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THE HIGH COMFORT CLASS APPENDAGE DESIGN FOR CRUISE LINERS, FERRIES AND ROPAX VESSELS

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Figure 1: Modern high comfort class appendages in cruise liner.

ABSTRACT

The initial design stage is very important for the new vessel hydrodynamic success, difficulties there can follow the vessel during it's whole life time.
With modern cruise liners the shaft line, brackets, and bossing play a very important role, due to the fact that they have a major effect on appendage resistance, the wake field and propeller cavitation.
The wake field is the most important source of propeller-hull excitations and noise. The advantages of POD propulsion are mainly caused by optimum hull lines, the best possible wake field and small appendage resistance.
A wide range of wake measurements together with aft appendage alternatives are described to study carefully their effects to wake field and propulsion coefficients.
The wake of conventional appendages is compared with the wake of a podded propulsor in order to get a good view of expectations.
Especially wake tangential component effects to propeller tip vortex and propeller noise are shown with some cruise liner examples.
The use of vortex generators are studied for wake and noise improvement purposes to modern ferry case.
Finally, it is shown that the influence of the scale-effects is very important and this effect is investigated with RANS-calculations and model test, followed by a summary and conclusions.

Keywords

Initial hydrodynamic design, CFD tools, different example appendages, optimal propulsion coefficients, modern high comfort class appendages.

NOMENCLATURE

a - Propeller tip clearance [%]
a/R - Gap ratio (rudder)
AST - Anti Suction Tunnel
b - Propeller strut clearance [%]
b/D - Distance ratio (rudder)
c - Propeller rudder clearance [%]
CFD - Computational Fluid Dynamics
D - Propeller diameter [m]
d – Shaft line diameter [mm]
Dp_x_hu - Propeller x distance from hull acc. to shaft line [*D]
Dp_y_hu - Propeller y distance from hull CL to shaft line [* D]
etar - rotation efficiency
FD - Towing force in a self-propulsion test
J - Advanced coefficient v/(n•D)
KT - Thrust coefficient THR/(ζ•n^2•D^4)
KQ - Torque coefficient THR/(ζ•n^2•D^5)
Lcb - longitudinal centre of buoyancy
MABS - Masa Air Blowing System
O - From open water tests
P - From propulsion tests
PD - Propulsion power
PE - Effective power
PIV-Particle Image Velocimeter
PS - Shaft power [kW]
Q - Torque
R - Propeller radius
RT - Total resistance
THR - Total thrust [kN]
t or THD - Thrust deduction fraction (1-R/T)
t/c - Bracket thickness / cord
w_eff -Effective wake fraction (1-Va/Vs)
w_nom -Nominal wake fraction ()
WT - Wake fraction
v - Speed of propeller
Vs - Ship speed [knots]
VA - Speed of advance in propeller [knots]
n - Propeller rotation rate [RPM]
η_D - Propulsion efficiency
η_H - Hull efficiency
η_R - Rotation efficiency
ζ **-** density of water

1 INTRODUCTION

Mistakes in the initial design can cost a lot to the shipyard and its reputation can suffer much. It is very important in the initial design stage to look for several alternatives in order to find the optimum vessel to build and which is economical and suitable to operate for the client.

Time for the initial design is short and the process is iterative. The influence of changes in the hull form can be very remarkable and that is why it is important that the starting lines should be close to the final one already at the beginning of the project.

The hull form is always a compromise between many subjects: seakeeping, manoeuvring, resistance, propulsion efficiency, excitations, stability, springing, general arrangement, hard points for engine arrangement etc. The power of the vessel should be the minimum, because it gives better competition position for the customer.

The designer can not affect much to the viscous resistance, but he can do a lot with the wave resistance if its part of the total resistance is large. Today the potential flow CFD-methods are in daily use at the shipyards and the viscous flow calculations are in practical use already.

CFD-tools have improved the required propulsion power levels dramatically. CFD-tools have resulted into new possible hull form ideas, such as the Wave Damping Aftbody (Hämäläinen et al 1998 and 2000), which has improved the wave making resistance in the afterbody remarkably. In some vessel types resistance reduction can be even 15 - 20 per cent and their usefulness is clear for everybody.

The building schedule today is much harder than earlier and the designer has to reach the optimum in the shortest possible time. The whole hydrodynamic optimisation process at the shipyard is playing a very important role.

For many years specialists have tried to design hull forms and appendages with low interaction properties. As a matter of fact the interaction phenomena are rather complicated and therefore the best conclusions can only be drawn from a comparison between models from the same type of vessels with similar restrictions. Today CFD RANS calculations are helping in this subject.

The thrust deduction can be much higher than normally if the pressure field of the rudder is larger and it effect to the screw race. In fact it means that the thrust deduction fraction will be influenced by the rudder profile.

The axial wake of a twin screw ship is primarily generated by the hull clearances and the bossing and shaft dimensions. The tangential components are caused by the angle between the shaft centre line and the buttock of vertical plane through the shaft centreline.

In the comparison between conventional and podded case it is possible to see what can be expected from the change of the propulsion system when propeller location and diameter are identical.

In aft appendage design a lot of critical hydrodynamic items have to be taken into account so that the whole ship behaves well. The rules of thumb for different hydrodynamic subjects are very useful at the beginning of a project, because they give a rough idea of the

critical points and help the designer to concentrate carefully on the correct, and most important, critical subjects.
Due to the high comfort class requirements for cruise liners, ferries and ropax vessels, special attention has to be paid to the tangential component of the wake fields in order to reduce the tip-vortex. STX Europe has been carrying out an extended research program at model basins to investigate the behaviour of the propeller induced tip vortex which could result in propeller induced broadband noise.
For a modern cruise liner, the use of vortex generators or specially twisted rudders is discussed with regard to wake and noise improvement purposes. Scaling the results from model to full scale values is very important in case of flow controlling devices and therefore the scale effects are carefully studied by means of RANS-calculations.

2 MODERN HULL FORM DESIGN TODAY IN THE SHIPYARDS

Nowadays, the use of CFD methods at the research institutes and shipyards has taught the designers a new way of thinking when designing hull forms. The most important is a comprehensive understanding of the physical phenomena around the hull, when it is moving in water.
The basic knowledge has to be used to start the initial design of the hull form, but this design can be further optimized by means of CFD calculations instead of extended model investigations. A great advantage of using CFD in the hull form design is that the main part of the modifications is realized in the early stage of the design. A lot of time and money can be saved. Also the quality of the optimisation process has improved by using CFD techniques.
For calculation of wave resistance and potential flow, the computer program potential flow CFD is used. Potential flow CFD solves the fully non-linear potential flow problem in an iterative way. Main target of this program is to minimize the wave making resistance. In addition to the wave pattern, hull pressure distribution and the streamline direction along the hull is presented. It is very important that design experts make use of this tool and combine the results of their analysis with creative suggestions for improvement. The modification will be checked by new calculations in order to efficiently and quickly optimize the design.
Wave resistance is very sensitive to sectional area curve and waterline shape. Sectional area curve and waterlines can control the phases of fore-and-aft waves. By using smooth shoulders the wave phase remains almost unchanged but amplitude is improved. We can improve wave resistance significantly by decreasing sectional area curve inclination (figure 2). The shape of the waterlines, in the entrance area of the forebody should be designed carefully in combination with the bulbous bow, because of their influence on the phases and amplitude of waves

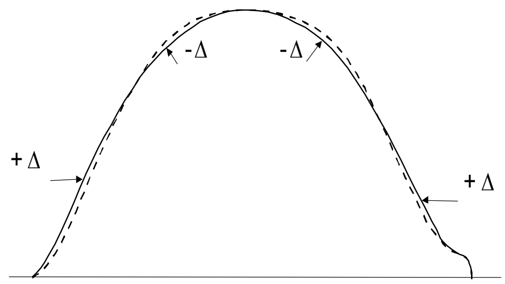


Figure 2. Sectional area curves

Another very important tool in modern ship hull design is the calculation of the viscous flow around the hull using the RANS CFD program. This program provides detailed information on the velocity and pressure field around the hull, the wake field in the propeller plane, the total resistance and the possible occurrence of flow separation. The RANS code predicts also the full-scale viscous flow around the ships.
Using RANS special attention can be paid to the development of the afterbody. Validation of calculated wake field with model experiments gives good results. Therefore the predicted wake field gives good information for further optimisation of the afterbody. The calculated wakefield sometimes is used as input for propeller design.
Model testing programs are still needed for validation of the by CFD optimised hull form and accurate prediction of performance of the ship and cavitation behaviour of the propeller. Only the number of modifications to be tested on model scale is limited and some earlier tests as paint tests and strut orientation tests are possible to be left out.
The experience of the designer can never be underestimated. By combining his experience with CFD results the designer can find the critical parts of the hull form, and thus improve it in an early stage of the project.
The following workflow scheme shortly describes the hull form optimisation process with hull definition and CFD-tools today at the shipyard.

2.1 The optimisation workflow

LIMITATIONS (general, seakeeping, manoeuvring)
⇩
STARTING HULL (S) SELECTION
⇩
GLOBAL/LOCAL MODIFICATIONS
⇨INITIAL HULL FORM
⇩
POTENTIAL CFD CALCULATION
⇦ ⇩ **MODIFY HULL**
⇩ ⇧
RESULTS EVALUATION ⇧

OK? **NO** ⇨⇨⇨
YES
⇩

RANS CFD CALCULATION ⇦
⇩ **MODIFY HULL**
⇩ ⇧
RESULTS EVALUATION ⇧

OK? **NO** ⇨⇨⇨
YES
⇩

MODEL TEST / CALCULATION COMPARISON

Limitations

At the beginning of a new design project the designer has to specify the limitations for the project. The limitations are some kind of instruction in the design process for the hydrodynamic expert.

Starting hull(s) selection, global/local modifications

In the next step the designer has to search in the shipyards database of previous designs in order to find the best possible starting hull to be used as the basis for the new project. The search is based on coefficients such as: L/B, B/T, D_p/T, C_b, LCB, $V_{service}$ etc. The result might be one of the following:

• No suitable hull forms are found. In this case the hull form can be defined well by parameter definition.
• One suitable hull form is found.
• Several suitable hull forms are found.

Potential CFD calculation

Potential flow CFD-software requires a set of points from NAPA program to define the hull form. The hull form should be divided to several parts in order to use offset information in Shipflow. In the following figure 3 a twin screw hull is divided into the five groups: forebulb, main hull, afthull, overhang and skeg.
The input file for the selected CFD solver has to be prepared. This includes the selection of the input parameters and creation of the hull/free surface mesh. An earlier input file normally is modified for project purposes.

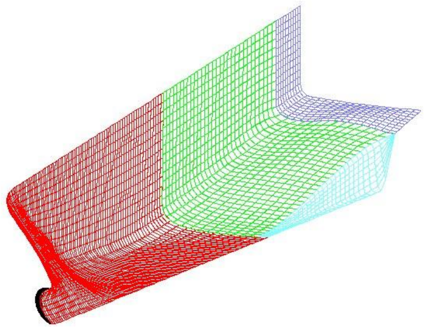


Figure 3. NAPA offset file for calculation.

After this the potential flow CFD calculation can be carried out.

Result evaluation

After the calculation the results are displayed numerically and visualized. The designer has to decide what modifications have to be performed in order to improve the hull form.
The results of the CFD calculations, which are most frequently used for analyzing the goodness of the hull, are:

• Wave pattern of the hull
• Pressure distribution
• Wave resistance
• Velocity vectors

By looking at the overall wave field it is possible to evaluate the wave making of the hull. Strong transversal waves dissipate a lot of energy and they should be avoided. A suitable interaction of the hull wave system might be seen as a calm area in the wave field. A regular shaped wave field is usually absorbing more energy than a messy looking wave system.
The most general method is to analyse the wave profile along the ship's hull. Aspects of most interest are the locations of wave humps and hollows, gradients of the waves and the wave amplitudes. If two wave humps occur at a distance of $2\pi F_n^2 L$ from each other, the other hump has to be moved by shifting of volume in the hull.

Modify hull

The actual hull form is modified and a new calculation loop is started. The modification lasts quite long in the traditional hull definition way, if the needed modification is large. In the quite new parametric way this process is faster.

RANS CFD calculation

The last decade, incredible improvements have been done in developing CFD programs.
RANS CFD calculations are done today always for bare hulls and often also for appended hulls. During the design process bare hull and appendage details that generate drag have been optimised by RANS CFD tool.
A lot of attentions is given to optimising brackets, bossing, bossing streamline particle, rudders, CL-skeg and aft frames.
The following figure 4 shows viscous flow calculations in model and full scale for conventional twin screw ship.

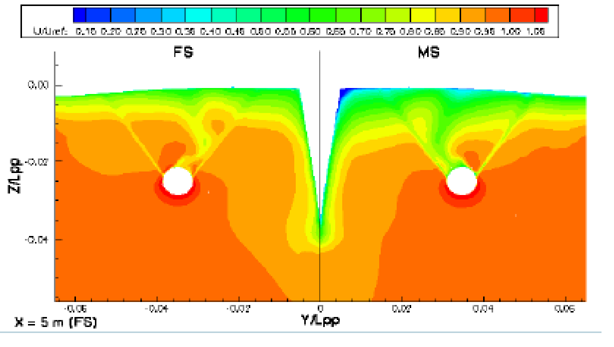


Figure 4. Viscous flow calculations results for full scale and model scale with conventional twin screw appendages

The following figure 5 shows the wave system close transom.

Figure 5. Transom wave system results.

Model test / calculation comparison

At some stage the shipyard is forced to terminate the calculation loop due to the time limits for the project and the hull form is sent to the model basin for testing.
After the model tests have been performed, the results are compared to the corresponding CFD results. This is done in order to gain more experience on the reliability of the CFD methods used.
Today the reliability of the potential flow method is well known and more validation work is done with viscous flow calculations.
Today viscous flow calculations with free surface effect: can calculate the total naked hull resistance very accurately, are useful to orientate appendages, give useful information from wake field, thrust deduction etc.

3 RELATION BETWEEN SHAFT LINE DESIGN, PROPULSION COEFFICIENTS AND WAKE FIELD

The shaft line design features for a buttock flow aft body on modern ferries and cruise liners are studied, which should fulfil the hardest latest requirements for fuel economy, vibration, noise, maintenance, erosion, manoeuvring etc.
Some typical examples are given with wake field information and propulsion coefficients. The starting point for appendage design is aft hull lines fullness with LCB and stability information, rudder steering room location, engine location and shaft line length.
When the length of the shaft tube is relatively short, bigger appendages are expected with big bossing. If longer or longest shaft tubes are possible to use, slender nice shaft arrangement with good wake can be reached. Normally longer shaft lengths (propeller shaft) give better wake field compared to short shaft tube with big streamline particle and bossing. Main reason for the wake improvements with long shaft lines is of course that the propeller is operating just out of the boundary layer. The subject is not always so simple and clear because the vessel length, fullness, LCB etc are effecting to the boundary layer thickness of the vessel and then to wake field quality. In this chapter is presented a general view what to expect from the wake field and propulsion coefficients of STX Europe in case a modern basic type of arrangement is used.

3.1 Typical today aft appendage design examples

In conventional propulsion the shaft line, brackets, and bossing play a very important role, because they have a major effect on appendage resistance, wake field and comfort levels. The wake field is today the most important source of propeller-hull excitations and is

playing even a more important role than earlier because there are now higher comfort class requirements.
The shaft line direction, in waterline section, should be converging to aft, but a shaft line parallel to the centreline is also good. The angle between flow-line (buttock line) and shaft-line should be less than 20 deg in profile view. The propeller and shaft line hull section distance should be more than 3.2×*Dp* (see Figure 8). The shaft length, shaft coupling size, and bossing construction have an effect on a lot of shaft bossing dimensions. Classification society requirements also influence bossing dimensioning.

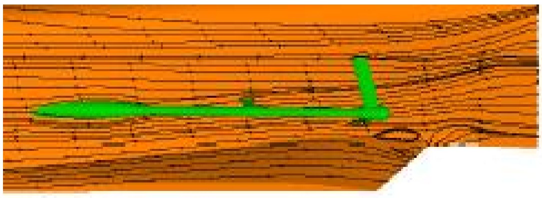


Figure 6. Appendage orientation by RANS-calculations.

The strength and vibration analysis defines bearing locations. The critical whirling frequencies are kept outside the operating RPM-range. This is achieved by spacing the supporting bearings. The first critical mode normally affects the aft part of the shafting.
Figure 8 shows a first bearing distance of 20.8×d (d=shaft diameter 547 mm) and a second distance of 11.3×d. In case an I-bracket is not present, the first bearing distance can be 27×d. The typical first bearing distance for Baltic ferries is 24×d and a typical value for cruisers is 25×d.
An I-bracket should be at least 0.9×Dp from the bossing. In closer situations, it is better to use a longer bossing and to remove the I-bracket.
Propeller distance from CL should be at least 98% of propeller diameter depending on CL skeg size (Figure 7). Too small a distance has a negative effect on propulsion coefficients, the extreme example is “overlapping propellers” as in figure 9. Quite typically, the propeller distance from CL in ferries and cruise liners is 103% to 111% of propeller diameter. The propeller distance from CL in our example vessels are as shown in table 1.

Table 1. Propeller distance from CL.

Ship example A	***102 % from Dp***
Ship example B	***119 % from Dp***
Ship example C	**104% from *Dp***
Ship example D	**143% from *Dp***
Ship example E	***85%* from Dp**
Ship example F	***101 % from Dp***

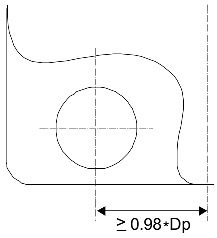


Figure 7. Minimum recommended propeller distance to centreline is 0.98*Dp

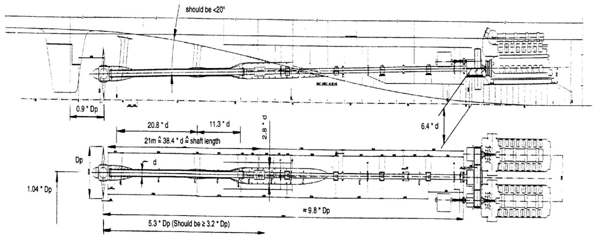


Figure 8. Shaft line arrangement

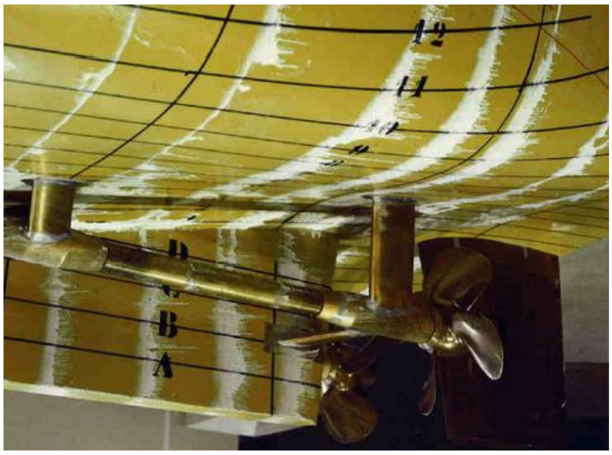


Figure 9. Overlapping propellers in ferry.

In the overlapping propeller (figure 9) case the idea is to combine advantages of single screw and twin screw cases.
Both propellers are located to the effective wake close CL of the ship, when higher hull efficiency is possible to reach and in the two propeller circle area is almost similiar with twin screw circle when higher open water efficiency can be reached compared to single screw case.
Appendage resistance is normally between single and twin screw cases.

The first aft appendage example A (Hämäläinen et al 2008) is a quite typical combination of long slender bossings supported by struts quite far from a propeller. This type of shafting arrangement has the advantage of a small wake peak, a protected shaft and an easy accessibility to the shaft. Nowadays, this alternative is used quite seldom for big cruise liners, because only one single big CL-rudder is used. Today cruise liners require higher manoeuvring capability than what can be obtained with this alternative with one large centre line rudder.

In this example A the intersection of the centre line of the bossing with the hull is drawn at a distance of about 5.1 times the propeller diameter from the propeller. The results of the wake measurements show an axial wake peak of about 31 % of the ship speed at about 0.8 R and at 0.7 R in a tangential velocity component of about 14% (reversing direction with regard to rotation angle)

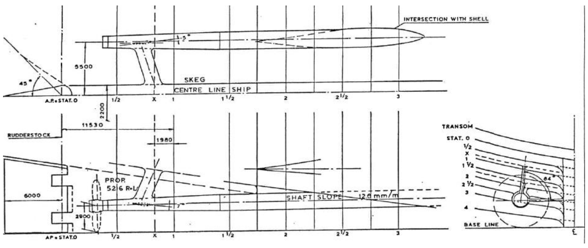


Figure 10: Long bossing supported with struts (example A)

The axial wake is primarily generated by the bossing and shaft. When the struts are well-oriented, quite far from the propeller and well fitted to the barrel and axial clearance to the propeller is adequate, the influence on the wake is small and negligible.

With this alternative, it is easy to observe the bossing effect in same bossing angle in the upper part of axial wake and specially Karman vortex (shaft shadow) of shaft tube in upper part of propeller hub. The bossing is located at such a distance that a deep wake peak is generated.

The outward rotating propellers were about 0.5-1 % better, which is roughly possible to see in tangential components: inward components are slightly bigger and that means bigger thrust for outward turning propeller.

The effective wake fraction is smaller than the nominal wake fraction and thrust deduction fraction is smaller than normally. CL-rudder is affecting to small thrust deduction values, because there is not anything behind the propeller. This type of CL-rudder compared two normal rudders behind the propellers improves the resistance by about 5 per cent and effects slightly negative to rotation efficiency, due to the fact that the flow straightening rudder is not positioned behind the propeller.

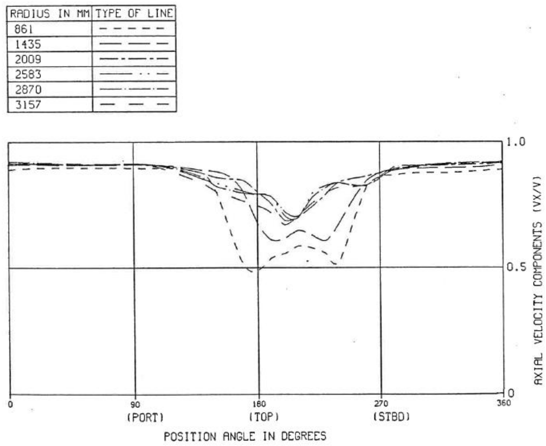


Figure 11. Axial wake for example A ship.

Generally, it can be concluded that in case of long bossing supported V-struts the tangential wake field shows larger inward directed components. Nowadays, the quite common appendages for twin screw vessels are open shaft with V-struts and a short bossing. For ferries and cruise liners this arrangement is often used.

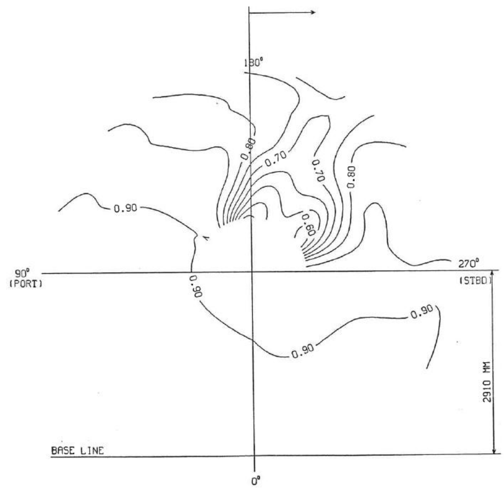


Figure 12. Axial wake field for example A ship.

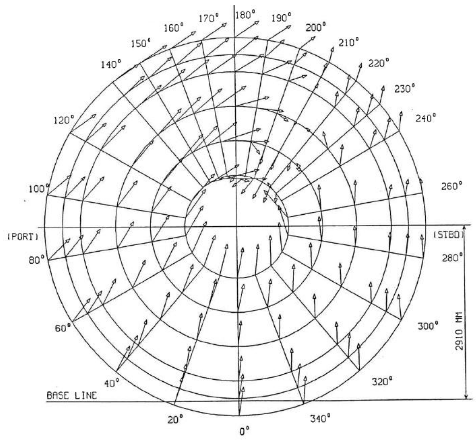


Figure 13. Wake field of long bossing with struts in example A.

In this B case the distance between the propeller plane and the protrusion of the shaft through the hull amounts about 4 times the propeller diameter. For this example attention has to be paid to the short bossing, due to the fact that this distance together with the distance to the propeller plane is responsible for the wake peak.

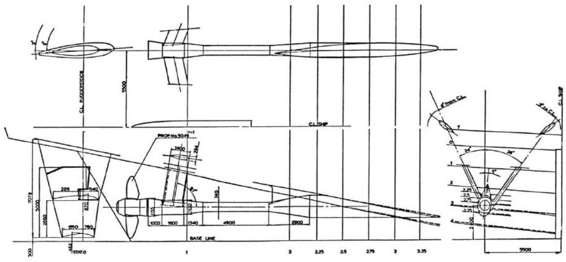


Figure 14. The most common appendages at present twin screw vessels, example B

It is noticed that the axial wake peak amounts to about 27% at the 0.7 R and 3 % at the 1.0 R radius. At 0.7R the tangential velocity component is about 17%. The influence of the struts is clearly noticed. This influence is the result of omitting the interaction of the propeller with the flow and the distance between the struts and the propeller. In this case the struts are tangentially fitted to the barrel. This is to be preferred, because struts pointing to the shaft centre line will easily hinder the flow through the struts.

In the axial wake a Karman vortex of the shaft tube is clearly visible and the bossing angle together with streamline particle is clearly noticed. It is important to realise that the waterflow is coming quite strongly from side to the CL direction and that is why this vortex and peak is located more to CL direction.

The hull boundary layer effect at the propeller tip area location is clearly visible. If it is possible to go more aft, propeller is located away from slow speed boundary layer.

The outward turning propellers are equal with inward turning propellers, resulting in the same propulsion efficiency in both rotation directions.

The differences between nominal and effective wake are small, this means that no extreme propeller interaction effects occur.

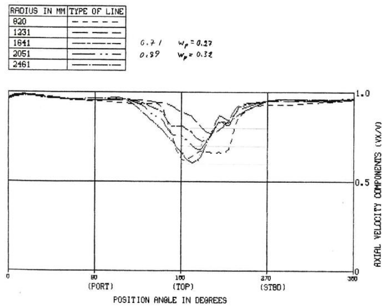


Figure 15. Axial wake for example vessel B.

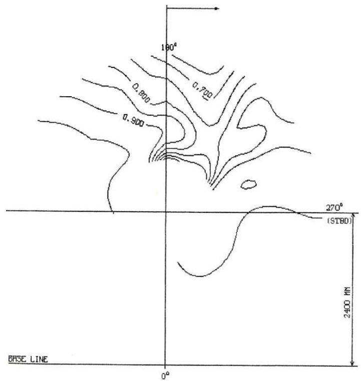


Figure 16: Axial wake for example vessel B.

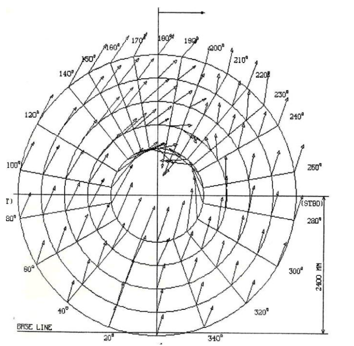


Figure 17: Tangential wake for example vessel B.

In the example C, we can see the most common appendages at present for twin screw vessels, open shaft with V-struts and I-struts (intermediate) and a short bossing.

For ferries, ropax and cruise liners this arrangement is often used. Sometimes second smaller V-strut is used instead of an I-strut to increase transverse support of the shaft system.

In this case the distance between the propeller plane and the protrusion of the shaft through the hull is about 5.3 times propeller diameter.

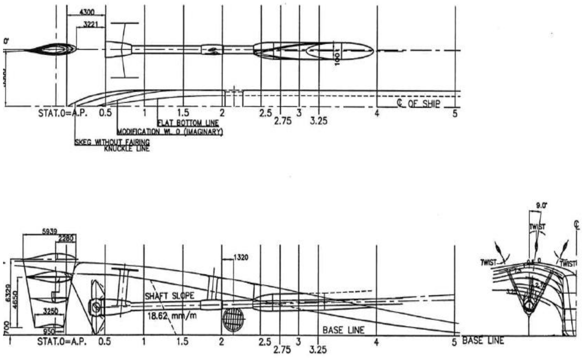


Figure 18. Typical shaft arrangement with intermediate strut for large RoPax vessel, example C

It is noticed that the axial wake peak amounts to about 22% at the 0.8 R and 17% at the 0.7 R, while both tangential velocity component amounts to 14%.

The circumferential distribution of the axial wake component is quite normal for this type of vessel. Only a small wake peak is visible in the area behind the inner struts of the V-brackets. The long shaft tube generates typical shaft shadow above propeller hub. The bossing is far enough to generate deep wake peak. The outer strut's small effect in wake field can be seen.

The tangential components are slightly bigger for outside direction. Bigger thrust when the propellers rotating inwards, but at the same time also bigger hull excitations.

No extreme propeller interaction effect occurs, when comparing nominal and effective wakes.

The inward turning propellers were about 1-2 % better.

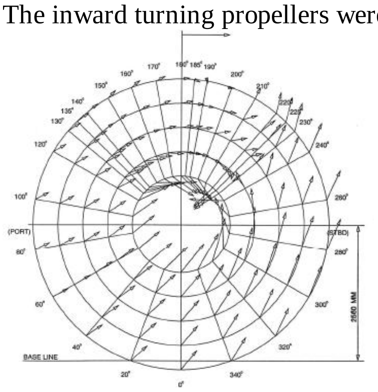


Figure 19. Tangential wake for example C.

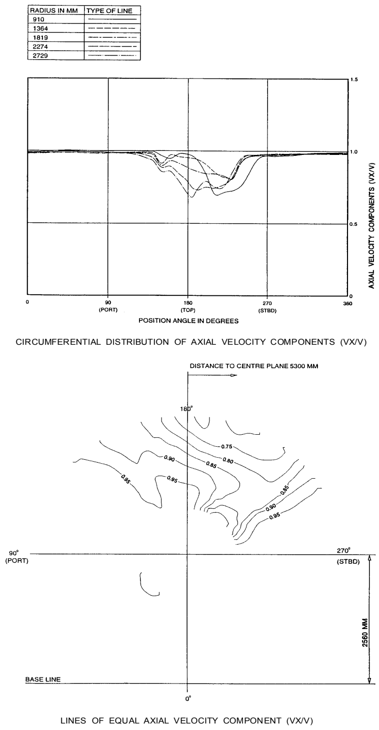


Figure 20. Example's C axial wake field.

The tangential components are somewhat larger for outside rotating direction. Therefore, inward turning rotating propeller is considerd favourable. The inward turning CPP propellers are also recommended when crabbing behaviour is compared to the outward turning propellers because they generate higher hull forces around aft body. In FPP propeller case outward turning propellers are better in crabbing behavoiur.

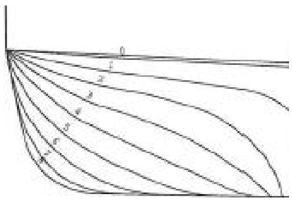


Figure 21. Example vessel D's aftbody lines

In the example D, quite common appendages for V-shaped aft frame twin screw vessels with open shaft with V-struts and a short bossing are used. The inner strut is supported to CL-skeg more horizontally (= L-strut). In the past this arrangement was often used for ferries, but it is not common anymore.

In this case the distance between the propeller plane and the protrusion of the shaft through the hull amounts about 4.5 times propeller diameter. Here water flow direction to CL and shaft direction to side direction are given special marks to the wake field. The wake field is anyway quite good; small wake peak, low axial wake gradients and tangential components which are equal to both directions.

It is noticed that the axial wake peak amounts to about 27 % at the 0.8 R and 26 % at 0.7 R. The tangential component amounts to about 14 % of the ship speed. The influence of the inner and outer struts is noticed. In this case the struts are tangentially fitted to the barrel.

In this example D propeller shafts are diverging aft, which is not common anymore today and the rudder is located at the inner side of the shaft line, which is not common today if we are thinking of a typical toe-out crabbing situation in harbours and propeller steering forces and moments. The rudder location from 0.3 - 0.5 *R from propeller line must be avoided normally, because it has a negative effect to rotation efficiency.

Maintenance has been a reason for this type of selection. Nowadays, the mostly used rudder location is exactly behind the shaft line. Sometimes, for special reason also outside location of the rudders are used.

The appendage resistance is quite high for this type of vessel. One reason for high appendage resistance is diverging shaft lines.

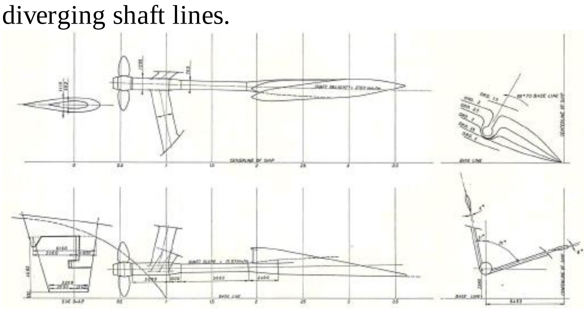


Figure 22. Example D with diverging shafts.

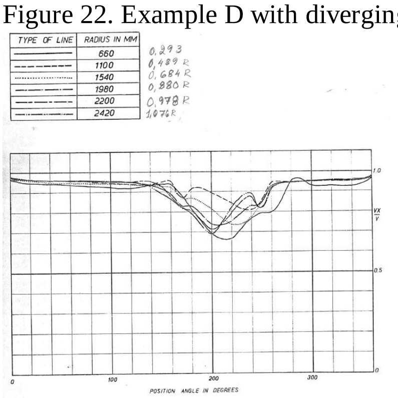


Figure 23. The axial wake for example D.

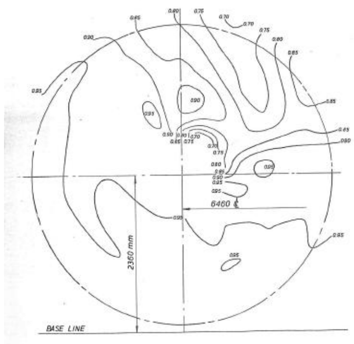


Figure 24. The axial wake for example D.

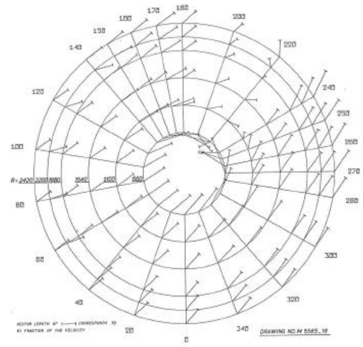


Figure 25. The tangential wake for example D.

In the axial wake plot, the bossings and shaft tube's boundary layer effects are clearly shown. The strength of the tangential component is identical in both directions, which means that inward and outwards turning propellers are equal from efficiency point of view. Here inward turning direction was selected.

In the following figure the body plan of the example vessel E. is presented. The 7 degrees converging shaft angle, splitter plate fitted on the shaft tube and CL-skeg L-strut support are used in this.

In the figures 28 and 29 are shown the axial wake for example E. Closer propeller connections are used than normally: 0.85*Dp distance to CL and 4.15*Dp from propeller to hull and propeller line connection.

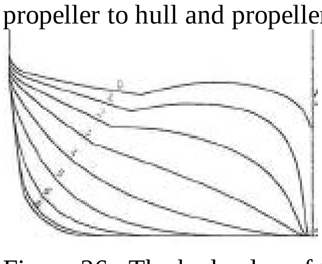


Figure 26. The body plan of the example vessel E.

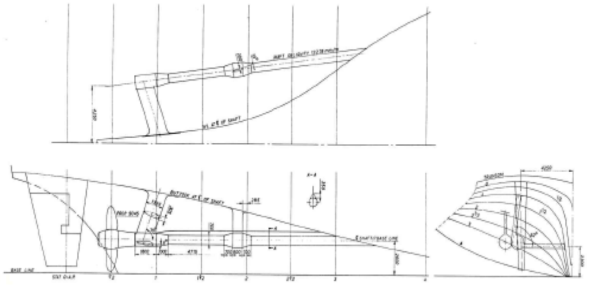


Figure 27. Example E with 7 deg. converging shaft angle and splitter plates.

A quite deep and narrow wake peak is shown in figure 28. The splitter plates have not positive effects to Karman vortices and the shaft converging angle is too big to the surrounding water flow. It is possible to see shaft/hull connection effect to wake without streamline particle and shadow of transverse strut to wake.
It is noticed that the axial wake peak amounts to about 38% at the 0.7 R and 41% at 0.8 R. The tangential component amounts about 15% of the ship speed. The influence of the inner strut (L-strut) is noticed. In this case the struts are tangentially fitted to the barrel.

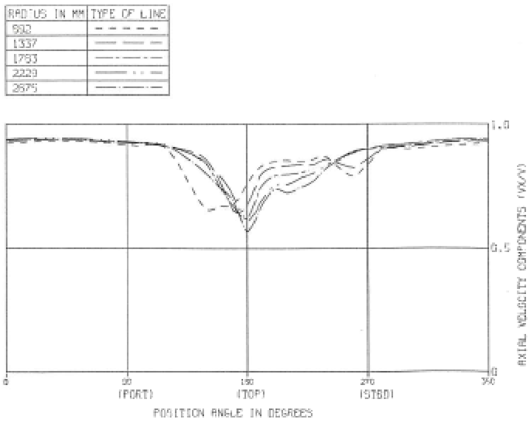


Figure 28. Axial wake for example E.

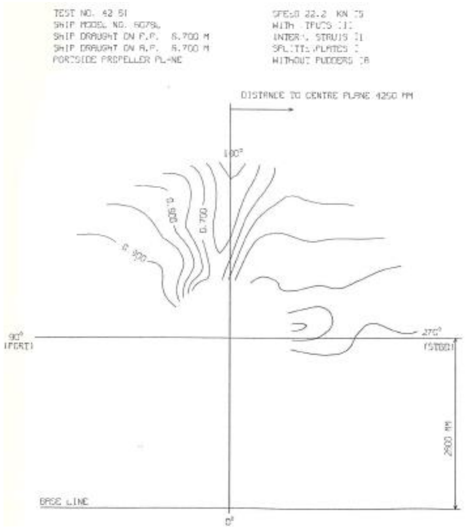


Figure 29. Axial wake for example E.

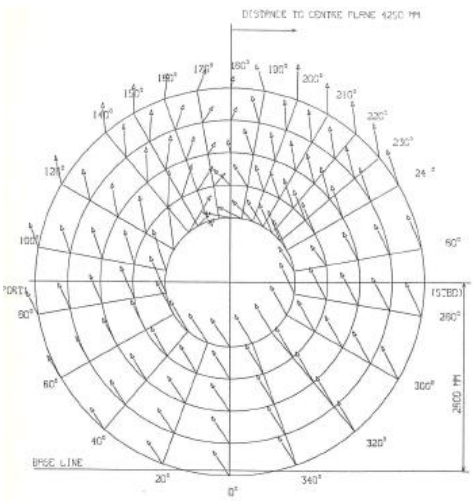


Figure 30. Tangential wake for example E.

In the example F, we can see modern high comfort class appendages for twin screw vessels. In this type of arrangements long shaft lengths are normally used.
The distance between the propeller plane and the protrusion of the shaft through the hull is almost 6 times the propeller diameter.
It is noticed that the axial wake peak amounts to about 27% at the 0.7 R and tangential velocity component about 11%.

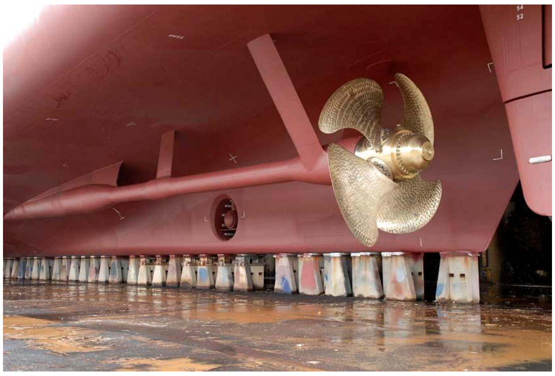


Figure 31. Modern aft appendages in example F.

The circumferential distribution of the axial wake component is quite normal for this type of vessel. Only a small wake peak is visible in the area behind the outer struts of the V-brackets. The long shaft tube generates typical shaft shadow above propeller hub. The bossing is far enough to generate deep wake peak. The outer strut’s small effect in wake field can be seen.

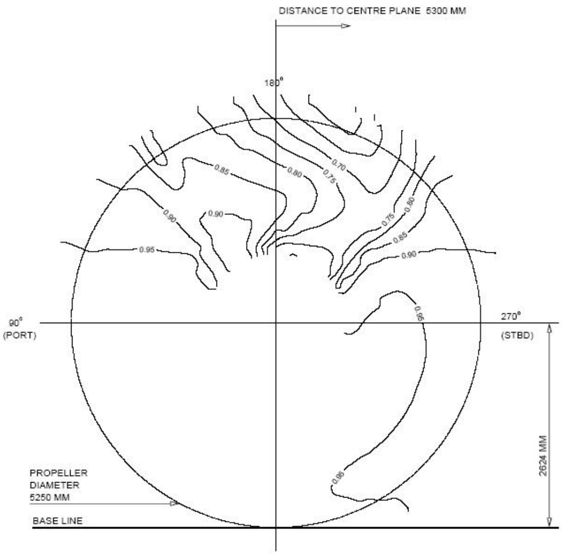


Figure 32. Axial wake for Ferry F.

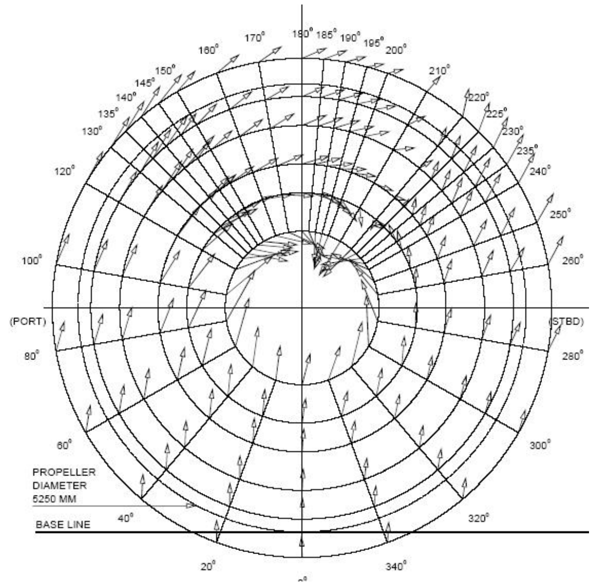


Figure 33. Tangential wake in example F.

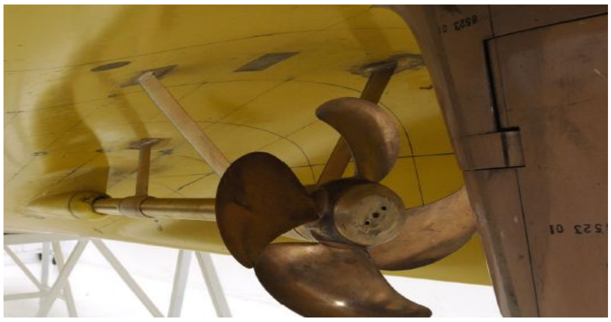


Figure 34. Ferry F in model scale.

In a conventional single screw vessel V-shaped sections are typically used when the big part of boundary layer is in propeller plane. The propeller is working in slow flow which it is once again accelerating. In this type of arrangement hull efficiency reaches a rather high level of about 1.2 compared to a twin screw vessel where values between 0.9-1.0 are often found.

In a conventional twin screw vessel both propeller circle area is quite much bigger compared to single screw case. Due to this effect, open water efficiency is normally higher compared to single screw case. In single screw case for shaft supporting struts, bossings etc are not needed and therefore appendage resistance is lower for single screw case.

In this example E, where propellers are quite close already, the idea is to combine partly the advantages of single screw and twin screw vessels. In the overlapping case this is clearly normally reached.

Today’s hard comfort requirements normally prevent the use of this type of “overlapping” type arrangement together with twin skeg arrangements for modern cruise liners, RoPax and ferries.

3.2 Interaction between ship and propeller

Wake is the velocity imparted to the surrounding fluid by a moving vessel. In a ship fixed reference frame it means velocity loss behind a vessel in a uniform onset flow.

In ship hydrodynamics a distinction is made between “nominal” and “effective” wake. Nominal wake means the wake of a towed vessel model in absence of the propeller. Effective wake is described as the wake that is experienced by the propeller while operating.

Nominal wake is a physically clearly defined concept. Effective wake is an artificial concept. The mean effective wake is usually determined from the results of propulsion and open water tests.

The spatial distribution of the effective wake cannot directly be measured. It must either be determined as the sum of the nominal wake and the interaction effect determined from the propulsion tests or as the difference between the total velocity with operating propeller and the propeller-induced velocities. The effective wake depends on the calculation method used.

Typically, flow speed fields are determined by means of model test without propeller by measuring the speed by a Pitot-tube. The ship’s wake field consists of three components:

-Potential wake (or displacement wake), which is the effect of the ship form in inviscid flow. The variation of the potential wake over the propeller disc is small.

-Wave wake, which describes the effect of the wave forming to the flow in stern ship.

-Viscous wake, which is the effect of the boundary layer to the speed distribution. This has the biggest effect to the wake field.

It may be observed that the scale effect on the potential wake as well as on the wave wake is small. For single screw ships the viscous wake is dominant while the effects of the smaller potential and wave components to the propeller can be almost neglected.

For twin screw ships a separation of the wake into various components is more helpful. The wake structure is here more simple because the hull boundary layer appears only at the border of the propeller disc. The contribution of shaft wake and supporting strut wakes can be separated and considered as being superposed on the potential wake.

In connection with the requested information for a propeller design, decomposition into the axial and the transverse flow field is quite common.

During model basin’s wake measurements the ship model is fitted with a 5-hole Pitot tube, which is mounted at the location of the propeller plane. The pressure differences are measured by a differential pressure transducer, which is fitted in the model. The angles and radii are adjusted by using a remote control system. During the test the rudders, including the horn, are not fitted when they are positioned behind the propeller disc. The results are not corrected for scale effects and will be valid for a speed range of a few knots.

In podded propulsor case, similar wake field measurements are conducted at the propeller plane. Due to practical reasons from a measuring point of view, the models of the pods are omitted. The measured values of this condition without pods are corrected for the influence of the pods behind the Pitot tube. These corrections are based on theoretical calculations of the flow around the pods, using CFD (potential flow) methods. It is important to notice this wake measurements and calculation difference between conventional and pod cases.

Nowadays, PIV (Particle Image Velocimeter) is giving more detailed information of the total wake of the propeller and of the complex interaction between the propeller and the rudder. PIV measurements are based on the illumination of seeding particles that move with the flow using a thin laser sheet and on simultaneous image acquisition of the illuminated plane.

The PIV information clearly illustrates the critical areas and sometimes large angles of attack that occur behind the propeller. Although sometimes high flow angles are found in the PIV results, this does not automatically mean that the rudder will experience these angles of attack. Critical for the dynamic onset flow of the rudder is the reduced frequency of the flow angle variations. Strong variations of the angle of attack might not lead to sharp leading-edge suction peaks on the leading-edge of the profile as might be expected.

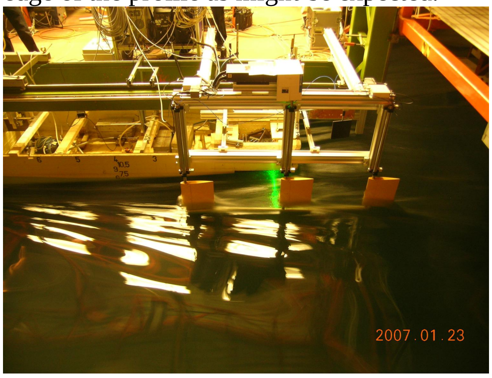


Figure 35. PIV measurements on a cruise liner.

PIV information gives totally new feature to the whole flow field around propeller and rudder in model scale. It gives also a more detailed view from propeller inflow flow. In figure 35 a test set-up of PIV measurements in towing tank in Helsinki University of Technology. In this figure, laser light is clearly visible.

In figure 36, an example of the results from PIV measurements is shown. This picture shows the velocity of the flow behind the running propeller. The propeller is rotating from up to the left in the picture. The propeller centre line is located at (0, 0).

In figure 37, the angle of attack, relative to the rudder chord line and derived from PIV measurements behind the propeller of a modern ferry, is shown. In this picture, the blue line is corresponding to an angle of attack of about 15 deg.

In figure 38, a picture of the results of PIV measurements at the location just in front of the propeller location is given. This figure clearly shows the boundary layer and strut effect. PIV-measurements in a model scale give very important information especially when something new and unknown is studied. It helps to understand interactions between appendages and propeller. Especially whole propeller vortices are important to understand in new, unknown designs where the designer can not use his earlier experiences.

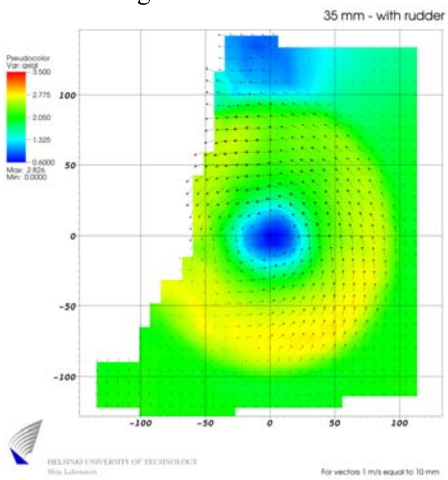


Figure 36. The velocity fields acc. to PIV measurements.

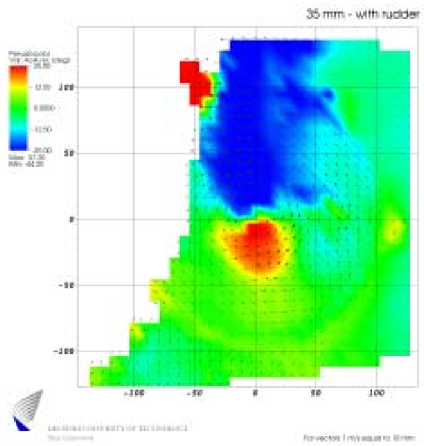


Figure 37. Angle of attack relative to the rudder chord line.

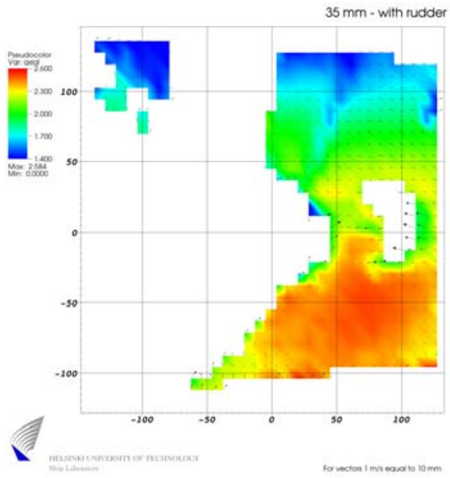


Figure 38. PIV measurements between V-strut and propeller

In the following figures (39 to 40) a wake comparison between examples A, B, C, D, E and F is shown. The results of this comparison show that the example C gives the best axial wake gradients and smallest wake peak value, while version E gives the deepest wake peak.

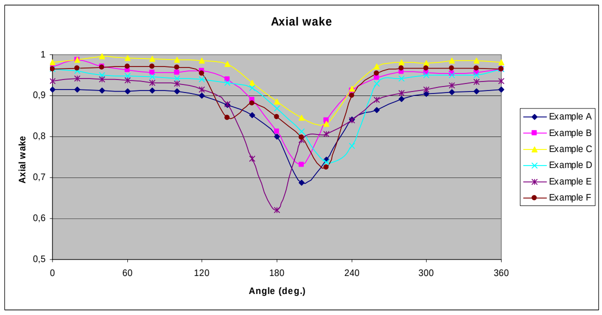


Figure 39. Axial wake at 0.7 R for examples A, B, C, D, E and F.

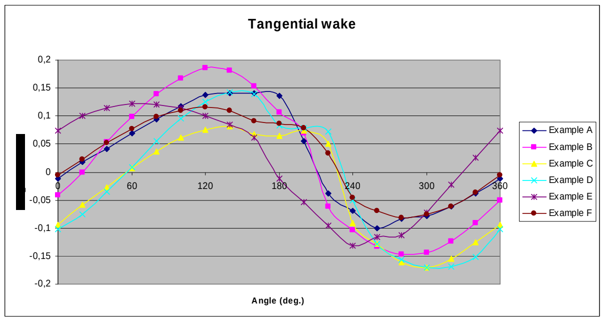


Figure 40. Tangential wake for examples A, B, C, D, E and F.

The results of example B show the highest tangential component at 0.7 R. The tangential components are caused by the angle between the shaft centre line and the buttock of vertical plane through the shaft centreline. This angle is typically varying between 1 and 2 degrees. Sometimes even 5 degrees occurs. When this angle increases, tangential components are increasing too.

The wake of the vessel is playing a very important role when we are looking at the highest comfort class levels. Today, when energy is more and more expensive in addition of wave resistance, the higest propulsion efficiency is tried to reach.
For presented example vessels, propulsion coefficients are shown in the following figures.
In the figure 41, effective wake is shown for example vessels. In B, where the distance is short between the propeller plane and the protrusion of the shaft through the hull, is high effective wake with version D, where V-hull form is used.

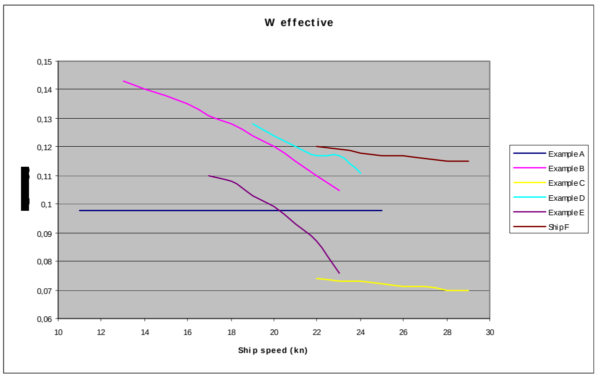


Figure 41. Effective wake between examples A, B, C, D, E and F.

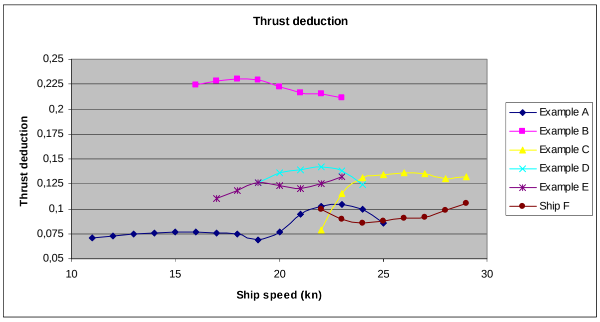


Figure 42. Thrust deductions for examples A, B, C, D, E and F.

In example A, where the rudder is not located behind propeller, the lowest thrust deduction values are obtained. In B, where the distance is short between the propeller plane and the protrusion of the shaft through the hull, the thrust deduction is the highest.

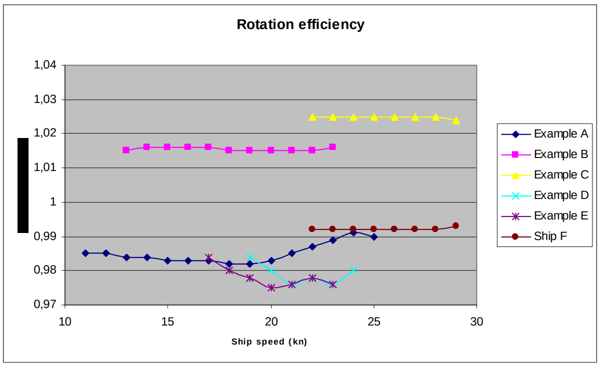


Figure 43: Rotation efficiency for examples A, B, C, D, E and F.

The rotation efficiency is the highest for the examples C and B, where the rudder is located parallel to the propeller shaft line. Lowest values are obtained for examples E and D where rudders are not parallel located with propeller shaft lines. The rudder should be directly behind the propeller as is normally the situation today.

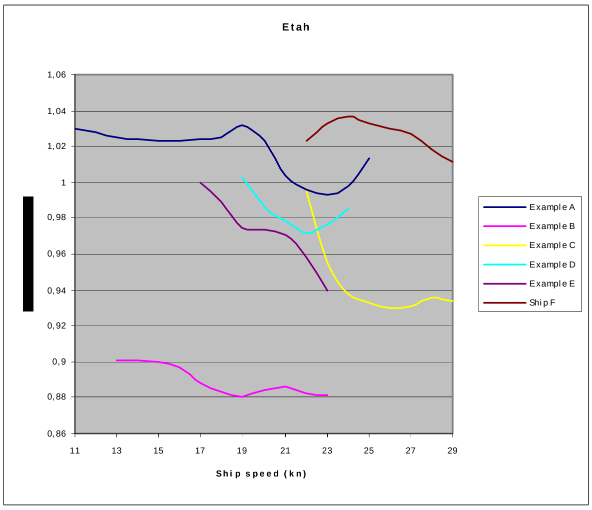


Figure 44. Hull efficiency for examples A, B, C, D, E and F.

In example A, where the rudder is not located behind the propeller, the higest hull efficiency values are obtained together with modern F ferry design.

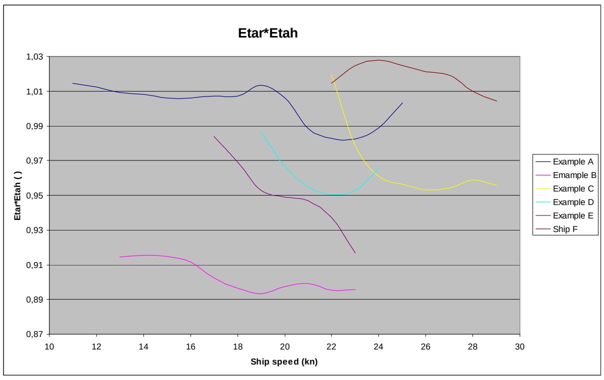


Figure 45. Rotation efficiency times hull efficiency for examples A, B, C, D, E and F.

In examples F and A are the highest rotation efficiency times hull efficiency.
There is a huge 5 % differency between C and F examples. The main dimensions and propellers are quite similiar in both cases, but in F more attention has been put for propulsion efficiency by using experiences and CFD.
The lowest rotation efficiency times hull efficiency value is in example B.

For many years specialists have tried to design hull forms and appendages with low interaction properties. As a matter of fact the interaction phenomena are rather complicated and therefore the best conclusions can only be drawn from a comparison between models from the same type of vessels with similar restrictions. Today RANS CFD calculations can help in this subject.

4 DIFFERENCES IN WAKE AND PROPULSION COEFFICIENT BETWEEN CONVENTIONAL AND PODDED PROPULSION

The wake field differences between conventional and podded cases are studied in identical propeller location.
The podded case is kind of best possible wake field case, where shaft tube, bossing and streamline particle is not effecting.

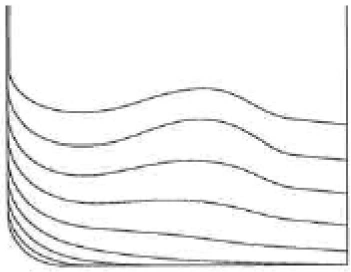


Figure 46. Aft hull lines for conventional and podded propulsion cases.

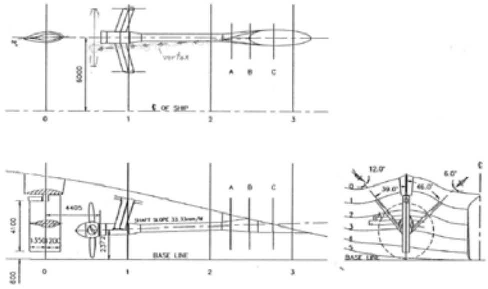


Figure 47. Conventional propulsion

In the previous figure conventional are looked together with podded case.

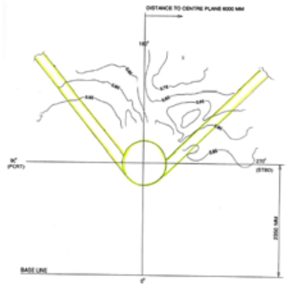


Figure 48. Axial wake in conventional case

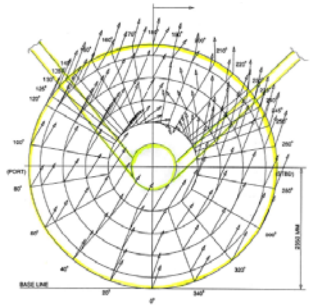


Figure 49. Tangential wake in conventional case

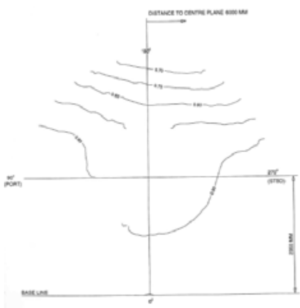


Figure 50. Axial wake in podded case

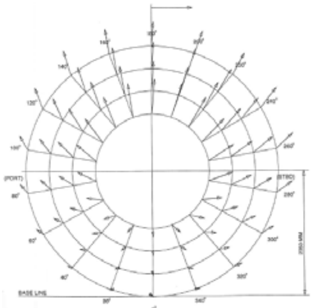


Figure 51: Tangential wake in podded case

When comparing axial and tangential wakes at 0.7 R, we can see that axial drop from 26 % to 15 % and tangential from 21 % to 9 %. Tangential wake is a big advantage for podded propulsion, it improves the tip vortex behaviour and thus noise and vibration characteristics.
In this comparison the optimum pod location is not used, it is possible to see what can be expected from the propulsion system, which has changed from conventional shaft lines to podded propulsion system:
-Aft appendage resistance decreases in pod case
-Wake is hull boundary layer together with pod arm effects in Pod case
-The biggest difference is possible to see in wake tangential components. That has big effects to high comforts classes.
-It is also important to realize that in the podded case tangential component changes when the ship is steered.

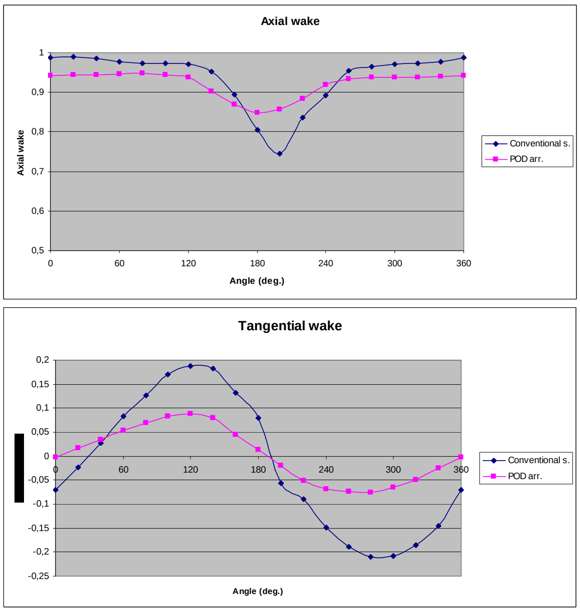


Figure 52. Axial and tangential wake comparison between conventional and podded case without pod arm and rudder effects

The following figure shows that propulsion coefficient for podded propulsion is about 6 per cent higher than at same propeller conventional propulsion case. Main reason for higher propulsion coefficient is higher rotation efficiency in podded case.

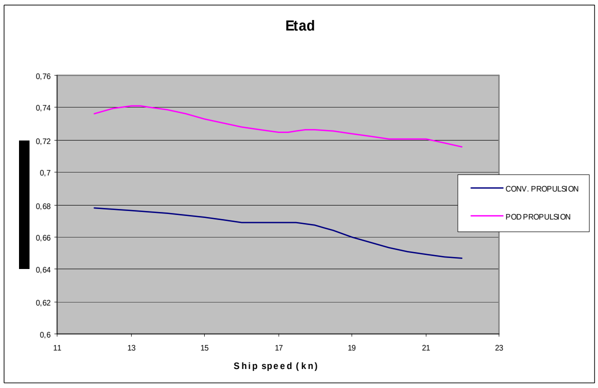


Figure 53. Propulsion coefficient differences between conventional and podded propulsion

5 THE HIGHEST PROPULSION COEFFICIENTS IN CRUISE LINER AFT BODY

Earlier hydrodynamic experts have examined mainly wave resistances and open water efficiencies of the projects and newbuildings. Today RANS CFD together with model tests make it possible to look the highest propulsion efficiency to the whole project.
The propulsion efficiency can be defined when open water characteristics are measured in open water test (=O) and thrust (THR) both torque (Q) are measured in propulsion test (=P):

$$\eta_D = PE/PD = (RT \bullet VS)/(2 \bullet \pi \bullet n \bullet Q) =$$

$$(1\text{-}THD) / (1\text{-}WT) \bullet (THR \bullet VA) / (2 \bullet \pi \bullet n \bullet Q) \bullet QO/QP =$$

$$\eta_H \bullet \eta_O \bullet \eta_R$$

$$WT = 1 - VA / VS$$

$$THD = (THR-(RT-FD)) / THR$$

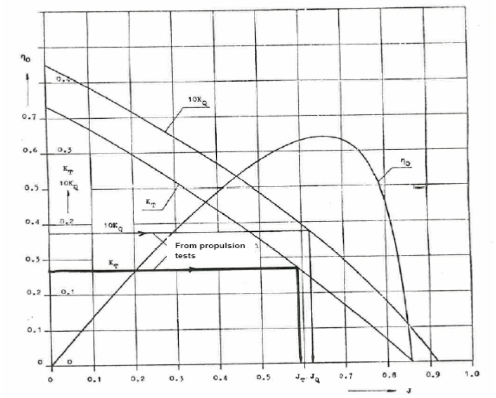
WT is the wake fraction, THD is thrust deduction and FD is towing force compensating for the differences in model and full-scale frictional coefficient..

The wake fraction has been defined by using the difference between the total velocity with operating propeller and the propeller-open water induced velocities. The following figure 54 show wake definition by using KT and J values.

$$WT = 1 - JO / JP$$

The propeller's thrust in the model is not the same as resistance, the reason for that is that the propeller is working in water flow, where the flow is effecting in different directions. This water flow generates low pressure in aftbody, which effect against sailing direction.

In a twin screw vessel, propeller diameter increase normally decrease THD and WT values.
The shaft struts and shaft tube effect the wake quite a lot but not so much the thrust deduction.
The rotation efficiency describe normally how suitable the propeller is to the hull and its flow field. How homogenous the flow is and how much vortex there are, effect the values.



igure 54. Open water coefficients.

The general type of explanation which is normally given to the interaction coefficients: thrust deduction fraction THD, wake fraction WR and relative rotative efficiency η_R, is based on the interaction of the propeller with the hull. The thrust deduction fraction is explained as an extra resistance of the hull, the wake fraction as a displacement and viscous effect of the hull and the rotative efficiency as a factor influenced by the irregular flow field behind the hull.
It is noticed that there is a rudder effect on the interaction coefficients. The water in the propeller slipstream is rotating, which is a loss of energy because the rotating motion contains kinetic energy that is transmitted from the propeller into the wake of the vessel. If the rudder is located directly in the propeller slipstream, it can recover part of the rotational energy. The amount of energy that is recoverd by the rudder is dependent on the rudder profile form, aspect ratio and rudder location.
The old Kafali (Kafali 1961) publication concerning propeller characteristics with different rudder locations is yet today current, because this type of studies are seldom done during normal model tests. In the following figures the rudder and its different location effects on open water values are shown.

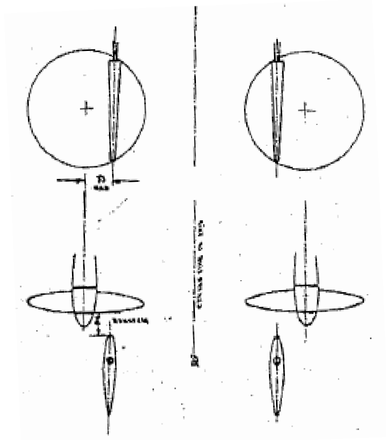


Figure 55. a is the gap between propeller centerline and rudder centerline. b is the distance between propeller blade and rudder leading edge.

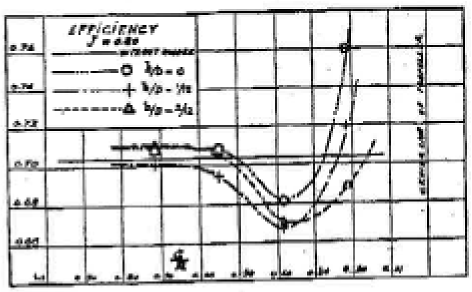


Figure 56. The distance ratios are as a parameter and the gap ratios as abscissa both open water efficiency as ordinate axis.

In the figure 56, the distance ratios (b/D) are as a parameter and the gap ratios (a/R) as abscissa at the convenient value of J=0.80, which corresponds to the maximum efficiency of the propeller without rudders.
It can be seen from these figures that the thrusts for different locations of the rudder seem to be improved in the propeller race.

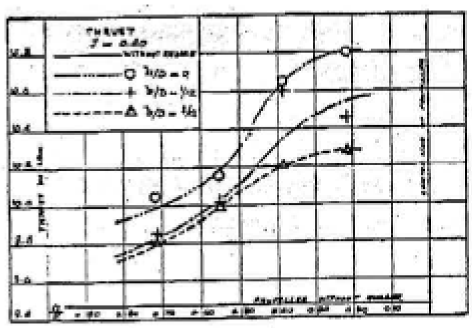


Figure 57. The distance ratios are as a parameter and the gap ratios as abscissa both thrust as ordinate axis.

In the figure 57, the distance ratios (b/D) are as a parameter and the gap ratios (a/R) as abscissa at the convenient value of J=0.80, which corresponds to the maximum efficiency of the propeller without rudders. The propeller without rudder is shown in lower part of the figure. It can be seen from these figures that the thrusts seems to increase gradually with distane ratio decreases, and toward the propeller blades tip the amount of improvement seems to diminish. In this study high drag coefficients generally lie within a/R=0.25-0.70. It can be seen that a low range of efficiency occurs about the same part of the propeller radius. In the figure 58, the distance ratios are as a parameter and the advance (J) as abscissa both propeller open water characteristics as ordinate axis.

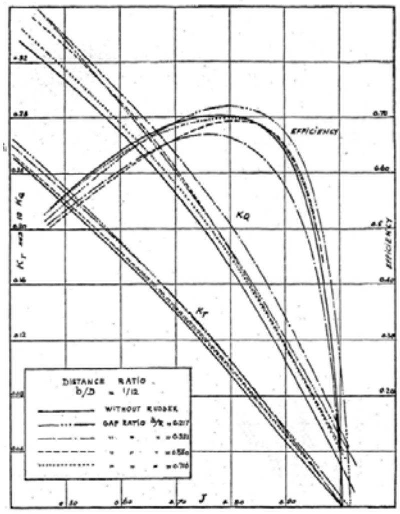


Figure 58. The distance ratios are as a parameter and the advance (J) as abscissa both propeller open water characteristics as ordinate axis.

According to work, the rudder should be located parallel with propeller line.

In the following figures 59 and 60 is summary from propulsion coefficient findings for typical flat cruise liner aft bodies with appendages.

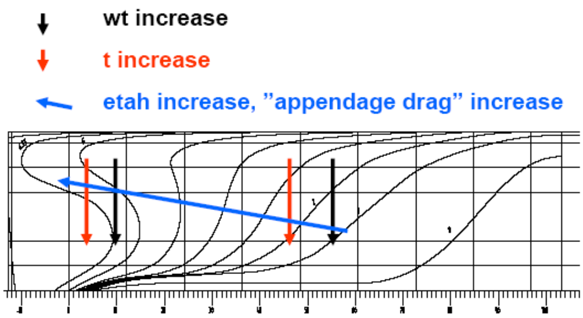


Figure 59. Wake, thrust deduction and hull efficiency increase directions in common modern flat aft body

In a typical flat cruise liner aft body wake and thrust deduction is increasing closer CL-skeg. The hull efficiency, η_H = (1-THD) / (1-WT), are increasing together with appendage resistance to the transom coner direction.

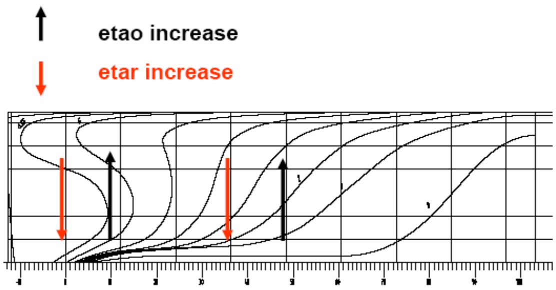


Figure 60. Open water and rotation efficiency increase directions in modern flat twin screw aftbody

In a typical flat cruise liner aft body open water efficiency is increasing outside direction and rotation efficiency is incresing closer CL.

In a narrow, fast pod cruise liner, skeg is effecting together with pod unit a lot to the resistance and propulsion efficiency. In the following figures from 61 to 63 are configuration of the hull with -5 m, -2.5 m, original and +4 m pod locations.

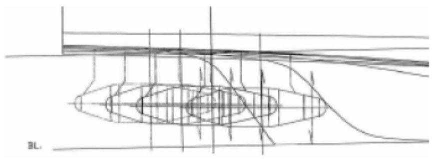


Figure 61. Four different pod locations in podded cruise liner.

The studied locations were: - 5 m (the aftmost) from original, -2.5 m from original, original, +4 m from original. The resistance, propulsion coefficients, wave profile in different distances and propulsion power were investigated. There were big interaction effects between the CL-skeg and the pod unit.

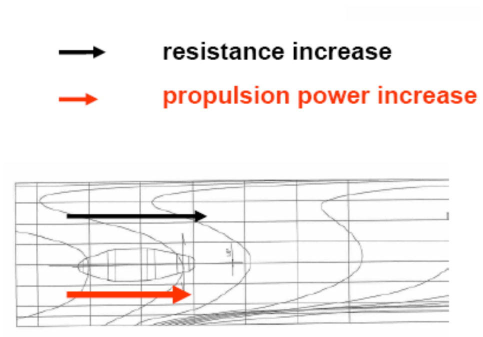


Figure 62. The resistance and propulsion power increases in podded cruise liner aft body

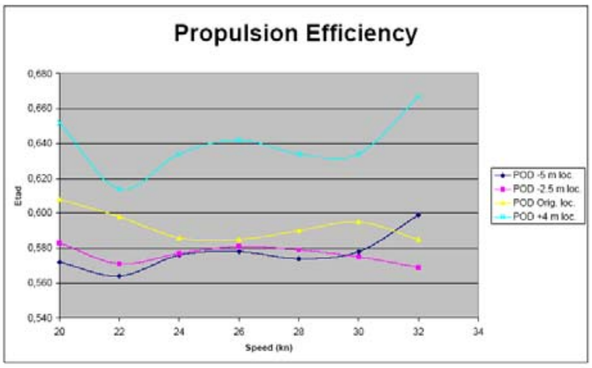


Figure 63. The propulsion efficiency in different pod locations.

The aftmost location (-5 m) is given the lowest propulsion efficiency and the foremost the highest (-4 m).
In the total optimisation the propulsion efficiency and the resitance have to take into account at the same time.

6 THE LATEST APPENDAGE DESIGNS TO REACH THE HIGHEST COMFORT CLASS

Appendage designs (Hamalainen et al 2008) such as shaft struts and rudders for modern high comfort class commercial vessels poses many challenges which earlier have been met only in naval ships. The commercial vessels offer an even more difficult task because they have to operate continuously in several engine modes as 2+2 engines, 2+1 engines and 1+1 engine modes. Naval vessels spend the vast majority of their life span at economical power or even at dockside.
Appendage cavitation and erosion have been a quite difficult subject to handle in model scale only but by using full scale feedbacks from shipyards and clients together with the latest CFD RANS calculations, their handling has been improved.
In a towing tank where the optimum alignment of the struts is investigated by means of paint on the strut plates, the results can cause difference with the final optimum inflow angle on full scale.

Also the results of 3-dimensional wake measurements show average velocities without propeller operation. What is happening behind the propeller, which is angle of attacks to the rudder has been earlier quite unknown information.
Generally, the rudder neutral angle is normally optimised for minimum power, not for the best cavitation, erosion and noise.
The traditional approach may be combined with CFD-studies in model scale and full scale.
Earlier mentioned ways can also be combined to PIV (Particle Image Velocimeter) measurements, which gives a good 3D view from the whole water flow around the propeller and the rudder in the model scale.
In earlier chapters a wide range of wake measurements and conventional aft appendage alternatives have been described to show carefully their effects on wake field and propulsion coefficients. This chapter concentrates on the most important part in the wake field when considering the highest comfort classes.
The wake field is the most important source of propeller-hull excitations and noise.
In conventional cases it is almost impossible by normal design ways to avoid tangential components against propeller rotation. The tangential components which effect to the same direction with propeller rotation are good but components which are against propeller rotation, they generate normally tip vortex which can be the reason to broadband noise.

Due to the high comfort class requirements for Cruise liners and high level ferries, special attention has to be paid to the tangential component of the wake fields in order to reduce the tip-vortex.
The STX Europe has been carrying out an extended research program at model basins and in full scale to investigate the behaviour of the propeller induced tip vortex which could be result in propeller induced broadband noise in some shipyard's reference cases.

Following appendage modifications or propeller modifications has been studied in order to reduce the tip vortex in this R&D ship.

- Vortex generators with different angles fitted to the I-bracket and bossing streamline particle. A vortex generator means a curved plate to the shell of the ship in order to influence the tangential wake field at the propeller tip. See figures 64 and 65 from different vortex generator possibilities.
- Propeller modification by partly cutting away the blade tips. The modification of the trailing edges of the blade sections has been made in order to reduce the loading of the propeller blades at the tip.
- Changing of the neutral steering angle of the rudder. Movable rudder and fixed rudder horn and

headbox have been investigated independently.

- Design of an asymmetric rudder. Neutral rudder and horn angles have been optimised for optimum tip vortex.

Figure 64. Vortex generator in intermediate strut

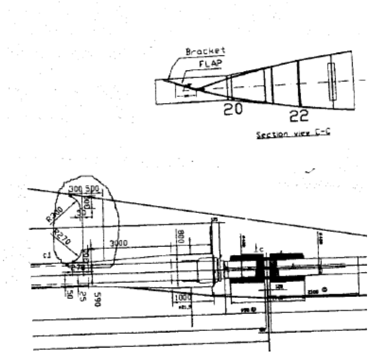


Figure 65. Curved plate Vortex generator in the bossing streamline particle.

6.1 Vortex Generators

The wake comparisons in figures 66, 67 and 68 show a more inward directed flow caused by this example vortex generator.
The wake field of a ship model fitted with a vortex generator show the following difference with regard to a traditional shafting arrangement:

- The axial wake distribution shows an increased vortex at the inner propeller radii just behind of the inner V-struts.
- The gradient of the axial wake field is good and the wake peak at the outer radii is less deep than in the original case.
- The tangential wake field shows a further inward directed component in the area behind the inner V-strut.

Cavitation observations in figure 69 show a significantly improved cavitation bucket for vortex generators, mainly caused by the reduction of the suction side tip-vortex.
In addition to the inception diagram, cavitation observations and pressure pulse measurements are needed to get good understanding from phenomena.

In a ship model fitted with different vortex generators it can be concluded that a vortex generator has a remarkably effect on the optimum setting angles of the V-strut.

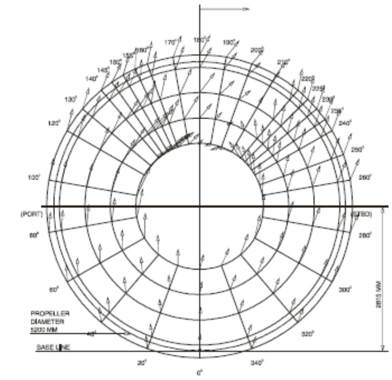


Figure 66. Tangential wake without vortex generator

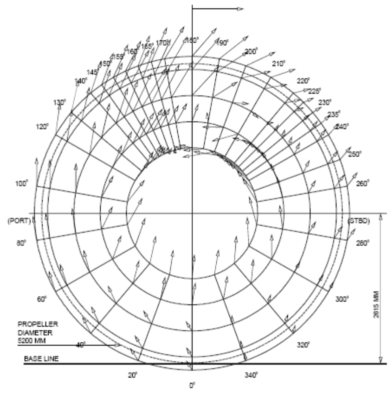


Figure 67. Tangential wake with vortex generator

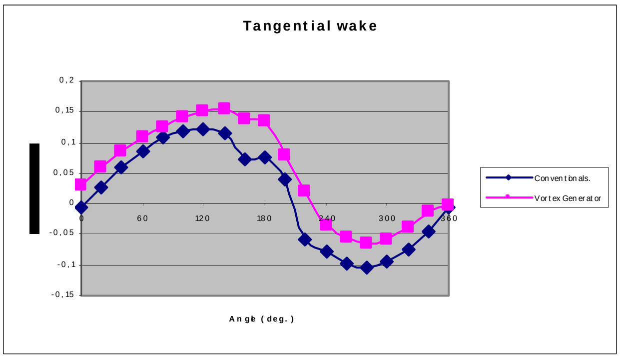


Figure 68. Tangential wake comparison at 0.8 R for conventional shaft with and without vortex generator.

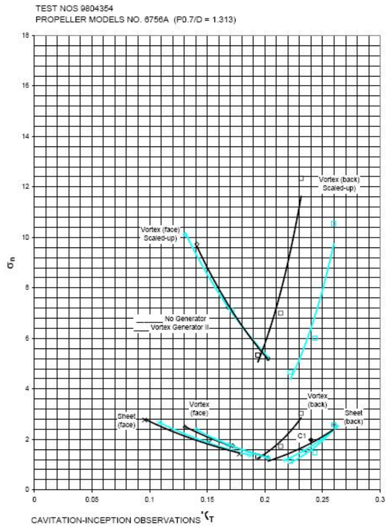


Figure 69. Cavitation inception diagram without and with vortex generator

6.2 Propeller modification

In addition to the reduction of the tangential component by means of vortex generaters, a modified propeller design is a good method to further improve the propeller tip vortex and thus to decrease the amplitude of the pressure pulse fluctuations.
In case of a new propeller design, unloading of the tip is a common solution and in case the full scale propeller already exists, blade edge and propeller tip cutting is a good compromise.
The propeller blade edge and blade tip cutting can in some case significantly improve the cavitation bucket, mainly caused by the reduction of the suction side tip-vortex and thus a reduction of the level of the pressures at the higher frequencies. This kind of propeller tip modification together with vortex generators will further improve this tip vortex reduction phenomenon.

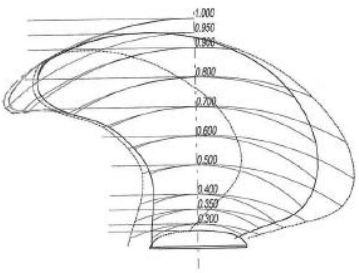


Figure 70. Example from cutted tip propeller blade

6.3 Rudder angle variations

Sometimes, the rudder angle optimisation test shows that the best power performance is obtained with the rudders at a rather wide range of angles, which is quite well in line with full scale observations. It is important to realize that powering is only one optimisation direction. Different optimum neutral angle can be for noise and manoeuvring items. Their correct findings are more complicated than powering.

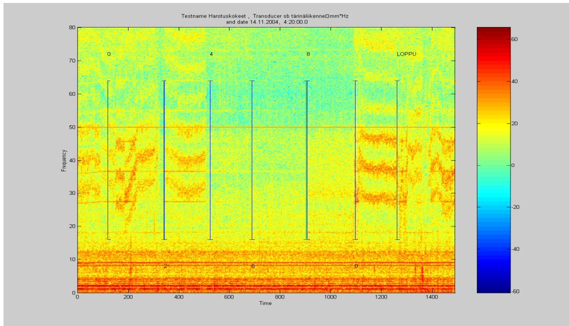


Figure 71. Example of rudder angle pressure pulse effect

6.4 Asymmetric or twisted rudder

When ships are sailing at higer speeds, the risk of rudder erosion increases rapidly. The combination of high axial flow velocity and the large transverse velocity angles generated by the rotation of the propeller often leads to damage to the rudder, just behind the propeller.
These large angles of attack could be eliminated by twisting the rudder entrance angles more with regard to the flow direction. The so-called asymmetric rudders are used quite often in modern ship design.
From a cavitation point of view it can be concluded that replacing the symmetric rudder by an asymmetric rudder will result in improved cavitation inception behaviour, a reduction of the tip vortex and an improved pressure distribution at the higher harmonics.
Figure 72 shows an example of an asymmetric rudder.
Changing the neutral tailing edge angle in a more out direction from CL can improve the propeller cavitation behaviour in some cases. Inception speed of the tip vortex can be remarkably improved in that kind of cases.
From a powering point of view it is observed that the increase of power due to the modified neutral angle is normally gained back by the improved asymmetric rudder shape.

Figure 72. Asymmetric rudder horn combination.

The high speed and high propeller loading is giving increase in the rudder cavitation risk. The rudder cavitation, typically sheet cavitation, is caused by the local angle of attack on the rudder profile and is best avoided by applying a rudder profile that is not sensitive to angle of attacks. The rudder cavitation may lead to severe damages on the rudder, depending on the intensity, type and spread of the cavitation.
If the rudder profiles are cambered or given a twisted leading edge the profiles become more efficient and will be able to recover more of the rotational energy. The profile should then be twisted or camber in one direction above the propeller shaft and in the opposite direction below the shaft line. The twist reduces the local angle of attack, which reduces the low-pressure region along the leading edge of the rudder that normally causes the sheet cavitation on the rudder surface. A well-designed rudder with twisted profiles can in other words both prevent or reduce cavitation and increase the propulsive efficiency.
Today twisted rudders and different type of “rudder bulb” are used in the high comfort class and high speed vessels.
The “rudder bulb” improves the propulsive efficiency. The main effects are that hub vortex losses are reduced and Taylor wake fraction is increased due to the potential effect of the bulb. In twin screw case efficiency gain is about 2 per cent.
In the following figures 73 and 74 are twisted leading edge spade rudder and “rudder bulb” connected to asymmetric rudder.

Figure 73.Twisted spade rudder.

Figure 74. “Rudder bulb” in the rudder

6.5 Viscous flow calculations by RANS code

Viscous flow calculations are today already a useful and reliable level to calculate different kind of appendage details. The effects of the propellers were included by a so-called actuator disk formula to the calculations.
To get a better insight into the effect of the vortex generator, the viscous flow calculations have been carried out in the high comfort class cruise liner. With and without vortex generator have been computed for model scale and full scale Reynolds numbers.
From these calculations the following observations have been made:
-On the model scale a clearly identifiable vortex in the wake field is predicted, in good agreement with the measurements, both with regard to the position as well as the strength.
-On full scale the vortex appears at the same position in the propeller disk but is more intense.
-Comparison of the results at full scale with and without the vortex generator reveals the effect of the vortex generator. Without the generator also a vortex

appears, but it is weak and positioned close to the shaft. By the vortex generator the strength of the vortex is increased and the vortex passes the propeller disk at a position further away from the shaft. The tangential velocities near the edge of the disk are augmented. The change in the vortex strength and position has also a clear effect on the axial velocity distribution: the speed is increased near the edge of the disk; while a speed reduction occurs near the vortex core.
-The trends found for the effect of the vortex generator are similar on model scale and full scale and a similar beneficial effect on the tip vortex behaviour is therefore expected.
-On model scale the I-strut clearly suffers from flow separation, but at full scale the flow behaviour is considerably improved.

The following figures 75 and 76 show RANS calculation results with vortex generator in the model scale and in the full scale.

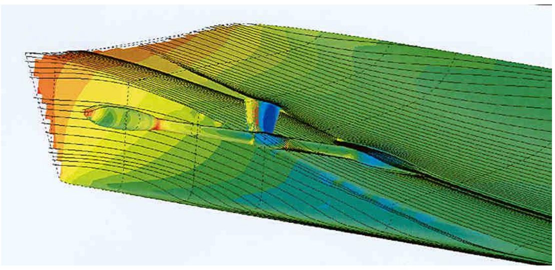
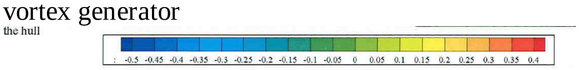


Figure 75. Viscous flow calculations on model scale for vortex generator



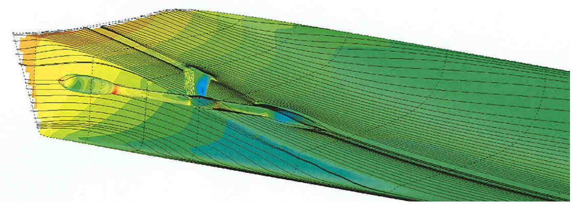


Figure 76. Full scale viscous flow calculations for vortex generator

Due to the high comfort class requirements for Cruise liners, ferries and fast RoPax vessels, special attention has to be paid to the tangential component of the wake fields in order to reduce the tip-vortex.

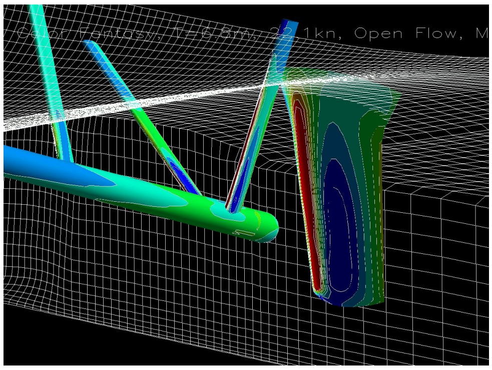


Figure 77. RANS calculation results for cruise liner aftbody.

Examples from normal appendage designs have shown their limits to effect on wake field. Some new possibilities to effect the wake field has been shown. The full scale feedbacks together with the latest CFD RANS calculations, model tests and PIV measurements are helping to reach the hardest comfort class requirements.

7 MABS-AIR BLOWING SYSTEM

STX Europe has invested significantly in the air blowing system research, which has been used to improve the noise characteristics of its ships when sailing in shallow water and running with asymmetric shaft loads. Air is injected along the hull surface above the propellers, which reduces the noise excitation on the hull. The air blowing system can also be used during other noisy conditions such as manoeuvring with large rudder angles.
The system consumes only a small amount of power and is easy to control from the bridge.
According to the shipyard's 'Continuous measurement system' the MABS-system has worked perfectly and has reduced noise effectively when the ship has sailed, for example, at high speed in waters ranging from 30 to 10m deep.

8 CONCLUSIONS

With the aid of CFD tools new hull form concepts can be developed prior to the model testing phase of a project. These tools can be helpful in developing new concepts such as the 'Wave Damping Afterbody' and they are already useful in appendage design and propulsion coefficient optimisation.
PIV measurements together with RANS calculations give important flow vortex information from appendage interactions with propeller.
The shaft line variation studies have shown that the designers' possibilities to effect on the wake field are quite limited when it is not possible to come more away from boundary layer by longer shaft line.
The axial wake of a twin screw ship is primarily

generated by the hull clearances, bossing and shaft. When the struts are well-oriented and well fitted to the barrel, their influence on the wake is small and negligible.
The tangential component is caused by the angle between the shaft centre line and the buttocks of vertical plane through the shaft CL both shaft tube itself.
In the comparison between conventional and podded case it is possible to see what can be expected from propulsion system change from conventional to podded case in the wake field.
The use of vortex generators or specially twisted rudders are more common in future ferries, cruise liners and fast RoPax vessels in order to reach the highest comfort levels.
To fulfil the highest comfort class, detailed investigation of the tip vortex strength and behaviour is required. Propeller noise is very difficult to predict and the scaling of the tip vortex is a demanding and important subject.
Rules of thumb and good examples as in this document for aft appendage designs are useful and can help hydrodynamic designers in their demanding work.

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