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On the Design and Analysis of Pre-Swirl Stators for Single and Twin Screw Ships

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ABSTRACT

Fuel saving and emission reduction are two of the main motivating factors for the current developments in the improvement of Marine Propulsor Technology. For this reason, and because of improved design and analysis tools, we see a renewed interest in Energy Saving Devices (ESDs).

This paper focuses on the pre-swirl stator device providing the possibility to reduce the rotational losses incurred by the propeller. The pre-swirl stator gives only a portion of the total gain to be attained, however. Additional features could be employed, particularly in high-block ships, such as a rational Van Lammeren L-J duct.

The general mechanism of pre-swirl stators to reduce fuel consumption is explained and the design problem is stated. Subsequently, the tools deployed for analysis and design of ship configurations fitted with propellers and pre-swirl stators are discussed with special attention for viscous effects.

An example of a pre-swirl stator for a single screw container vessel is worked out using lifting line theory. A full viscous analysis is illustrated with our RANS code ReFRESCO. The use of a potential flow BEM code is then illustrated for a first assessment of propeller-stator performance. Estimates are also made in the paper for the energy saving potential of pre-swirl stators applied to twin screw ships.

Keywords

Energy Saving, Propulsion, Pre-swirl stator, Upstream Duct, Efficiency

1 INTRODUCTION

The combination of a pre-swirl stator and a main propeller have once been called the “poor man's contra-rotating propellers” as this solution is comparatively cheap and simple to apply in ship propulsion. Fitting a pre-swirl stator ahead of a propeller can offer an attractive saving of fuel in the order of 4½ % without the high costs and other adverse effects associated with the far more complex real contra-rotating propellers driven by concentric shafts. Notice that a pre-swirl stator offers only a part of a total potential gain. Additional devices as upstream ducts which appear effective in high-block, single-screw ships may contribute to another 2-5%[1] of fuel saving. A pre-swirl stator can successfully be combined with an upstream duct such as, e.g., the Mewis duct®, (Mewis 2009, 2011). Alternatively, a large pre-swirl stator can be combined with an upstream duct according to the L-J shape proposed by Stierman (1987) who continued on the early conceptual ideas of Van Lammeren (1949) who developed and tested upstream nozzles of non-circular shape.

In an attempt to qualitatively understand how the positive contribution of the ESDs is attained, it is fruitful to consider the energy balance about a control volume containing the ship. If the control volume is taken sufficiently large, then the energy fluxes leave the control volume essentially through a transverse plane behind the ship (also referred to as Trefftz plane). The propeller losses that can be found here can be identified as axial kinetic energy losses (typically the largest loss factor and completely accounted for in the ideal efficiency), rotational kinetic energy losses, viscous energy losses, and losses due to the finite number of blades and the consequent non-uniformity of the generated flow field. Consequently, ESDs should reduce these losses without causing additional losses in other categories to exceed the benefits. Reviews of ESDs as they developed in the past were given by Muntjewerf (1986) and Blaurock (1990).

The purpose of a pre-swirl stator ahead of a propeller is to generate a swirling flow opposite to the sense of the rotation of the propeller. The propeller blades experience this rotating flow as an additional blade loading, through which the delivered thrust per unit of power is raised. Of course, this increase of the propeller thrust should be greater than the resistance experienced by the pre-swirl stator itself in order to attain a positive net gain. In terms of the energy balance, the power saving can be explained just as easy because the objective of the pre-swirl stator is to reduce the kinetic rotational energy in the flow behind the propeller. The pre-swirl stator induces rotation of the

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[1] Note that savings mentioned are indicative only. Values are based on MARIN experience

flow downstream which is absorbed and diminished to a great extent by the opposite rotation induced by propeller, thus leaving less rotation in the final slipstream. This is because, in comparison to a single propeller, less rotational energy is carried away by the flow passing through the propeller disc.

Although there is a lot of debate surrounding the energy-saving mechanisms of upstream ducts, experience based on model tests indicates that they affect both the resistance of the hull with driving propeller (often expressed in thrust deduction) and the efficiency of the propulsion. Both the concentration of viscous hull wake in the propeller disc and the generation of a small amount of thrust are factors to be considered here. A single screw ship fitted with a combination of a pre-swirl stator and an upstream L-J duct is shown in Figure 1.

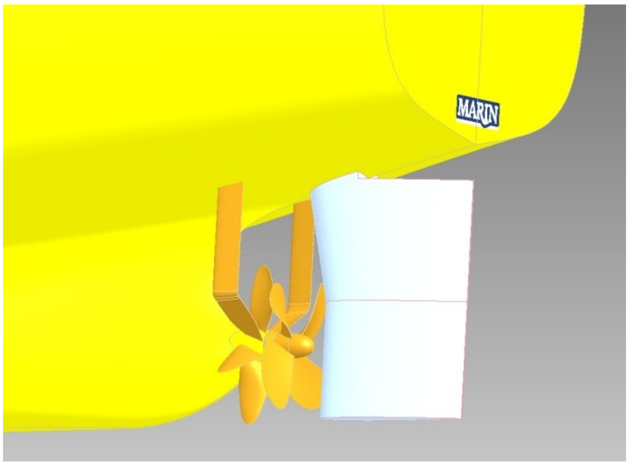

Figure 1: Illustration of a Bulk carrier fitted with an L-J duct and pre-swirl stator

2 HYDRODYNAMIC ASPECTS

2.1 Pre-Swirl

From a hydrodynamic viewpoint, the difference between the pre-stator propeller combination and counter-rotating propellers is small. The pre-swirl stator is the front-propeller of which the rotation is zero.

The numerical scheme of calculations for the combination of a pre-swirl stator and a propeller can conveniently be kept the same as that followed for the design of contra-rotating propellers. In such computations each of the two propellers works in an initially unknown flow field. The entrance velocity of a propeller is determined not only by the hull wake but also by the flow field induced by the other propeller. Upstream induced velocities are supposed to be axially directed because torque cannot be exerted on the upstream flow if viscosity effects are small. The velocities induced downstream of a normal propeller can be decomposed into an axial and a circumferential component. Upstream velocities are much lower than those downstream of the propeller. This implies that the flow though the propeller disc is converging towards a smaller cross section in aft direction.

A slightly different situation arises in the flow around the pre-swirl stator. The induced velocities are directed almost fully in circumferential sense with a comparatively small component directed forward. The character of the flow through the stator disc is rather divergent and it lacks the spiralling nature that is typical of rotating propellers.

Further, in contrast to real contra-rotating propellers and post-swirl stators, a pre-swirl stator has an average pitch which is of the same sign as that of the rear propeller. So, in front of a right-handed propeller a right-handed pre-swirl stator is to be fitted. It has been observed in all previous design studies of pre-swirl stators that the pitch angle of the stator blades in the tip region should approach 90 degrees. Therefore, it appeared necessary to expand the applied theoretical vortex model for trailing vortices leaving the lifting line at extremely large pitch angles.

The optimum diameter of the propeller behind a pre-swirl stator has appeared to be smaller than that of the open single propeller in all cases studied by MARIN. These cases invariably concerned a fixed combination of the delivered power and the rotative speed of the propeller. Apparently, by a certain reduction of the diameter a small but distinct additional gain in viscous losses emerges. Thanks to the reduction of the optimum diameter, the required decrease of the pitch to restore the original combination of the power and rotative speed is quite modest. This offers prospects to apply pre-swirl stators successfully to existing ships as a retrofit. The original propeller can be made to serve again by a combination of cropping and trailing-edge cutting.

The rudder, which can be considered a two-bladed post-swirl stator, will deliver a different longitudinal force owing to the changed rotation in the flow through the propeller disc. This change in stator action is not included in the parameter studies presented here. However, separate computations of the rudder forces have been made with the rudder located both in the original slipstream and in the altered slipstream with the pre-swirl stator fitted in front of the propeller. From the calculated rudder forces it was found that this effect amounts to a reduction of the gain of about 1½ %. This figure has been adopted here as a general correction of the computed gain.

2.2 Stator drag

The thrust of the pre-swirl stator is always negative. The increase of the thrust of the propeller is caused by the additional loading of the propeller blades. This increased loading is mainly due to the rotating flow leaving the stator in opposite sense as the blade rotation, a feature which is comparable to a (fictitious!) increase of the rotative speed of the propeller. The stator blades generate an induced flow which also has a forward axial component, next to the much larger induced velocity component in circumferential sense. In the pre-stator design computations, the sum of the propeller and stator thrust is maximized, while for reference, the thrust of the single open propeller without stator is taken. The question has not yet been resolved if the sum of the propeller, stator and rudder thrust needs to be the same to attain the same ship's speed. It is quite conceivable that by the axial redistribution of the thrust, the thrust deduction is slightly changed.

3 THE DESIGN PROCESS

For the design of the pre-swirl stator and propeller combination, a lifting-line model is used (see Figure 2). The propeller design module solves the pitch for a certain type of radial blade loading distribution, and it determines the induced flow field and the flow curvature due to the loading. The sectional profiles are determined on the basis of shock-free entry in the circumferential average flow conditions. The blade thickness is determined from strength requirements using a cantilever beam theory. The blade friction is calculated using a strip-wise approach. For each strip at a certain radius, the flat plate friction is determined involving a form factor allowance and effects of the blade roughness. The resulting forces are decomposed in thrust and torque contributions. The induced flow field at the lifting line can either be determined by the traditional methods of Goldstein, Lerbs, and Wrench or by integration of the trailing vortex sheet using the law of Biot-Savart. In the latter case, effects of rake and skew can be taken into account. The pitch, acknowledging the specified character of its radial distribution, is found by an iterative process in which the average pitch is varied such that the delivered power is absorbed at the prescribed rotative speed.

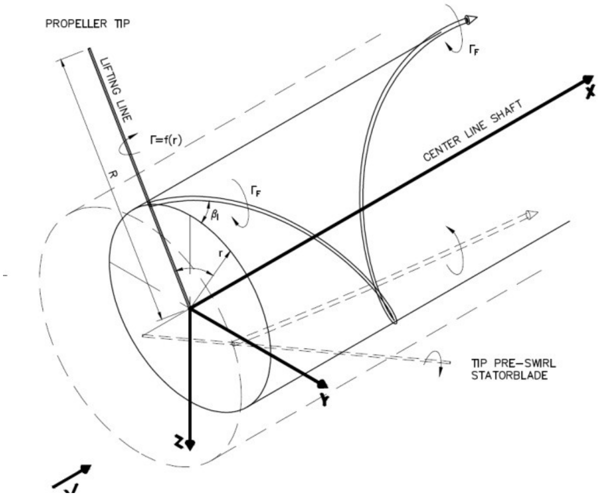

Figure 2: Lifting-line model of the pre-swirl stator-propeller combination

In the design calculations, the magnitudes of the induced flow fields of both the stator and the propeller are initially unknown. These induced flow fields are tuned iteratively. The process starts by the assumption that the propeller does not have any influence on the flow entering the pre-swirl stator. The calculated induced flow field downstream of the stator is added to the wake flow. In this combined flow field, the propeller is designed and the upstream induced axial flow field in way of the stator is computed. Already after three cycles, the induced flow fields are accurately tuned to each other and calculated thrust values of the two components do not change any more. The module in which the pre-swirl stator is handled is quite similar to that of the rotating propeller. Adaptations have been made in the formulation of the fundamental lifting-line equations which are now no longer based on the circumferential velocity but on the axial velocity component. In addition, several other elements of the method have been adopted to allow pitch values of +/- infinity to be handled. For the sake of simplicity, the blade thickness ratio, the chord length ratio and their radial distributions are fixed values. There is, however, a major difference with rotating propellers: In rotating propellers the blades are intended to be perfectly equal. But here, in the case of the non-rotating pre-swirl stator, thanks to its stationary character, the stator blades should be mutually different to accommodate them to the local flow field governed by the wake distribution and, to a lesser extent, to the propeller-induced axial flow field. The blade loading is determined by the circumferential average flow conditions. For achieving shock-free conditions for each of the stator blades, the blades should be tilted by the angle between the local flow vector and that of the circumferential average flow vector. By this measure conditions of zero angle of attack are attained and cavitation and flow separation on the stator blades can be avoided. These adaptations to the wake can be accomplished not only by tilting each of the geometrically identical blades but also by correcting the pitch of the individual blades at the stations along the span of each of the stator blades.

3.1 Two design stages

The design process of the stator blades consists of two stages. In the first stage the solution of finding the best geometry for the circumferential-average wake field is determined. The wake data are represented by the radial distributions of the axial and tangential velocity components, the latter being zero for symmetric single-screw ships. By random number optimisation using an embedded search strategy the best radial loading distributions and the thrust distribution between the main propeller and the pre-swirl stator are found. Diameters of the propeller and the pre-stator can be brought into the optimisation scheme as well.

If the stator blades would be designed as geometrically equal without any tilting of the blades to the local flow condition, the loading of the blades would differ substantially owing to the non-uniformity of the hull wake. As a consequence, also the induced flow field varies in circumferential direction. This strategy would lead to a more homogeneous flow field entering the propeller disc. The heavy loading of some of the non-tilted blades might on the other hand easily lead to flow separation at the stator blades, increased drag and other unwanted effects as cavitation.

In the second stage of the design process the pitch of the stator blades is corrected for the difference between the local flow and the circumferential average flow condition. The angle between these flow vectors is imposed as a pitch correction of the stator blades. As a result, the blades are oriented to the local flow direction and experience a shock-free entry condition and their hydrodynamic loading is mutually equal. By a secondary adaptation of the camber and the pitch, a small additional power saving and a more homogeneous propeller blade loading might be attained. Through the latter, the cavitation on the main propeller could be minimised.

Omitting blades and re-adjusting the angular position of a few of the stator blades is quite feasible owing to the stationary character of the pre-swirl stator. When tilt angles become such that the local pitch angles of the stator blades are considerably reduced, the effectiveness to generate the rotational flow diminishes because the lift vector becomes more and more directed in forward direction and the drag of the stator blade increases progressively. Another feature, not yet explored in this paper, is to control the propeller cavitation by a re-adjustment of the stator blades near the top-wake peak. By a local pitch decrease the pre-swirl is then to be reduced leading to improved propeller cavitation.

4 PRE-SWIRL STATOR FOR A CONTAINER

The first presented design study focuses on the case of a typical large container ship originally fitted with a 6-blade 8.75 m diameter propeller. For this ship a model was available in the stock of MARIN as well as results of model tests including wake field data.

The propulsion tests on model scale predicted a trial speed of 25 knots for the ship at the design draught. The propeller thrust at this speed and draught is 3558 kN. Full-scale trials, though on a lighter draught, fully confirmed the model test predictions, both regarding the ship's speed and the propeller RPM.

By variation of the diameter it was confirmed that the code gives the same optimum diameter.

4.1 Number of stator blades

In the input of the lifting-line code, the radial distribution of the blade loading of the propeller is entered together with ranges of the hydrodynamic pitch angles of the stator blades at four radial stations. By optimisation and variation of the hydrodynamic pitch distribution of the stator blades, the diameters and the type of radial loading distributions of the propeller are found. In these calculations only those combinations of diameters have been considered in which the stator was greater than the propeller. The choice of a stator which has a greater diameter than that of the propeller is motivated by avoiding the interference between tip-vortex cavitation for the stator blades and the propeller blades. On the other hand, the diameter difference and also the longitudinal distance between stator and propeller should not be too great because then a portion of the deflected flow is passing along the propeller disc without any contribution to the total efficiency.

Initial calculations were based on a 6-bladed propeller and allowing a maximum lift coefficient of $C_L = 0.9$ of the profiles of the stator blades and a chord length in the interior of the stator of 0.15 D. The screw diameter has been put at 8.50 m as a result of a diameter-variation study (not included). This corresponds to an optimum propeller diameter approximately 0.3 m less than that of the screw without pre-stator. This is fully consistent with previous results where invariably slight reductions of the optimum propeller diameter were found if a pre-swirl stator is being applied in front of the propeller. From these calculations the results in Table 1 were obtained:

Table 1: Variation of the number of stator blades

# blades	*T-total (kN)*	*T-prop (kN)*	*T-stator (kN)*	*CL max*	*% gain*
5	3686	3792	-106	0.9	6.1
6	3688	3771	-83	0.9	6.2
7	3672	3788	-116	0.78	5.7

It is noted that the choice of the diameter of the stator, in this case 8.80 m, is based on the observation that pre-swirl stators that are larger than the propeller tend to give some extra gain. If the constraint of $C_L<0.9$ would not have been imposed a 5-blades stator would have come forward as the best choice. The extremely high lift coefficients prevent this solution from a practical viewpoint. From these calculations it follows that the choice of a 6-bladed stator is not so bad from an efficiency point of view.

4.2 Pre-swirl stator ahead of a 6-bladed propeller

In the next series of calculations, the diameter of the stator was chosen as 9.10 m as this is about the maximum size that can be applied provided that two of the stator blades are placed in the 5 and 7 o'clock position.

Table 2: Variation of the propeller diameter

	Orig. Diam	***Cropped propellers***					***No stator***
D_{prop}	8.75	8.45	8.35	8.25	8.15	8.05	8.75
T_{prop}	3710	3720	3724	3724	3721	3724	3475
T_{stator}	-105	-105	-105	-105	-105	-105	--
T_{total}	3605	3615	3619	3621	3621	3619	3475
T_{prop}/T_{total} (%)	102.9	102.9	102.9	102.9	102.9	102.9	100
N (RPM)	96.1	96.4	96.8	97.2	97.7	98.1	100
% gain	3.8	4.0	4.1	4.2	4.2	4.1	0

These calculations (see results in Table 2) show that in this case it is worthwhile to crop the current propeller to restore the combination of power and rotative speed. It also appears that the optimum reduction of the diameter achieved by cropping is not sufficient to preserve the original power-rotation rate combination. So, an additional measure, such as "trailing-edge cutting", will be necessary.

4 PRE-SWIRL STATOR FOR A TWIN-SCREW PASSENGER VESSEL

For a twin-screw vessel with controllable-pitch propellers on exposed shafts that are supported by shaft brackets, calculations were made for pre-swirl stators to be fitted just ahead of the propellers. The CP-propellers of the ship are 4-bladed and have a diameter of 5.6 m. The thrust produced by the original propellers in their design pitch P/D=1.57 is 1380 kN at a ship speed of approximately 26 kts.

Two of the pre-swirl stator blades are supposed to be the arms of the shaft brackets, while the other 3 or 4 blades are supposed to be fitted to the shaft bossing, see Figure 3. So, the bracket arms need to be given a special shape and twist to make them work efficiently as pre-stator blades.

From the calculations for the configuration without pre-swirl stator it became evident that if the diameter of the propellers would have been optimised for the design rotative speed without any space restriction, a diameter much greater than 5.6 m would emerge.

From the initial calculations involving the pre-swirl stator it became clear that a 5-bladed stator would be just a little better than a 6-bladed one. The required lift per blade is greater in 5-bladed stators but since the maximum lift coefficient Cl of 0.84 for a 5-bladed stator is not regarded as imperative, a 5-bladed stator was adopted for the other calculations.

The influence of the diameter was investigated as well. It appeared that the optimum diameter of the propellers with pre-swirl stators fitted would be a little greater than the maximum diameter of 5.6 m. By variation of the stator diameter it was found that a greater diameter than that of the propeller would be beneficial. Given the limited space, and the desire to fit the best possible pre-swirl stator the diameter was put at 5.9 m. It is not known at this stage if by this combination the propeller will just be free of the cavitating tip vortices shed from the stator blades. The thrust for the design condition with the same power absorption and rotative speed is predicted to be 1445 kN for each of the propellers. This corresponds to thrust gain of 4.7 %. If we would consider conditions of equal total thrust and if we would take into account the changed rudder effect, we conclude that a power saving at equal speed of almost 5 % would be feasible here. It is noted that a part of this gain is due to the far more optimum combination of propeller diameter, power and rotative speed in the case of the configuration with the pre-swirl stator.

Finally, by variation it was examined if a more favourable radial distribution would offer a higher efficiency gain. It appeared that by applying propellers with more heavily loaded tips a distinct gain could be achieved. Given the restricted tip-hull clearance and critical situation as regards vibration and cavitation, propeller configurations with more heavily loaded outer sections have not been evaluated further.

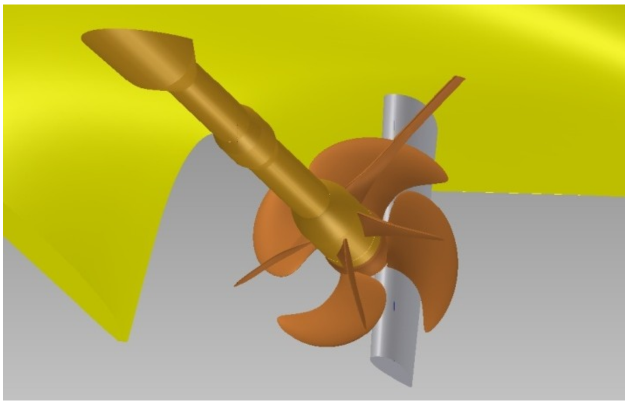

Figure 3: Illustration of typical twin screw vessel with pre-swirl stator

5 VISCOUS FLOW CALCULATION

To analyse the pre-swirl stator design in detail, viscous flow calculations have been performed with MARIN's in-house viscous flow solver ReFRESCO (Vaz, Jaouen & Hoekstra 2009).

Here we present preliminary results for the flow around the container ship fitted with the 6-bladed pre-swirl stator. Wave making is neglected, i.e., we performed double body calculations using symmetry conditions at the water surface. This simplifies the calculation and, hence, avoids additional inaccuracies due to the free surface with respect to the prediction of the resistance of the ship and stator. All calculations were done for a ship speed of 18 knots which gives a Reynolds number of 1.35×10^7 and 2.65×10^9 for model- and full-scale, respectively. To avoid a non-physical flow around the bow, due to the double body conditions, we used a deeper draught of 14.0. All calculations were done using the k - ω turbulence model of Menter. To incorporate the propeller action, an actuator disk model is used, with a thrust coefficient equal to 0.636 and 0.703 for the bare hull and hull fitted with the pre-swirl stator respectively.

The computational mesh was built with the commercial package Hexpress, which generates full hexahedral unstructured meshes with a proper boundary layer insertion. To examine the quality of the resistance predictions, a limited grid study was performed. The total number of hexahedral elements ranges from 6.5 million to 13.3 million elements.

The calculations for the bare hull at model-scale show that the predicted wake field agrees well with experiments. The predicted resistance at model scale (54.9 N) is quite insensitive to the number of cells: A doubling of the number of elements (from 6.5 to 13.3 million) decreases the total resistance 0.25%. At full scale, however, (1064 kN), the resistance reduces with nearly 1%, which is quite high in view of the expected gains of only a few per cent. To minimise errors, we used a similar grid density at the hull for the situation with and without the stator. For the pre-swirl stator, we only discuss results obtained with a rather coarse grid consisting of 10.6 million cells. The grid density on the hull was comparable to the 6.5 million cells bare hull grid.

The preliminary results show that all blades of the stator are well aligned with the flow. At full-scale, no flow separation is predicted, except on one blade close to the hull. At model scale however, all blades show flow separation close to the trailing edge. This is as expected because scale effects on the lift and drag of the relatively small stator blades are significant: The Reynolds number on model scale, based on the ships speed and the diameter of the stator is equal to 4×10^5. An example is given in Figure 4 for the blade at the 7 o'clock position looking from behind.

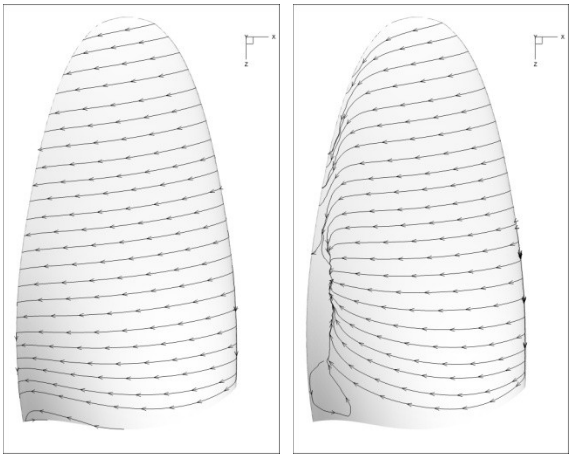

Figure 4: Limiting streamlines on the suction side of the blade at the 7 o'clock position. Left figure: full-scale; right figure: model-scale.

The calculated forces on the blades show that the contributions of the separate blades to the total resistance of the stator differ significantly. From 1 o'clock, 3 o' clock to the 11 o'clock position: 18%, 35%, 20%, 14%, 6% and 7%. For model scale conditions, these percentages are comparable.

Figure 5 shows the calculated axial wake field at model and full-scale.

6 POTENTIAL FLOW COMPUTATIONS

A potential flow panel code (PROCAL, see, e.g., Vaz & Bosschers (2006) and Bosschers et al (2008)) has also been used for the analysis of the propeller-stator configuration.

This code can be used for a first assessment of the stator-propeller configuration, or for a final performance assessment of the propeller that operates in the distorted wake of the pre-stator. In the latter case, one can choose between the RANS computed wake in the propeller plane and the BEM computed wake. A cavitation and pressure pulse analysis can then subsequently be conducted with PROCAL.

6.1 Modelling of propeller-stator in PROCAL

The interaction between the stator and the propeller is accounted for through the mutually induced velocities. First, a stator analysis is made with the stator in its correct axial position, where the effective wake field at the propeller position is used. For the present case, the stator is positioned half of the propeller diameter upstream of the propeller reference plane.

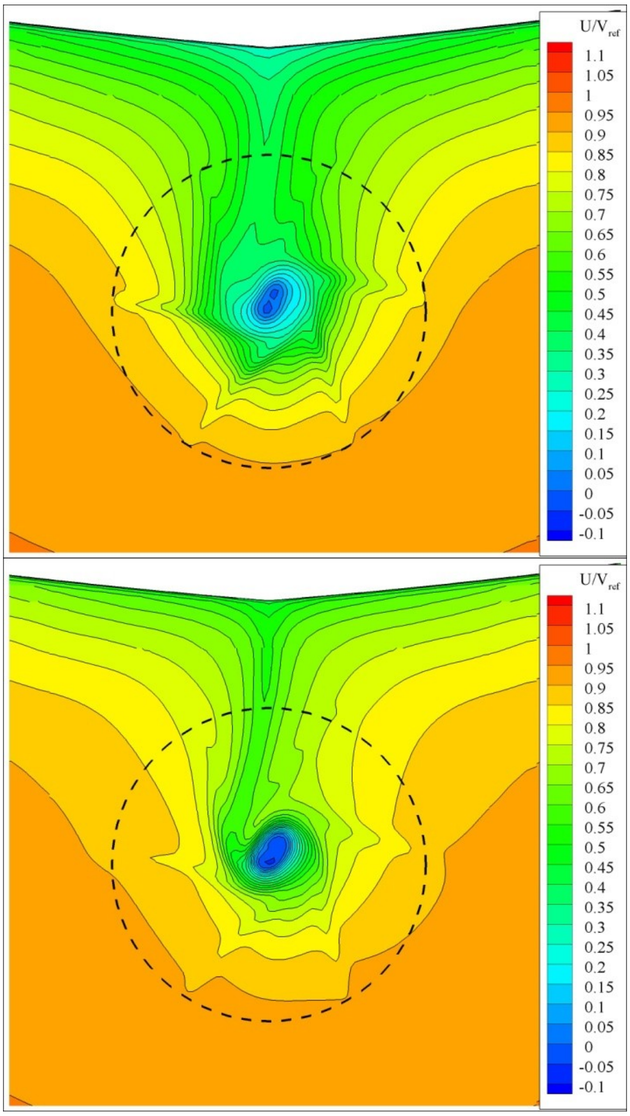

Figure 5: Axial wake field at the propeller plane. Top figure: model-scale; bottom figure: full scale.

At this stage this distance is sufficiently small to neglect changes in the wake field. The stator induced velocities are computed in the propeller reference plane, and superimposed on the effective wake distribution. The resulting total field is then used for a renewed propeller analysis, which then includes the effect of the stator. Because the upstream influence of the propeller on the stator only goes through axially induced velocities, it is expected that the induced effect of the propeller on the incoming velocity field is sufficiently well addressed through the use of an effective wake field for the stator. Another issue is the modelling of the trailing vortex system leaving the stator blades. No good empirical models are currently available and an iterative wake alignment appears the best solution here. For the current computations, the initial wake leaves the trailing edge with a pitch that is the average of the pitch at 70% radius and the advance ratio at zero iterations.

6.2 Validation of PROCAL for performance analysis

The performance prediction of the propeller-stator configuration has been validated with experiments for the pre-stator configuration described by Hooijmans et al (2010). This stator design was tested under the same container vessel as is used for the current case (where for this new stator no experimental results are available yet). A review of results from this validation study is given in Table 3.

Table 3: Comparison of propeller stator performance computed by PROCAL with experimental results. All comparisons made at equal ship speed.

	Computations	Experiments
η Stator-Propeller / η Propeller	1.022	1.025
K_T Stator-Propeller / K_T propeller	1.13	1.10
n Stator-Propeller / n propeller	0.94	0.96
T stator / T stator-propeller	-0.01	

A comparison of the PROCAL computed results with the experimentally obtained results reveals a fair correspondence. It is noted that the predicted gain for this stator design is approximately 2-3%. The increase in thrust coefficient is significant (some 13% at equal ship speed), whereas the computations showed an increase in K_T of even about 22% at equal advance ratio (which doesn't, however, correspond to the working point of the propeller-stator combination behind the ship). The difference between the predicted rotation rate reductions is about 2%, the computations predicting a 6% lower propeller rotation rate.

6.3 Results from PROCAL in comparison to ReFRESCO

To get an impression of the agreement of the BEM computations with the RANS computations, the relative contribution to the drag force for all six stator blades is given in Figure 6.

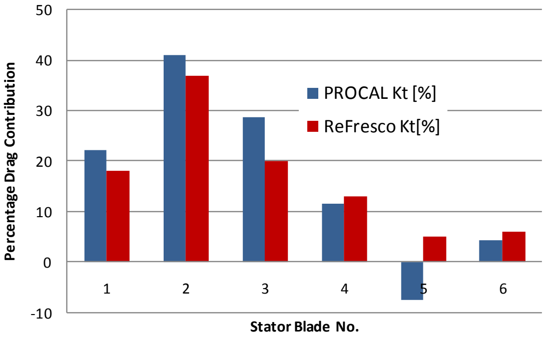

Figure 6: Relative drag contribution of stator blades. Comparison of PROCAL (BEM) with ReFRESCO (RANS)

It is seen that there is a fair correspondence in the relative drag contribution of the stator blades between both codes.

A noticeable difference occurs for blade 5 (9 o'clock position) where PROCAL predicts a thrust force, whereas ReFRESCO predicts a drag for all blades. It is noticed that both contributions are small however. The total stator drag predicted by PROCAL agrees fairly well with the drag in the lifting-line model. Another interesting observation follows from a comparison of torque contributions of the stator blades (Figure 7).

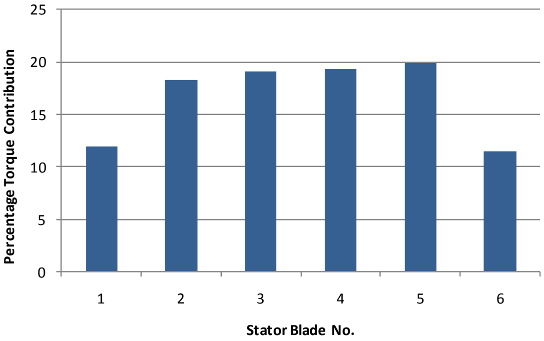

Figure 7: Relative contribution of stator blades to total stator torque

This figure shows that the stator blades which are essentially outside the wake peak contribute almost equally to the total torque of the stator. Only the stator blades inside the wake peak (blade 1 in 1 o'clock position and blade 6 in 11 o'clock position) contribute approximately 60% of the other contributions. This equal distribution of torque on the stator confirms the intended equal loading distribution of the stator blades, as designed with the lifting line code.

Further work will consist of a validation of the cavitation extent and dynamics from PROCAL with experimental results. Using calculated pressure distributions (see, for example, Figure 8) and cavitation patterns on the propeller behind the stator, the propeller-stator combination can be further tuned to obtain acceptable cavitation and pressure fluctuations on the hull.

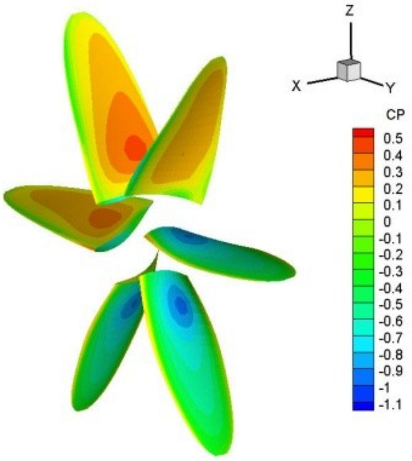

Figure 8: Illustration of pressure distribution on Pre-Stator as computed with PROCAL, three blades showing pressure side and three blades showing suction side distribution. X directed upstream, Z upward.

5 CONCLUSIONS

Pre-swirl stators mounted in front of the propellers can bring a substantial energy saving of up to 5 % for both single and twin-screw ships as well. For high block ships an additional saving in the order of 2-5% is to be attained by, e.g., an upstream nozzle as the Van Lammeren L-J shape nozzle. As shown in this paper, with the hydrodynamic advantages well considered, a successful design of the propeller-stator combination can be made using an effective combination of traditional lifting-line theory, an unsteady BEM code and fully viscous flow simulations using a RANS code. Optimisation of major design parameters using the lifting-line model has turned out quite successfully. Since a serious scale effect on the stator action is bound to be present in model experiments, CFD computations are important to assess these scale effects.

A reliable procedure for designing and optimising propeller-stator combinations includes both the application of numerical methods as well as validation of the results by means of dedicated model experiments. Since serious scale effects on the performance of stators on model scale should be reckoned with a strict geometrical similarity might have to be sacrificed (see Schuiling et al (2011)).

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