RECENT DEVELOPMENTS IN PREDICTING PROPELLER-INDUCED HULL PRESSURE PULSES

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ABSTRACT

Collapsing cavities on or in the vicinity of ship propeller blades cause pressure pulses which excite the hull structure above the propeller. Inevitably, this leads to higher noise and vibration levels in public spaces on board. Because of the more demanding comfort criteria the prediction of propeller-induced hull pressure pulses is still an important issue in ship design.

In this paper some recent developments are presented in the prediction of hull excitation forces either through model basin tests, by computational means, or through feedback obtained from sea trials. Special attention is paid to ongoing European projects and other cooperative research initiatives that are considered helpful in improving prediction techniques.

INTRODUCTION

Ever increasing demands regarding comfort levels on board ships have led several classification societies to the development of rules for inboard noise and vibration levels [1,2]. For example, in order to meet requirements for DnV's Comfort Class 1 as recently on M/S Color Fantasy (see a dedicated paper elsewhere in the proceedings) the generation and transfer of noise and vibration had to be kept within stringent limits.

Regarding the main sources of noise and vibration one may distinguish between engine forces, propeller thrust and bearing forces, as well as propeller-induced hull pressure forces. In this paper we focus on the generation of propeller-induced fluctuating pressure fields and their transfer to the ship structure. A brief overview is given of ways in which the propeller action may excite the ship together with several trends witnessed during the last decades to reduce excitation loads. Then, we turn our attention to the prediction of such excitation loads. Recent developments are presented either directly or indirectly concerning propeller-induced hull pressure pulse prediction by means of scale model testing, computations, and feedback from sea trials on board ships.

For a proper prediction of hull vibratory forces a chain of cause and effect relations must be taken into account from the effective ship wake field at the propeller disc, via the propeller design, its loading distribution and the resulting cavitation dynamics, to the radiation of pressure pulses and eventually the hull pressure field itself. After spatial integration over the aft body the latter yields the vibratory hull forces. Finally, the source strength of the propeller is computed from hull pressure measurements by means of inverse scattering techniques. In each component of this chain we touch upon developments in European research projects as well as in the author's daily practice at a ship model basin.

NOMENCLATURE

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>$J$</td>
<td>advance coefficient</td>
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<td>$V$</td>
<td>velocity (m/s)</td>
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<td>$D$</td>
<td>propeller diameter (m)</td>
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<td>$n$</td>
<td>revolutions (1/s)</td>
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<td>$w$</td>
<td>wake fraction (-)</td>
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<td>scale factor (-)</td>
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<td>$K_T$</td>
<td>thrust coefficient (-)</td>
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<tr>
<td>$\alpha$</td>
<td>cavitation number based on revs (-)</td>
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<tr>
<td>$k$</td>
<td>wave number (rad/m)</td>
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<td>$\omega$</td>
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<tr>
<td>$s,m$</td>
<td>refers to ship/model scale</td>
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<td>min, max</td>
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<td>wpi</td>
<td>wake peak identity</td>
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Abbreviations

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<tr>
<th>Abbreviation</th>
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<tr>
<td>LDV</td>
<td>Laser Doppler Velocimetry</td>
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<td>PIV</td>
<td>Particle Image Velocimetry</td>
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<td>BEM</td>
<td>Boundary Element Method</td>
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<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>RANS</td>
<td>Reynolds-Averaged Navier Stokes</td>
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<tr>
<td>Parnassos</td>
<td>RANS solver for flow around ships</td>
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<td>Procal</td>
<td>BEM solver for two phase flow around propellers</td>
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<td>MARIN</td>
<td>Maritime Research Institute Netherlands</td>
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<td>HSVN</td>
<td>Hamburgische Schiffbau-Versuchsanstalt</td>
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<tr>
<td>INSEAN</td>
<td>Instituto Nazionale per gli Studi ed Esperienze di Architettura Navale</td>
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<tr>
<td>Effort</td>
<td>EU 5th Framework Project on the refinement and validation of CFD prediction methods for the viscous flow around a ship hull at full scale, and their introduction into practical ship design</td>
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DESIGN CONSIDERATIONS ON NOISE & VIBRATION

When considering ways in which the propeller action can excite the aft body structure the fluctuating pressure field induced by the blades passing the hull surface comes to mind first. This pressure field is built up of components relating to the blade thickness and thrust loading, thus showing a displacement effect and a force field. Consequently, the fluctuating pressure field on the hull surface in the immediate vicinity of the blades is predominantly of a dipole nature, showing large phase differences over the area of application. As a result, the net vibratory force production has to remain limited. However, locally, the excitation pressures may still be substantial.

Pulsating or collapsing cavities on or in the vicinity of propeller blades are a more important cause of hull excitation. Stationary cavities rotating with a propeller blade show a displacement effect much like blade thickness. However, the net cavity volume variations that are also present form a source of monopole character. Such sources produce pressure fluctuations that are largely in phase over the aft body surface, thereby being very effective in generating hull excitation forces.

Obviously, for successful noise and vibration abatement the cavitation performance of the propeller is crucial. The quality of the design is not only reflected in the reduction of the cavity volume but also in the reduction of its dynamic activity. The magnitude and frequency content of the latter must be viewed in light of the vessel’s vibration response characteristics.

How should one then achieve small cavity volumes showing low dynamic activity? Typical designers’ answers to this question given in the past are summarised in accordance with Figure 1. For low noise and vibration levels, the propeller inflow (i.e. the ship’s effective wake field) must be as uniform as possible. Whenever hull form designers achieve this their reward is in the form of reduced dynamic cavitation activity. Propeller designers in their turn try to adapt the radial loading distribution and geometry of blade sections. The trend has been to increase the blade tip loading in order to reduce sheet cavity extents, and to apply skewed blade shapes to reduce dynamic sheet activity.

If one is not interested in the other detrimental effects of cavitation, i.e. underwater radiated noise, erosion, and thrust breakdown, its presence need not be a problem as long as one can isolate the source. At speeds at which the aft body is no longer submerged the excitation area is automatically reduced considerably, thus effectively isolating the source from the structure. Obviously, at design speeds the aft body must be submerged and the source can only be isolated by artificially introducing a jump in acoustic impedance. This is achieved by injecting compressed air between the propeller tip and hull. On a number of ships this approach has proven successful at and around higher orders of the blade rate frequency at the expense of a small increase at the lowest orders.

Apart from the application of bubble screen isolation measures, the reduction in the level of pressure fluctuations at orders of the blade rate frequency has mainly been obtained by a significant reduction in sheet cavity dynamics. A value of about 8 kPa for allowable maximum hull pressure amplitude at blade rate was often used for single screw ships. Nowadays, normal values are closer to 4 kPa, while for twin screw passenger vessels amplitudes of less than 2 kPa are measured.

With such low blade rate amplitudes cavitating and non-cavitating pressure contributions often become of the same order of magnitude. Yet the total excitation forces are still determined by cavitation effects. One reason for this is the homogeneous phase distribution of monopole sources such as collapsing cavities. Another reason is that non-cavitating propeller blades produce spectra in which only a few tonal components at the lowest orders of blade rate are significant. If this holds true the inevitable conclusion must be that the maximum amplitude at blade rate is not an adequate measure of the excitation force. Nevertheless, contract requirements are often based on this very number.

It is often advised to separately treat cavitating and non-cavitating contributions to the pressure field. This is especially true for vessels operating with propellers inside nozzles. Then, propeller-hull clearances are very small and cavitation, thrust...
and blade thickness effects together determine the pressure field on the complex shaped stern. Ref. [6] reports on the irregular hull pressure amplitude distributions measured on dredgers. The exact choice of measuring locations on the hull outside the nozzle then becomes of great influence on the evaluation of contractual requirements.

However fortunate may be the decrease in hull pressures at the lowest blade rate frequency components, an opposing trend of increasing, broadband hull pressure fluctuations is also observed in the range of about 20-70 Hz. Despite the low magnitude of these excitation forces they may easily excite structural resonances. As a result of ‘designing out’ sheet cavitation many propellers predominantly show leading edge or tip vortex cavitation, which are considered responsible for broadband excitation [3]. However, certainly not all propellers showing vortex cavitation generate broadband excitation.

It is all-important to be able to accurately check the design against the specifications as this increases the chance of reaching them without sacrificing too much in other areas. The prediction of the excitation forces or propeller source strength is treated in the remainder of this paper. Recent developments are informally presented, starting at the prediction of the ship’s wake field at the propeller location, and then followed by the other items indicated in Figure 1.

**EFFECTIVE WAKE FIELD**

A first prerequisite to the correct prediction of the hull pressure field is to have knowledge of the effective wake field at the propeller plane. This is by no means straightforward as the whole notion of the effective wake field is fictitious in the sense that it is not directly measurable. One has to revert to either the measurement of the nominal wake field and correct for the propeller-hull interaction, or one has to measure the total wake field and subtract the propeller induction velocities.

The standard procedure is to measure the nominal wake field on model scale using Pitot tubes (Figure 2). If a ship model is available this is a straightforward procedure, also applicable to the positioning of appendages so as not to disturb a good wake field. However, two drawbacks are apparent. First, the wake field at model scale may be subject to a scale effect due to the Reynolds number of the flow being two orders of magnitude smaller than on full scale. Second, the propeller-hull interaction component still has to be estimated. Therefore, the result will be of an unknown accuracy.

The alternative of measuring the total wake field at model scale by means of Laser Doppler Velocimetry (LDV) has often been successfully attempted, but is expensive and laborious to apply in everyday practice. A non-intrusive technique that has recently entered the market is Particle Image Velocimetry (PIV). Stereo PIV is a ‘whole flow field’ technique providing instantaneous 3D velocity vectors in a cross-section of the flow. The importance of PIV lies in its ability to reach a high spatial resolution at a certain instant. LDV on the other hand delivers high temporal resolution at a certain point. Both techniques are important since spatial and temporal variations in the wake may be quite substantial, thus having a bearing on the cavitation dynamics and the spectral content of excitation forces. PIV has the added advantage of being less complex and potentially cheaper as it measures a whole measuring plane at once.

Within EU project ‘Leading Edge’, PIV techniques were applied to the flow directly behind the blade tip of a non-cavitating propeller [8]. Figure 3 (bottom) presents velocities in axial direction as measured by the stereo PIV system, non-dimensionalised by the propeller tip speed. These velocities are compared with computations (top).

The wake field on full scale is hardly ever determined as it involves the measurement of the total wake (i.e. with operating propeller) using the non-intrusive means of LDV. A successful measurement was made on board of M/S St. Michaelis by HSV in the past. Figure 4 shows the total, axial velocity distribution in the propeller plane at locations reachable by the laser. Recently, the computation of the wake field at full scale Reynolds numbers has come within reach.
Figure 5 shows the computed version of the distribution of axial velocities in the total wake field of St. Michaelis. MARIN's RANS-solver for ship flows 'Parnassos' was used with a $k-\omega$ SST turbulence model. The propeller action was modelled by means of a force field. Correctly flow disturbances may reach the propeller disc and disturb the wake field, causing deteriorated cavitation performance. Figure 8 shows a streamline traced from a fin to a location well outside the propeller plane. Noise and vibration hindrance is therefore not expected from this origin.

Figure 5. Prediction of the total, axial wake field for M/S St. Michaelis by means of 'Parnassos' (courtesy MARIN).

The computations were performed within the scope of the EU project 'Effort'. On model scale LDV measurements were made to obtain the nominal wake field of Figure 6. This may be compared with its computational equivalent depicted in Figure 7.

Apart from their use as input to propeller models RANS calculations themselves serve a purpose when judging flows from the point of view of noise and vibration. For example consider the positioning of struts or fins. When this is not done correctly flow disturbances may reach the propeller disc and disturb the wake field, causing deteriorated cavitation performance. Figure 8 shows a streamline traced from a fin to a location well outside the propeller plane. Noise and vibration hindrance is therefore not expected from this origin.

Figure 6. Nominal wake field measured on model of M/S St. Michaelis by means of LDV (courtesy HSVA).

Figure 7. Prediction of the nominal wake field on model scale for M/S St. Michaelis by means of 'Parnassos' (courtesy MARIN).

The next step in the development of RANS codes is the direct coupling with a propeller code for the simulation of the propeller-hull interaction. The subtraction of the interaction component will then yield the effective wake field.

Summarising, it may be stated that the importance of the accurate determination of the effective wake field shows in propeller design and analysis, in the positioning of struts and fins, but also in the determination of the direction of propeller rotation, and finally (and perhaps most importantly) in the prediction of boundary layer separation on the hull in the aft body region.
of a blade in top dead centre position. Using this Standard at a level corresponding to 0.9R (with R the propeller radius) cavitation number, \( \sigma \), wake fraction. By adjusting the tank or tunnel pressure, the ship; is the effective propeller rotation rate; and \( A \) is the model scale factor is \( \lambda \); \( V \) denotes the forward speed of the ship; \( n \) the propeller rotation rate; and \( w \) is the effective wake fraction. By adjusting the tank or tunnel pressure, the cavitation number, \( \sigma \), is made to agree with that on full scale at a level corresponding to 0.9R (with R the propeller radius) of a blade in top dead centre position. Using this standard procedure both cavitation patterns and dynamics on model propellers were considered to be representative of full scale with the exception of light, free vortex cavitation of which the inception is seriously affected by the scale effect on Reynolds number.

However, the wake scale effect is generally not uniform over the entire propeller disc, but predominant in the wake peak. For achieving equivalence in cavitation patterns and dynamics the distribution of velocities in the wake peak must therefore be made equivalent to their full scale counterparts. Using standard set points the propeller is still overloaded in the region where cavitation is expected to occur. Although not significant for the wake fields of modern passenger ships, this scale effect can become serious in case of slender, single screw ships as the model scale hull pressure amplitudes were found to be too high.

The obvious way to go forward is then to simulate the blade loading in the wake peak itself without considering the average propeller loading. The model forward speed should then be selected in such a way that the ratio between the circumferential tip speed of the propeller blades and the local axial velocity in the wake peak is equal on model and full scale. This condition, referred to as \( J_{\text{wp}} \) identity (with wp: wake peak identity), is defined by

\[
J_{\text{wp}} = V_{\text{wp}} / (nD)
\]

with \( V_{\text{wp}} \) denoting the minimum velocity in the wake peak. The method requires that the scale effect on the wake peak depth is known. Some typical data have been collected from a number of RANS computations on a wide range of Reynolds numbers, which may serve to predict the scale effect on the depth of the wake peak. More computational data are needed in this respect. As the number of RANS calculations is growing rapidly improved insight will become available in due course. For the time being, the following simple prediction rule, proposed by Holtrop, may be used

\[
V_{\text{wp}} = V_{\text{ma}} \left( V_{\text{f}} / V_{\text{ma}} \right) \left( 1 + \frac{V_{\text{ma}} / V_{\text{f}}}{V_{\text{min}} / V_{\text{ma}}} \frac{1}{V_{\text{min}} / V_{\text{ma}}} \right)
\]

If this procedure is used in a (depressurised) towing tank, where Froude scaling of the rotation rates is applied, the model speeds may become so high that free surface effects start to affect the stern flow. Therefore, in routine model tests the speed of the ship model must be chosen as \( V_{\text{ma}} \), which is the highest allowable speed of the ship model, where free surface effects on the wake still match those in reality. This ensures the highest possible Reynolds numbers being applied without any non-realistic, free surface effects. The same rule is applied, but now we solve for the model rotation rate,

\[
\frac{1}{n_m} = \frac{V_{\text{f}} / V_{\text{ma}}}{\lambda n} \left( V_{\text{ma}} / V_{\text{f}} \right) \left( 1 + \frac{V_{\text{ma}} / V_{\text{f}}}{V_{\text{min}} / V_{\text{ma}}} \right)
\]

The effect of choosing the set point in the way described above was studied on a typical single screw vessel. Pressure pulses were measured at various model speeds, meanwhile keeping RPM constant at its Froude equivalent. In Figure 9 the maximum pressure amplitude at blade rate frequency is plotted against the speed of the ship model. At 0 the model speed equals its Froude equivalent. The highest pressure amplitude
found there is set at 100%. The test was repeated at higher model speeds, each time increasing the speed by a percentage equal to the average wake scale effect. Thus, at 1, the maximum amplitude (i.e. 85%) is the one obtained from the standard method, where the average propeller loading is correct. For the new wake peak scaling method the results have to be interpolated at an estimated value of 3.3 times the average wake scaling effect (indicated in Figure 9 by a vertical black line), thus leading to an amplitude of only 39%. It may be concluded that the new choice of set point has led to a reduction in the prediction of maximum blade rate amplitude by more than a factor of two.

![Figure 9. Hull pressures as a function of ship model speed in terms of the number of times the average wake scale effect is added to the Froude-scaled speed.](image)

Although the discussed refinement in the measuring procedure is necessary for a more correct pressure fluctuation measurement, one must be aware of the fact that other factors also play a role. For example, the velocity gradients in the wake peak may still differ from the gradients experienced on full scale. Nevertheless, the application of the new method so far shows a clear improvement in prediction accuracy. In the near future the author hopes to publish actual correlation data that is being collected at the time of writing.

### Cavitation Dynamics

Having demonstrated the importance of using accurate wake fields and load distributions in modelling hull pressure pulses, the question that remains is whether inaccuracies that are bound to exist have a great bearing on the cavity dynamics, and consequently on predicted pressure pulse levels.

The study of cavity dynamics is greatly enhanced by the advent of high-speed video techniques, which are now in regular use at ship model basins. High-speed video has also been used on full scale, an example of which is shown in Figure 10 [3]. Regular video techniques only show time-lapse images and are therefore not very well-suited to the study of dynamic events. Nevertheless, they are still often used, also in combination with boroscope techniques, which allow for easy observation 'around corners' and need only a very small hole to protrude the hull. It is hoped that in the near future high-speed video recordings may be made using boroscopes.

![Figure 10. Top view of the tip vortex cavity looking aft of a container ship (the four snapshots are taken during one blade passage, from the top left to the bottom right).](image)

Obtaining additional information from flush mounted pressure transducers is of great importance. On model scale an extensive research programme was carried out by CRS, where high-speed video recordings were made in synchronisation with measurements of hull pressures. The analysis of the data was done using the simple software tool depicted in Figure 11.

![Figure 11. Synchronised pressure time series and high-speed video recording of a propeller blade with a sheet cavity.](image)

For the flow around ships advanced RANS-codes are available, capable of computing full scale Reynolds number flows. Within EU project 'Virtue' such computer codes are also being developed for propeller flow including cavitation. However, they are still very much in an academic stage of development. It will still take many years of work before the status of 'practically applicable' is reached. In the meantime...
cavitating propeller flows are being computed by non-viscous codes based on boundary element techniques. Many of such codes have been developed, very few, however, have been well-verified and validated. One code that is currently being validated within CRS is called 'Procal' (see References [4,7]). Figure 12 shows a result from its validation study. The computed sheet cavity thickness distribution is compared with snapshots of an equivalent model scale experiment.

Figure 12. High-speed video snapshots (courtesy INSEAN) and Procal cavity thickness survey (courtesy MARIN).

Validated boundary element codes are useful in propeller design if provided with accurate effective wake fields. Also in cavitating flow analysis such codes may be used as a workhorse for the study of cavity dynamics as a function of propeller design and wake field parameters. Unfortunately, the modelling of leading edge and tip vortices (as well as their cavitating counterparts) by boundary element methods is by no means straightforward. This would not be a problem if tip vortex cavities were simply transported downstream without showing any acoustic activity. However, this simple view does not hold true. The cavitating leading edge and tip vortices are held responsible for the broadband excitation sometimes found on passenger vessels (see Ref. [3]). For this reason it is important to extend BEM codes with models capable of showing the effect of pulsating cavitating tip vortices. Obviously, this can only be successful once a proper understanding is obtained of the underlying hydrodynamic/acoustic source mechanisms.

VIBRATORY HULL PRESSURE DISTRIBUTION

When the effective wake field, propeller geometry, propeller loading distribution (especially in the wake peak) and set point in the towing tank or cavitation tunnel are all reasonably well modelled, the prediction of the hull pressure may still be slightly inaccurate, because of scale effects on the acoustic hull diffraction. The use of a geometrically scaled ship model (see Figure 13) reduces this effect to a minimum, at least when a free surface is present to model the pressure release effect. Even then, the scattering of hull pressure pulses will still suffer from incorrect scaling of the Mach number. Fortunately, at low frequencies this effect is negligible.

Figure 13. Set of flush mounted pressure transducers for measuring the hull pressure distribution.

Figure 14. Distribution of solid boundary factors (left) and boundary elements (right)

The diffraction effect of the hull and free surface is computed by an appropriate boundary element code solving the Helmholtz equation. Figure 14 shows a distribution of solid boundary factors to be multiplied by the propeller-radiated free field pressures in order to obtain diffracted hull pressures. Recently, this code was integrated with propeller analysis code 'Procal' and furnished with the capability of solving inverse scattering problems. Thus, it becomes possible to determine the propeller acoustic source strength by an inverse computation. An example is given in Figure 15, where the strength of a monopole source is determined in terms of...
volume acceleration, given a set of pressure amplitudes and phases in a number of points on the hull. The latter may be obtained from an appropriate model test where measurements are made of the hull pressure distribution with and without cavitation. The difference between the two serves as input to the inverse computation of the source strength. Analogously, the non-cavitating pressure field may be inversely computed in terms of point dipoles.

Figure 15. Determination of source strength (green circle) using measured hull pressure data (coloured squares).

CONCLUDING REMARKS

In this paper several recent developments are presented in the experimental and computational prediction of propeller-induced hull pressure forces. It is shown how RANS codes may be used to compute the effective wake field at full scale Reynolds numbers. An example of their use in the positioning of appendages is also given. On the experimental side PIV-based techniques are becoming available, which may serve in detailed wake field analyses.

Whenever scale effects are present on the ship model wake, for example in the case of slender, single screw vessels, the accuracy of predictions of propeller-induced hull pressures has to be improved. An improved procedure is proposed for performing hull pressure measurements in cavitation tunnels and depressurised towing tanks, allowing for wake scale effects in the wake peak area. The procedure ensures the correct propeller loading in the area where the cavitation actually occurs. Input data for the wake scale effect in the wake peak may be obtained from RANS computations. It is essential that such methods are correlated with full scale data.

The added value is highlighted of observing cavitation dynamics by means of high-speed video techniques in sync with measurement of hull pressures, both on model and full scale. The availability of such data is a good starting point for a detailed signal analysis on the basis of which contract requirements may be evaluated. The use of a maximum, single amplitude pressure level as a measure of excitation force is discouraged, especially for cases where the non-cavitating contribution to the total is significant.

On the computational side the use of validated propeller boundary element codes including the effect of dynamic sheet cavitation is promoted. However, for the proper simulation and study of tip vortex flows specialised RANS codes need to be developed. In the meantime further study of the broadband excitation caused by cavitating tip vortices is considered necessary. The mechanisms underlying the cavitating tip vortex dynamics must be well-understood. Only then one is able to judge whether and how improvements can be made in the prediction of broadband excitation levels.

Finally, the simulation of the hull pressure field is discussed by means of boundary element based diffraction codes. It is shown how the effect of propeller cavitation may be modelled by one or more simple monopoles, thus enabling the derivation of the propeller source strength, either based on measured or computed hull pressure input data.

REFERENCES

[8] Berchiche, N., Janson, C-E., Numerical computations and comparison to experiments for a propeller in open water condition, To be submitted to Int. J. Ship Techn. Research.