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The Influence of the Wake Scale Effect on the Prediction of Hull Pressures due to Cavitating Propellers

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ABSTRACT

In this paper, the scale effect on the wake field of ship models is shown to be an important cause of prediction inaccuracies of hull pressure amplitudes at the first blade rate frequency, as induced by the cavitating propeller in model experiments. It is investigated how the scale effect on the wake field, caused by failing to adhere to the full scale flow Reynolds number in model scale experiments, affects the propeller loading, cavitation dynamics and eventually hull pressure fluctuations. A RANS code is used to inversely design a scale model hull that generates a wake field more closely resembling the ship scale target wake field than does the geometrically similar ('geosim') hull model. As a demonstrator, a non-geosim scale model of a container vessel has been designed, manufactured and tested. Some full scale data is available for correlation purposes. It is concluded that the wake scale effect may largely explain the model to full scale correlation error on the blade rate hull pressure amplitude, and the use of a non-geosim afterbody design may correct for this error.

Keywords

Scale model testing, hull pressure fluctuations, scale effects, ship wake field, propeller cavitation

1 INTRODUCTION

Although model basins have often been successful with their predictive capabilities, this is not always the case for predictions of propeller-induced vibratory hull excitation pressures. Several fundamental problems are hampering an accurate prediction of such excitation pressures. This may lead to comfort levels being inferior to contract specifications, or to efficiency losses being greater than necessary.

When model testing large single-screw container ships, the measured hull pressure fluctuations sometimes turn out to be too high compared to full scale. One likely cause of such overpredictions is the so-called wake scale effect. This effect refers to the difference between the wake fields of model and ship, resulting in a difference in cavitation behavior and propeller-induced hull excitation forces.

Although generally not considered important for the wake fields of modern passenger ships, the wake scale effect may become significant, e.g., in the case of single screw container ships. This type of ship is growing beyond previously imaginable proportions, and excitation forces are of great concern. In a joint industry project (Ligtelijn et al 2004), the correlation between model and full scale propeller cavitation was studied for five ships, two of which were container ships. This study confirmed the correlation deficiency for the latter type of ship as the model scale hull pressure amplitudes were found to significantly overpredict ship scale values.

In this paper, the problem of the wake scale effect is addressed with the objective of increasing our insights regarding its influence on the prediction of hull pressure fluctuations. Derived from the main objective is the development of improved prediction methods for propeller-hull excitation forces based on experimental and numerical procedures.

The study of the wake scale effect is performed on a large container vessel for which numerical simulations have been made. By means of a RANS solver, the difference between model and full scale wake fields has been evaluated. Two ways to correct for this difference have been tried. One way is to choose the model ship speed such that the ratio between the circumferential speed of the propeller blades and the axial velocity in the wake peak becomes equal for model and full scale. For this condition, the local thrust loading in the wake peak rather than the total thrust loading should be equal at model and full scale. The operating condition (i.e., the model speed given a propeller RPM) was predicted by means of a procedure involving numerical tools. Cavitation tests were performed to obtain hull pressure amplitudes.

The other way to correct for the wake scale effect is presented here as the 'Smart Dummy' concept. The Smart Dummy is a geometrically non-similar ship model with full scale wake field resemblance. The name 'Smart Dummy' originates from the dummies used in cavitation tunnels in which large geometrically similar models would not fit. In this study, CFD tools are employed to determine the shape of a dummy that generates the full scale wake field, thus 'making the dummy somewhat smarter'. Then, geometric similarity is sacrificed for the sake of local kinematic similarity. Results of cavitation tests performed on the Smart Dummy are presented.

2 SCALE EFFECT ON SHIP MODEL WAKE

Discrepancies in similarity between the effective wake fields on model and ship scale are easily imagined, as the model scale wake differs in Reynolds number from its full scale counterpart by one to two orders of magnitude. The wake flow behind the model ship is more retarded due to the boundary layer being thicker, thus causing the average effective inflow velocities in the propeller disc to be too small by several percent. As a result, the propeller will be overloaded when model ship speed and propeller rotation rate are based on identity of Froude number and apparent advance coefficient. The correct propeller loading is obtained by adjusting the model ship speed by a few percent on the basis of an estimated propeller-disc averaged wake scale effect, expressed as a fraction of ship speed.

Therefore, in model testing, the set point is chosen by simply adhering to identity of advance coefficients, which is almost equivalent to thrust coefficient identity. In cavitation testing, this is correct as long as the scale effect on the model wake can be assumed as uniform across the entire propeller disc. Then, the forward speed of the ship model is simply adjusted by the average scale effect on the entrance velocity, i.e., the wake scale fraction,

$$J_s = J_m \quad \Rightarrow \quad V_m = \frac{V_s\, n_m}{\lambda\, n_s} \frac{1-w_s}{1-w_m} \tag{1}$$

with J the advance coefficient, V the advance velocity, n the propeller rotation rate, λ the model scale factor and w the wake fraction. Subscripts m and s refer to model and ship scale, respectively. By adjusting the towing tank pressure, the cavitation number, σ_n, is made to agree with that on full scale at all depths (or, in cavitation tunnels, at a level corresponding to a percentage of the propeller radius of a blade in top dead center position). Using this standard procedure, both cavitation patterns and dynamics on model propellers are considered to be representative of their full scale counterparts with the exception of light, free vortex cavitation, of which the inception is seriously delayed by viscous scale effects on the propeller blade flow.

However, it is well known that the wake scale effect is generally not uniform across the entire propeller disc, but predominant in the top sector, where it is referred to as the wake peak. For achieving equivalence in cavitation patterns and dynamics, the distribution of velocities in and around the wake peak must be made equivalent to full scale values. Using standard set points, the propeller will still be overloaded in the region where cavitation is expected to occur because the wake peak on model scale is deeper and wider. In other regions, the propeller will be underloaded, which may trigger pressure side cavitation before it would occur in full scale.

It follows that similarity in cavitation behavior and hull pressure fluctuations requires (amongst others) local similarity of propeller inflow velocities at those locations where cavitation is expected on full scale. This is by no means straightforward, as the effective wake field is not directly measurable. One has to revert to the measurement of the nominal wake field and then add propeller-hull interaction velocities, or one has to measure the total wake field and subtract the propeller induction velocities. The wake field on full scale is hardly ever determined. The lack of information on ship scale wakes is the main reason for the lacking knowledge on the actual magnitude of the wake scale effect. Fortunately, nowadays, the computation of the wake field at full scale Reynolds numbers has come within reach. For example, MARIN's RANS-solver for ship flows, called 'PARNASSOS' is used for this purpose (Hoekstra 1999, van der Ploeg et al 2000/2010).

3 WAKE PEAK THRUST IDENTITY

A simple way to go forward is to simulate the local blade loading in the top sector of the propeller disc, e.g., at the position of the wake peak itself without considering the average propeller loading. For this condition, Holtrop coined the term J_{wp} -identity (wake peak identity), which is defined as,

$$J_{wp} = V_{\min} / nD \tag{2}$$

if it is based on $V_{\min}$, the minimum axial velocity in the wake peak. It may also (and perhaps more sensibly) be based on a weighted average velocity in the wake sector where cavitation is expected, so that in that particular sector the average thrust loading is similar to full scale.

The method requires that the scale effect on the effective wake peak depth is known from computations. For a number of years, wake fields can be computed reasonably accurately for Reynolds numbers ranging from model to ship scale values. These computations are fast enough to be used in day-to-day work and may involve a force field representation of the propeller action, thus enabling the computation of the propeller-hull flow interaction from which the effective wake field follows.

In principle, such computations can be used to determine the scale effect on the effective wake averaged over the area of the propeller disc where cavitation is expected. The final result is a percentage with which the ship model speed should be increased in cavitation tests to obtain correct average loading in the cavitating sector of the propeller disc.

A simpler option is to use the scale effect on the wake peak depth only as a determinant for the increase in ship speed during testing. Even more pragmatically, one could take the scale effect on the nominal wake peak depth at the risk of overshooting the increase in model speed. The model speed then follows from Eq. (1),

$$V_m = \frac{V_s\, n_m}{\lambda\, n_s} \left[1 + \frac{[V_{\min}/V]_s - [V_{\min}/V]_m}{[V_{\min}/V]_m} \right] \tag{3}$$

This procedure was suggested by Holtrop and applied in van Wijngaarden (2005) and Bosschers et al (2008).

As an example, the container vessel shown in Figure 1 was studied. It is a typical example of a modern container ship with a six-bladed propeller. The result of a nominal wake field measurement is depicted in Figure 2. In the same figure, the results of RANS computations of the nominal wake are presented for model and full scale Reynolds numbers. These computations were made with an undisturbed free surface (‘double body flow’ approach including trim and sinkage). Using these computations in the wake peak scaling method yields $\left[V_{\min}/V\right]_m \approx 0.40$ and $\left[V_{\min}/V\right]_s \approx 0.51$. The suggested speed increase then becomes no less than 27.5%. Although the speed set points derived above are for nominal wakes, the derivation should actually be based on effective wakes. Straightforward application of a simple force field method to these wake fields yields a still significant 18.5% for the necessary speed increase.

Cavitation tests in the Depressurized Towing Tank (DTT) were performed at two speeds. One is the speed where thrust identity is found, i.e., the Froude speed plus almost 6% to account for the *average* wake scale effect; the other speed is the Froude speed plus 18.5% to account for the *local* effective wake scale effect. At the latter speed, the total thrust is reduced to 70% of the one found at thrust identity. Full scale data is available for comparison (courtesy of Lloyd’s Register).

To measure hull pressure fluctuations, nine pressure sensors were flush-mounted in the model directly above the propeller. The transducers and the one pressure sensor for which full scale data is available are shown in Figure 3. The result of the experiments is shown in Figure 4. Pressure amplitudes at the first four blade rate frequencies are given for the central pressure transducer, no. 5, which is closest to the full scale sensor position. All amplitudes are divided by the first order pressure amplitude measured on full scale.

Using thrust identity, the model tests overpredicts the pressure at the blade rate frequency by about a factor of two. The application of an increased model speed, while maintaining Froude-scaled RPM, leads to an expected decrease in blade rate amplitude. The pressure amplitude at the first harmonic of the blade passing frequency is close to the full scale value (which was measured at a slightly different location). For higher orders of the blade rate frequency, the reduction in thrust loading caused somewhat increased pressure levels and the measure of correlation with full scale values has deteriorated. Measurements on other ships for which the wake scale effect was treated by increasing the model speed led to similar conclusions. First order predictions became much better, the higher ones change for the better or the worse.

Figure 5 shows a full scale video image and a model scale high-speed video snapshot taken from the measurement at increased speed. Although the difference in viewing angle makes a comparison difficult, the cavity volumes look reasonably similar. However, the way in which the sheet cavity rolls up under the action of vorticity seems to differ and scale effects on the blade flow cannot be ignored. The effect of unloading the propeller on the appearance of sheet cavitation can be seen in Figure 6. Cavitation volumes at corresponding time instances have reduced. It is concluded that at the blade rate frequency the new set point for the model test is a great improvement over the one obtained by adhering to total thrust identity. Still, the wake peak on model scale is too wide. Also, higher blade rate orders cannot be improved similarly.

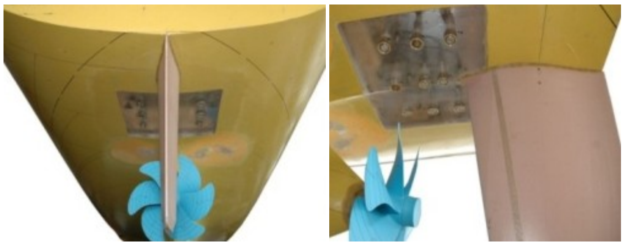

Figure 1: Set of flush mounted pressure transducers for measuring the hull-pressure distribution on model scale.

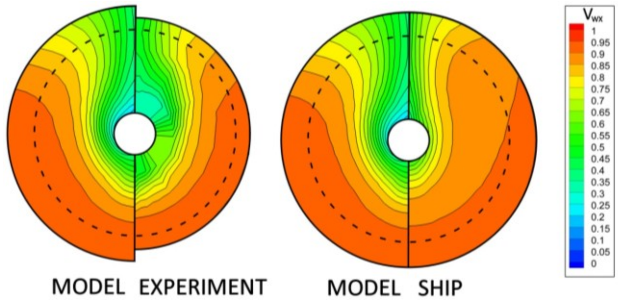

Figure 2: Left: comparison of the computed axial component of the nominal wake field with model scale measurement. Right: comparison of computed wake fields at model and ship scale Reynolds numbers. The dashed line shows the propeller outer perimeter.

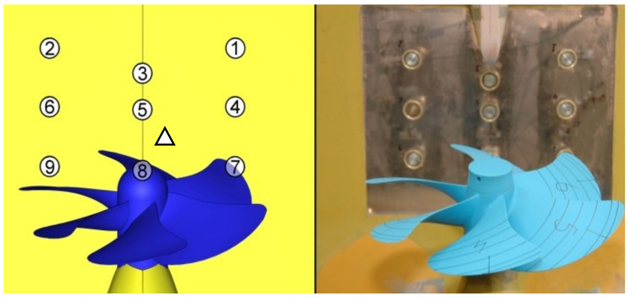

Figure 3: Afterbody with propeller and pressure transducers mounted. Triangle denotes full scale measuring location. The propeller plane intersects sensors nos. 4, 5 and 6.

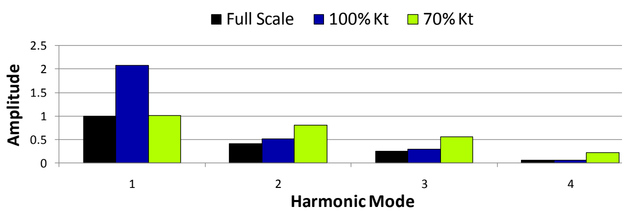

Figure 4: Comparison of non-dimensional full scale (in black) and model scale pressure amplitudes at the first four blade rate orders. The measurement at thrust identity is in blue, the one at 18.5% speed increase (=70% Kt) is in green.

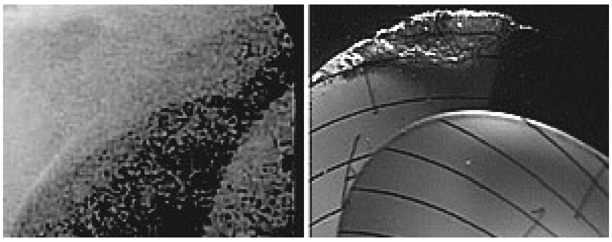

Figure 5: Full scale snapshot (left, courtesy LR); Model scale snapshot (right, from model test at 18.5% increased speed).

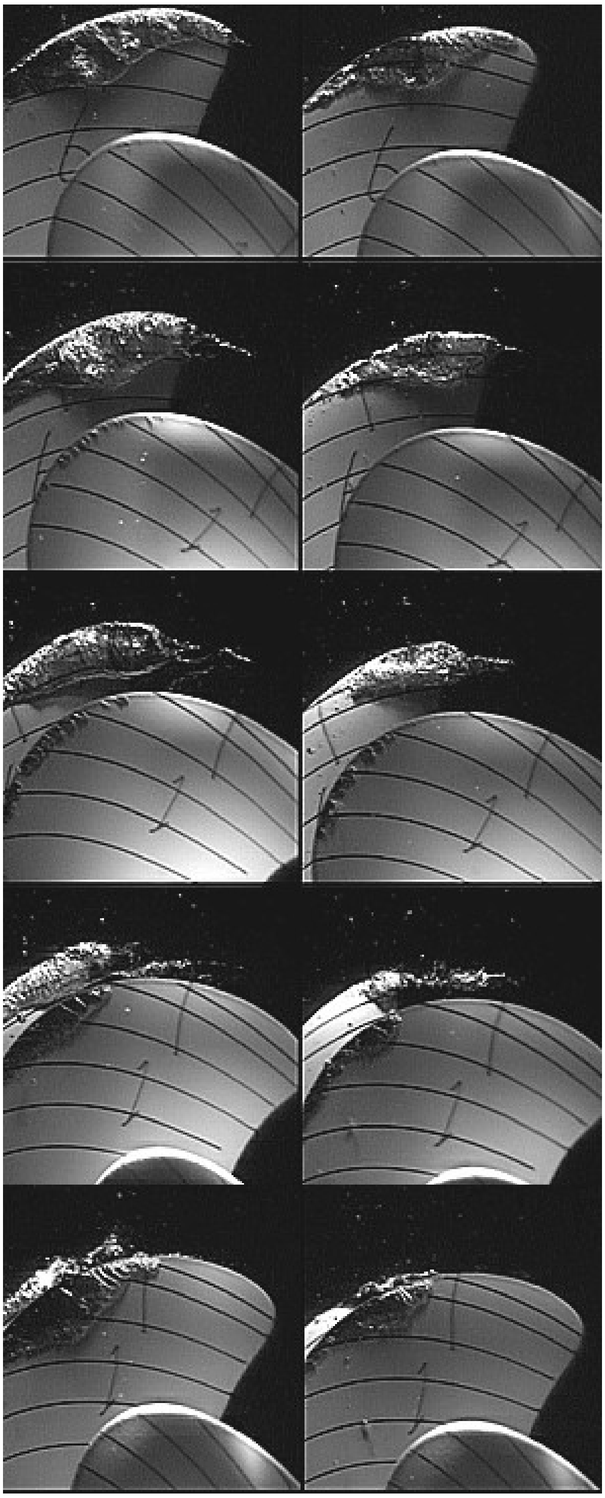

Figure 6: Comparison of cavitation extents. Left: thrust identity, Right: 18.5% speed increase.

4 INVERSE SHIP MODEL DESIGN

In the previous section, it was attempted to improve the prediction of hull pressure fluctuations by making adjustments to the experimental set point. Although, the results obtained with that approach show a clear improvement for first order pressure fluctuations, one could argue that they are based on 'suppressive therapy'.

Alternatively, in the past, attempts were made to solve the problem at the origin by modifying the ship model's wake field. This was done, e.g., by blowing or sucking the boundary layer or shortening the midbody; the former too complicated, the latter not effective. Nowadays, most model basins use the geosim models from speed-power towing tankery. In the past, dummy models were also used in cavitation tunnels in which a large size geosim would not fit. In all of the aforementioned cases, the afterbodies would still be geometrically similar.

The solution is sought in abandoning geometric similarity in the afterbody. Thus, the challenge becomes one of inversely designing a dummy model for cavitation experiments in which the effective wake field resembles the one of the ship. Geometric similarity is thereby deliberately sacrificed in favor of kinematic similarity. This concept is tentatively called the 'Smart Dummy' and involves the use of CFD tools to determine the shape of the dummy that serves best as a wake field generator in model testing.

It is instructive to see the effect of simple changes in width and length of the ship model. Therefore, four parent hull forms were chosen to form the four corners of the space in which the dummy hull form is to be found. The width is varied by narrowing the ship without changing the gondola shape. The length is varied by shortening the midbody without changing the afterbody. Thus, four shapes are generated as depicted in Figure 7,

1. A ship model with original length and half breadth.
2. A ship model with half length and original breadth.
3. A ship model with half length and half breadth.
4. The original ship model (i.e., the geosim).

The RANS code PARNASSOS was then applied to these forms as well as to many intermediate ones. All computations were performed as double body flows. Axial wake field results for the first three models are presented in Figure 9 to Figure 11 at the cross sections indicated in Figure 8.

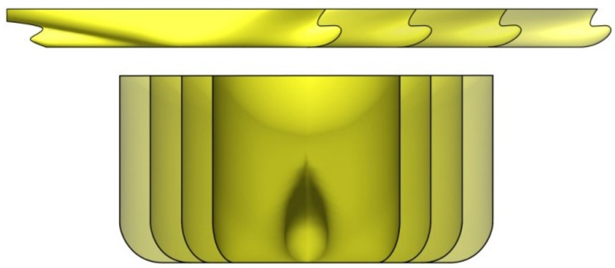

Figure 7: Examples of intermediate forms in systematic hull form variations of width and length.

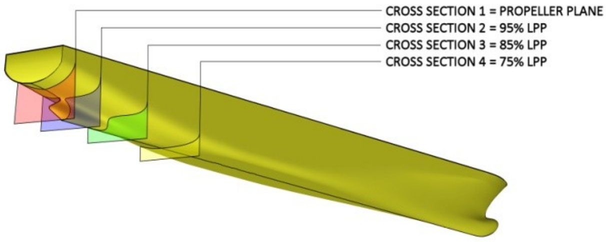

Figure 8: Cross sections used in discussion of wake fields.

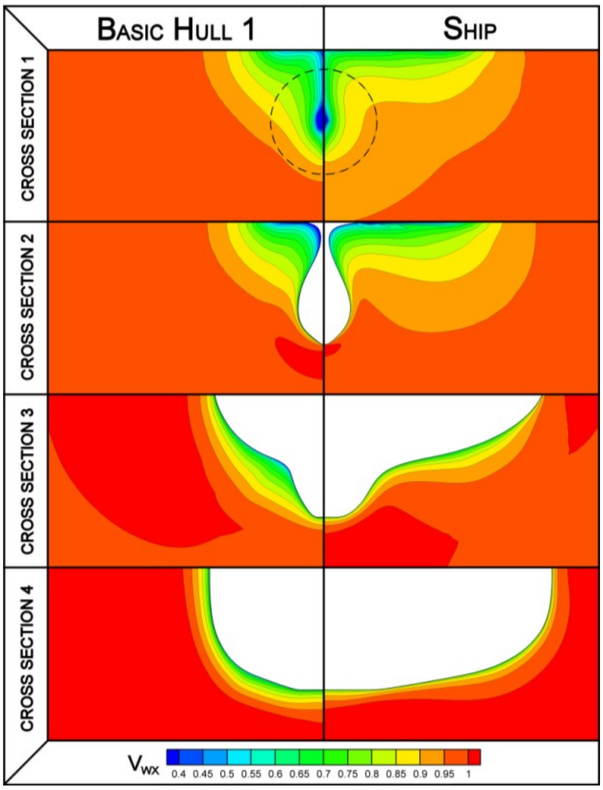

Figure 9: Axial wake field of long and narrow model.

For the narrowed model of Figure 9, Cross Section 4 shows that the boundary layer is thicker than at full scale. At the run of the ship, the boundary layer is growing fast. Although the boundary layer in the propeller plane has become thinner, the velocity difference observed in the wake peak is negligible. It is concluded that by only reducing the width of the model, the width and depth of the wake peak are not altered sufficiently.

Hull no. 2 also fails in generating a wake field that corresponds with full scale by only shortening the model. In Cross Section 4 of Figure 10 it is clear that the boundary layer is much thinner in comparison with the original model. However, at the run of the ship, the boundary layer is growing fast enough to cause a wake field almost equal to the one of the original model. These results confirm that the pressure gradient is a very important mechanism in generating the wake field. Only adjusting the length of the model by removing the midbody has an even smaller effect on the wake peak than altering the width of the model.

Reducing both length and width has a significant effect on boundary layer development. In the propeller plane at larger radii, the axial velocity outside the wake peak is even higher than at full scale, as can be seen in Cross Section 1 of Figure 11. Nevertheless, the velocity distribution in the top sector of the propeller plane still does not correspond to full scale.

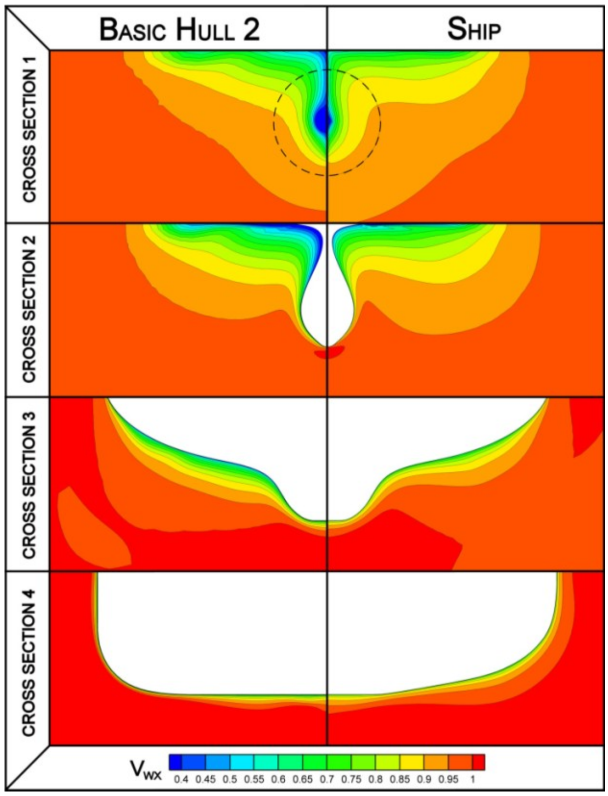

Figure 10: Axial wake field of short and wide model.

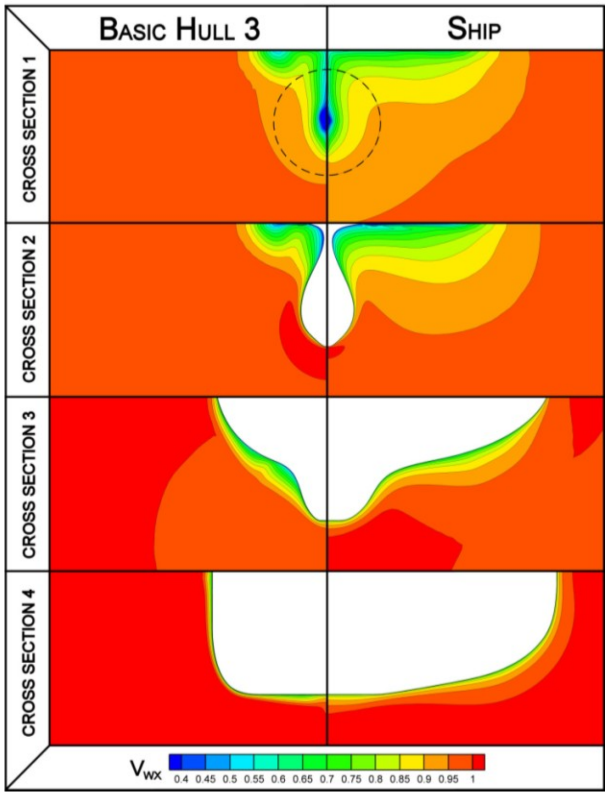

Figure 11: Axial wake field of short and narrow model.

All hull forms, including the intermediate hulls not shown here, suffer from the fact that the magnitude of the axial velocity in the top position is significantly lower than at full scale. This is illustrated in Figure 12, which shows the axial wake velocity at 80% of propeller radius. It may be concluded that only variations in length and width will not provide the desired ship wake field.

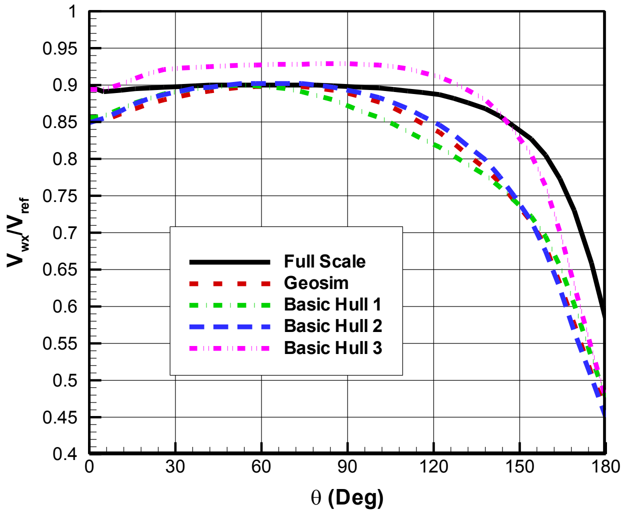

Figure 12: Axial wake velocities in propeller plane at 80% of propeller radius for four parent models and ship. Top dead center corresponds with 180 degrees.

In the application of the Smart Dummy concept, one does have to account for several practical limitations. The most important one is the geometric similarity of the stern above the propeller. The pressure sensors have to be placed at positions corresponding with full scale. Also, the clearance between the hull and the propeller shaft needs to be kept similar. Furthermore, within the Smart Dummy, there should be enough space to install the propeller powering system. The stern tube must be large enough to house the powering shaft of the propeller and allow for a smooth transition to the propeller hub. When applied in a free surface facility such as the DTT, the length, trim and sinkage must be retained to prevent significant changes in the wave system.

The apparent challenge is to locally modify the aft part of the model in such a way that the minimum axial velocity in the wake peak compares better with full scale. If this would be possible by, say, modifying the gondola area only, then it might also be possible to achieve our aim without changing the length and width of the model. Even better, it might be possible to arrive at a model that could be milled with the geosim model as input. With the additional restriction of keeping the clearance this would fulfill all requirements imposed on the model earlier.

To obtain the wanted wake field, changes in the afterbody were made. As a starting point, the geosim model was taken and the upper part of the gondola was made more slender. After several attempts, the Smart Dummy depicted in Figure 13 and Figure 14 was obtained. According to the computations it generates, the axial wake field shown in Figure 15 (left). For best full scale wake resemblance the model speed still needs to be increased somewhat, but only by 2%. This is several percent lower than the classic condition of thrust identity prescribes.

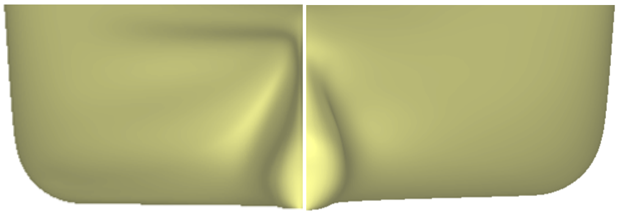

Figure 13: View from behind the Smart Dummy design (left), and the original geosim hull (right).

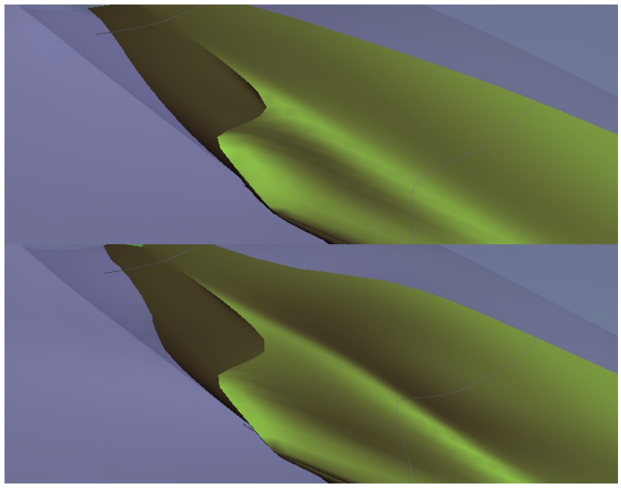

Figure 14: Underwater view of the Smart Dummy (bottom) and geosim hull (top) at the Froude speed.

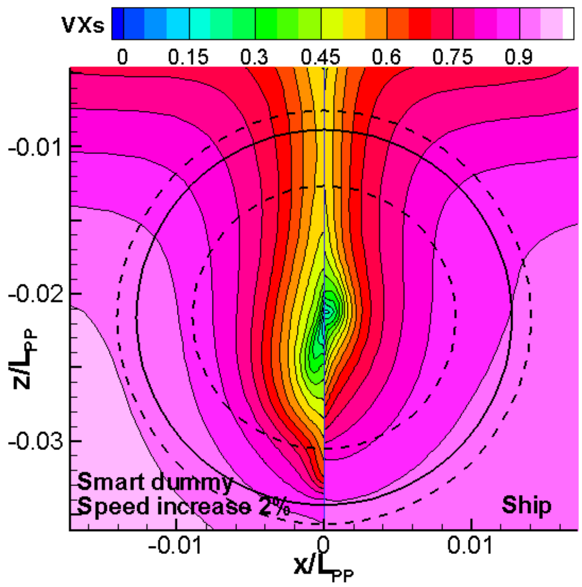

Figure 15: Axial wake velocities of the Smart Dummy design (left) compared to those at ship scale (right). The dashed lines are at 1.1 and 0.6 times propeller radius. The solid line is at the propeller radius.

This particular Smart Dummy was chosen because it best resembles the ship scale wake between the dashed lines in the upper part of the propeller disc in the figure. Figure 16 zooms in on the wake peak area and adds tangential velocity vectors. It must be noted that several alternative hull forms approximate the ship scale wake in the wake peak area equally well as the chosen one. However, none of them could reach the target wake at such a small speed increase relative to Froude speed and, more importantly, none of them could resemble the target wake for such large circumferential angles. The latter is important when pressure side cavitation is of concern. Figure 17 shows axial wake velocities at 80% of propeller radius as a function of circumferential angle (with zero at bottom dead center). The Smart Dummy (in red) follows the ship scale wake (in black) accurately everywhere except in the bottom quarter of the propeller disc. The figure also shows the axial velocity mismatch between the target wake and the geosim at the classic thrust identity condition (in blue). The wake peak identity method is shown in orange and appears to follow the target wake only in the top of the propeller disc.

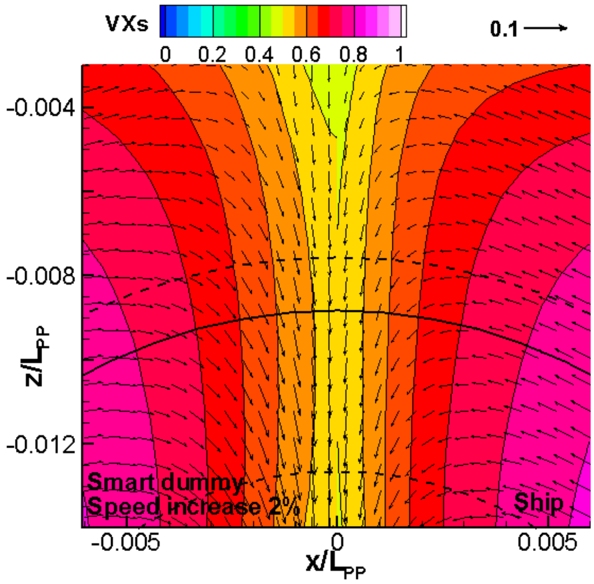

Figure 16: Axial/Transverse wake velocities of Smart Dummy design in top sector (left) compared to those at ship scale (right). See also Figure 15.

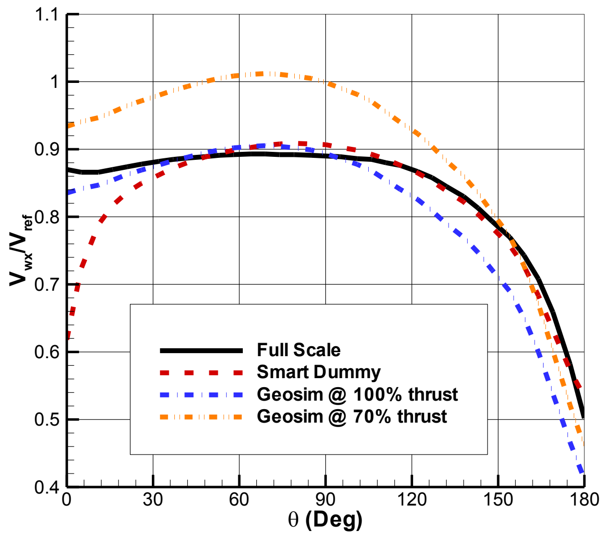

Figure 17: Axial wake velocities in propeller plane at 80% of propeller radius for geosim model, Smart Dummy and ship.

5 HULL PRESSURES ON SMART DUMMY MODEL

The Smart Dummy was tested in the DTT at 2% above Froude speed (while maintaining Froude RPM) with the pressure sensors at the same positions as before. Ample nuclei were provided through the use of upstream electrolysis strips. No provisions, however, were made to control the dissolved gas content. The results are shown in Figure 18 in the form of high speed video snapshots. The cavity volumes are slightly reduced. For the Smart Dummy, blade no. 1 shows inception of sheet cavitation later than with the geosim at increased velocity, indicating that the wake peak has indeed become narrower.

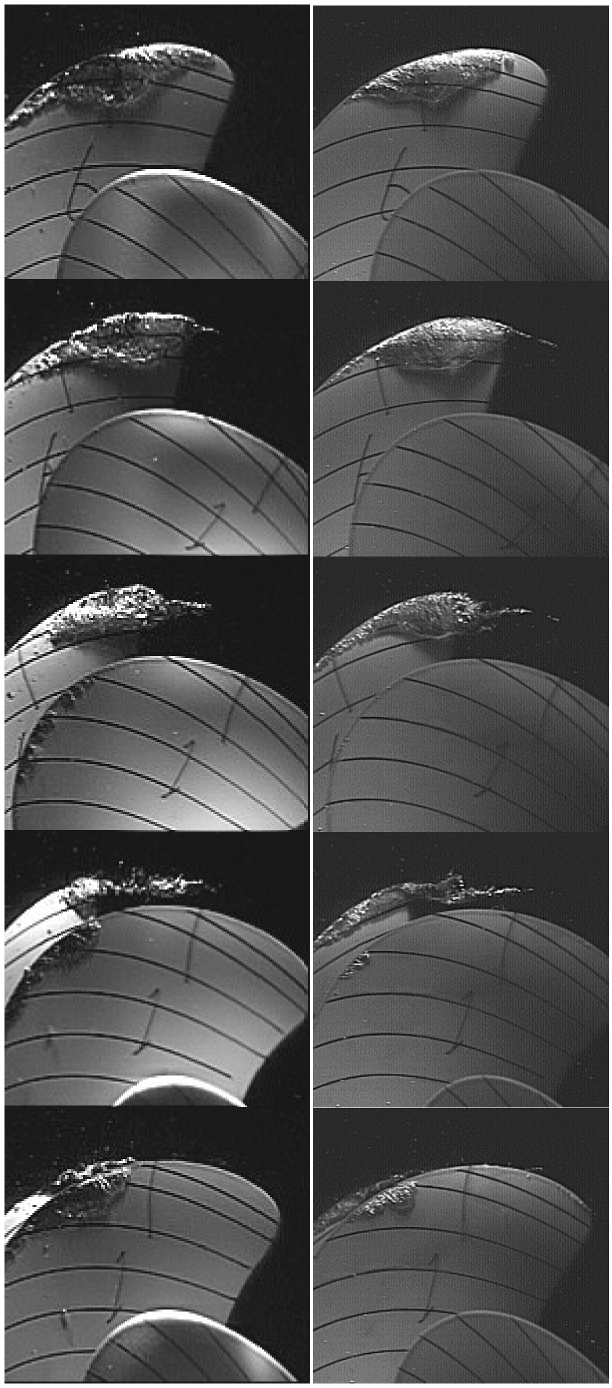

Figure 18: Comparison of cavitation extents. Left: Geosim @ 18.5% above Froude speed; Right Smart Dummy @ 2% above Froude speed.

Figure 19 shows the results in terms of hull pressure amplitudes. As before, amplitudes at the first four blade rate frequencies are given for the central pressure transducer, no. 5, which is closest to the full scale sensor position, and all amplitudes are divided by the full scale first order pressure amplitude.

In the Smart Dummy wake, the propeller generates pressure pulses much like in previous experiments with the geosim at increased speed. The narrower Smart Dummy wake causes later inception and earlier desinence, but the larger wake gradient causes a somewhat more rapid growth of the cavity. Also, the cancelling effect of cavities on neighbouring blades at the same time is reduced. As a result, despite the smaller cavity volumes, the pressure amplitude at the blade rate frequency is still slightly higher than the full scale value.

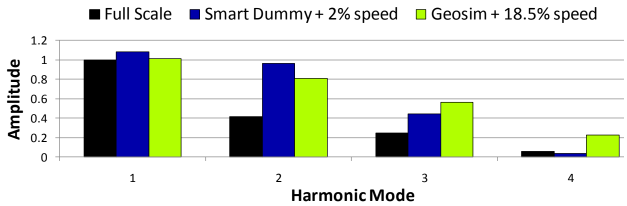

Figure 19: Comparison of non-dimensional full scale (in black) and model scale (in blue and green) pressure amplitudes for first four blade rate orders.

Higher orders of blade rate frequency are still strongly overpredicted. The Smart Dummy concept does not correct for the influence of the difference in Reynolds number on the propeller flow, possibly resulting in a different cavitation behavior. For example, the interaction of sheet and tip vortex cavitation may still not be properly modeled. Other limitations are related with scaling effects due to differences in gas content. The latter effects have not been incorporated in this investigation. In literature, a reduction in pressure pulses has been reported after changing the gas content from 40% to 80% oxygen saturation (Johannsen 1998).

6 CONCLUSIONS

The scale effect on the wake of a container vessel was counteracted, and thereby quantified, by two methods. The first method concerns the application of a different testing condition, called 'wake peak identity', which leads to similarity of thrust in the wake peak of the disc rather than similarity of the average total thrust. The second method was by means of a non-geosim model, called 'Smart Dummy', designed using a RANS code, with a full scale equivalent nominal wake field in those areas where cavitation may occur. Blade rate order hull pressure fluctuations were thus significantly reduced to values close to those found on full scale. Higher order blade rate components were not improved by correcting the wake field.

The feasibility of designing, manufacturing and testing of non-geosim models with prescribed wake characteristics has been proven. Only local modifications to the gondola area in the afterbody were necessary to achieve this. Shortening or narrowing of a ship model proved not to be effective for this purpose.

The lacking correlation for higher orders of blade rate shows that these are subject to other scale effects, supposedly due to Reynolds effects on blade flow (cavitating vortices) and water quality (gas content).

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