VTT INDUSTRIAL SYSTEMS

REVIEW OF PROPELLER HYDRODYNAMICS FOR "*LIIKKUTEHO*"

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REVIEW OF PROPELLER HYDRODYNAMICS FOR *LIIKKUTEHO*

This report reviews the accuracy of methods developed to predict propeller induced hull excitation. Unsteady lifting surface codes often provide acceptable prediction results for unsteady pressures induced by conventional propellers with reasonable computing efforts. In the 1990's unsteady panel method codes have been developed into rather reliable tools for predicting the unsteady pressures induced by conventional propellers. A few organisations have applied unsteady Reynolds-Averaged-Navier-Stokes (RANS) equation codes to the analysis of hull-propeller interaction flow. Free water surface and cavitation were not modelled in these interaction flow calculations. Several research groups are currently developing RANS equations codes to model cavitation. In spite of the recent developments of the numerical prediction methods for cavitating propellers, there are still uncertainties in the estimates for propeller induced hull-pressure fluctuations using theoretical calculations. Therefore, model measurement of hull pressure fluctuations in a cavitation tunnel is the most reliable method to estimate the ship scale hull pressure performance. The difficulties in the simulation of ship scale wake field are one of the major sources of the scatter in the predicted fluctuating hull pressures. For a new type unconventional hull form and/or for a new type unconventional propulsor concept, it can happen that the prediction accuracy is substantially worse than for conventional hull/propulsor concepts for which the method has been validated.

This report also reviews statistical methods developed for early design stage use. Published evaluations of statistical methods are summarised.

Espoo, 08 April 2002

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1 INTRODUCTION

The number of papers and reports on propeller induced hull pressures, hull forces and shaft forces is large. The list of references of this report includes recent textbooks on ship propellers and propulsion, state-of-the-art surveys, representative technical reports and scientific papers. The textbook of Carlton (1994) and the lecture notes of MARIN (parts written by van Wijngaarden, Jonk, Kuiper) were drawn on in writing this survey. Breslin & Andersen (1994) and Törnblad (1985) have also written textbooks on ship propellers and propulsion. The reports of Cavitation Committees, Propulsor Committees, and related specialist committees (1999, 1996, 1993, 1990) of International Towing Tank Conference (ITTC) contain state-of-the-art reviews on cavitating propellers, unsteady excitation forces induced by cavitating propellers, and propeller design in cavitating environment. State-of-the-art surveys of important aspects of the problem area have been written by Kinnas et al. (1998), Kinnas et al. (1997), Koyama (1993), Lee (1987), Patience & Bodger (1995), Skaar & Raestad (1979), and Wilson (1991). Blaurock & Meyne (1984), Schwanecke (1984), and Weitendorf (1984a, 1984b) have written lecture notes on the topic. Van Wijngaarden (1990's(b)) has also written lecture notes on ship acoustics. Kuiper (2001) has written a state-of-the-art paper on sheet and tip vortex cavitation. The excellent photos of Kuiper's paper facilitate understanding cavitation physics.

The contents of this report are as follows. Section 2 states the goals of this report. Section 3 gives a short introduction to the physics of propeller operation in non-homogeneous onset flow. Section 4 gives a short introduction to the physics of unsteady pressures and forces induced by a conventional cavitating propeller. Section 5 discusses the related problem of propeller induced noise. Section 6 reviews the work on hull response. Section 7 discusses the role of hull form as a parameter affecting the magnitude of hull pressures and shaft forces. Section 8 presents the possibilities of propeller design in reducing unsteady hull pressures and shaft forces. Section 9 gives an outline of cavitation tests and related scaling problems. Sections 10 ad 11 describe statistical and theoretical methods of predicting unsteady pressures and forces. The relative accuracy of the prediction methods is elaborated. Section 12 presents a couple of propeller design case studies that give an idea of the trade-offs between optimum cavitation performance, i.e. minimum induced hull pressures, and optimum hydrodynamic efficiency.

2 GOALS

The *LIIKKUTEHO* Project has specified four general goals for this report. As the first goal VTT/LAI is requested to provide a brief introduction into the physics of propeller induced hull pressures, hull forces, shaft forces, and noise. The second goal is to discuss the role of hull form as a parameter that influence propeller induced pressures and forces. The third goal is to discuss the role of propeller geometry and design technique as parameters that influence the induced pressures and forces. The fourth goal is to present examples that illustrate the accuracy of the experimental and numerical methods used for predicting propeller induced hull forces and shaft forces.

Because of the limited budget of this report, the following propeller operation modes that often exhibit high induced pressures are not discussed.

- Ship manoeuvring and heavy seas can also cause large propeller induced vibration excitation forces.
- Cavitation on rudders is known to have caused structural damage in the after part of the ship and on the rudder itself.
- Excitation forces caused by unconventional propellers such as contra-rotating propellers, ducted propellers, super-cavitating propellers, and surface piercing propellers.
- Fluctuating pressures on hull and noise can be reduced by using air. Details of the techniques tried can be found in the references (Friesch, 2000, p. 90; ITTC Committee on Cavitation Induced Pressure Fluctuations, 1999, p. 570).

3 SHIP PROPELLER IN UNSTEADY ONSET FLOW

The rotation of a propeller in the spatially varying wake field of a ship gives rise to variations in the angle of attack and variations in the incident flow velocity at each propeller radius wake (van Wijngaarden, 1990's(a), pp. 7-8). Hence the thrust, torque and other components of propeller forces on each blade vary due to the different inflow velocities encountered at different angular positions of the wake. As each blade rotates, it carries with it a varying pressure field that is due both to the lift of each section and to the fluid displacement effects caused by the section thickness. For the majority of hull forms, the axial wake field dominates the fluctuating thrust generating component. Local turbulence levels in the inflow due to the boundary layer and propeller hull interaction give rise to higher frequency variations in propeller experienced forces.

There are two general categories of propeller exciting forces and moments that cause hull vibration (Wilson, 1991, p. 320).

(1) Bearing or shafting forces and moments comprise (I) the vertical and athwartships transverse forces and moments and (II) the fluctuating thrust and torque that are developed on the propeller as it operates in a non-uniform wake.

(2) Surface forces are the oscillating loads associated with the propeller induced fluctuating pressure and velocity fields. They act on the hull surface. The surface forces are the spatially integrated unsteady loads associated with the travelling unsteady pressure footprint created by the passing blades.

The effect of cyclic pressure field of non-cavitating blades is small when clearances from propeller to hull surface are greater than 15% of the propeller diameter. Once cavitation appears, the surface forces become dominant especially at the highest speeds. On the hull surface area close to the propeller, total pressure impulses consist of both the contributions from the non-cavitating propeller and the attached cavitation. Both contributions may be important when considering fatigue problems in the after peak. However, for conventional hull girder and superstructure response calculations, only the total integrated hull surface excitation forces are of importance. In that case the contribution from the non-cavitation pressure impulses may be neglected. The basic reasons for this are as follows. (I) The pressure from a non-cavitating propeller is approximately proportional to the second inverse power of the distance to the propeller as opposed to a cavitating propeller where the pressure decreases approximately inversely proportionally to the distance. (II) The phase angles of the pressures due to cavitation are almost constant over large parts of the hull. This tends to produce a large integrated surface force, which for most after-body forms has a big vertical component. For a non-cavitating propeller the phase angles of the pressure will vary along the hull.

When a solid boundary, for example ship hull, is introduced into to the vicinity of the propeller then the pressure field is altered substantially (Carlton, 1994, p. 261). In the case of a flat plate extending into infinity above the propeller, the pressure acting on the plate surface is twice the free field pressure, which leads to the concept of solid boundary factor. The solid boundary factor S_{BF} is defined as the ratio of the pressure acting on the surface to the free field pressure in the absence of the solid boundary. In the case of ship hull a lesser value than 2.0 would normally be expected due to the real hull form being different from flat plate and also to the pressure release at the sea surface. Potential flow calculations have suggested that a value around 1.8 is more appropriate for ship calculations.

4 CAVITATION INDUCED EXCITATION

4.1 Types of cavitation - sheet cavitation

Cavitation can have several detrimental effects: vibrations, erosion, radiated noise, and loss of thrust (Kuiper, 1990's, p. 9; 2001). From the point of view of hull excitation, the following cavitation types have been identified as major contributors: (I) suction side sheet cavitation on the blade, (II) tip vortex, (III) sheet cavitation collapsing off the blade, (IV) propeller-hull vortex cavitation (van Wijngaarden, 1990's(a), p. 10). Experience gained from the scaled model tests and full scale observations indicate that mid-chord cavitation, cloud, foam, streak cavitation and sheet cavitation on the face of the propeller blade are the prime reasons for propeller erosion, whereas extensive sheet cavitation on the back of the blade (covering 50% or more of the blade area) is responsible for thrust breakdown. Except for ships requiring a low radiated noise signature, the majority of excitation problems from cavitating propellers are associated with well-developed cavitation. In general, cavitation on the blade is responsible for the blade passage frequency component and a few harmonics, whereas cavitation off the blade often collapses in a semi-random manner mainly giving rise to pressures at higher harmonic multiplies of the blade passage frequency.

The process of beginning of cavitation is called cavitation inception. Pure water can withstand very low pressures without cavitation inception. A prerequisite for cavitation inception is the occurrence of weak spots in the flow, which break the bond between the water molecules. These weak spots are generally tiny gas bubbles called nuclei. The presence of nuclei in water depends on the circumstances. In seawater ample nuclei of all sizes are present, and the inception pressure will be equal to the vapour pressure. On model scale a lack of nuclei is common and the inception pressure will be lower than the vapour pressure. This is a major cause of scale effects on model scale, which means that the model conditions differ from those on full scale.

4.2 Cavitation number

On full scale cavitation inception occurs when the local pressure is equal to the vapour pressure. The local pressure is expressed in non-dimensional terms as the pressure coefficient C_p. The condition that cavitation occurs when the local pressure is equal to the vapour pressure, means that e.g. a profile or a propeller will begin to cavitate when the lowest pressure is at the vapour pressure. This is expressed in the non-dimensional cavitation number

$$\sigma = -C_p(\text{min}). \quad (1)$$

The susceptibility of a propeller to cavitation depends on the relative velocity at a propeller section and the immersion depth of the section. The principal component of the relative velocity is the rotation velocity of the tip, whence the cavitation number definition based on rotational speed

$$\sigma_n = (p_A - p_V)/(0.5\ \rho\ (\pi n D)^2) \quad (2)$$

is often used. The symbols are

D	= diameter
n	= rate of rotation of propeller
p_A	= ambient pressure, static pressure at shaft axis
p_V	= saturated vapour pressure
ρ	= density.

When the pressure distribution has a strong adverse pressure gradient the flow will separate from the body and a region of cavitation occurs (Kuiper, 1990's, p. 2). This happens typically when a leading edge suction peak is present on a profile while the minimum pressure is lower than the vapour pressure. In such a case sheet cavitation occurs. Sheet cavitation is attached to the foil and the flow moves around the sheet cavity. The pressure in the cavity is approximately equal to the vapour pressure.

4.3 Vortex cavitation

At the tip and hub of a propeller blade strong vortices leave the blade or the hub (Kuiper, 1990's, p. 4). The pressure in the core of these vortices is low and when this pressure is lower than the vapour pressure vortex cavitation occurs. The vortex is generally very stable, so that the end is far downstream in the flow. When the vortex passes a strong wake peak it may break up and cause a complicated type of cloud cavitation. In general the tip vortex is connected with a sheet cavity at the leading edge.

It is not yet possible to provide fully validated recommendations for scaling model propulsor tip vortex cavitation inception results to ship scale. The dominant physical effects have been identified and some workable empirical guidelines have been proposed and should be applied with a margin of caution.

A special form of vortex cavitation occurs when a strong wake peak interacts with the propeller in such a way that the tip vortex connects with the hull (Kuiper, 1990's, p. 4). In that case a propeller-hull vortex occurs. This PHV-cavitation causes damage to the plating and an extremely high noise level. Propeller-hull vortex cavitation is most pronounced for small tip clearances (Carlton, 1994, p. 205). It has also been observed that the advance coefficient has a significant influence on the occurrence of PHV cavitation. The lower the advance coefficient is the more likely PHV cavitation is to occur.

On commercial propellers the sheet cavity gradually merges with the tip vortex. The extent of sheet cavitation can vary with the blade position when the propeller operates in a wake as illustrated in Figures 3 and 4 of this report.

4.4 Cavity collapse

The development of cloud cavitation occurs when during the development of the sheet cavity a part of the cavity separates from the main cavity and collapses separately while moving with the fluid. Due to the shock nature of the pressure wave, the hull experiences an almost instantaneous pressure pulse over the aft area of the hull plating and consequently a maximum force is exerted (van Wijngaarden, 1990's(a), p. 11). This contrasts with the non-cavitating case in which the plating experiences large differences in the phase of the pressure peak and consequently a smaller force is generated. For single screw hull forms with relatively short stern overhangs, the dominating phenomenon is the dynamic suction-side sheet cavity and its extension into the wake. For twin screw buttock flow hull forms tip vortex and collapsing sheet cavitation off the blade are also of importance.

The pulsating pressures interacting with the hull give rise to vibration of the structure of the ship that in turn generates a reactive pressure field (van Wijngaarden, 1990's(a), p. 11). The mode profile of the hull affects the dynamic loading and hence the level of response of a given structure to the excitation pressure distribution that emanates from the propeller. Pressure applied at, or near node-points has little or no dynamic effect while the reverse is true with regard to anti-nodes.

4.5 Means to reduce induced excitation forces

The hull excitation force due to cavitating propellers may be reduced by (I) reducing the hull excitation pressures (propeller design), (II) increasing the phasing relationships between surface locations (propeller skew), (III) reducing the solid boundary factor (afterbody hull form), (IV) reducing the effective wetted surface area on which the pressure field acts (afterbody hull form), (V) adapting the longitudinal distribution of force to the mode profile of the hull. The last option has not been tried on full-scale ships.

Huse and Wang (1982, p. 89; van Wijngaarden, 1990's, p. 27) have proposed a simple mathematical model for describing hull pressure generation due to cavity dynamics, i.e. volume variation of cavitation bubbles. This model assumes a system of N cavities of volume V_i located at a distance a_i from the hull point. By representing the volume by a point source, using Bernoulli's equation, neglecting a velocity dependent term, and assuming constant rate of rotation, the dominant pressure term at a hull point is obtained as

$$p_{cvv}(t) = S_{BF}\,\rho\, n^2 \sum_{i=1}^{N} (a_i)^{-1} \frac{\partial^2}{\partial \phi^2} (V_i)\,, \qquad (3)$$

where

a_i	= distance between cavity volume and hull point, i.e. clearance
N	= number of cavities assumed
$p_{cvv}(t)$	= pressure due to the dynamic activity of the cavity
S_{BF}	= solid boundary factor
V_i	= volume of cavity
ϕ	= the angular position coordinate on the propeller disk.

Inspection of Equation (3) shows that the hull pressure is reduced when (I) the rate of rotation is reduced, (II) the volume acceleration decreases, (III) the clearances are increased. The hull pressure is also reduced when (4) the volume velocity decreases (van Wijngaarden, 1990's(a), p. 29). In practical terms Eq. (3) implies that intermittent sheet cavitation and the dynamics of tip vortex cavitation strongly influence propeller excited hull pressure fluctuations (Induced Pressure Fluctuations Committee, 1999, p. 577).

Reducing the rate of rotation, and selecting an optimum propeller (increased diameter) can be shown to decrease [nD], and hence increase the cavitation number (van Wijngaarden, 1990's(a), p. 29). This gives a consequent increase in the margin against cavitation, and a reduction in cavity volume V_i in a given wake field. Increased diameter generally leads to higher propulsive efficiency and, consequently to lower thrust. This also reduces propeller loading and increases the margin against cavitation inception.

By designing highly swept leading edges, the growth and/or collapse phases of cavitation on sections at adjacent radial locations near the tip may be used to reduce the peak-to-peak variations in the pressure signal given by Eq. (3).

The magnitude of a_i is dominated by the tip clearance and the section angle. An increase in a_i can be obtained by spreading the cavity volume over a larger radial extent or reducing the section angle by incorporating steeper V-shaped afterbody sections.

For a given design in which thrust, rate of rotation and diameter are fixed, the principal parameters by which the cavity and its volume variation may be reduced, fall into three categories, wake distribution, propeller geometry, and propeller loading (van Wijngaarden, 1990's(a), p. 32).

4.6 Cavitation bucket

The cavitation behaviour of a propeller is represented in the inception diagram as given in Figure 1 (Kuiper, 1990's, p. 16). The inception lines of the various types of cavitation are given on the basis of the propeller thrust coefficient. The sets of curves for sheet and tip vortex cavitation form again a kind of bucket. The cross in Figure 1 indicates the design condition of the propeller.

On profiles the minimum pressure coefficient determines the inception of cavitation (Kuiper, 1990's, p. 11). The minimum pressure coefficient is generally plotted as a function of the angle of attack as is shown in Figure 2. At small angles of attack the minimum pressure varies only slightly with the angle of attack (e.g. 1 deg < α < 2 deg in Figure 2). The corner points of the bucket indicate the angles of attack where the leading edge suction peaks begin.

The two-dimensional cavitation bucket is used to judge the risk of cavitation on the profile (Kuiper, 1990's, p. 13). The criterion for occurrence of cavitation is the minimum pressure being equal to the vapour pressure. When the cavitation index and the angle of attack are known the risk of cavitation can be read from the bucket. The negative value of the cavitation number [-σ] is plotted on the C_p axis of the cavitation bucket. The range of angles of attack at that C_p value within the bucket is the range where the minimum pressure is higher than the vapour pressure. No cavitation will occur there. The cavitation bucket belongs to specific profile geometry.

Instead of the angle of attack a cavitation bucket can also plotted against the lift coefficient. Because of the nearly linear relation between the two this does not change the shape of the bucket.

Cavitation margin for a non-cavitating propeller profile is defined as the distance between the end point of the actual angle of attack range and the end point of the “no cavitation” part of the C_P=constant line in Figure 2. Van Gunsteren and Pronk (1973, p. 267) included cavitation margin in the formulation of the lifting line propeller design process.

4.7 Flow separation and cavitation in bow thrusters

There is often a significant excitation from bow thrusters (Raestad, 1992, p. 459). The bow thruster in the thruster tunnel operates in strongly separated flow. If the natural frequencies of deck structures in the vicinity of the thrusters coincide with the blade frequency, large vibrations may occur. Severe vibrations excited by vortex shedding from propeller nozzles and rudders occur sporadically (Raestad, 1992, p. 453).

5 PROPELLER INDUCED NOISE

All types of cavitation generate noise. Bubble cavitation is generally considered to be erosive. Cloud cavitation is considered very erosive. From experience pressure side cavitation is also erosive. In propeller design it is therefore tried to avoid these types of cavitation.

The mechanism of erosion and noise generation is as follows. Generation of vapour from the fluid is a very rapid process (Kuiper, 1990's, p. 9). This means that a vapour bubble, which moves into a lower pressure, will expand rapidly while the pressure inside remains very close to the vapour pressure. When such a cavity arrives in a region with a pressure higher than the vapour pressure the analogous occurs: the bubble decreases in size without the pressure inside becoming higher. When the bubble becomes very small the surface tension also becomes large and this accelerates the collapse. The cavity therefore collapses violently. This is the source of noise. When this occurs close to or on the surface, the surface may be damaged. This damage is called erosion.

The occurence of relatively large amplitudes of propeller induced pressure fluctuations at higher than blade rate frequencies is important for the possible excitation of troublesome shipboard noise (Induced Pressure Fluctuations Committee, 1999, p. 566). Recent investigations have identified unstable or excessive tip vortex cavitation as the cause of elevated unsteady pressures for frequencies higher than the blade rate (Raestad, 1996). Sudden breakdown of blade tip vortex cavitation into cloud like clumps or "vortex bursting" are the physical mechanisms. Time series display of pressure signals facilitates the understanding of the role of cavitation for higher harmonic components.

Sevik (1996) considers that at this time, the complex flow fields and the response of structures cannot be reliably predicted by numerical techniques. Large, quiet, high-speed water tunnels have been equipped with acoustic arrays in order to assess the performance of alternative propulsor designs.

Carley (2000), Kauffmann (1999), Thompson & Rattayya (1964), and Tsakonas et al. (1964) among others have developed numerical methods for propeller acoustics.

6 HULL RESPONSE AND VIBRATION

The vibrations of hull surface affect the measured pressure amplitudes, when the pressure gauges are mounted in the hull surface (Induced Pressure Fluctuations Committee, 1999, p. 577). The hull vibrations can interfere with the interpretation of both full scale and model scale measurements (van Gent, 1990; de Jong & de Regt, 1998, p. 921). Correction procedures have been developed to estimate these effects. Wilson et al. (1995) applied Kurobe's & Yoshida's (1985) correction approach to a circular pressure gauge mounting plate imbedded in the hull surface. In this case the measured vibration accelarations of the gauge mounting plate did not produce high enough pressure amplitudes to cause a problem with the transducer measured pressure values. However, the general case is far more complicated as was shown by van Gent (1990) and (de Jong & de Regt, 1998).

Van Gent (1990) conducted measurements with a hydrodynamic monopole exciter in order to distinguish the propeller induced pressure from the hull-vibration induced pressure. This was done to substitute the cavitating propeller by a calibrated artificial excitation, which made it possible to find transfer functions of the vibration induced pressures at the location of the pressure pick-ups. Phase information was found to be as important as amplitude information. Van Gent also performed full-scale measurements of the pressure fluctuations induced by two kinds of propellers together with the accelerations. The measured pressures on full scale were corrected using the transfer functions and the measured accelerations at the pressure pick-ups. The correlation between model and full scale was considerably improved in this way. Simplifying the ship structure to an infinite thin flat elastic plate and the propeller cavitation to a monopole, van Gent evaluated numerically the equations for a fluid loaded elastic plate by direct integration and indicated that the pressure on the plate surface was strongly reduced for practical values of plate thickness, monopole-to-plate distance and frequency.

7 INFLUENCE OF SHIP HULL FORM

The angle of attack is determined primarily by the axial component of wake and the loading distribution on the blade. The tangential wake component is less important for single screw ships. The importance of the axial component derives from the fact that the pitch angle is small for the outer radii. Tangential wake velocity component is less important for single screw ships than the axial component because it is relatively small compared with the rotational velocity of the propeller blade section (van Wijngaarden, 1990's(a), p. 34).

Thin sections have narrow cavitation buckets, and, in a non-uniform flow, have low margins against suction and pressure side cavitation. Propeller profiles in the outer 20 % of the blade are typically less than 3 % thick.

The solid boundary factor accounts for the hull shape as far it differs from the infinite flat plate and the proximity of the free surface on which constant pressure exists (van Wijngaarden, 1990's(a), p. 47). The free surface component has been found to be dominant of the two influences. Ideally V-shaped transverse sections with angles to the horizontal in excess of 30^o should be adopted where possible (van Wijngaarden, 1990's(a), p. 49).

Total surface force is also reduced when the area on which the pressure acts, is reduced (van Wijngaarden, 1990's(a), p. 48). However, in attempting to design extremely small surface areas, other full-scale phenomena need to be accounted for. Wetted surface area increases due to ship motions and following seas. The time periods involved are of the order of 100 times the blade passage period. Wide shallow transom sterns, e.g. RO/RO hull forms, provide the most effective transfer mechanisms for propeller excitation to hull. Rolling, pitching and following seas can increase the effective area for surface excitation by a factor of 2.

8 INFLUENCE OF PROPELLER GEOMETRY

8.1 Parameters influencing shaft forces

In principle there are two methods of changing the shaft forces (Skaar & Raestad, 1979, p. 23), (I) changing the fluctuating loading on the blades, (II) changing the number of blades. The fluctuating loading on the blades can be reduced by applying skew to the blades in such a way that the blade will enter the wake peak progressively. It is generally considered that propellers with an odd number of blades induce smaller thrust fluctuations but larger bending moments than propellers with an even number of blades. The bending moments have a tendency to decrease with increasing number of propeller blades.

8.2 Parameters influencing hull surface forces

The most important parameters for changing the hull surface forces induced by non-cavitating propellers are (I) number of propeller blades and (II) blade thickness (Skaar & Raestad, 1979, p. 24; van Wijngaarden, 1990's(a), p. 32). The key parameters influencing the pressure pulses induced by cavitating propellers are (I) propeller skew, (II) blade area, (III) pitch, (IV) section thickness distribution, (V) camber, (VI) blade number, (VII) radial blade loading, (VIII) proportion of lift to incidence. Pitch may not be considered to be an explicit design parameter, since the normal propeller design process requires the circulation distribution to be prescribed, pitch being derived subsequently.

8.3 Skew

Skew is the single most effective design parameter next to the rate of rotation for reducing hull excitation pressures, forces and shaft forces and moments (van Wijngaarden, 1990's(a), pp. 20, 53). The mechanisms by which skew, in effect, leading edge sweep affects the various hydrodynamic processes are not fully understood. Hsiao & Pauley (1998) and Stanier (1998) analysed skewed propeller flow patterns using Reynolds-Averaged-Navier-Stokes (RANS) equation codes. Hsiao and Pauley developed a grid suitable for the accurate calculation of the tip vortex flow. Stanier (1998, pp. 244-245) compared the chordwise static pressure distributions of two propellers. The calculated pressures at the leading edge showed the better back sheet cavitation performance of the skewed propeller. The difference between the maximum and minimum pressure in the leading edge area at a representative radius for the skewed propeller was smaller than for the straight propeller.

8.4 Blade area

Lifting line calculations yield the radial distribution of [C_L (c/D)], where C_L is section lift coefficient and c is section chord length (van Wijngaarden, 1990's(a), p. 39). The radial [C_L (c/D)] distribution obtained satisfies the design specification for thrust or torque. The designer must identify a radial distribution of [c/D] which, together with a radial distribution of thickness, will satisfy strength, back-bubble cavitation and cavitation erosion constraints, avoid thrust breakdown, and avoid high levels of vibration excitation.

Increased area, i.e. increased chord-length, leads to a reduced C_L requirement, and hence to reduced incidence angle and camber ratio (van Wijngaarden, 1990's(a), p. 39). Increased chord length, without a proportional increase in thickness, implies a reduced cavitation bucket width, and hence lower margins against cavitation inception. However, the lower lift requirement results in a blade section pressure distribution, which is less conducive to cavity growth. Therefore cavity volumes and hull pressures should decrease for most applications.

8.5 Determination of camber and thickness

Superior cavitation performance blade sections have been developed for the delay of blade section surface cavitation flow (Cavitation Committee, 1996, p. 91). The “new blade section” design method or the “Eppler method” has concentrated on widening and enlarging the hydrofoil section cavitation bucket. The main design strategy for these advanced sections is to unload the leading edge and move the loading as far to the rear as possible without introducing separation. The design procedure yields camber and thickness distributions. The “new blade section” design techniques have been successfully applied to propeller designs at several establishments worldwide (Jessup & Wang, 1997; Lee et al., 1991; Stanier, 1992). Eppler initially applied the design concept to glider wings, i.e. low Reynolds number profiles.

8.6 Number of blades

The number of blades has, in general, no significant effect on the magnitude pressure pulses from cavitation (van Wijngaarden, 1990's(a), p. 42). Blade number primarily affects the frequency of the excitation. Some benefit may be derived from other factors associated with the change in blade number, such a section thickness, section chord length, etc.

8.7 Loading distribution

Optimum circulation loading of propeller is characterised by strong circulation gradients near the hub and tip, which tend to form hub and tip vortices which become visible under cavitating conditions, even in uniform flow context (van Wijngaarden, 1990's(a), p. 42). Since model scale and full scale wakes differ in non-uniformity, and the best (or optimum) radial variation of the circulation on model scale may not be the best for the ship scale. For wake distributions having high levels of non-uniformity a moderate degree of tip off-loading may be necessary, even for a highly skewed propeller.

Reducing tip loading is a well-established mean to reduce hull pressures and forces. Reducing tip loading has several benefits, (I) tip vortex cavitation inception is delayed, (II) rudder damage due to tip vortex impingement is reduced, (III) propeller induced noise may be reduced, (IV) blade erosion may be reduced.

8.8 Proportion of lift due to incidence

Standard propeller design strategy involves shockfree pitch orientation of the section (van Wijngaarden, 1990's(a), p. 44). It can be reasoned that an alternative design strategy of increasing the camber to chord ratio involves a reduction in pitch and hence section incidence. In non-uniform flow a less stable cavitation may be generated with higher pressure amplitudes at some multiplies of blade frequency.

8.9 Blade tip geometry

Successfull delay of tip vortex cavitation on propulsor blade flows can be accomplished by reducing the magnitude of the spike of low pressure within the vortex core, which will have the effect of diminishing the strength and organisation of the vortical flow (Cavitation Committee, 1996, p. 88). However, to be of practical interest, a workable vortex control concept should have a limited deleterious effect on hydrodynamic performance. There are three main approaches: reduce the peak tangential velocity magnitudes, increase the vortex core diameter, and directly increase the pressure within the vortex core region. Selected concepts for tip vortex delay/control are placed in two categories: hydrofoil and tip geometry treatments and mass injection. Unconventional hydrofoil and tip geometry treatments include bulbous tip, tip duct, end plates or winglets, and roughened tip region.

9 MODEL TESTS AND SCALING

Cavitation is generally investigated on model scale using a cavitation tunnel (Kuiper, 1990's, p. 14). In cavitation testing scaling problems are dominant. There are basically two categories of scaling problems: (I) wake scaling and (II) scale effects on cavitation, especially on cavitation inception.

In general a cavitation tunnel has no free surface. Consequently the Froude number disappears as a scaling law and propellers can be tested at higher rotation rates than according to the Froude scaling law. The absence of a free surface does not completely remove effects of gravity. There is still a variation in pressure over the height of the test section. This results in a distribution of the cavitation index over the height of the test section, and thus over the propeller disk.

An important aspect of cavitation testing is the scaling of the wake. Most tunnels are too small to accommodate the complete ship model, and even when that is possible the wall effects will be large. Instead of using a complete model, a scaled dummy model is often used in front of the propeller. This dummy is often not a geometrically scaled part of the hull. Reynolds numbers on model scale and ship scale differ which leads to differences in boundary layers between the model and the ship (Carlton, 1994, pp. 67-72). Models have relatively thicker boundary layers. If Reynolds number wake scaling is to be applied, the practical recommendation is to target the three-dimensional full-scale nominal wake (Induced Pressure Fluctuations Committee, 1999, p. 564).

In model scale testing, the levels of unsteady pressure amplitudes can be seriously affected by the size of the test section, the method of wake simulation, and operation at very low Reynolds number (Induced Pressure Fluctuations Committee, 1999, p. 578).

10 STATISTICAL PREDICTION METHODS OF UNSTEADY PRESSURES

The calculation methods for predicting unsteady induced hull and shaft forces can be organised into to four categories; (I) empirical or statistical methods, (II) lifting surface methods, (III) panel methods, (IV) Reynolds-Averaged-Navier-Stokes equation methods.

Elementary criteria for evaluating propeller induced surface force excitation can be organised into four categories, (I) pressure amplitude limits, (II) surface force amplitude limits, (III) wake quality, and (IV) vibration limit (Wilson, 1991). The prescriptions can also be divided into two types, (I) criteria for evaluation or judging whether a troublesome condition could exist, and (II) techniques for estimating either the magnitude of certain point pressure pulse amplitudes or surface force amplitudes.

Holden: Holden (1979) published empirical formulae based on regression analysis for determining the induced surface pressures. The blade rate pressure amplitude induced by a non-cavitating propeller is

$$\Delta p_{1Zo} = (0.01245)\ \rho n^2 D^2((t_m/D)^{1.33}/Z^{1.53})(a_{09}/R)^{-\kappa}, \quad (4)$$

where

a_{09}	= distance from the r/R=0.9 position to the field point on the hull		
R	= propeller radius		
t_m/D	= blade thickness to diameter ratio at 0.7*R		
Z	= number of blades		
$\kappa = 1.8+0.4(a_{09}/R)$		for $a_{09}/R<2.0$	(5a)
$\kappa = 2.8$ (possibly should read 2.6)		for $a_{09}/R>2.0$.	(5b)

There seem to be errors in Equation (5a) or (5b) both in the original papers of Holden and in Wilson's review. The parameter κ is continuous, if Eq. (5b) reads $\kappa = 2.6$.

The blade rate pressure amplitude induced by a cavitating propeller is

$$\Delta p_{1ZC} = (9.8*10^{-5})\ \rho n^2 D^2\ (J_1 - J_M)\ (f_2/\ \sigma^{0.5})(\ a_{09}/R)^{-\kappa}, \quad (6)$$

where

f_2	$= (P\ f_m)_{0.95} / (P\ f_m)_{0.80}$	
f_m	= maximum camber	
J_1	= advance ratio corresponding to mean effective inflow velocity minus correction for tip geometry (Holden, 1979)	
J_M	$= V_S\ (1.0 - w_{Tmax})/(nD)$, advance ratio corresponding to minimum	
inflow	velocity to the propeller in the region r/R=0.9…1.0	
P	= propeller pitch	
V_S	= ship speed	
w_E	= effective mean wake	
w_{Tmax}	= maximum value of the effective wake peak	
Δw	$= (w_{Tmax} - w_E)$	
σ	= cavitation number based on peripheral speed at r/R=0.7	
$\kappa = 1.7-0.7(a_{09}/R)$	for $a_{09}/R<1.0$	(7a)
$\kappa = 1.0$	for $a_{09}/R>1.0$.	(7b)

Holden's method is used by DNV (Johannessen & Skaar, 1980).

Johnsson. Johnsson (1983) developed diagrams to estimate the fluctuating pressure amplitude of blade frequency. The diagrams account for the vertical clearance, wake peak, propeller skew, tip loading of the propeller, developed blade area ratio of propeller, and the height of stern wave.

Fitzsimmons & Rutherford. Fitzsimmons (1977) suggested an approach to evaluate wake quality based on a wake factor and a cavitation number with limit regions determined empirically by plotting data of both satisfactory ships and ships with unacceptable vibration performance.

Rutherford built on the concept of the Fitzsimmons plots and suggested new limits in the plots. The axes of the Fitzsimmons (1977) and Rutherford (1979) plots are

$w_{\Delta} = \Delta w/(1.0 - w_E)$ (8)

and

$\sigma_{nt} = (p_{atm} + \rho g h_{tip} - p_V)/(0.5\ \rho\ (\pi n D)^2)$, (9)

where

h_{tip}	= depth of propeller tip
p_{atm}	= atmospheric pressure
w_E	= circumferential effective mean wake at a characteristic radius
Δw	= $(w_{Tmax} - w_{Tmin})$.

Evaluation of the earlier statistical methods. Wilson (1991) reviewed the practical criteria that can be used to assess the acceptability of propeller-hull arrangements from the excitation point of view. The pressure amplitude formulae of Holden (1979) give fairly believable results (Wilson, 1991, p. 329). Skew effects should be added, however. Skew can have a large beneficial effect by reducing inducing pressure amplitudes. The Fitzsimmons plots seem to give a reasonable idea about the trend of possible excessive hull girder vibration, but not about allied problems such as propeller excited inboard airborne noise. The wake gradient factor of Odabasi & Fitzsimmons (Wilson, 1991, p. 326) seems to point in the right direction for identifying wakes with potential for making trouble. The basic idea of the SSPA (Johnsson, 1983) correlation seems to work.

Difficulty index of MARIN. A high value of the difficulty index of MARIN may indicate that the propeller/vessel system will exhibit unacceptable vibrations (Jonk, 1990's, p. 3; Holtrop, 1990's, p. 57). The difficulty index of MARIN is defined by

Difficulty Index of *MARIN* = $(T + 0.61\ (n\ D^3\ V\ \Delta\{w_{0.8R}\}))/((h_{tip} + 10)\ D^2)$, (10)

where

D/m	propeller diameter
h_{tip}/m	head of water above propeller tip
n/RPM	rate of rotation
T/kgf	thrust
V/knots	ship speed.

The maximum value of this difficulty index should be lower than 740 to avoid the risk of vibrations.

Formula for tip-hull clearance of MARIN. MARIN has also published a formula for the tentative assessment of the required tip-hull clearances for ferries and cruise liners with twin screws on exposed shafts at the preliminary design stage (Holtrop, 1990's, p. 58). The formula is

$\Delta p = 0.635\ (0.001\ P_S/(C^2))^{0.8}$ (11)

where

C/m	tip-hull clearance
P_S/kW	delivered power
Δp/kPa	hull pressure amplitude.

Tip vortex index of DNV. DNV uses tip vortex index "TVI" for predicting tip vortex noise and acoustic pressure. The formulae are (Raestad, 1996)

$$p_a = TVI \; C_{1pa} \; (n\,D)^2 , \tag{12}$$

$$TVI = (k_{tbl}\, k_{tip})^2 \; Z^{0.5} / \sigma_n , \tag{13}$$

where

C_{1pa}	= proportionality factor
k_{tbl}	= K_T/Z
k_{tip}	= actor representing the degree of tip loading on the propeller compared to standard distribution
p_a	= resulting acoustic pressure.

The resulting acoustic pressure is assumed to be a function of the volume acceleration of the tip vortex cavities from each blade.

DNV has developed a database for inboard propeller noise on twin-screw passenger ships (Raestad, 1996). The experience of DNV from high-powered cruise ships indicates that the noise generated by propeller tip vortices is much more important for inboard noise than was previously assumed. Raestad's paper gives a couple of examples in applying the tip vortex index.

MARINTEK. Koushan et al. (2000) reported on a new software developed for the prediction of pressure pulses. The software is based on measurements performed since 1980. The database was analysed by means of artificial neural networks method. The software requires a minimum amount of input to predict pressure pulses with reasonable accuracy that is adequate at an early design stage.

HSVA experience. Table 1 gives the HSVA recommendations based on their experience for blade frequency single amplitude maximum pressure levels (Friesch, 2000, p. 87).

Table 1. Recommendations based on HSVA experience for hull surface pressure (Friesch, 2000, p. 87)

Ship Type	Maximum level of single amplitude blade rate surface pressure / kPa
Cruise liners, fast ferries	2
Post PanMax container ships, RoRos	4
Feeder container ships	3
Bulkers, tankers	5-6

Evaluation of criteria for maximum thrust density of open propellers. Van Rijsbergen & van Terwisga (2000) reviewed existing criteria for maximum thrust density on open and ducted propellers. Their conclusions were as follows.

1. The maximum thrust capability of a propeller is determined by two criteria: a non-dimensional thrust density criterion K_T/σ_n and a non-dimensional tip speed criterion σ_n .
2. The thrust capability of a propulsor is dependent on wake field, propulsor type, and propeller design.
3. The existing empirical criteria show good correspondence with experimental results for conventional propellers when the maximum thrust capability is defined as the point where a 2 % thrust breakdown is reached.

11 NUMERICAL PREDICTION METHODS OF UNSTEADY PRESSURES

The term CFD (Computational Fluid Dynamics) generally implies numerical methods in which a large number of discretised equations are solved and the boundary conditions are satisfied on a large number of points on bounding surfaces of the fluid. Panel method and RANS equations method codes are generally classed as belonging to CFD. Cavity models have been added to both steady and unsteady lifting surface and panel method codes. From the point of view of applying numerical methods to predicting unsteady shaft and hull forces, the first validation task is to compare measured and calculated unsteady pressure distributions on blade surface. The second validation task is to compare the calculated and observed extent of cavitation on blade surface on model scale and ship scale. The third validation task is to compare the calculated and measured fluctuating hull pressures, hull and shaft forces on model scale and ship scale.

11.1 Unsteady lifting surface methods

In the lifting surface approach the singularities modelling lift effects (e.g. vortices), thickness effects (e.g. sources), and the control points where the boundary conditions are satisfied, are located on the camber lines or camber surface of the foil. A lifting surface method where the lift is modelled by discrete vortex elements is called vortex lattice method. Lifting surface codes provide acceptable prediction results with reasonable computing efforts. Fluctuating surface pressures due to a cavitating propeller calculated with these methods give relatively good correlation with experimental results provided the code has been validated with ships similar to the case at hand.

The inherent singularity of the linear theory in leading edge pressure distribution can be modified using Lighthill's leading edge correction (Cavitation Committee, 1996, p. 93). Calculations for a marine propeller show that cavity extent, especially near the leading edge of the blades, is reduced by applying the leading edge correction and gives a better correlation to the model test results. Since computational efforts needed by a lifting surface codes are much less than those needed by surface panel method codes, a more rigorous cavity model for bubble and tip vortex cavitation, such as Rayleigh-Plesset equation for a spherical bubble cavity or Rankine vortex model for tip vortex cavitation, has been incorporated in some lifting surface codes.

11.2 Unsteady panel methods

In the surface panel approach, the flow boundary is discretised without linearizing the boundary geometry, e.g. singularities modelling lift effects, thickness effects, and the control points for the boundary conditions are located on blade surface. There are also formulations, where the singularities modelling lift effects are located on the mean surface (Achkinadze et al., 2001). Non-linear boundary geometry is especially important near the blade leading edge where linearization is not valid. Remarkable progress has been made in cavitation prediction using surface panel methods (Cavitation Committee, 1996, p. 93; Computational Method for Propeller Cavitation Committee, 1999, p. 457). Surface panel methods can accurately compute the pressure distributions around the leading edges of propeller blades within the inviscid flow assumption. Numerical techniques, such as hyperboloidal panels, trailing wake alignment, improved blade surface grid generation, and satisfying cavity boundary conditions on the blade surface, have been evolved to improve the robustness of the methods and to improve the computational efficiency.

Surface panel methods are especially efficient for the accurate prediction of cavitation inception (Cavitation Committee, 1996, p. 93-94). In order to exploit the advantages of panel methods in this respect, new cavitation inception models should be developed. Prediction of viscous effects on propeller performance was attempted using a three-dimensional boundary layer method. The boundary layer approach may not be desirable when cavity displacement effects are important as the interaction between the cavity bubble and boundary layer becomes significant.

11.3 Application of lifting surface and panel methods

Kinnas & Lee & Muller (1998) and Koronowicz & Szantyr (1995) have recently developed theoretical models for cavitating tip vortices that can be implemented in vortex lattice and/or panel method codes. Methods for the prediction of free vortex separation points and vortex strengths depending on blade geometry and loading distributions should be developed. Accurate prediction of tip vortex cavitation requires a separation model of free vortices from arbitrary points on the blade surface, not only from the trailing edge (Cavitation Committee, 1996, p. 94).

Some research organisations use steady lifting surface and panel method codes in quasi-steady way to analyse propeller flow in the wake field. When used with experience, this approach may yield accurate estimates of the unsteady hull pressures or forces.

Most mathematical propeller models, the conventional lifting surface and panel method codes assume only propeller blades and in some cases propeller hub as fixed boundaries. Kehr et al. (1996) and Kruger (1998) have modelled the complete hull-propeller interaction problem using a panel method. In the sample calculations illustrating these two methods the prediction accuracy of performance coefficients and induced hull pressure amplitudes was about 15-25 %.

11.4 RANS and Euler equation methods

RANS equations methods that model cavitation are at the initial stages of their development curve. RANS equations methods are used successfully for predicting propeller open water performance, for calculating the pressure within tip vortex, for predicting multi-component propulsor open water performance, and for modelling the hull-propeller interaction problem without free surface. Abdel-Maksoud et al. (2000) simulated the turbulent flow around the KCS container ship with and without propeller in steady and unsteady modes, respectively. The standard k-ε turbulence model with wall functions was applied. Free surface effects were not considered. Table 2 gives the grid sizes. Table 3 compares measured and calculated integral values. In the computations of Table 3 free surface effects were not included and, therefore, the total resistance coefficients are not directly comparable. The calculated K_T and K_Q are 7.2 % lower and 5.2 % higher than the measured results. Abdel-Maksoud et al. considered that the cell numbers were too small. Cavitation was not modelled and induced hull pressures were not given in the paper.

Table 2. Grid sizes in KCS container ship simulations (Abdel-Maksoud et al., 2000)

Propeller	Cells for hull	Blocks for hull	Cells per blade	Blocks per blade
Without	400 303	239	-	-
With	921 158	285	107 867	10

Table 3. Measured and calculated integral values for KCS container ship (Abdel-Maksoud et al., 2000)

	Measured	Calculated
C_T x 10^3 without propeller	3.56	3.65
K_T	0.158	0.170
K_Q	0.0303	0.0288

Choi & Kinnas (2000a, 2000b) developed and applied a fully three-dimensional unsteady Euler solver based on finite volume scheme and the pressure correction method to the prediction of the effective wake for propellers subject to non-axisymmetric onset flow. The propeller is modelled as unsteady force at the location of the blade, and appears as a body force term in the Euler equations. The propeller vortex lattice method, named MPUF-3A was used to solve for the perturbation potential of the cavitating propeller. One of the validation cases consisted of the nominal wake of a test series in MIT cavitation tunnel and the DTMB 4148 propeller working at the advance number J_S = 0.9087. DTMB 4148 has very narrow blades with no skew. The time averaged unsteady effective wake was found to be very close to the steady effective wake in this case. The predicted cavity planforms were very similar to the observed cavity planforms.

Several research groups are currently developing and extending RANS equations codes to model cavitation. The papers presented at the CAV2001 Symposium give an idea of recent advances in this area.

11.5 Correlation between analyses and measurements

Gindroz et al. (1998), Koyama (1993), Lee (1987) and ITTC Propulsor Committees (1990, 1993, 1996) reported on comparative investigations of the accuracy of propeller analysis methods.

The 22th ITTC Propulsion Committee organised a workshop on propeller RANS/Panel methods (Gindroz et al., 1998). The conclusions of the comparative calculations for three propellers were as follows.

- RANS equations and panel method codes can predict the open water performance of a propeller very accurately and therefore can be used in the design stage of marine propellers.
- RANS equations and panel method codes can predict precisely the pressure distributions on the blade of a propeller operating in uniform flow.
- RANS equations method codes can predict the velocity distributions of propeller slipstream with reasonable accuracy. The accuracy of the velocity predictions by panel method codes is not enough because of the lack of viscous effect in the theory.
- Panel method codes can predict the pressure fluctuations on the blade surfaces of a propeller operating in non-uniform flow behind a ship with reasonable accuracy and therefore would be able to predict the occurrence of cavitation on the blade.
- All the panel method codes over-predicted the pressures on the back side near the trailing edge of the blade section at 0.9R radius for the “Seiun Maru” highly skewed propeller. This is considered to be due to viscous effects.

The 22th ITTC Propulsion Committee (1999) reported that changes in the vortex wake configuration might change the thrust and torque predictions by about 13 % for some particular propellers.

The 21st ITTC Cavitation Committee (1996, p. 95) selected the propeller of a 4400 TEU container ship to compare the computation results by lifting surface theory and surface panel method with experimental results. Cavity extents, computed by a lifting surface theory without and with leading edge correction and a surface panel method, are shown at selected angular positions in Figure 3. Experimental results of the same propeller operating behind a simulated wake field in a cavitation tunnel are also shown. Computed results by the lifting surface theory without the leading edge correction show excessive cavitation extents, especially near the leading edges, due to the unrealistic negative pressure peak values at the leading edge. The Lighthill leading edge correction reduces the leading edge cavity extents significantly. Cavity extents predicted by the panel method are even smaller that those from the lifting surface theory with leading edge correction. Computed cavity extents by the lifting surface theory with leading edge correction and by the surface panel method are generally in good agreement with experimental results for this particular case.

The 21st ITTC Cavitation Committee (1996, p. 66-71) conducted comparative pressure fluctuation measurements at three Japanese facilities; Mitsubishi Heavy Industries (MHI), Mitsui Engineering and Ship Building (MES), and Ship Research Center (SRC). The highly skewed propeller for the training ship "Seiun Maru" was selected as the propeller for the comparative tests. Measurements of the pressure fluctuations induced by the propeller and the pressure distribution on the propeller blades were conducted on model scale and ship scale. Good correlation of wake peak and width are observed for each facility and tunnel speed as expected. The peak value at top position for the wake measured at SRC is slightly higher than those measured at MHI and MES.

Measurements of pressure fluctuations in the artificial wake were conducted in cavitating conditions for the propeller rate of rotation range of 17-30 rps. In order to get stable cavitation on the blades, the operating condition of the propeller was determined by thrust coefficient $K_T=T/(\rho n^2 D^4) = 0.25$ and cavitation number $\sigma_n = 1.5$. Clearance between the propeller tip and flat plate was selected as 0.254D, which corresponds to that of the full-scale ship. Pressure fluctuations were measured at several points in axial and transverse directions varying σ_n by changing the propeller rotation speed. The pressure amplitudes of the blade rate and twice blade rate harmonic components were used to form non-dimensional pressure amplitudes

$$K_{piZ} = \Delta p_{iZ} /(\rho n^2 D^2), \quad (14)$$

where

i	= number of blade rate harmonic
Δp_{iZ}	= amplitude of hull surface pressure.

Cavitation patterns observed at propeller rotation rate of 20, 25, and 30 rps are compared with those obtained on full-scale test as shown in Figure 4 (Cavitation Committee, 1996, p. 70). Extents of the cavitation patterns on model scale are slightly smaller than those observed on full scale. The transverse distribution of pressure fluctuation amplitudes measured on model scale for the first blade rate harmonic is compared with those measured on full scale as shown in Figure 5. There exists a small influence of propeller rotation rate on the pressure fluctuations. The agreement between the model and ship scale is good.

12 EXAMPLES OF PROPELLER DESIGNS

Lee et al. (1991) applied the new blade section propeller design method to a container ship propeller. Four propellers were designed, (I) a conventional propeller with NACA type sections and three new blade section propellers, KP192, (II) more loading near the leading edge, KP190, (III) less loading near leading edge, KP191, (IV) more loading near the leading edge at the outer radii and less loading near leading edge at the inner radii, KP197. KP197 was the final propeller. The propulsive performance of the four propellers was nearly identical. Only KP192 exhibits leading edge face cavitation. Figure 6 shows the cavitation buckets for KP192 and KP197 at two radii. KP197 has the most stable sheet cavity. Figure 7 shows that the most stable sheet cavity resulted in the smallest fluctuating double pressure amplitudes.

Jessup and Wang (1997) reported on the propeller design for the PC-1 Cyclone high-speed patrol boat class. Three propeller designs were compared; (I) the first estimate for the propeller used in the concept design phase, (II) profile design based on conventional NACA type profiles, (III) new (blade) section design. It was found that the new blade section profile is cavitation free up to the speed of about 28 knots. A constant 5 % increase in chord length resulted in an almost uniform spanwise 1 knot improvement in cavitation inception. The effect of the chord length on the calculated propeller loading is given in Table 4. The data in Table 4 illustrate the trade-offs between blade area, efficiency, and cavitation inception speed.

Table 4. The effect of uniform chord length increase on propeller loading for PC-1 class (Jessup & Wang, 1997).

Increase in c/D	Improvement in cavitation inception	% change in K_Q	% change in K_T	% change in η
5 %	1.05 knots	-1.8 %	-0.9 %	-0.8 %

13 CONCLUSIONS

The selection of the radial distribution of skew, pitch, chord length, together with the type of camber line and section thickness for the profiles is crucial for the reduction of cavity volume variation, and hence hull pressure and hull exciting force.

Unsteady lifting surface codes often provide acceptable prediction results for unsteady pressures induced by conventional propellers with reasonable computing efforts. In the 1990's unsteady panel method codes have been developed into rather reliable tools for predicting the unsteady pressures induced by conventional propellers. However, there are cases where only a RANS equations method code predicted the open water performance accurately and widely used panel method and lifting surface method codes yielded clearly erroneous performance predictions. Results of RANS equation simulations of propulsion tests with rotating propellers have been published by some organisations. Several research groups are currently developing and extending RANS equations codes to model cavitation.

In spite of the recent developments of prediction methods for cavitating propellers, there are still uncertainties in the estimates for propeller induced hull-pressure fluctuations using theoretical calculations. Therefore, model measurement of hull pressure fluctuations in a cavitation tunnel is the most reliable method to estimate the ship scale hull pressure performance. However, the typical agreement of pressure fluctuations between model scale and ship scale results are not completely acceptable and there exists scatter in hull pressure measurements between different facilities.

One of the important sources of the scatter in hull pressure fluctuations is considered to be the wake field simulated in each facility. The target wake and the wake simulation method can be different from one cavitation tunnel to another depending on previous experiences with model-ship scale correlation and on available facilities. Simulation of the total wake with a working propeller would enhance the accuracy of model tests and allow direct correlation with ship scale observations. It appeared to the 21st ITTC Cavitation Committee that the discrepancies found between recent results for the pressure fluctuations of an easily reproducible wake simulated by a wake generator consisting of flat plate obtained in the different facilities were smaller than in the comparative tests reviewed by the 19th and 20th ITTC. The influence of propeller revolution rate on the pressure fluctuations was also smaller than for the earlier comparative tests.

The development of a validated and acceptably accurate approach for the correct interpretation of propeller induced unsteady hull pressure measurements remains unsettled. Even after the introduction of many corrective experimental techniques, such as the simulation of a ship scale wake and the use of flow liners, the criterion of success has been to obtain agreement between model and ship scale pressure amplitudes in many cases. This approach is not complete in some cases, particularly in full ships. The dynamic response of the structure, both on model and ship scale and the reflection and transmission characteristics of the facility structures have received relatively little attention.

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15 NOTATIONS

A_E	expanded area of propeller
A_O	disk area of propeller
a_i	clearance (= distance) from an elemental cavity to the hull
a_x	axial propeller clearance
a_z	vertical propeller clearance
B_P	$= n(P_D)^{0.5}/V_A^{2.5}$, propeller load coefficient
C_D	section drag coefficient
C_L	section lift coefficient generally
C_p	pressure coefficient
C_{Th}	$= (8/\pi)\ K_T\ /J^2 = (8/\pi)\ T_T/(\rho\ D^2\ V_A^2)$, thrust loading coefficient
C_{TVI}	proportionality factor of the reference pressure in DNV formula
c	chord length
D	propeller diameter
d_h	hub diameter
F_n	$= V/\ (g\ L_{WL})^{1/2}$, Froude number
f_m	camber (maximum)
g	acceleration due to gravity
H	head, distance from propeller centerline to water surface plus atmospheric pressure minus vapour pressure
h	immersion of reference point with location indicated by subscript
h_O	immersion of shaft axis
J	$= V_A\ /(nD)$, advance number
K_{p1}	$= \Delta p_1\ /(\rho\ n^2\ D^2)$, blade frequency pressure coefficient
K_{p2}	$= \Delta p_2\ /(\rho\ n^2\ D^2)$, twice blade frequency pressure coefficient
K_Q	$= Q/(\rho\ n^2\ D^5\ )$, torque coefficient
K_T	$= T/(\rho\ n^2\ D^4\ )$, thrust coefficient for conventional propeller
k_{tbl}	$= K_T\ /Z$
k_{tip}	factor representing the degree of tip loading compared to DNV standard
L	length, representative length of ship
N	number of elemental cavities
n	propeller rotational speed
P	pitch
P_D	$= 2\ \pi\ n\ Q$, delivered power
P_S	shaft power
p	pressure
p_A	ambient pressure
p_a	acoustic pressure

p_{atm}	atmospheric pressure
p_V	vapour pressure of water
p_O	pressure at depth of the shaft at upstream infinity
Q	torque
R	radius of propeller
R_n	$= L\ V / \nu$, Reynolds number generally
R_n	$= c\ V_x / \nu$, Reynolds number of section
r	radial co-ordinate
S_{BF}	solid boundary factor
T	thrust
T_D	duct thrust
t	blade section thickness
t	thrust deduction factor
t	time
t_m	thickness of propeller blade section (maximum)
V	local velocity at profile section
V	ship speed
V_A	= V(1-w), speed of advance of propeller
V_i	volume of elemental cavity
V_S	alternative symbol for ship speed
V_x	$= ((2\ \pi\ n\ r\ )^{2} + V_A{}^{2}))1/2$, section advance speed
w_E	$= (V-V_A(\text{effective}))/V$, Taylor wake fraction, effective
w_N	$= (V-V_A(\text{nominal}))/V$, Taylor wake fraction, nominal
w_{Tmax}	maximum value of effective wake
x	= r/R, non-dimensional radius
Z	number of blades
α	angle of incidence, angle of attack
β	$\tan^{-1}(V_A/(2\ \pi\ n\ R))$, advance angle of propeller blade section
ΔK_T	$= ((K_T(\text{calc}) - K_T(\text{meas}))(100.0^* K_T(\text{meas}))$, error in predicted thrust coefficient
Δp_1	blade frequency amplitude of hull surface pressure
Δp_2	twice blade frequency amplitude of hull surface pressure
Δw	$= (w_{Tmax} - w_E)$, wake peak parameter
η_O	$= J\ K_T /(\ 2\ \pi\ K_Q)$, propeller open water efficiency
θ_S	skew angle
θ_{EXT}	skew angle extent, difference of the maximum and minimum skew angle
κ	experimental coefficient in Eqs. (14) and (16)
ν	kinematic viscosity

σ_n	$= (p_O - p_V)/(0.5\ \rho\ n^2\ D^2)$, cavitation number based on propeller rotational speed
σ_r	$= (p_a - p_V + \rho\ g(h - r))/(0.5\ \rho\ ((2\ \pi\ n\ r\ )^{2} + V_A{}^2))$, cavitation number at radius r
$\sigma_{0.7R}$	σ_r for = 0.7R
σ_{VA}	$= (p_O - p_V)/(0.5\ \rho\ V_A{}^2)$, cavitation number at shaft centerline
ϕ	angular position of propeller
ϕ(r)	$\tan^{-1}((P / D)/(\pi\ r / R))$, pitch angle

16 FIGURES

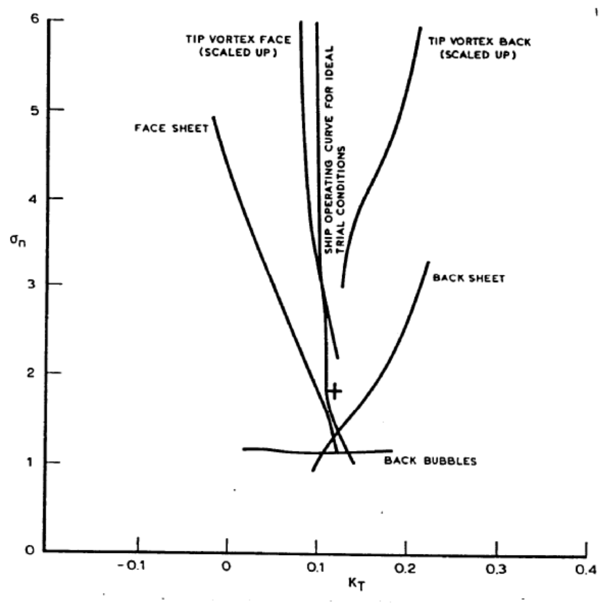

Figure 16: Inception Diagram of a Propeller.

Figure 1. (Kuiper, 1990's, p. 16)

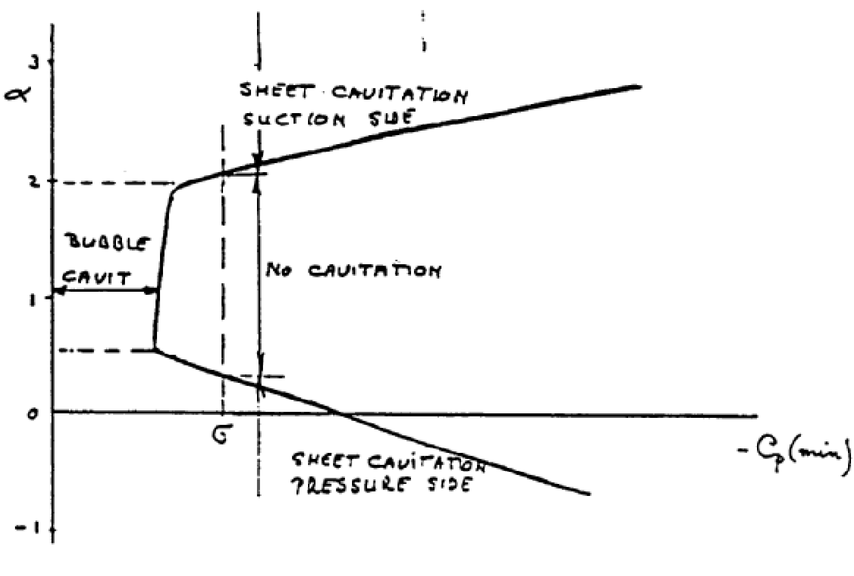

Figure 13: Cavitation Bucket of a Profile.

Figure 2. (Kuiper, 1990's, p. 13)

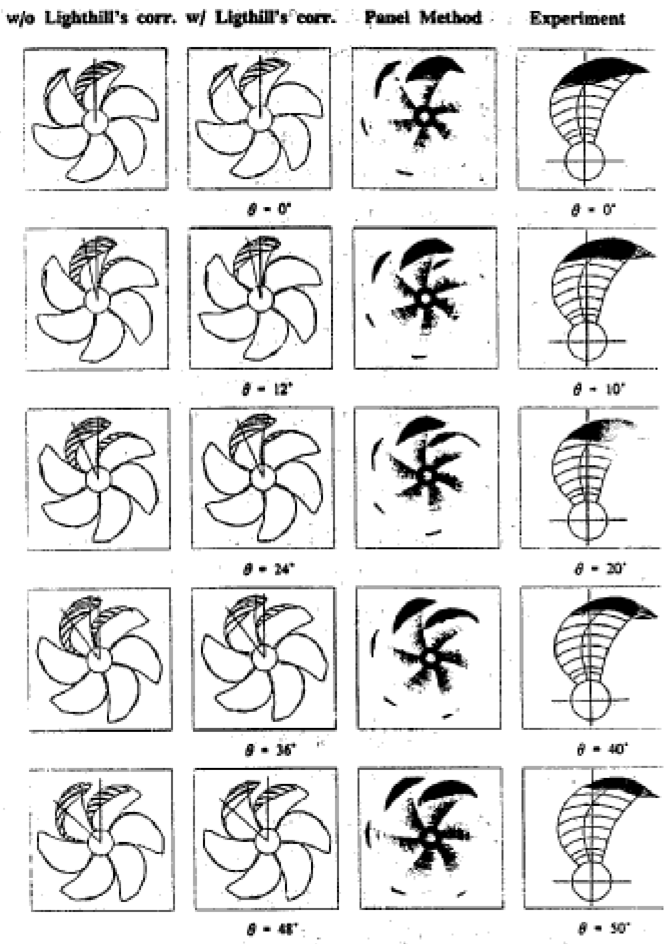

Figure 23: Comparison with experimental results of computed cavity patterns of a 4400 TEU container propeller by a lifting-surface theory without and with leading edge corr[illegible], and by a surface panel method (Han 1995)

Figure 3. (21st ITTC, p. 95)

Figure 4. Comparison of model scale and ship scale cavitation patterns at one Japanese tank (21st ITTC, 1996, p. 71).

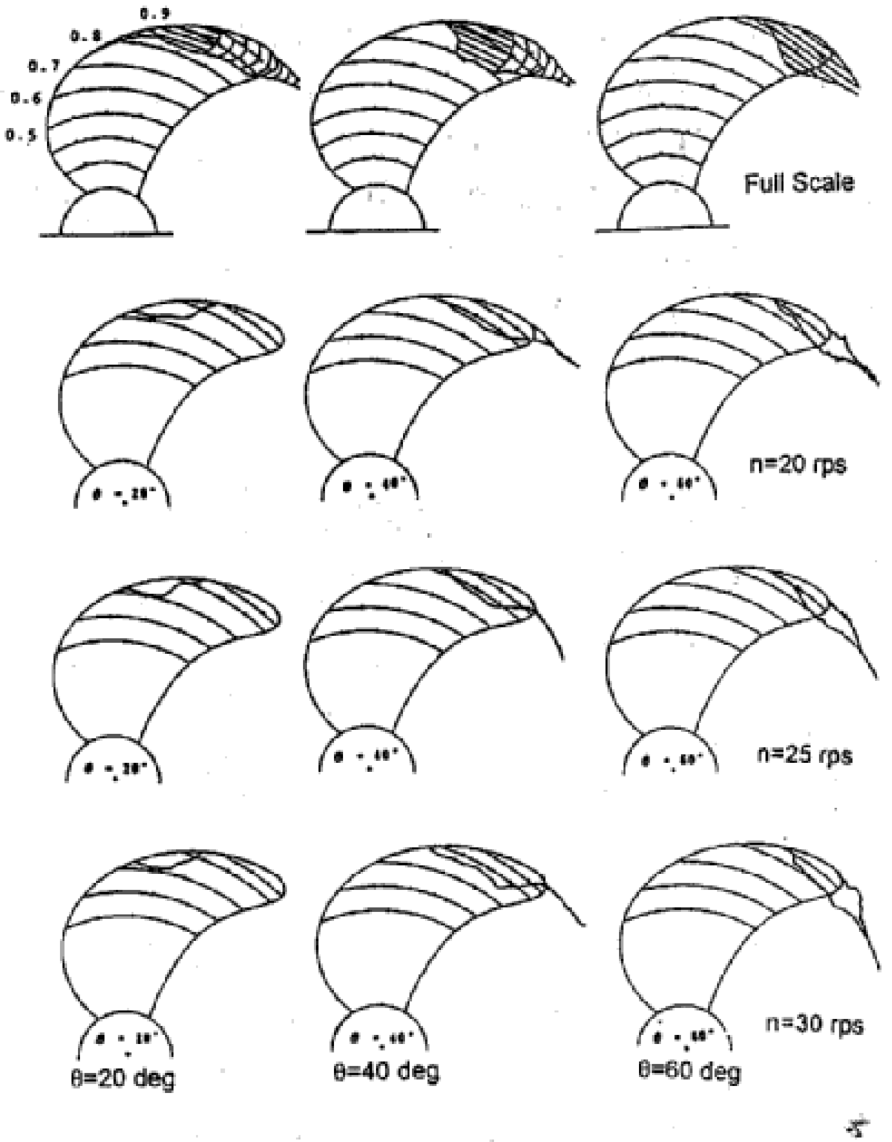

Figure 11. Comparison of cavitation patterns.

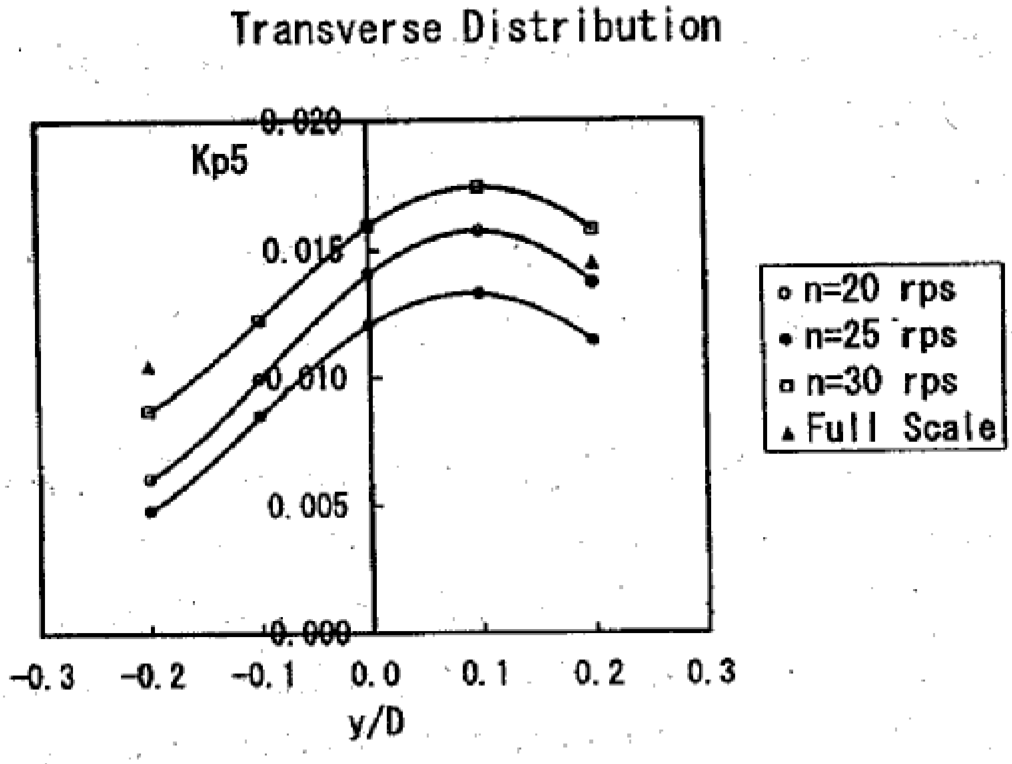

Figure 12. Comparison of transverse distribution of pressure fluctuations.

Figure 5. Comparison of model scale and ship scale transverse distribution of pressure fluctuations at one Japanese tank (21st ITTC, 1996, p. 71).

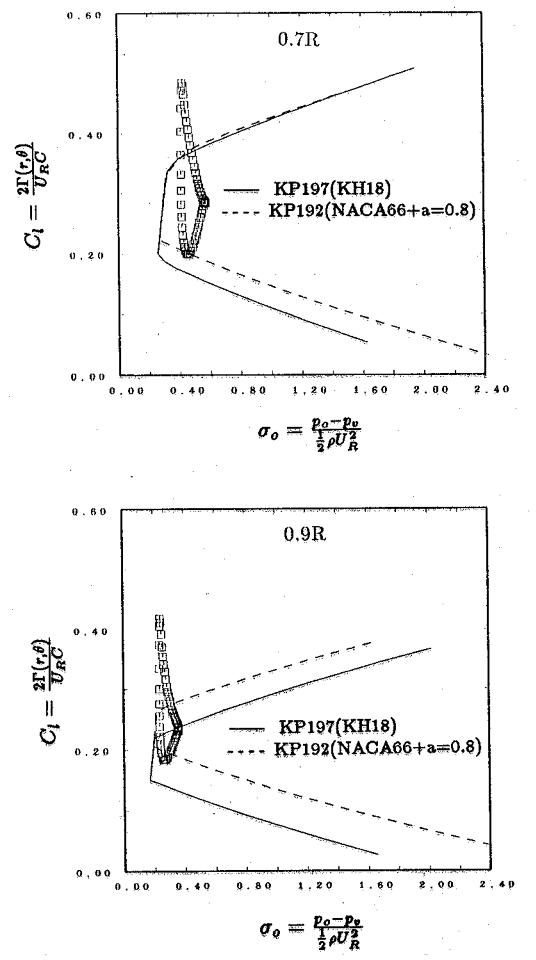

Fig.16 Operating points of the KP192 and KP197 propellers calculated by an unsteady lifting surface theory on the cavitation-free bucket diagrams.

Figure 6. Cavitation buckets at the 0.7R and 0.9R radii for KP192 and KP197 propellers for a container ship (Lee et al., 1991, figure 16). KP192 has NACA type sections and KP197 is of new blade section type ("Eppler" section).

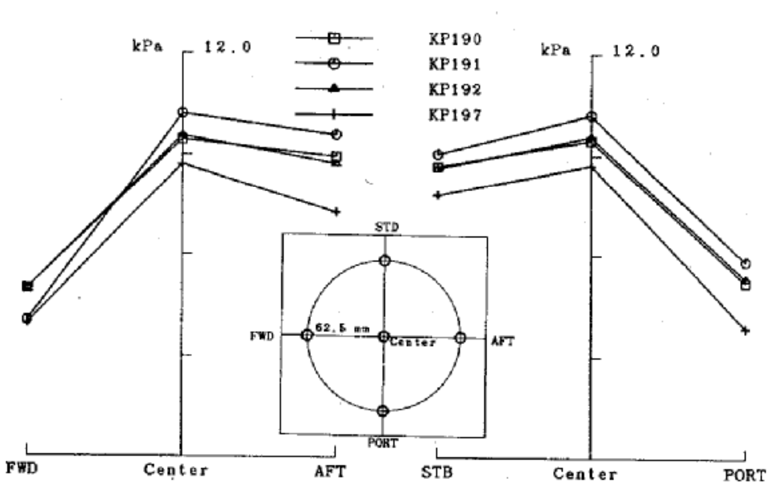

Fig.18 Comparison of the total fluctuating pressures by KP192,KP191 and KP197 propellers.

Figure 7. Predicted fluctuating double pressure amplitudes on the basis of the model tests for a container ship (Lee et al., 1991, figure 18).