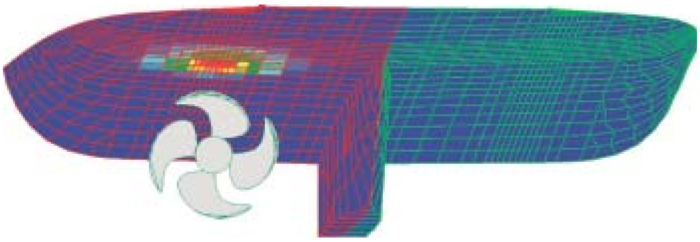

Fig. 6 Integration of pressure pulses on the hull as input for vibration analysis.

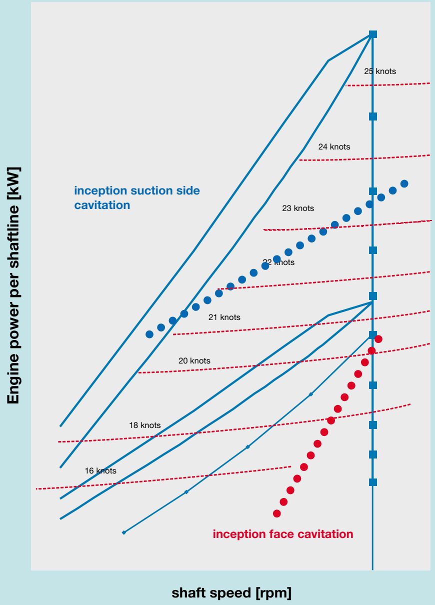

Fig. 7 Engine load limit curves and propeller cavitation limits.

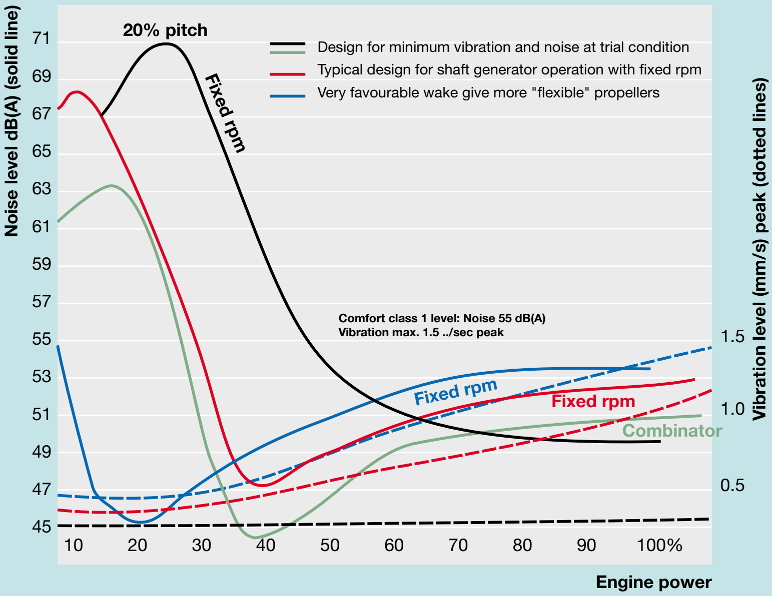

Fig. 8 Effect of using a combinator for quiet operation on a RoPax vessel.

It should be noted that the behaviour is different for fixed pitch propeller and controllable pitch propellers. For fixed pitch propellers the direction of rotation is reversed. This leads to increased loading on the area of the blade tip, which restricts the amount of skew that can be applied for fixed pitch propellers. For controllable pitch propellers the direction of rotation is not changed and stresses are not critical.

Pressure pulses

Using the calculated cavitation pattern the pressure pulses on the hull can be calculated. The pressure pulses are related to vibration by means of the so-called "integrated force". When the propeller rotates, the force on the hull varies with the rotation. The variation in time versus the variation in size of the force generates noticeable vibration inside the ship. Depending on the strength of the vessel and the occurrence of resonance (this is to be avoided) the vibration limits in the ship are either met or not.

Tip clearance is clearly an important aspect in preventing vibration onboard a ship. Doubling the tip clearance reduces the pressure pulses and the integrated force by a factor of two.

Optimum control of propeller and diesel engine

A controllable pitch propeller can generate a given thrust or power with infinite combinations of pitch and shaft speed. Various control strategies can achieve the required propeller thrust.

The classical approach is to programme a pre-set combination between pitch and shaft speed, making it possible to control the generated power easily by a lever on the bridge. This so-called combinator control is ideal for stationary ship conditions and a propulsion system without propeller-shaft power take-off (PTO) systems, such as shaft-generators.

To avoid overloading the main diesel engine, this means in practice that load control is needed in addition to the combinator. The load control keeps the diesel engine load within the operating envelope of the engine.

A combinator curve is designed taking into account engine requirements, the cavitation patterns of the propeller in various conditions, and the mission profile of the vessel. The load control reduces the pitch as required by the combinator in case of acceleration of the ship during manoeuvring and when PTO power is taken. Figure 7 shows a power absorption diagram for a RoPax vessel. Shown are the operational limits of the engine for the two- and one-engine condition. Lines are plotted for a given ship speed but at different propeller pitch.

An increase in propeller pitch indicates a lower revolution rate and shows a lower power absorption closer to the load limits of the engine. This is the result of a larger propulsive efficiency. Also plotted are dotted lines indicating the limits in cavitation for various pitch settings.

Given a number of revolutions at increased pitch more cavitation will appear on the suction side of the propeller and the pressure pulses will increase. The pressure pulses and the amount of suction side cavitation will be highest at the maximum power point at the highest rpm.

The same diagram also indicates the limit against pressure side cavitation. This appears when the pitch is reduced at given rpm. The propeller starts to cavitate on the pressure side and, if the pitch is further reduced, the propeller thrust in the tip area will become negative. The propeller will then generate an unsteady type of cavitation and this will be observed inside the ship as increased noise.

This is also demonstrated by Figure 8, which shows the measured noise levels for various control options. At constant rpm, reducing the pitch from full power to a lower power first reduces the propeller excitation and thus the noise. Reducing the propeller pitch further will pass the point of pressure side inception. At the point where the thrust at the tip becomes negative the noise will increase again and be larger than when operating at full power. The use of a combinator will then reduce the noise level significantly. The level can be further increased when the wake distribution at the propeller is improved.

The Efficiency Rudder

Wärtsilä carries out research projects to improve propulsive performance even further. One result of this work is the design and application of the so-called Efficiency Rudder, see Figure 9.

The Efficiency Rudder is a horn rudder with a slim rudder profile extending all the way up to the hull. Model tests have shown that compared to rudders with a large rudder trunk, the propulsive efficiency alone is as large as 1-3% due to the slim rudder profile.

The torpedo profile of the Efficiency Rudder reduces drag since there is no blunt hub end. This gives an increase in propulsive efficiency. A further increase in propulsive efficiency is obtained because, due to the torpedo, the regain of rotational losses is higher with the Efficiency Rudder. Accounting for the drag of the torpedo itself, this effect gives an additional increase in efficiency of 1-3%.

Fig. 9 The Efficiency Rudder on a twin-screw vessel.

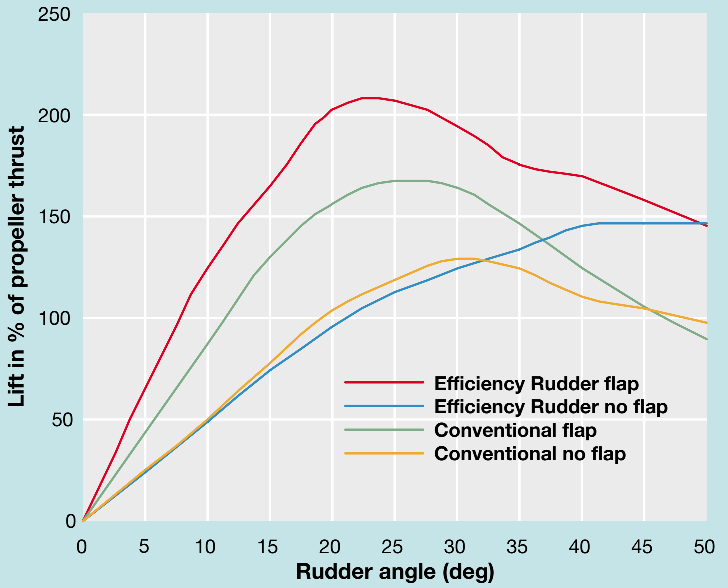

Fig. 10 Lift of the Efficiency Rudder compared to conventional flapped rudders and rudders without flaps in free-running condition.

Another effect of the torpedo is to increase the wake (the torpedo diameter is larger than the hub body). Model tests and theoretical analysis have proved that the wake gain gives an increase in propulsive efficiency of 1-5%, the highest wake gain for single-screw ships.

Altogether the Efficiency Rudder increases the propulsive efficiency by 5-8% for single-screw vessels and 2-5% for twin-screw ships.

The reduction in hub vortex strength also reduces the pressure impulses on the hull. Pressure impulses are further reduced due to the improved wake field produced by the influence of the torpedo in combination with the slim rudder profile.

The manoeuvring performance is dominant in the application of any rudder. It is the rudder's main function and should therefore be the main selection criterion for any type of rudder. The profile of the Efficiency Rudder is optimized to fit the operational conditions of the ship. Since the torpedo reduces the balance of the rudder, the steering gear torque will be higher for the Efficiency Rudder than for conventional rudders (spade rudders or conventional horn rudders). Comparing the Efficiency Rudder with conventional flapped or unflapped rudders the lift generated by the Efficiency Rudder in terms of the propeller thrust is the largest (Fig. 10).

Lift as a percentage of propeller thrust for a rudder with rudder length of 69% of the propeller diameter and at a given angle of 25°:

Efficiency Rudder with flap:	205%
Conventional rudder with flap:	160%
Efficiency Rudder without flap:	112%
Conventional rudder without flap:	118%

Therefore the Efficiency Rudder will be beneficial for vessels especially where manoeuvring is an important aspect of the vessel's operating profile. The application of the rudder will thus be attractive for the following vessel types:

- Container feeders due to the combination of high manoeuvring requirements, application of controllable pitch propellers and limited clearances in the aftbody
- RoPax vessels due to the combination of high manoeuvring requirements, application of controllable pitch propellers and high power densities
- Chemical tankers due to the high efficiency gain and frequent manoeuvring.

The HR (high-efficiency) nozzle

Nozzles are aerofoil shaped rings placed around the propeller. Nozzles have found their application in ships for decades with good results.

The main advantage of the nozzle is that it increases the thrust on the propeller. Comparing propellers with and without nozzles shows that the nozzle propeller offers about 25% more total thrust (nozzle and propeller) than an open propeller at zero ship speed (bollard condition). At high ship speeds this difference becomes less up to the point where the nozzle generates drag instead of thrust.

For decades all nozzles have been of the 19A or 37 type, see Figure 11. The 37 nozzle has been applied in cases where astern thrust is needed, such as in harbour tugs. The 19A nozzle is usually applied to all other cases. Recent developments in computational tools have accelerated the application and use of new types of nozzles. A good example of this is the HR nozzle.

The Lips HR nozzle is very useful for improving the performance of the propulsion unit of tugs and dredgers. This nozzle generates more thrust at dredging conditions in combination with more thrust at free-sailing speed, compared with conventional nozzles such as the 19A and 37 Marin nozzles.

This is made possible by the specially shaped profile of the nozzle. Experience with this nozzle has been obtained for about 300 installations in inland vessels. Model tests with the nozzle, however, indicated lower performance gains than actually obtained from full-scale experience.

Extensive CFD analysis was carried out in order to understand the basic flow properties causing this difference. (CFD stands for Computational Fluid Dynamics; these are new tools which enable flow phenomena to be calculated including the effects of friction and flow separation). It appeared that at the model scale the flow at the trailing edge of the HR nozzle showed local flow separation, which affected the lift on the nozzle profile. CFD analysis carried out for the full-scale Reynolds number showed that in those conditions the flow separation is not present. The results are shown in detail in Figures 12 and 13.

The shift in the local separation point at the trailing edge creates additional lift on the HR nozzles, which is then manifest at full scale. This has set a basis for detailed prediction of the performance of the HR nozzle. Performance improvements of 8% in bollard condition have been achieved. In free running the improvements can be as high as 10%.

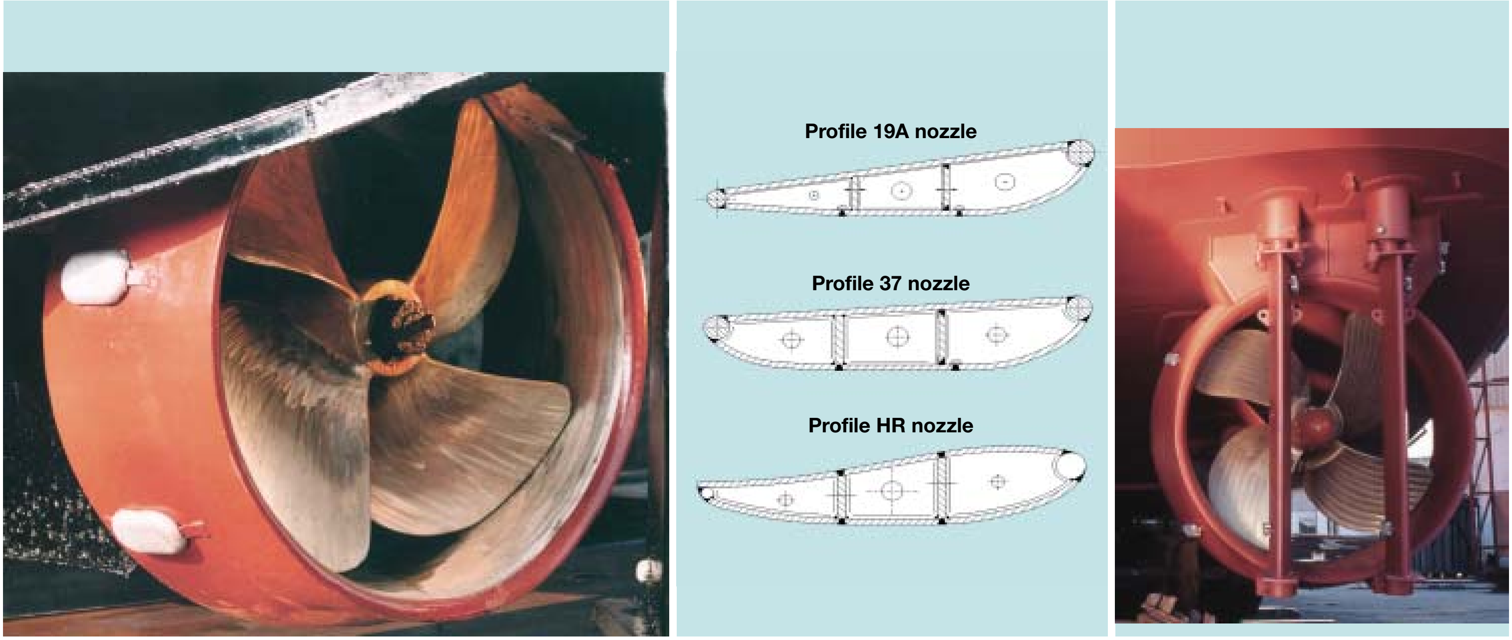

Fig. 11 Examples of propeller nozzles used by Wärtsilä.

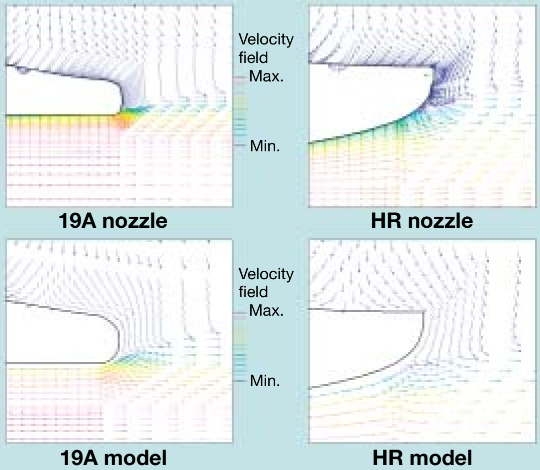

Fig. 12 Calculated flow pattern at the trailing edge of the HR nozzle and the 19A nozzle.

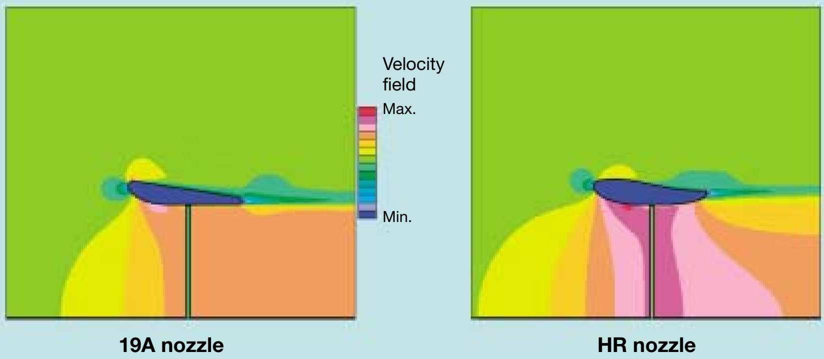

Fig. 13 Calculated velocity field for the 19A nozzle (left) and the HR nozzle (right).

In the case of the 19A nozzle, the flow separation which occurs at the outer surface of the nozzle at high speed will increase the nozzle's drag. The HR nozzle does not have this disadvantage as its leading edge is very round. This shape allows the flow to follow the nozzle contour at much higher speeds and therefore the improvement of the HR nozzle over the 19A nozzle at high speed is even larger. A typical improvement in free-running conditions is 10%, although detailed figures will clearly depend on the actual case.

Summary

The design and operation of propulsors has changed in recent years. Powers have gone up and the power density of propulsors has increased significantly. As a result cavitation performance and pressure pulses in the hydrodynamic design of propellers have become more critical. Moreover, the specification for comfort levels on board has become more demanding.

Wärtsilä has met these targets by developing a sophisticated approach to propeller design based on a delicate balance of efficiency, cavitation patterns, hull excitation and noise, while still meeting the blade integrity requirements. In particular, this is made possible by appropriate selections of pitch, camber and chord distributions.

The combination of the propulsor with the engine requires optimum layout of the combinator modes for the CP propeller. Examples are shown for a RoPax application where the propeller characteristics are matched to the operational limits of the diesel engines.

The Efficiency Rudder is presented. This rudder is especially attractive for vessels needing to combine strict manoeuvring requirements with low fuel cost and low vibration levels.

New nozzle designs are available today including the HR nozzle. The application of the HR nozzle is supported by extensive CFD calculations showing the details of the flow phenomena and confirmed by full-scale experience. Significant improvements can be found which are of special interest for tugs, offshore applications and dredgers with their wide operational profile. ■