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Cavitation Research on Ship Propellers

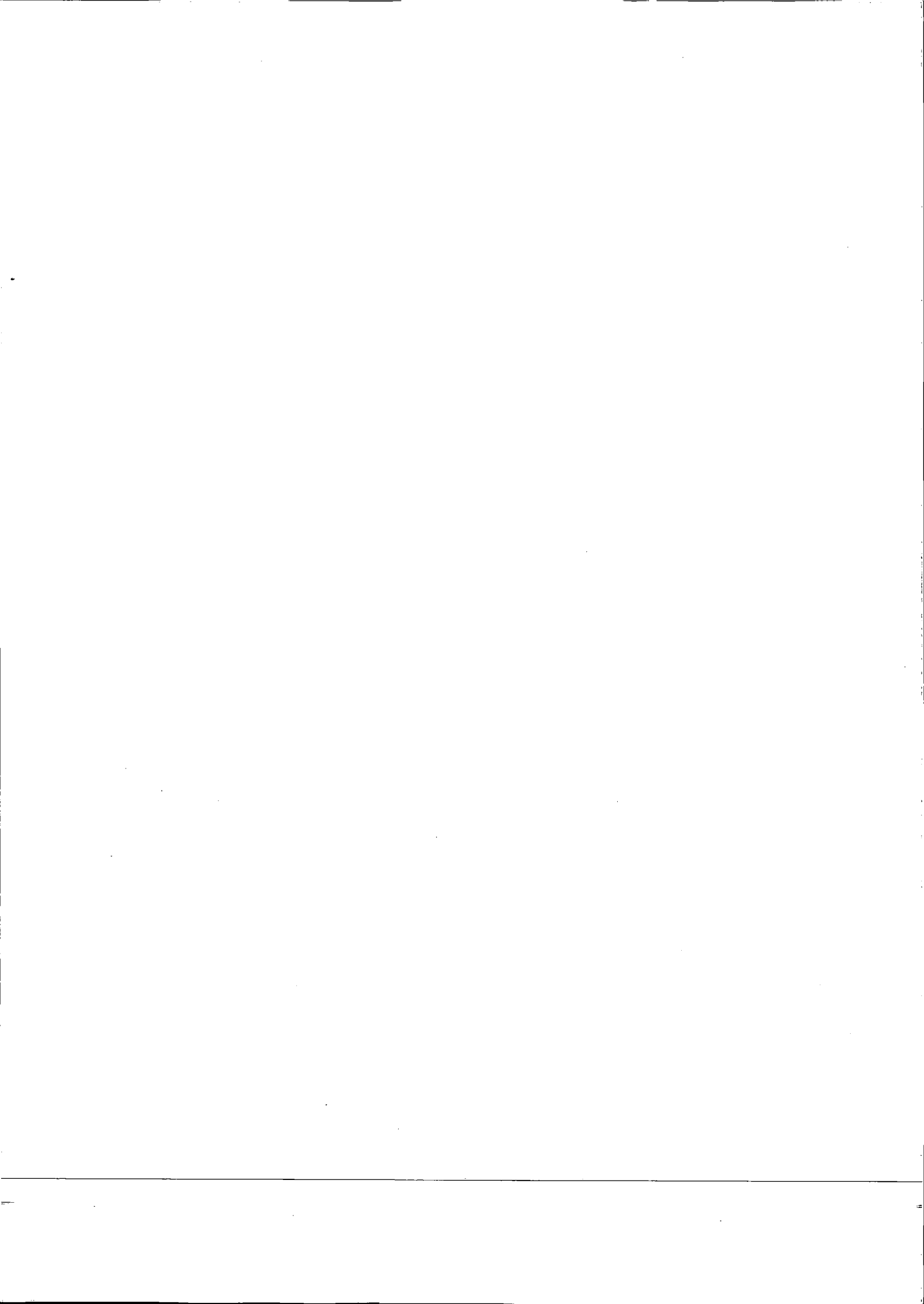
by

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CAVITATION RESEARCH ON SHIP PROPELLERS

A REVIEW OF ACHIEVEMENTS AND CHALLENGES

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ABSTRACT

This paper reviews cavitation research on ship propellers performed in the recent past in MARIN's Depressurized Towing Tank and cavitation tunnels. Cases are presented through which advances have been made possible in the design of propellers and ships, and unresolved issues that form the challenges of future research are discussed. Our focus is on cavitation inception, cavitation-induced hull-pressure fluctuations, and cavitation erosion on propeller blades and rudders.

INTRODUCTION

Cavitation occurs on nearly all ship propellers. It may lead to expensive problems if not acknowledged in an early design stage. The two most frequently occurring problems are vibrations and noise in the afterbody due to cavitation-induced pressure fluctuations on the hull, and cavitation erosion on propeller blades and appendages. Early recognition of these adverse effects is important, not only to ensure compliance with contract requirements, but also because often cavitation has to be controlled at the cost of propeller efficiency.

To ensure that the propulsor meets the requirements that relate to comfort (vibration and noise) and safe and economic operation (erosion), model scale experiments or computations that address cavitation are conducted prior to construction. As reliable computational techniques that incorporate all aspects of cavitation that relate to noise, vibration and erosion are lacking, scale model experiments are still the preferred choice.

From experiments in the first cavitation tunnel, built by Parsons in 1895, insights were built up as to how one should model cavitation phenomena to allow for full scale predictions. This has led to the use of medium sized cavitation tunnels in the mid nineteen hundreds and eventually to the large cavitation tunnels of today which allow for complete ship models to be installed in front of the propeller. At MARIN, propeller cavitation behavior is investigated in the Depressurized Towing Tank (DTT) which allows for the testing of large scale ship models in

the presence of a free surface. The DTT is in operation since 1972 (Kuiper [1974]) and has been modernized in 2001. A medium sized cavitation tunnel and a small high-speed cavitation tunnel are also available. They are primarily used for background research on cavitating propellers and wing type geometries.

Reliable predictions of full scale cavitation behavior have become more important with the ever increasing powers that must be absorbed by a single propeller. This necessitated the careful validation of predictions made by cavitation laboratories through full scale measurements and observations. This paper addresses a number of such validation studies and argues that despite the undeniable success of cavitation facilities around the world in qualitatively aiding in the design process, the reliability of predictions is not yet such that problems are avoided at all times. It must be understood that propeller designers, in order to meet the often contradicting requirements of high comfort and propulsive efficiency, are in need of a more quantitative improvement of prediction capabilities.

Whilst showing areas where successes are scored, the paper also indicates topics where further research is necessary. In brief, cavitation research has allowed for today's greatly improved design of propellers and afterbodies, resulting in much reduced levels of noise and vibrations. Also our understanding of the phenomenological nature of cavitation erosion has greatly improved. Nevertheless, the state-of-the-art is such that several research issues are still outstanding and hamper our capability to predict cavitation behavior. In this respect one should think of hull-pressure fluctuations at orders of blade rate, which are observed to be sensitive with respect to environmental conditions, leading to varying accuracy in predictions. A similar statement holds for low frequency broadband pressure fluctuations. Also worth mentioning are the practical prediction of cavitation erosion due to a lack of detailed understanding of the erosion mechanism and the delay in inception of certain types of cavitation on model scale.

Each of the main topics identified above is treated separately, starting with inception, followed by hull-pressure fluctuations, and finally erosion.

CAVITATION INCEPTION

Cavitation inception is of direct importance to Navy vessels, because of the sudden increase in noise levels at the onset of cavitation. Indirectly, however, it is also important to other problems caused by cavitation, for if cavitation inception does not occur, or at slightly different conditions, this is likely to affect predictions of erosion and radiated pressure fluctuations. Cavitation inception forces us to look into micro-scale phenomena, which are not easily observed or measured on propellers. Therefore, fundamental research on hydrofoils in dedicated scale model experiments is imperative on improving general understanding and predictions.

The results of cavitation inception tests are often summarized in an inception diagram, i.e. a plot of the inception number against a parameter related to the operating condition of the propeller, e.g. a thrust or torque coefficient. The simplicity of such a representation is misleading in the sense that the underlying phenomena are complex and sensitive with regard to environmental conditions. A nice review of phenomena and sensitivities associated with cavitation inception is given by Rood [1991]. Performing repeatable cavitation inception tests with acceptable uncertainties is no matter of course. Experience and proper facilities with ample opportunities for visual observation are indispensable for obtaining meaningful results.

To better understand the inception behavior of sheet cavitation on propellers, a four year research project on the delay of sheet cavitation inception was started. The David Taylor Model Basin (DTMB) and MARIN were involved in the program which came to be known as 'AFDEASR'. The program was a success in that sheet cavitation on the demonstrator propeller showed a significantly later inception than tip vortex cavitation on full scale (Kuiper and Jessup [1993]). The next challenge was to delay the inception of tip vortex cavitation as well. The same model basins then started a new research program, called 'TIPVOR' (tenure 1996-2001), on the origin of tip vortex cavitation and the possibilities for its suppression (Kuiper et al. [2006]). With their focus on cavitation inception the two programs produced a wealth of knowledge and practical experience on the subject. The remainder of this section attempts to give a brief account of the state-of-the-art, largely based on the 'AFDEASR' and 'TIPVOR' programs, as well as some open literature.

Cavitation inception is affected by a great number of parameters, such as the character of the wetted flow (laminar vs. turbulent), the occurrence of boundary layer separation and the density of nuclei. Inception often shows a strong sensitivity with regard to minor deviations in geometry and flow conditions (Figure 1).

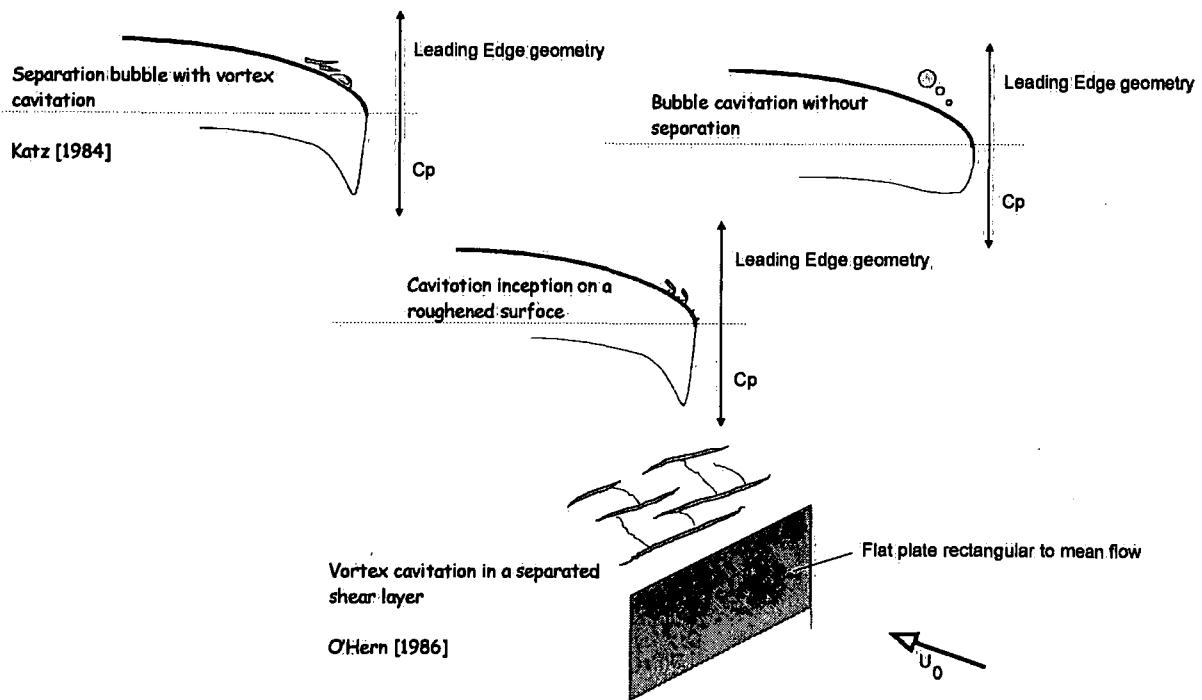


Figure 1. Mechanisms of cavitation inception at the leading edge of a foil and in the shear layer of a separated flow (Katz [1984] and O'Hern and Acosta [1986]).

The repeatability of the cavitation number at which inception on a propeller blade occurs is therefore by no means guaranteed. Within the 'TIPVOR' program, DTMB and MARIN studied the repeatability and checked the effect of the respective laboratories on inception.

With sand roughness applied to the tip and leading edge the repeatability was found to be within about 4% in inception number, based on tests performed at an air content of about 5.5 p.p.m. (van Terwisga and Borg [1997a]). An unexplained bias error of some 20-25% is also reported for different test sessions. Differences between blades were found to account for 20%. This scatter was the same for a 320 mm propeller manufactured by MARIN and a 400 mm propeller made by another reputable institute.

Regarding water treatment, a significant difference between 'old' and freshly supplied water in the cavitation tunnel could not be observed. An average change in inception number of 2-4% occurred after 'old' water was deaerated and subsequently aerated to the same standard air content of 5.5 p.p.m. Also no effect in inception number between two different observers could be found.

As to the difference between MARIN's cavitation tunnel and Depressurized Towing Tank, it should be noted that in the DTT cavitation desinence is usually established, whereas in the cavitation tunnel cavitation inception is determined. The procedure followed for the determination of cavitation inception or desinence is also different (see van Terwisga and Borg [1997b]). These differences result in a cavitation desinence number from the DTT that is about 10% higher on average than the inception number found from the Cavitation Tunnel, in a K_T range of 0.3 to 0.4.

Concerning MARIN's cavitation tunnel, with a cross-section of 900 by 900 mm, and DTMB's open jet cavitation tunnel, measuring 1100 mm in diameter, the difference in inception number for suction side tip vortex cavitation did not exceed 11% in cavitation number, σ_n , in the K_T range of 0.27 to 0.38. Large differences occurred, however, in pressure side cavitation inception between the two facilities (Figure 2). These differences may well be caused by the application of tip and leading edge roughness in MARIN's Cavitation Tunnel and by the faintness of the cavitating vortex, when only a bubble trace is visible.

After an indication of the uncertainty in the model test results had been obtained, a systematic optimization study was conducted, eventually leading to the redesign of a propeller for a naval supply vessel. This propeller was tested, built and fitted to the ship, after which extensive viewing trials were held in the Mediterranean.

Figure 3 shows a comparison between the predicted cavitation inception results for this newly designed propeller and full scale trial results. The figure compares visual inception data with scale model results from the DTT, extrapolated to full scale. One clear observation is that the predicted operating point with the lowest cavitation inception number for an off-design pitch of

approximately -7 degrees corresponds well with the optimum operating point following from the full scale measurements.

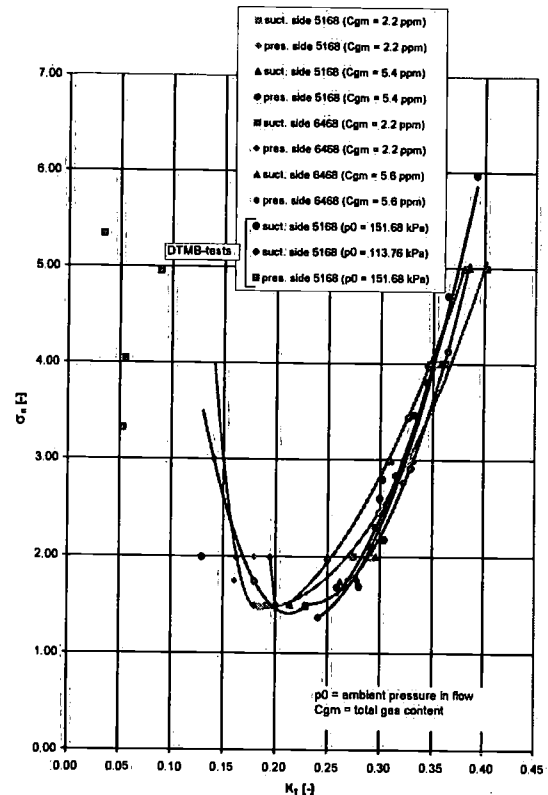


Figure 2. Scatter in repeated experiments of cavitation inception in two facilities with two propeller models representing the same geometry (P5168 and P6468).

For a further comparison of the predicted and full scale cavitation inception curves, one should compare inception numbers at equal pitch setting. However, such a comparison is not straightforward as insufficient data are available for a proper interpolation between pitch angles, both for model and full scale. Since the ship is of the single screw type, a variation in operating points could only be obtained through a variation of propeller pitch. Error bars around the full scale observations indicate the estimated uncertainty in the derived torque coefficient K_Q .

The difference in pressure side cavitation inception between the best and worst blade was determined to be about 2 degrees in pitch. A corresponding uncertainty of ± 1 degree in pitch has been assumed. The scatter between blades in cavitation inception point on suction side appeared to be smaller than on pressure side. The difference on suction side between the best and worst blade was approximately 1 degree in pitch. All indicated inception points are based on inception of the 'median' blade.

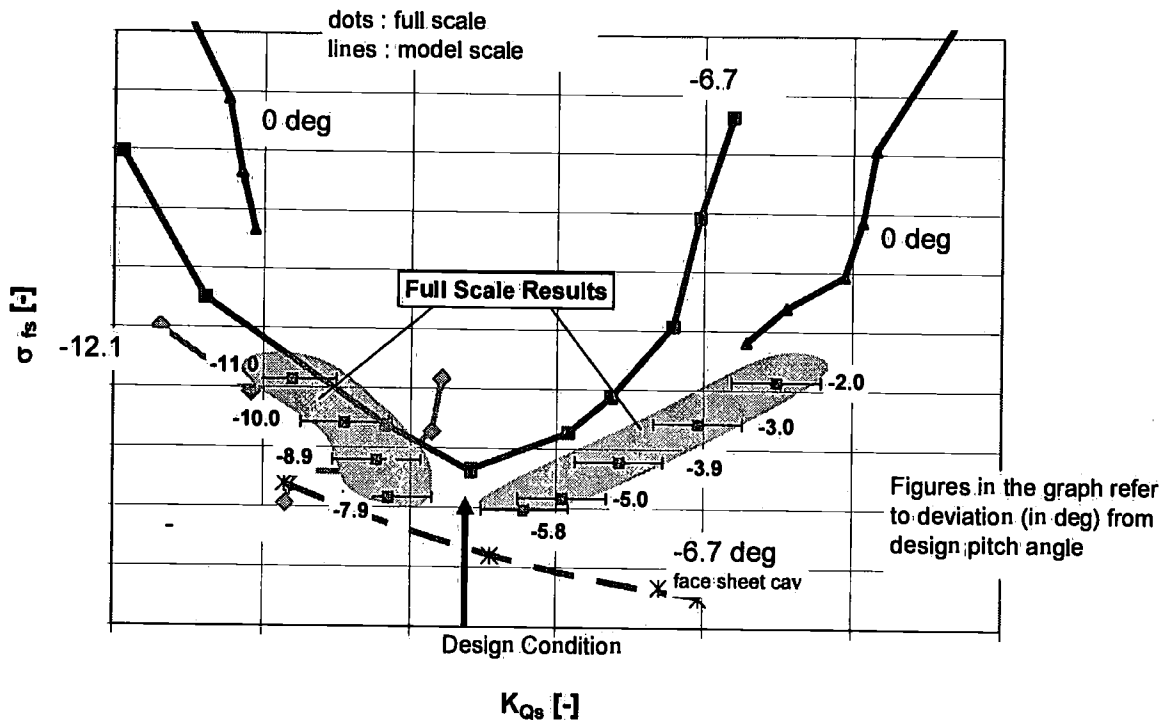


Figure 3. Comparison of full scale (visual) cavitation inception with similar results from model tests in the DTT.

The correlation between predicted and observed cavitation inception on pressure side is very satisfactory for the lightest propeller loadings. This holds for both the character of the cavity and the inception numbers. It is noted that in the model tests the first type of cavitation to become visible on the pressure side was leading edge vortex cavitation. During full scale observations, the images were made at a lower resolution, making it more difficult to discern leading edge vortex and sheet cavitation. Nevertheless, cavitation was observed in the same tip region as in the model tests, whether it was sheet or leading edge vortex cavitation.

The correspondence between model scale prediction and full scale measurement becomes less favorable for operating points closer to the design operating point (i.e. the deepest point of the cavitation inception bucket, see Figure 3). A possible explanation for this fact is that closer to the design condition the blade tip loading becomes lighter. From model scale observations one could clearly observe the lower vorticity associated with the shed bubble trace from the leading edge. Therefore, it is likely that hardly any vorticity is shed in the bubble trace that trails the leading edge at pressure side. Still, all model scale inception points on pressure side were attributed to leading edge vortex cavitation, thus indicating that extrapolation from model to full scale should be done according to McCormick's scaling rule for cavitation inception of vortices (McCormick [1962]).

Looking at the increasing deviation between model and full scale inception when getting closer to the design condition, it seems plausible that there is a transition

from leading edge vortex cavitation to leading edge sheet cavitation with a corresponding transition in the correction for model scale effects in inception. This suggestion is confirmed by the good correspondence in predicted and measured inception, when it is assumed that there is no vorticity in the leading edge region for the pitch setting closest to the design condition (at a pitch reduction of -7.9 degrees), and the cavitation inception scales as if it were sheet cavitation, hence without any shift in the inception diagram.

Observations on suction side show a somewhat different picture. Regarding the character of the incipient cavitation, it was observed that both at model and full scale the first type of cavitation to occur appears to be local vortex cavitation attached to the aft part of the tip (van Terwisga et al. [1999]). At higher propeller loadings an isolated suction side sheet develops near the tip at the leading edge and occurs almost simultaneously with the local tip vortex at inception (Kuiper et al. [2006]). Despite this agreement in character of the cavity, inception of tip vortex cavitation on full scale occurs significantly later than predicted. Based on the similarity in cavitation behavior between model and full scale, however, it is concluded that scale effects in the local propeller flow are not likely to cause the discrepancy.

Scale effects in the wake are more likely to be responsible for the difference. These wake scale effects are expected to become apparent predominantly in suction side cavitation, as this type of cavitation occurs first in the wake peak, where one would expect the strongest scale effects. Pressure side cavitation inception

occurs well outside the wake peak, where the local axial flow speed is at a maximum. Due to the afore-mentioned deviations around the optimum operating condition for cavitation free operation, the predicted inception speed of the vessel appeared to be lower than the actual inception speed determined during the trials.

It is concluded that inception of pressure side cavitation is predicted very satisfactorily in this case (where the locus of inception is in the propeller blade tip region), and that the art of making adequate full scale predictions is in distinguishing between vortex cavitation and vorticity free cavitation, be it in the form of bubbles or a sheet. This requires very careful observations. On the suction side the viscous scale effects in the wake peak should be corrected for to arrive at a better full scale prediction. This scaling can be most adequately achieved by computing both model and full scale wake, and then using the wake deficit at the observed location of inception to correct the inception speed prediction. This procedure is only valid if the scale effect in the wake is sufficiently small, otherwise, the locus and character of inception may change.

Having demonstrated the satisfactory performance of DTT predictions with full scale observations, a few remaining issues should be mentioned. These relate to the delayed cavitation inception for pressure side sheet cavitation at the inner radii of propeller blades and on rudders. In both cases, the delay may possibly be ascribed to extended laminar flow in the leading edge region. A flow condition which fails to produce micro-vortices that instigate cavitation inception (Rood [1991]). Delay of cavitation inception is a problem of all experimental facilities, including large cavitation tunnels.

To solve this problem, experimental studies have been and are still being conducted for the DTT and cavitation tunnel. Initial studies have been made of the effect of propeller Reynolds number, $Rn_n = nD^2/\nu$, on cavitation inception in the Rn_n range of 0.9 - 2.4 million in the cavitation tunnel. Within this range, no systematic tendency of inception with changing Rn_n was found. Experimental values appeared to be within a band of 10% of K_T .

Also a similar study in the DTT with Reynolds numbers between 0.6 and 1.0 million showed no systematic tendency of inception with varying Rn_n , but a larger scatter in K_T was found. At the inner radii of the propeller blades at very low local Reynolds numbers, cavitation inception failed to occur. In the Cavitation Tunnel, however, at the same Reynolds number and positions on the blades, cavitation inception was indeed observed. Because the Cavitation Tunnel has a turbulence level which is at least ten times higher than that of the DTT, it is hypothesized that at these low local Reynolds numbers, further to leading edge roughness, a sufficient turbulence level is required to invoke cavitation.

Other tests, yet unpublished, also suggest that turbulence levels, provided they contain the spectra that affect inception, indeed do have a significant effect. These findings correspond to results of investigations by van der Meulen and Yuan-Pei [1982], who investigated the effect of an upstream wire on cavitation inception on a foil.

Research in the coming years will be directed towards a better understanding of the scale effects mentioned and attempting to either account for them or find ways to alleviate or annul their effects. The advent of RANS codes for the computation of multi-phase flows is expected to enhance our understanding of the sensitivity of cavitation inception for e.g. local flow separation. However, it is noted that RANS codes are not expected to be capable of computing all micro-scale phenomena that appear to affect local separation and cavitation inception, such as transition from laminar to turbulent boundary layer flow or the onset of cavitation through micro-vortices in the boundary layer.

CAVITATION-INDUCED HULL EXCITATION

Pulsating or collapsing cavities, caused by varying propeller loading, radiate pressure fluctuations that exert a vibratory excitation force on the ship's afterbody. Thus, cavitation can become the primary cause of inboard noise and vibration. Propeller and ship designers have long been trying to improve their designs in order to keep excitation forces below certain limits that would cause noise and vibration problems or violate contractual requirements. In order to succeed in designing low-noise and vibration propellers, the items in the cause and effect chain that lead to vibratory hull-forces must be carefully considered. These items, as indicated in Figure 4, are briefly discussed below.

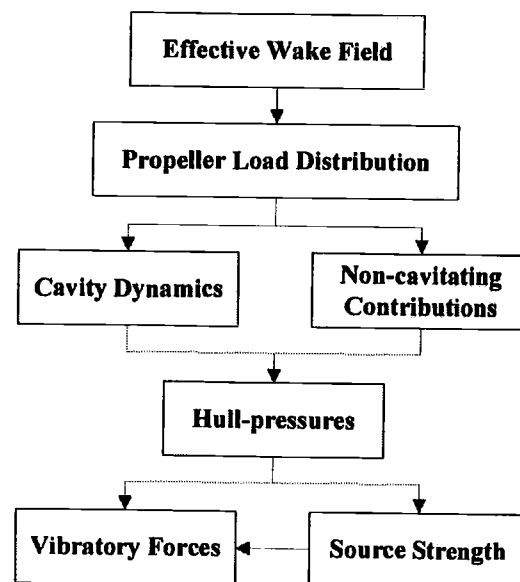


Figure 4. Chain of events leading to vibratory hull-forces.

Effective Wake Field

Obviously, the quality of the wake field is essential for a good propeller design. From a vibration point of view, improvements are made by paying close attention to the afterbody shape and to the orientation of appendices in order to make the propeller inflow more uniform. For the accurate prediction of hull-pressure forces, the correct representation of the effective wake field on model scale is a prerequisite.

However, inherent to model scale experiments, performed at Reynolds numbers much lower than on full scale, is a difference between the model and full scale wake distributions. An extensive correlation study, called 'CoCa', of hull-pressure fluctuations predicted at model scale and measured at full scale, confirmed the importance of correctly modeling the effective wake (Ligtelijn et al. [2004] and [2006]). When the wake scale effect is small (e.g. in passenger ships and other twin screw vessels), the prediction of the maximum pressure amplitude at BPF is generally good (see e.g. Figure 5), whereas for some classes of single-screw ships the correlation is unsatisfactory.

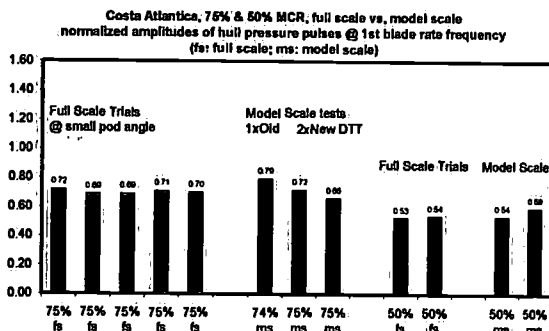


Figure 5. Correlation of normalized hull-pressure fluctuations for 'Costa Atlantica' @ 75% MCR and 50% MCR (from Ligtelijn et al. [2004]).

By default, the model test conditions are chosen such that the correct *average* propeller loading is attained and measured pressure fluctuations are scaled without any correction. As the sector of the propeller disc from where the cavitation originates is around the centerline wake peak, a correct level of the pressure fluctuations can be predicted only if in this sector the wake distribution, and hence the blade loading, are properly represented. When this is not the case, e.g. when the average wake scale effect is small, whilst the scale effect on the wake peak *depth* is large (as e.g. in container ships), there is a clear tendency to overpredict the maximum pressure amplitude at BPF. On the other hand, if the average wake scale effect is of the same magnitude as the scale effect on the wake peak depth, the correlation between the model and full-scale of the hull-pressure amplitudes is much better.

As an improvement on the choice of model test conditions, the blade loading in the upper wake peak

sector may be adjusted to that in full scale by requiring equal advance ratios in that area. In this manner the propeller becomes less heavily loaded on average, but the loading of the blades passing the wake peak is much better simulated.

The application of the above procedure improves the accuracy in predicting the level of hull-pressure fluctuations. However, the influence of the scale effect on the circumferential gradient of the wake field may still not have been taken into account properly. For instance, the widening of the wake peak may influence the time history of the cavitation volume. Falcão de Campos et al. [2006] studied the effect of the wake peak gradient on the cavity volume history in 2D by applying the boundary element method to the cavitating flow over a blade section placed in a gust. To perform a similar study in 3D, using realistic wake fields, is the next challenge.

For the time being, another computational approach may be adopted. Holtrop and Kuiper [2003] suggest to determine the wake scale effect on the hull-pressure fluctuations by computing the hull-pressure amplitudes caused by the cavity dynamics for both model and full scale wake distributions, and to use the ratio found as a correction factor on the pressure levels measured in the model scale experiment. This method requires that the results of the hull-pressure fluctuation measurements can be divided into a non-cavitating and a cavitating part, since only the latter needs to be corrected. Furthermore, the computation of the pressure amplitudes needs to be reliable and should take into account the effects of the various forms of cavitation. At present, the method can only be applied to sheet cavitation.

Both procedures, which obviously may be used in conjunction, require knowledge of the scale effect on the wake distribution, in particular the scale effect on the centerline wake peak. This scale effect has to be computed, e.g. by a RANS code, or alternatively, simply estimated.

Propeller Load Distribution

With the introduction of highly skewed propellers at the end of the seventies, a significant reduction in hull-pressure amplitude at the first blade passing frequency (BPF) was obtained. For propellers with more stringent noise requirements substantial tip unloading was applied, causing a further decrease in pressure amplitude at BPF, be it at the expense of efficiency. The same can be said of the choice of propeller rotation direction. When the propeller rotates against the tangential flow, as a rule, an increase in efficiency must be weighted against a decrease in comfort level.

Cavity Dynamics

Sometimes, reduced hull-pressure amplitudes at BPF are accompanied by increased amplitudes at higher orders. These higher harmonic pressure fluctuations are caused, amongst others, by the interaction of the

collapsing sheet cavity and the cavitating tip vortex which may lead to oscillations of the cavitating vortex and possibly break-up of the cavitating structure followed by rebounds.

The break-up of the cavitating vortex structure is often called 'bursting', which may be a somewhat confusing term due to the analogy with non-cavitating vortex bursting which is a different phenomenon. It has been shown by various researchers that the air content of the testing facility has a significant effect on the higher harmonics and that they can be reduced by injecting air into the cavitating tip vortex.

Non-cavitating Contributions

It is sometimes argued (see e.g. van Wijngaarden [2005a]) that contract specifications based on maximum pressures levels above the propeller at BPF are inadequate when they are influenced too much by non-cavitating contributions due to blade thickness and loading. This is because, in general, the latter effects are not contributing much to the integrated forces (see Holtrop and Kuiper [2003]).

In this regard it is noted that modern passenger ships show hull-pressure amplitudes at BPF of only 1-2 kPa at maximum. A significant percentage thereof is caused by the effects of blade thickness and (although usually to a smaller extent) blade loading.

Hull-pressures

The pressure pulses that are radiated by the cavitating propeller are diffracted by the wetted hull. This transfer path may be interrupted by injecting air at the fluid-structure interface. This has proven to be an effective isolation measure (Ødegaard [2006]). Isolation is especially effective when the risk of vibration is in broadband excitation, rather than in excitation at orders of BPF, since then it becomes rather difficult to prevent structural resonances from occurring. Obviously, the cheapest solution is to design out the cavitation that causes broadband excitation.

The interest in broadband excitation due to propeller cavitation has increased much recently. For this reason a separate section is devoted to it.

Source Strength

An inverse boundary element method for acoustic wave diffraction can be applied to determine the acoustic source strength of the propeller (see Van Wijngaarden [2006a]). Based on source strength, the quality of a propeller design can be better assessed, independent of clearance and hull diffraction effects. Perhaps, the source strength may serve as a useful parameter in contractual specifications, since it is not influenced by the non-cavitating contributions. Requirements based on the maximum pressure amplitude above the propeller are indeed biased in this respect.

Vibratory Forces

The integrated vibratory forces are what need to be minimized in a design. Model experiments by means of a set of flush-mounted pressure transducers can only give limited information on the pressure distribution, and sometimes integration to an effective excitation force is not possible at all. Van Wijngaarden [2006b] suggests a method to obtain such a force, even when sparse hull-pressure data is available. The latter method is based on the source strength concept, which can be used to compute complete hull-pressure distributions from which forces can be integrated.

Broadband Excitation

A phenomenon which has been observed in numerous cases is that of so-called broadband pressure fluctuations. It has become of increasing importance, for which reason it is separately treated here in some detail. Unlike the BPF orders which are of a tonal nature, broadband pressure fluctuations show a hump like increase of the pressure levels in the spectrum. As the hump extends over a limited frequency range, typically between 20 and 100 Hz, it should actually be interpreted as a narrowband stochastic process. It is obvious that the ship structure may easily be excited at one of its natural frequencies within this broadband region. In general, vibration problems due to broadband pressure fluctuations are observed in two different situations, described below.

The first situation involves ships with controllable pitch propellers sailing at low speed with significantly reduced pitch. Due to the reduction in pitch, the loading of the propeller will become negative at the outer radii and a strong leading edge vortex may arise on the face of the propeller (Okamura et al. [1994]) in combination with a vortex of opposite rotation direction trailing from the tip region. Either one or both vortices may cavitate. Due to their mutual interaction, short waves arise on the cores which ultimately cause the vortices to spiral around each other. If one vortex is significantly weaker than the other, the weakest vortex will break-up, causing the formation of ring vortices around the strongest vortex. If the strength of both vortices is more equal, both will break-up or collapse, thereby causing large hull-pressure pulses.

The second situation involves ships with stringent noise and vibration requirements that are running at service speed. In order to meet the requirements, the propeller tip is unloaded and the wake field is smoothly varying in tangential direction. One of the first examples of this situation is found on the well-known cruise liner 'QE2' (Brubakk and Smogeli [1988]). For this particular ship the broadband levels were occurring aft of the propeller suggesting that the pressure amplitudes are related with a collapse of the cavitating tip vortices.

Figure 6 shows the pressure spectra of 'QE2'. Even though the broadband character is not exactly reproduced by the model tests, it was sufficiently present

to make a sound judgment for new propeller designs, which eventually solved the problem for the ship. This situation is typical of the problem considered (see e.g. Hämäläinen et al. [2005]).

The broadband character of the pressure pulses in the frequency domain is a result of stochastic variations of the cavity dynamics. Due to the periodicity of the blade passing below the hull, the low frequency hull-pressure spectrum is typically dominated by values at harmonics of BPF. Obviously, if the acoustic source would be perfectly repetitive one would *only* see values

at orders of BPF. In reality, however, significant variability occurs due to geometric variations between the propeller blades, temporal variations in the ship's wake field and variability of the cavitation dynamics including inception, desinence and rebounds. Due to such stochastic variations of the cavity behavior, 'leakage' of power from the tonals to the sidebands will occur. A detailed discussion of the influence of stochastic variations on cavitation noise is presented by Baiter [1986].

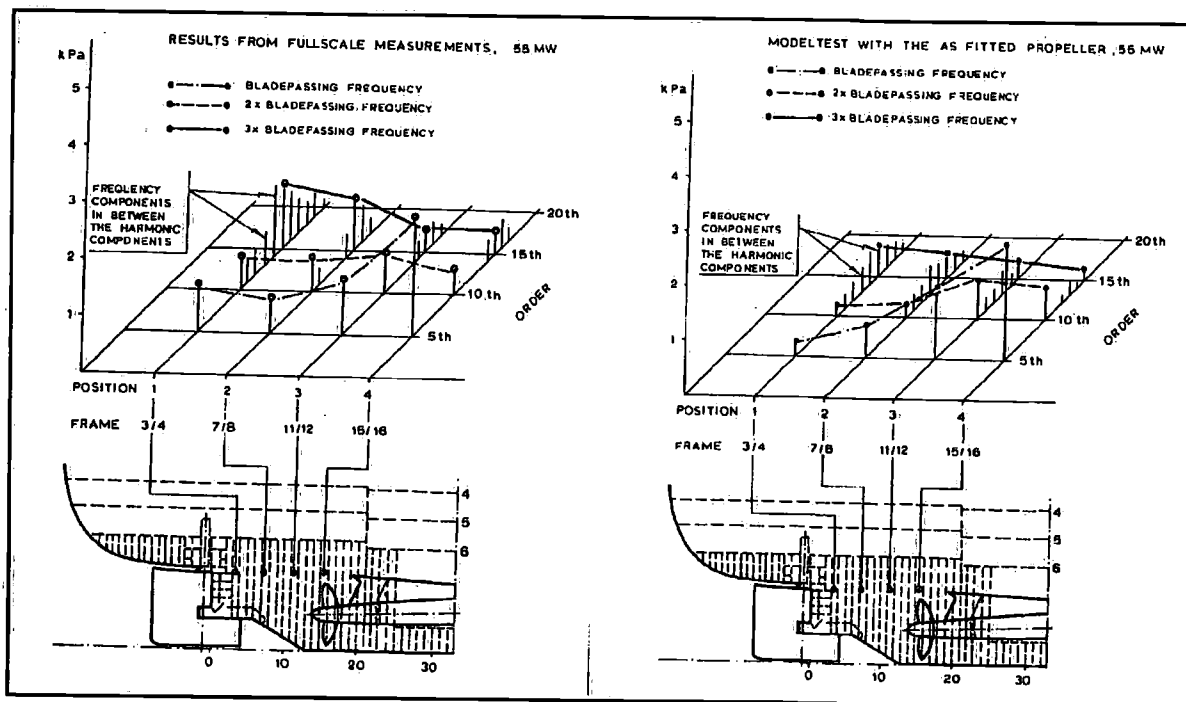


Figure 6. Comparison between full scale (left) and model scale (DTT) (right) measured broadband hull-pressures (from Brubakk and Smogeli [1988]).

The influence of random amplitude and phase modulation on a periodic signal is also discussed by Bark [1988]. The amplitude modulation causes a continuous spectrum of which the shape is identical to that of the isolated acoustic phenomenon. The amplitudes of the tonals, at orders of BPF, are not affected. However, random phase modulation will decrease the tonals and distribute or 'smear' the power over a range of frequencies; the smearing becoming most effective at higher frequencies. Depending on the shape of spectrum of the isolated acoustic phenomenon, the tonals at higher harmonics may even 'drown' in the continuous spectrum and this will have the character of a hump with a maximum located at a higher harmonic.

An example of model scale measured pressure spectra for two different ships cruising at service speed is presented in Figure 7. Ship 'A' has a propeller with a high tip loading and a pronounced wake peak, which results in a strong interaction between the sheet cavity,

its re-entrant jet, and the cavitating tip vortex. Due to the interaction a collapse of the cavitating tip vortex is observed. As the collapse is highly repetitive, strong tonals are observed at the higher harmonics with only some smearing at the root. For the fourth BPF and higher orders, however, the BPF values are only slightly above the broadband levels. Ship 'B' has a propeller with an unloaded tip and a more smoothly varying wake field. The cavity pattern is then characterized by a cavitating tip vortex, which, when the blade is in the top position, grows and turns into an attached cavity of elliptical shape. Due to the growth and shrinking of this cavity, the cavitating tip vortex becomes distorted and may start to radiate noise.

However, as no collapse occurs, the radiated noise is not as high as for ship 'A'. Furthermore, it appears that there is a strong variability of the cavity dynamics. Analysis of the hull pressure variation from revolution to revolution for frequencies between the second and sixth

order of BPF shows that the standard deviation of the pressure at each blade position is an order of magnitude greater than the average value. The variation is well described by a Gaussian probability distribution. An example of the ensemble average of the pressure taken over all revolutions and the pressure variation for one distinct revolution is presented in Figure 8. In the individual revolution, a 'ringing' phenomenon composed of higher order frequency components, can be clearly identified. These events vary significantly in amplitude and phase from blade to blade and from revolution to revolution. As a result, the ensemble average of the pressure signal is mainly determined by the first and second order of BPF and the higher harmonics are hardly visible.

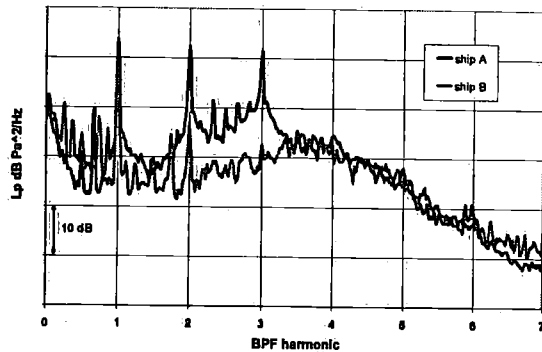


Figure 7. Examples of hull pressure spectra for two different ships, obtained from DTT experiments.

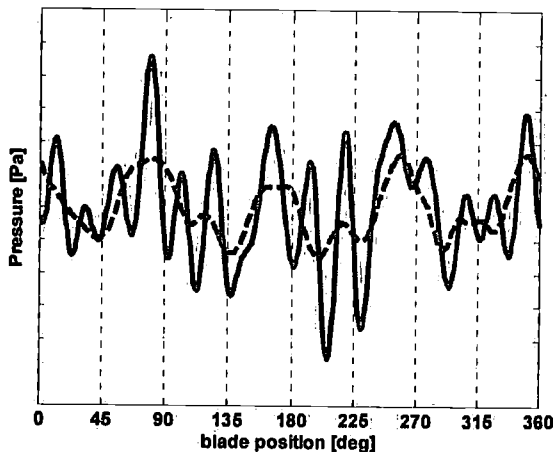


Figure 8. Typical hull-pressure variation with blade position for ship 'B' for a single revolution (red) and averaged over a number of revolutions (blue).

In some papers describing experimental data for the low frequency radiated noise of cavitating tip vortices it is suggested that a strong local increase in the spectrum is related to distortions of the cavitating vortex core, propagating as so-called Kelvin waves on the core surface (Briançon-Marjollet and Merle [1996], Sponagle

[1990]). The presence of these waves for different modes on cavitating vortex cores and their dispersion relation was first found by Lord Kelvin (Thomson [1880]), while acoustic aspects were derived by Morozov [1974].

The lowest order mode is the breathing mode which can be represented by a line array of monopoles. The following mode is a bending mode causing a 'serpentine' motion of the cavitating core which can be represented by a line array of dipoles. Higher order modes are represented by higher order poles which have very low radiated noise efficiency and are therefore less interesting from a radiated noise point of view.

So far, however, in literature only the dispersion relation has been analyzed from which the frequency components of the various wave types can be derived. The relation for the frequency, f_n , of mode n can be generalized to

$$f_n = c_n \frac{V_t}{r} = \frac{c_n}{r} \sqrt{\frac{2(p_0 - p_v)}{\rho}}$$

where c_n is a constant depending on the mode number, r is the radius of the cavitating core, $p_0 - p_v$ denotes the difference in free stream and vapor pressure, ρ is the density, and V_t is the tangential velocity component at the core which is related to the free-stream pressure through Bernoulli's equation.

It is observed that, with an increasing amount of cavitation due to higher propeller loading, the hump in the spectrum increases in height and its centre moves to lower blade passing frequencies, see Figure 9, which is consistent with the formulation given above. At some point, however, the broadband levels no longer change, and only an increase in level of the tonals at BPF harmonics is observed.

Empirical relations between the diameter of the cavitating vortex core, the cavitation number, and the propeller loading for a propeller in the open water condition appear hard to develop due to e.g. the diffusion of non-condensable gas into the vortex core (Briançon-Marjollet and Merle [1996], van Terwisga et al. [1999]). Instead, a simple Rankine vortex model can be used, and the relation for the mode frequency is then written as,

$$f_n \propto \frac{\sigma_n}{K_T} f_b$$

in which f_b denotes the BPF. The trend is confirmed through the analysis of a limited number of model tests. It is noted that a similar relation for the centre frequency of the hump is derived by Raestad [1996] in his empirical model for tip vortex cavitation noise using full scale data, be it for the fact that his relation is based on a bubble collapse frequency.

Kelvin waves may also occur on the viscous core of non-cavitating vortices and may grow in the presence of strain as shown e.g. by Leweke and Williamson [1998].

For cavitating vortices, the relation between standing Kelvin waves and observed distortions of the cavitating core has been investigated e.g. by Keller and Escudier [1980]. The general trends were well captured by the theory, but quantitatively only a moderate correlation with experiment was obtained. Even though the above suggests the presence of Kelvin waves on cavitating tip vortices of ship propellers, their importance for hull-pressure pulses should be further investigated. In this respect note the well known fact that waves on an infinite cylinder do not radiate noise at low frequencies (Junger and Feit [1986]).

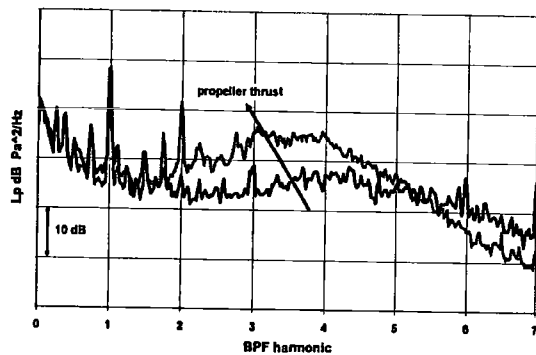


Figure 9. Example of the influence of propeller thrust on hull-pressure spectrum for ship 'B'.

The cavitating tip vortex distortions may have several causes, examples of which have been presented by Kuiper [2001] and van Wijngaarden et al. [2005b]. Here, only a brief discussion of some of these causes is presented.

For highly tip-unloaded propellers, on the pressure side a leading edge vortex appears, which has a rotation direction opposite to the vortex coming from the tip region. These vortices interact which might cause the formation of ring vortices or a complete break-up of both vortices. This likely explains the broadband levels observed on controllable pitch propellers operating at a highly reduced pitch setting.



Figure 10. Example of tip vortex cavitation in a smoothly varying wake field.

The attached tip vortex cavity may grow on the blade forming a cavity, which has an elliptical cross-section. While shrinking, the elliptical shape is shed

downstream, causing a ribbon like appearance of the tip vortex cavitation. An example is given in Figure 10. This type of cavitation may be present on ships with weak tonals and low frequency broadband hull-pressures such as ship 'B' of Figure 7.

The most common observed distortion of the tip vortex, however, is caused by the interaction with a sheet cavity on the blade, which can take many different shapes. A cavitating vortex structure may come out of the sheet or the re-entrant jet may form a vortex structure, which interacts with the tip vortex. Another possibility is that the re-entrant jet destroys the tip vortex when large velocity components are directed towards the tip. An example where the sheet collapses towards the tip, thereby destroying the tip vortex is shown in Figure 11. This is typically the behavior that is observed on ships with high tonal amplitudes at the higher harmonics, such as ship 'A' of Figure 7.

Current research at MARIN is directed towards further understanding of the stochastic variations of hull-pressure fluctuations on model and full scale in order to improve the interpretation of pressure spectra using Fourier analysis. Additionally, further theoretical and experimental study of low frequency radiated noise from cavitating vortices is needed. This should involve arbitrary vortex core deformations, distortions by Kelvin waves as well as the collapse and rebounds of cavitating structures.



Figure 11. Example of tip vortex cavitation which is about to burst due to the interaction with the sheet re-entrant jet.

CAVITATION EROSION

Of all adverse effects of cavitation, erosion is perhaps the most complicated to assess. The difficulty is caused by the energy cascade that eventually leads to erosion. This cascade of energy conversions, from macro-scale cavity through micro-scale bubble collapse, and pressure wave generation to material damage, is described in a generic model by Fortes-Patella et al. [2004] and [2001]. The present understanding of the hydrodynamic part of this cascade of energy is concisely described by Bark et al. [2004a].

The challenge in research on cavitation erosion is first to improve the quality of erosion risk assessments. A second objective is to predict the erosion rate, thereby including the last step of the energy cascade. However, the first aim is not yet met to full satisfaction. This is illustrated by a statement of Bark et al. [2004b]: "Some full scale results from EROCAV indicate however that

quite badly looking pressure side cavitation is in fact not always very erosive”, a statement which is also confirmed by Ligtelijn et al. [2004]. This statement reveals the weakness of current experimental practice, a practice based on careful visual observations, linking the observer’s interpretation of the dynamics of the cavity on model scale to a prediction of the risk of erosion.

The contribution of the EU-sponsored ‘EROCAV’ project consists of a set of basic guidelines and nomenclature to assist the observer in analyzing the dynamics of the cavity pictures, and then translating them into an assessment of the risk of erosion. These guidelines are presented in the ‘EROCAV’ handbook (Bark et al. [2004a]), which is an important contribution to the enhancement of erosion risk assessment. The reliability of this method, however, still depends strongly on the experience of the observer and of the quality of the pictures.

Bark et al. [2004b] present a brief review of erosion prediction techniques that were evaluated within the ‘EROCAV’ project. We mention the ‘High Speed Video Method’, the ‘Paint Test Method’, the ‘Impact Method’, the ‘Soft Metal Method’, and the ‘Acoustic Emission Method’. The ‘High Speed Video Method’ and the ‘Paint Test Method’ were reported to be the most reliable methods at present. However, it should be recognized that these methods are still of a qualitative nature and the quality of prediction still depends on the experience of the observer.

As the ‘High Speed Video Method’ is concerned, Tukker and Kuiper [2004] concluded that high speed video is the preferred way of making observations (see Figure 12 for a few high speed video stills). It was argued that a conventional video camera, applying a time lapse principle to collect images, may yield misleading results. This is caused by the fact that in erosion risk assessment cavity dynamics is important, something that is not captured by time lapse methods. Until recently, the latter methods were used at low frame rates (25 or 30 Hz), sometimes supplemented by high resolution stills from photo cameras. It is concluded that high speed video significantly improves the visual judgment of the risk of cavitation erosion.



Figure 12. Comparison of full scale cavitation (left) with observations from MARIN’s DTT (right). The tip vortex leads to erosion in the propeller blade tip region (from Bark et al. [2004b]).

The ‘Impact Method’ and the ‘Acoustic Emission Method’ are of a more quantitative nature. In the ‘Impact Method’, high frequency pressure transducers are used to determine both the fluid and the structure borne noise up to about 200 kHz. Exploratory experiments with this technique are reported by Foeth and Kuiper [2004]. The authors applied the technique to single bubble collapses near a surface as well as to sheet cavitation. The experiments with a single bubble collapse were made in a dedicated set up, whilst the experiments with sheet cavitation were made on a NACA 0018-45 foil in MARIN’s high speed cavitation tunnel (40 by 80 mm measuring section). Observations on the foil with the sheet cavity indicate that the collapse of the main cavity structure migrates from the foil surface at decreasing cavitation numbers, which is expressed in a decrease in the ratio of structure versus fluid borne noise. Further studies are necessary to show whether this ratio can indeed be used as a signal to indicate the risk of erosion.

The ‘Acoustic Emission Method’ is a technique largely similar to the ‘Impact Method’. The technique is further developed for full scale application at Lloyd’s Register (see Boorsma [2004]). The acoustic signal associated with impacting cavitation is measured by means of high frequency pressure transducers. The technique not only aims at indicating erosion, but also in localizing it. However, further development of this technique is needed for it to be used on ships in service.

The ‘Soft Metal Method’ uses a soft metal insert in the body that is to be tested, with the aim to increase cavitation erosion on model scale. As such, this method has much in common with the ‘Paint Test Method’. A difference is that the ‘Soft Metal Method’ might have the capability of predicting damage rates. However, more research is necessary for the method to be used in a quantitative way. For the latter purpose this method is not yet recommended in practice.

As it must be realized that a reliable prediction of the erosion rate is not yet within reach (Billet et al. [2005]) our aim must be limited to the prediction of the risk of cavitation erosion. Although an improvement in the assessment of the risk of erosion has been made through the use of high speed video cameras and their improved resolution, a more quantitative assessment is still to be aimed for. Therefore, MARIN has chosen to further develop the ‘Impact Method’, which promises to produce quantitative data that can be used in conjunction with case independent threshold levels. Thus an independent judgment can be made in addition to the one made on the basis of high speed video pictures.

Obviously, the above-mentioned techniques only work adequately if the character of the cavitation observed and measured on model scale is similar to that on full scale. Ideally, this similarity constraint should hold for both the macroscopic structure of the cavity, as well as the microscopic structure. More studies on the similarity of these structures for model and full scale are needed to get a better understanding of those cases where cavitation erosion occurred, but was not foreseen, not even from high quality experiments. The ‘EROCAV’

project has already greatly contributed to this need, but it is widely felt among the members of this project that additional high quality correlation data are needed.

CONCLUSIONS

The present paper gives a review of cavitation research on ship propellers performed by MARIN in the recent past. Investigations regarding cavitation inception, cavitation-induced vibratory hull-forces and cavitation erosion are treated. Below, a summary is given of achievements made in these areas and outstanding issues that challenge future research.

Regarding cavitation inception, it is concluded that a rise in the inception speeds for naval vessels has been obtained, as well as a better knowledge regarding the fundamental mechanisms controlling the inception process. Thus, it becomes possible to find the right balance between the inception of e.g. sheet and tip vortex cavitation in propeller design.

There are, however, still problems remaining with reproducing cavitation inception at model scale, predominantly at the inner radii on the pressure side of propeller blades, on shaft struts and on rudders. In the mentioned cases, cavitation inception in model experiments is delayed compared to full scale observations. Hypotheses for these phenomena have been suggested and work is ongoing to verify them.

Cavitation-induced hull-pressure fluctuations at blade passing frequency have been significantly reduced through improved propeller and afterbody design. Passenger vessels are now reaching amplitudes as low as 1 kPa, and rarely show values much higher than 2 kPa. The large cavitation facilities are capable of predicting these levels quite well. However, when the wake scale effect becomes strong in the sector of the propeller disc where cavitation occurs, as with the large container vessels of today, the accuracy deteriorates and there is a tendency to overpredict. Methods to counteract this tendency are proposed.

For propellers showing tip vortex cavitation, the hull-pressure spectrum is often characterized by a high broadband region. In a qualitative sense, this broadband region can be captured by model tests, which enables comparative propeller analysis. Quantitatively, however, differences occur which emphasize the need for further research on the variability of the pressure signals due to tip vortex cavitation and for mathematical models for the radiated noise of cavitating vortices.

More reliable predictions of the risk of cavitation erosion have recently been obtained using observations made by means of high speed video. Furthermore, a better insight in cavitation erosion has been gained, but there is still an undesirable uncertainty in the prediction of the risk of erosion.

A quantitative, less expert dependent procedure is needed in the assessment of the risk of cavitation erosion on propellers and rudders. To this end, MARIN is further developing the so-called 'Impact Method' for use in their Depressurized Towing Tank.

Notwithstanding the improved understanding of the fundamentals of cavitation on propellers and rudders, it must be realized that some scale and laboratory effects, are difficult, if not impossible, to overcome. Reliable methods to treat the scale effects are therefore needed, which may not come from simple empirical rules, but may need dedicated flow solvers for the solution of the complicated flow over propulsors and rudders. To this end, MARIN is involved in the development of an analysis tool based on potential flow for cavitating propellers within the Cooperative Research Ships (CRS) (i.e. the 'PROCAL' working group, see Vaz and Bosschers [2006]). Furthermore, MARIN is developing a propeller dedicated RANS solver for cavitating flows in cooperation with HSVA (the Hamburg Model Basin). This code aims to accurately predict the local flow phenomena, such as local separation and vorticity generation. A better insight in and prediction of these flow phenomena is expected to raise the reliability of cavitation related predictions further.

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