The Specialist Committee on Cavitation Induced Pressure Fluctuation

Final Report and Recommendations to the 22nd ITTC

. MEMBERSHIP AND MEETINGS

Members

The membership of the specialist committee on Cavitation Induced Pressure Fluctuation includes:

Prof. Göran Bark, SSPA Maritime Consulting AB and Chalmers University of Technology, Göteborg, Sweden.

Dr. Giovanni Caprino, Italian Ship Research Centre (CETENA), Genoa, Italy

Mr. Jürgen Friesch (Secretary), Hamburg Ship Model Basin, Hamburg, Germany.

Dr. Hong-Gi Lee, Hyundai Heavy Industries Co., Ltd., Hyundai Maritime Research Institute, Ulsan, Korea

Dr. Dmitry Sadovnikov, Krylov Shipbuilding Research Institute, St. Petersburg, Russian Federation.

Dr. Michael B. Wilson (Chairman), Carderock Division, Naval Surface Warfare Center, West Bethesda, Maryland, U.S.A.

Prof. H. Yamaguchi, Dept. of Environmental and Ocean Engineering, University of Tokyo, Japan.

1.2 Date and Venue of Meetings

Four formal meetings of the Committee were held as noted:

Göteborg, Sweden, February 5 - 6, 1997, hosted by SSPA Maritime Consulting AB and Chalmers University of Technology.

Washington DC, USA, September 24 - 25, 1997 hosted by the Carderock Division of NSWC, the Naval Surface Warefare Center. This meeting was held in conjunction with the SNAME Symposium Propellers/ Shafting 97, Virginia Beach, USA.

Hamburg, Germany, April 2 - 3, 1998 hosted by HSVA, the Hamburg Ship Model Basin. This meeting was held in conjunction with the Third International Symposium on Cavitation CAV 98, April 1998, Grenoble, France.

Genoa, Italy, January 19 - 21, 1999 hosted by CETENA, the Italian Ship Research Center.

1.3 Members Attending the Meetings

All members attended the first, second and fourth meeting. The third meeting was attended by all members except Dr. Hong-Gi Lee.

2. INTRODUCTION

The specification for a modern propeller will normally include a requirement of maximum levels of hull excitation pressures and/or forces. Those excitations should not be exceeded in order to achieve acceptable levels of vibrations. In practice, this requirement can vary from a simple statement to a very detailed specification with clearly defined pressure or force levels.

Because the propeller is one of the main sources of excitation of the ship structure, it is an important focus of efforts to improve shipboard noise and vibration level. The simplest indicator of the level of propeller-induced excitation is the amplitude of unsteady hull pressure at a point over the propeller tip. Based on experience, a variety of recommended blade rate single-point pressure amplitudes have be suggested (15th ITTC, 1978 and Wilson, 1991). It has been difficult to settle on a widely-agreed upon value because the peak level of pressure cannot be used alone as a reliable indicator, without taking into account the response properties of the hull.

Over the past years significant advances have been made in identifying the causes of excessive vibration observed principally in the aft end of ships. Ship trials, model experiments and analytical studies have shown that unacceptable levels of aft end and superstructure vibration can be attributed both to structural causes, such as inadequate local stiffness and resonant response of aft end configurations and shafting systems, and to pulsating propeller cavitation. The principal source of forced excitation occurring in modern ships has been the partially cavitating propeller characterized by sheet cavity in the upper half of the propeller disc and by strong, developed tip vortex cavitation.

In general terms, the excitation caused by the propeller operating in the non-uniform wake field behind a ship may be considered in two parts:

(i) Forces and moments on the propeller blades are transmitted to the hull structure via the stern tube bearing and thrust block (referred to as shaft forces or bearing forces)

(ii) Forces acting on the hull surface plating above the propeller, which result from the integrated effect of surface pressures induced by the blade loading and thickness and from the fluctuating pressure field produced by pulsating cavitation.

Under non-cavitating conditions, excitation forces from (i) and (ii) are generally of the same order. However, when the propeller cavitates the contribution from (ii) becomes dominant, with pressure fluctuations taking values as much as five to fifteen times greater than encountered in non-cavitating flow conditions. The resultant hull excitation force can be many times greater still, due to reductions in the phase angle differences between port and starboard locations. The influence of cavitation on bearing forces has been found to be relatively small (14th ITTC, 1975).

The significance of cavitation on pressure fluctuations became clear when the work of Huse (1972) was published. The influence of the cavitating propeller with its cavity volume variation on the ship vibration excitation was fully explained by this work. Also the paper by van Oossanen & van der Kooij (1972) which contains results of comprehensive measurements, contributed to the understanding of the pressure fluctuation mechanism.

Highly skewed propellers (Cumming et al., 1972 and Björheden, 1979) have been used extensively to reduce the hull fluctuating pressures as well as shaft excited forces and moments. It was shown that skew can reduce the hull fluctuating pressures by more than 50%. The Propulsor Committee of the ITTC several times reviewed other devices that showed some reduction in fluctuating forces, such as vane wheels, propeller with winglets at the blade tip and air injection on the hull, but all were much less effective than skew.

3. REVIEW OF SOME FUNDAMENTALS

In this section the main results of the theoretical foundations for prediction of propeller induced pressure pulses are reviewed. Previous discussions of the development of the field can be found in the proceedings of the 14th through the 16th ITTC.

3.1 The Structure of the Problem

The generation of pressure pulses by a ship propeller and the resulting excitation of ship vibrations includes the processes of:

1. Hydrodynamic generation of pressure disturbances in source regions around the propeller blades.

2. Establishment of a pressure field outside the source regions with account of the boundary conditions at the propeller and cavity as well as at the wetted surface of the hull, the free water surface and possibly other bounding surfaces such as a cavitation tunnel walls.
3. Excitation of the hull structure by the pressure at the wetted surface of the hull.

3.2 Sources and General Properties of Propeller Induced Pressure Pulses

A cavitating propeller operating in a wake behind a ship generates pressure pulses due to:

A. The blade thickness
B. The lift of blades in homogenous stationary flow
C. The fluctuating lift of blades in inhomogeneous and possibly unsteady flow
D. The cavity of constant volume in homogenous stationary flow
E. The fluctuations of the cavity volume in an inhomogeneous and possibly unsteady flow.

It is usually supposed that the pressure pulses from all source types A – E are related to velocity potentials satisfying Laplace's equation. From the linearity of this equation it follows that the potentials from the different sources can be added. The pressure pulses are then obtained from the "Bernoulli equation for unsteady irrotational flow".

In addition to the superposition of pulses from different source types on the same blade, the pulses from all blades add up to a total sequence of pressure pulses from the propeller.

The generated pressure field propagates according to a wave equation, which however, at the close distances between the source regions and the field points can be approximated by a Laplace equation for the pressure. The latter approximation, corresponding to a completely incompressible approach, implies that the finite time of propagation of the pulses from the source regions to different points on the hull is neglected and thus that the phase angles of the different contributions are determined only by the times of generation, i.e. by the angular positions of the blades.

3.3 Some Properties of Pressure Pulses from Different Source Types

Although the focus will be on pressure pulses due to cavitation some discussion of pressure pulses from non-cavitating propellers is of interest, particularly when considering propellers with slight or stationary cavitation. The fundamentals of the different source mechanisms on propellers are discussed by several authors, three examples being Isay (1967), Tamborski (1979) and Breslin & Andersen (1994).

In fact all source types A to D can in the present application be approximated as dipole sources. For bodies with thickness, a propeller blade without lift for example, a distribution of dipoles with the axes aligned with the incoming flow is needed.

The blade lift force, corresponding to different pressures on the blade sides, constitutes another dipole (distribution), with the axis perpendicular to the blade section.

Analogous to the "thickness-dipole" the differently orientated "lift-dipole" of constant strength in a homogenous and steady inflow to the propeller will generate a fluctuating pressure in any point outside the symmetry line of the propeller shaft. The different orientations of the dipole distributions imply that the corresponding pressure fields will have their maxima at slightly different axial positions. While the thickness-dipole will have a maximum straight above the propeller the lift-dipole will have a maximum slightly downstream the propeller, see for example Tamborski (1979) and Breslin & Andersen (1994).

Particularly in model experiments compared with full scale testing the combination of low or transitional Reynolds number, higher turbulence level, and low or insufficient cavitation nuclei can cause the cavitation extent to exhibit significant fluctuations in time and possibly even intermittent cavitation (the occasional complete disappearance of cavitation during some blade passages). In this case the typical scale of the fluctuations correspond to lower frequencies than the blade rate or even shaft rate frequency, and the intermittence will influence the mean amplitude at blade frequency.

Wake fluctuations can contribute to the disintegration, collapses and oscillations of tip vortex cavities at five to fifteen times the blade frequency (low frequency noise) observed by Ingelsten & Johansson (1997) and Johannsen (1998). Mechanisms related to the collective behaviors of cavitation clouds may be involved in the oscillations, Kumar & Brennen (1993). Skewed propellers, with tiny sheet cavitation continuously transforming into vortex cavitation along the blade tip, often have an amplitude maximum in this frequency range.

A tip vortex cavity downstream of the propeller and of constant thickness is mainly convected with the flow past a point on the hull and will thus not generate any disturbance above that generated by the pressure field due to the moving vortex. The creation, possible oscillations and collapse of the tip vortex cavity can however yield significant monopole or line sources as described below.

For generation of pressure pulses by cavitation, the most important mechanism is usually the volume pulsations of the cavity caused by the variation of the angles of attack of the blade in an non-uniform wake.

Except for the region very close to the cavity the generated pressure disturbance is, according to the linear approximation, proportional to $(1/r)d^2V/dt^2$, where r is the distance from the cavity center to the free field observation point, V is the cavity volume and t is time. This is a source of monopole type, being the most efficient radiator of pressure.

The importance of the different sources A - E will however also depend on the strengths of the sources. When a pulsating cavity exists, of sheet or vortex type, this source will often be more important than all the others together. For ships with almost uniform wakes and highly skewed propellers with tiny cavitation, the contribution from the cavity pulsations can however be so small that the contributions from the dipole sources can be important, particularly close to the propeller. Examples of the contribution of different sources are demonstrated by Tamborski (1979).

3.4 Influence of Boundary Conditions

In practice the pressure sources are located in a fluid domain bounded by interfaces of different properties and at different distances from the sources. This means that the pressure field can be significantly influenced by the boundary conditions. For example the 1/r - decay of the pressure will not be valid to the same extent as in an unbounded fluid. The fundamentals of the boundary value problem are discussed for example by Catley (1984).

For a ship at the surface of the deep ocean the two dominating boundaries close to the propeller are the hull plating, partly flexible, and the free water surface, completely flexible to the pressure pulses. Obviously the two boundaries with quite different conditions join in the region of interest.

An example of "distant" boundaries are the walls in a cavitation tunnel. Sometimes they can be close enough to the pressure transducer to influence the measured hull pressure, particularly if the pressure transducer is far from the propeller. If standing waves are excited, measurements rather close to the propeller can also be influenced.

The boundary value problem of the pressure field around the hull is a diffraction problem, i.e. the incident pressure waves are scattered by the hull. The diffraction problem becomes quite complex and an alternative formulation yielding the surface force on the ship was suggested by Vorus (1974). A problem with this formulation is however that results are difficult to verify experimentally, particularly in full scale.

Breslin, et al. (1982) made computations (PUF-3 plus potential theory for boundary conditions) for a container ship with the free water surface simulated as a free, rigid and non-reflecting surface respectively. In comparisons with measurements in the SSPA tunnel with the water surface simulated by an immersed plywood board the best agreement was obtained with the computations for a rigid board, Breslin & Andersen (1994) pp. 446-447. This is particularly true for transducers rather close to the water line while the pressure computed at a transducer position close to the propeller and far from the water line is not very sensitive to the free surface condition.

Huse & Wang (1982) developed a general procedure for transformation of pressure amplitudes measured in a cavitation tunnel to data for correct boundary conditions. They introduced a "combined solid boundary and free surface factor" defined to be the product of the "solid boundary factor" and a "free surface factor". A systematic study of the combined effects of a rigid surface and a free surface at the water line for different locations of sources and field points on four different hulls was also presented.

A particular problem discussed for measurements in model as well as in full scale is the influence of hull vibrations on the measured pressures. The influence of global and local hull vibrations on measured pressures were studied for full scale ships by Frivold (1976) and Sunnersjö & Janson (1987). Both studies indicate a rather small influence, a fact not implying however that the problem always can be neglected.

The often used solid boundary factor = 2 (and neglect of the free surface effect) can be adequate, although conservative, for field points far from the free surface. Close to the surface and far from the propeller it will however result in significant over-estimation of the pressure.

3.5 Comments on the Statistical Properties of the Cavitation Process and Scaling Problems

The main assumption in scaling of model results is that the model and full scale processes are exactly similar and measured and analyzed in ways preserving this similarity. For example the simple scaling of pressure amplitudes by the dimensionless parameter K_p is based on such assumptions. Scale effects in the extent and the dynamics of the cavitation will influence the results but this is true also for the statistical properties of the cavitation process.

Ideally the pressure signal is periodic with the blade frequency as the lowest frequency. This corresponds to a line spectrum with spectral lines only at multiples of the blade frequency.

If not all blades are identical there will be a periodic modulation of the signal and spectral lines separated by the shaft frequency will appear as "side-bands" around all lines at blade frequency multiples. The lowest frequency appearing now will be the shaft frequency.

If the wake is fluctuating, because of turbulence, separation or ship motion in waves, the cavitation at different blade passages can generate pulses of different amplitudes, phases and shapes. The deviations from the ideal signal can be periodic (due to regular waves for example) and/or random. Depending on the statistical character of the disturbing or modulating process the spectrum will be modified in different ways. Random modulations will introduce a continuous spectrum.

In a comparison of a typical model test with a full scale test in sea state zero the general impression is often that the cavitation in full scale has the more periodic and stable behavior. If the gas content of the water in a model test is on the low side and the cavitation is only of tiny extent it happens that the cavitation becomes intermittent. Also this is a type of modulation, usually random and of very low frequency. All these types of modulations caused by external processes, manufacturing, operation etc. affect the statistical properties of the pressure signal.

The spreading of energy from the ideal lines by phase modulation is more accentuated at higher harmonics than at lower. This implies that phase modulation of the sheet cavity will generate a spectrum approximately similar to that which is supposed to emanate from the pulsating tip vortex cavity according to Ingelsten & Johansson (1997) and Johannsen (1998).

In practice different types of modulations will coexist. Some can be due to scale effects at model testing, others can be the result of operation or wind and sea state in full scale and still others can be "natural" and exist at both model and full scale.

In computations no modulation appears, but still the effects have to be noticed in comparisons with full scale results.

The most extensive discussion of modulation effects in cavitation is found in the paper by Baiter et al. (1982).

4. COMPUTATIONAL METHODS FOR INDUCED HULL PRESSURES

4.1 Introduction

Prediction of unsteady hull pressures is one of the traditional yet unsolved issues in propeller design. The previous ITTC Cavitation Committee reports show the following history of the prediction work.

1970’s: Empirical equations developed statistically from databases.
1980’s: Importance of cavitation prediction was focussed on. As a first step, non-cavitating propeller computation was mainly utilized. Cavita-

tion was predicted for non-cavitating propeller computation results. Effect of cavitation on propeller performance was not taken into account.
1990’s: Fully 3-dimensional computation methods have been developed. As a result, several computer codes have become available for propeller designers.

The committee recognizes the importance of fully 3-dimensional propeller cavitation computations. But since cavitation is very sensitive to the surrounding conditions, the prediction methods are still in developing stage.

4.2 Treatment of Hull and Free Surface as Boundary

A solid boundary factor of 2.0 is often used to calculate the pressure fluctuation level due to propeller. This means that the hull is treated as an infinite flat plate placed above the propeller. This assumption is reasonable if we discuss the maximum value of fluctuating pressure. But this factor should be reduced towards the surroundings. Wang (1981) proposed an equation for this factor. Pressure fluctuations on the hull can also be obtained by solving the boundary-value potential problems (for example, Vorus, 1974). On the other hand, van Gent et al. (1989) investigated the effect of hydroelasticity.

Recently, Kehr et al. (1996) calculated the pressure fluctuations on a stern hull geometry and a flat plate, discussing the effects of hull geometry and free surface boundary.

Choi & Kinnas (1997) and Kinnas et al. (1998a, 1998b) simulated cavitation tunnel tests by combining the tunnel wall boundary conditions with cavitating/noncavitating propeller computations, and discussed the effect of tunnel walls on propeller performance, cavitation and fluctuating pressure.

As such, remarkable progress was not seen on this subject during the 22nd ITTC. This is because everyone recognizes that the prediction of unsteady propeller cavitation is the most important issue at the present state of the knowledge.

4.3 Prediction of Cavity as a Source of Fluctuating Pressure

A rotating propeller is a source of hull vibratory force, consisting of rotating blade loading as rotating vortex sheet, rotating displacement of blade thickness and cavity as rotating source/sink (dipole), and variation of cavity volume as pulsating source. Among them, the effect of cavity volume variation is the most significant and difficult to predict. We need to predict the 2nd time derivative of cavity volume to calculate the fluctuating pressure. Since the work on propeller cavitation prediction is reviewed by another committee report (Specialist Committee on Computational Methods on Propeller Cavitation), this committee only comments on the future direction from the viewpoint of pressure fluctuation prediction.

The following is the list of MIT propeller computation codes (Kinnas & Pyo, 1997), which clearly shows the general progress of propeller and cavitation analysis not only on the MIT codes.
FLAG: FLow Adapted Grid.
BEM: Boundary Element Method.
VLM: Vortex Lattice Method
PSF-2: Propeller blade analysis code in Steady Flow based on VLM.
PSF-2IS: PSF-2, 1979 version, which includes Inclined Shaft effects.
PUF-2: Propeller blade analysis code in Unsteady Flow based on VLM.
PUF-3: Propeller Unsteady cavitating Flow analysis code based on VLM, 1979 original version.
PUF-3A: PUF-3, 1986-93 versions, which include leading edge correction.
HPUF-3A: PUF-3, 1994 version, which includes

effects of Hub.
HPUF-3AL/INC: PUF-3, 1996 version, which includes effects of wake ALignment and effects of INClined Flow.
PSF-10/PUF-10: Propeller blade analysis code in Steady/Unsteady Flow based on BEM.

As such, propeller analysis codes have progressed from lifting surface (e.g. VLM) to lifting body (e.g. BEM) expressions. Although lifting surface computations are still mainstream in the case of unsteady propeller cavitation, emphasis will shift to lifting body expressions soon. Kim et al. (1995) presented a propeller cavitation computation based on lifting body expression and used it to predict pressure fluctuations on flat plate and stern hull geometry. They showed good agreement with the measurement on the cavitation pattern. But they did not compare the pressure fluctuations.

The committee agrees that the analysis of blade sheet cavity is the first step. But since highly skewed propellers became popular, the effects of blade sheet cavity on hull pressure fluctuations have been much reduced. Now, it seems that the tip vortex cavity also plays an important role on fluctuating pressures particularly at high frequencies. Prediction methods for vortex cavitation have been proposed by Szantyr (1994) and Kinnas et al. (1998b). There is room for further developments. More efforts should be paid to simulating the tip vortex cavity.

The researchers on this subject should also keep it in mind that the demand for twin-screw vessels is increasing.

It is still difficult to assess the accuracy of pure computational prediction of hull pressure fluctuations. Good agreements with the measurements are reported in some papers (for example, Szantyr, 1994, and Wilson & Jenkins, 1988). But significant discrepancies are shown in other papers (for example, Bjärne & Bergholtz, 1995).

4.4 Comparative Study

The old Seiun-Maru, a 105m long training ship in Japan, has been used for successive and extensive full scale experiments for a long time. Model tests were carried out mainly at the Ship Research Institute, Japan (1997). They also measured the 3-dimensional shape of cavity surface by a laser optical method (Ukon et al., 1989). Using their database and the computer codes owned by the organizations in the SR230 research panel, the Japan Shipbuilding Research Association carried out a comparative study on the prediction of hull pressure fluctuations (SR230, 1999).

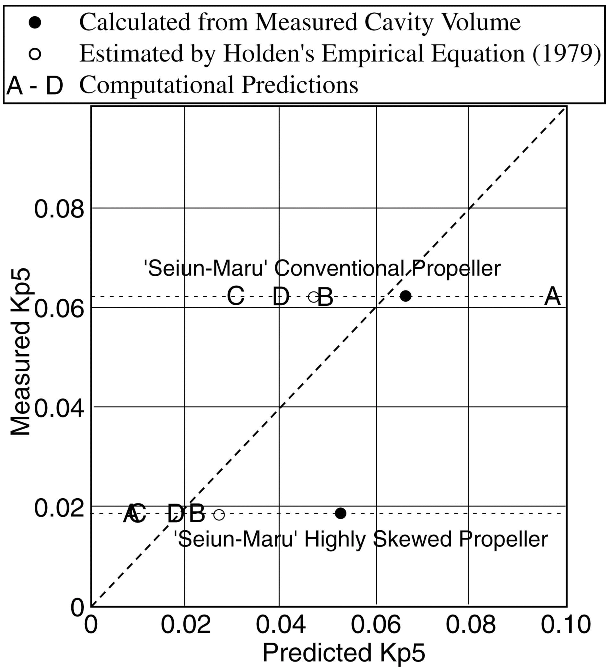

Figure 1. Comparison of measured and predicted fluctuating pressure coefficient at the first blade rate for the Seiun-Maru's conventional and highly skewed propellers; In the full scale measurements, the Kp5 values are about 0.052 for the conventional propeller and 0.014 for the highly skewed propeller.

Figure 1 compares the predicted and measured fluctuating pressure amplitudes at first blade harmonics. The points denoted by A – D are computational predictions. The A is a method based on the Szantyr's UPCA91 code (Szantyr, 1994). The B is a vortex lattice method including cavitation, where computation is made in a quasi-steady manner. The C and D are the predictions based on noncavitating propeller computations where the effect of cavitation on propeller performance is not taken into account. In the method D, only the cavity thickness is predicted by theory, adjusting the cavity extent to that of the experiment.

As shown in this figure, the computational predictions show significant scatter and discrepancy from the measurements. Holden's empirical equation (1979) gives fairly good results. The fluctuating pressure level calculated from measured cavity volume shows fine agreement with the measured one for the conventional propeller. Significant discrepancy, however, is seen in the case of highly skewed propeller. One possibility for the large discrepancy of the highly skewed propeller is the characteristics of blade sheet cavity. It is often observed that the trailing edge of the blade cavity of a highly skewed propeller is lifted away from the blade surface near the tip. Since Kudo et al. (1989) measured the coordinates of cavity surface only (not the thickness), the cavity volume might be overestimated.

4.5 Conclusions and Recommendations

The key for the accurate prediction of unsteady hull pressures is accurate prediction of <u>time variation</u> of cavity volume. In this regard, the present computational prediction methods are not yet fully validated for practical use. In some cases, the predictions agree very well with the measurements. But significant discrepancies are seen in other cases. More efforts are required to improve the cavitation modeling and numerical procedures. At present, a computational method might be used to estimate the improvement in the process of designing new propellers, if the user knows the characteristics of that particular computer code well. But the final results should be evaluated by accurate experiments. The following items are recommended for future improvements:

1. Cavitation modeling: It is often observed in the experiments that the trailing edge of the blade cavity of a highly skewed propeller is lifted away from the blade surface near the tip. The present computational methods do not take this fact into account in their blade cavity modeling and they should do that for more accurate prediction of blade cavity volume. Also, the effect of tip vortex cavity would not be negligible, particularly in highly skewed propellers. More accurate modeling of tip vortex cavity should be developed.
2. Some papers on propeller design with help from a computer code showed the variation of predicted cavity volume, but did not show the hull pressure level. As mentioned above, the current status of computational hull pressure prediction is not so reliable. The improvement should be done step by step with careful comparison to experiments. Since it is very difficult to compare the cavity volume variation to measurements, they should show the hull pressure level to contribute to the future improvement of the computational methods they used.
3. Studies of comparative computations with measurements are recommended to do under ITTC. What should be compared is not only predicted hull pressure fluctuations but also 3-dimensional cavity shape if the data is available.

5. FULL SCALE MEASUREMENTS OF UNSTEADY HULL PRESSURES

5.1 The Need for Full Scale Measurements

Predictions made by analytical means or by model experiments can be made reliable only by subjecting them to some systematic comparisons with measurements made on ships. This was mentioned in several previous ITTC Cavitation and Propeller Committee reports (1978, 1984). There is a further need for shipboard experiments in that they alone can provide the data from which valid empirical relationships between vibration and ship characteristics can be deduced, and finally they provide limiting values for criteria such as hull pressure and vibration amplitudes on which the acceptability of a ship design can be based.

Correlation between model test results and full scale data are somewhat mixed. However, it is clear that cavitation accentuates the fluctuating pressures, and when cavitation patterns are not well simulated, the fluctuating pressures are also not well correlated. Therefore cavitation observations at full scale are of fundamental importance and are strongly recommended to be carried out in parallel with pressure fluctuation measurements.

5.2 Procedure for Full Scale Measurements

5.2.1 Full Scale Measurements, the General Picture

Measurements on real ships are of great importance for scale effect studies, since they should prove whether or not the predictions from model tests are correct. There are many difficulties. The first one is the **speed measurement**. It should be noted that one needs to measure the speed through the water and not the speed over the ground. The speed we would like to know is influenced by current. Traditionally for instance the “measured mile” is used. This, or a similar procedure using satellites, can be used when there is no current. Unfortunately, there always is one, and often it varies in strength and direction. It is quite impossible to measure the current’s speed and direction in practice. Therefore sea trial procedures have been worked out by which the influence of current can be corrected for. However, even nowadays an accurate ship speed measurement is a difficult task.

In addition to current there are factors like water **depth**, **wind** and **waves**. For all these parameters methods have been developed that can be used to correct measurements on board a ship. Apart from the fact that these methods are mostly semi-empirical and have a limited accuracy, the largest problem is still how to determine accurately the wind speed and direction, the wave height, period and direction, and the water depth when the sea bottom is not flat.

For a proper judgment of the quality of the speed prediction, one should also know at what **power** the required speed is achieved. In addition, for the determination of scale effects on propeller performance it is recommended to measure the **propeller thrust**. To perform a reliable thrust measurement is very difficult, and therefore almost no full scale data are available. The existing test techniques need to be improved. Power is determined by measuring the **rotational** **speed** of and the **torque** in the propeller shaft. The torque is measured by means of strain gauges that are glued on the shaft. The stresses in the shaft due to torque are small, but due to developments regarding sensitive strain gauges and electronic processing equipment this kind of measurement can now be considered as very accurate and reliable.

Vibration and viewing trials have been carried out on ships during trials and in service. During these sea trials, hull pressure measurements were taken and procedures were developed to allow the observation and filming of the propeller under working conditions (Blake et al., 1990, Friesch, 1984, Lindgren et al., 1972, Huse, 1972, Huse, 1975, Johnsson et al., 1976, Ukon et al., 1989 and Okamura et al., 1988).

Even more complex trials were undertaken to measure the flow just forward of the propeller by means of a laser doppler velocity meter (Kux & Laudan, 1985) and to measure the air content of the sea water (Weitendorf & Keller, 1978).

From these trials the response characteristics of good and bad ships in relation to propeller-excited vibration and the large exciting forces which can be set up by a cavitating propeller have been demonstrated. Severe excitation set up by a propeller with pulsating volume cavities is characterized by large amplitudes of pressure at frequencies which are multiples of the propeller blade passage frequency. The resulting integrated unsteady surface forces can lead to local aft-end structural failure. Advanced propeller designs can sometimes lead to improved cavitation and lower blade frequency excitation characteristics. In some cases shipyards have adjusted the construction of their new designs to take advantage of the lower level of blade rate amplitudes. This often leads to a lighter and weaker structure. But it should be remarked here, that the strong reduction in blade rate components sometimes leads to problems with the higher order components. For example for an open top containership, cavitation observations and pressure fluctuation measurements have been performed and the results are shown in Fig. 2. The important result of those investigations was, that the pressure amplitudes of the blade frequency were rather small, clearly below 1 kPa, which means below the often recommended boundary region between 4 and 8 kPa (Friesch, 1995). However, the values of the higher harmonics are of the same height or even higher. Friesch (1998) and Hämäläinen & van Heerd (1998) showed that this behavior was observed in more than one case.

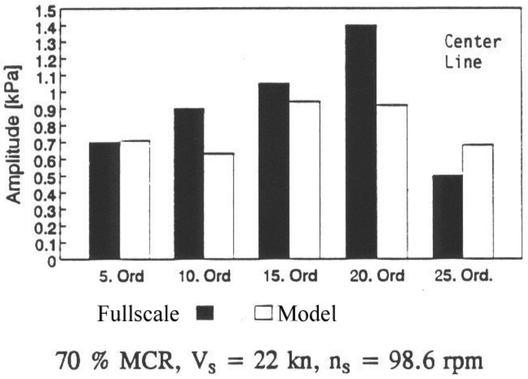

Figure 2. Harmonic components of the pressure fluctuations (containership, 5-bladed propeller).

However the lack of sufficient full scale data means that further validation is necessary. It is also important to keep in mind, that the level of excitation forces only forms one part of the ship vibration characteristics and that the question of structural response is at least of equal importance. An interesting proposal for an excitation criterion is to take the total integrated force over a defined area of the hull, although this means more instrumentation at both model and full scale.

5.2.2 Conventional Propeller Viewing

Conventional propeller viewing systems typically use ports for observing the propeller. Generally four to eight ports are necessary to adequately illuminate and observe both sides of a propeller, depending on the hull geometry. It is frequently necessary to view a propeller from far upstream to get a desired view. This may not be possible using flush mounted ports alone, because of the steep viewing angles required, although the problem can be alleviated somewhat through the use of prisms.

A typical arrangement of windows for full scale cavitation observations on a single screw ship includes circular windows with diameters up to 600 mm, mounted flush into the ship’s hull, and 2 tube windows fitted into the stern, about half a propeller diameter in front of the propeller plane. These tubes - with a diameter of 100 to 200 mm, depending on the video- and camera equipment - should be directed to a point in ship center line, in the propeller plane and 80% of the radius above the middle of the shaft. The circular windows are used for illuminating and for observing the blades (including the face side). The tube windows allow detailed photography and video imaging of the cavitation phenomena. Such an arrangement of windows allows the observation of the suction side and the tip of the propeller blade between 90° and 270° (180° means blade at top position) and of the pressure side approximately from 270° to top position.

For gauging the exact location and extent of the various cavitation patterns, an identification grid should be painted on the propeller blades, for example with two-component epoxy color.

Photographing and viewing is normally carried out at night with artificial lighting. A stroboscopic effect is necessary to study the cavitation behavior in detail and this is obtained by flashing at shaft frequency, for example with flash duration 10 ms, light energy per flash 10 Ws.

Table 1. Recommended Measurements for Full Scale Pressure Fluctuation Testing

	Absolutely necessary	**Worthwhile to have**	**Others**
Environmental Data **Weather** **Sea**	- water temperature - wave height - sea state - wave heading	- wind speed/direction - water depth - information on current Turbidity	- turbulence - bubbles (history)
Ship Data	- draft - stern wave height - type of ship (frame plan, section shape) - clearances - height of shaft center above basis - arrangement of windows and transducers	- wetted beam in the propeller plane - rudder movements	- type of aftbody structure - state of the ships hull (roughness)
Propeller Data	- type of propeller - main data (Ae/Ao, P, Z, skew, D)	- propeller design conditions (n, P_D, V_S)	
Instrumentation Type	- type of stroboscopic lights - type of transducer - type of amplifiers - description of the measuring chain - storage medium	- frequency range - accelerator measurements close to the transducers	- filtering frequency
Test Condition	- propeller rpm - ship speed - torque - power - course - pitch setting	- thrust - place where pitch setting is measured	
Data Evaluation	- measuring time - number of points per revolution - number of revolutions taken for the harmonic analysis	- time signals	

One requirement of a propeller viewing system is the ability to view the propeller at specific angular positions in its rotation. In most cases this is done to within one degree. Another requirement is to be able to rapidly observe a blade as it passes through all angles. This is done be freezing the blade on each revolution plus or minus one degree, which makes the propeller appear to rotate in one direction or the other. This shows how the cavitation changes as the blade rotates. There are different ways to get this required information.

Formerly a toothed wheel was attached to the shaft to provide the required angular location information.

Nowadays, improved optical sensors are used. As the shaft rotates, a magnetic or optic sensor detects the passing of the teeth or a special mark, sending out a digital pulse to the phase lock loop system. This in turn sends its output to a propeller viewing controller. Here the signal is manipulated to allow the operator to freeze a blade in any position or to allow it to appear to rotate in either direction. The output pulse from the viewing controller governs the firing of the strobe lights which effectively freezes the view of the propeller.

Recording of the cavitating extent can be done by sketches (viewing), photographing (color slides) and by video-pictures. Photos and videotapes can be made from inboard, so that normal photo-equipment can be used.

In order to gather information about the fluctuation of sheet cavitation, three to five photos should be made in every position of the propeller blade. There have been a few attempts to measure the thickness or the volume of the sheet cavitation (Kurobe et al. 1983) . Those measurements are important for correlation, especially with computations, but they are rather difficult.

The camera of the video system should have high resolution to show the detailed behavior of the cavitation, as well as high sensitivity to allow a large separation between the propeller and the locations of the camera and lights. These specifications can be met with different types of CCD color cameras.

While propeller viewing trials are very valuable, the cost of installing the viewing ports makes a conventional viewing trial expensive. Therefore it is recommended to install the viewing ports during the construction phase of the ship, which minimizes the cost dramatically.

Improvements of video systems and the prospect of miniaturizing the components suggested that a new technique could be developed which did not require the costly viewing ports (Kennedy et al., 1990). The number and the size of the viewing ports can be reduced, sometimes even down to only one which can be used for both, lighting and observing. Additionally fiber optics came into use again for both, illuminating and observing the propeller. They need only small holes which can be installed without dry-docking. The small sized electronic equipment can in some cases even directly be attached to the hull from outside, so that nothing needs to be changed at the ship’s hull. Additionally the new systems allow viewing and recording the cavitation phenomena during daylight. During the daylight observations the electronic shutter of the camera should be used, so that the electronic frame storage system can work.

5.2.3 Pressure Fluctuation Measurements

Arrangement of Pressure Transducers. Part of the performance evaluation involves pressure measurements on the hull above the propeller and vibration measurements on the hull in the vicinity of the pressures gauges and in the superstructure. Typically this involves one to twenty pressure transducers located above the propeller. In practice the pressure transducers for a single-screw ship extend roughly from a distance 0.8D ahead of the propeller disc to 0.6D behind the propeller disc (D = propeller diameter). The maximum extension to port and starboard amounts to about 0.6D to 0.8D, depending on the section shape. The distances between the transducers are in the range of 0.15 and 0.35 D. For a twin-screw or triple-screw ship more transducers may be required in most cases, while attention also has to be paid to the synchronized rotation of the propellers. A typical distribution of 10 pressure pick-ups for a single-screw ship is shown in Fig. 3, which is also sometimes used in model tests. The location of the measuring points needs to be chosen in a way that the distribution of the pressure amplitudes and the phase angles can clearly be deduced.

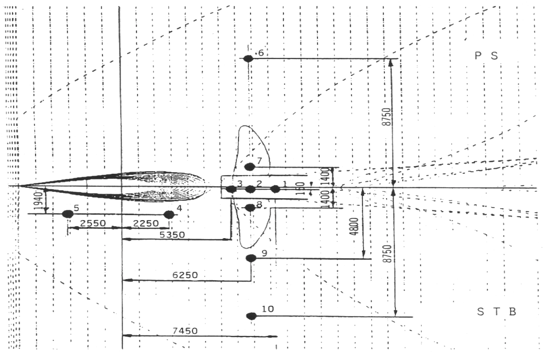

Figure 3. Arrangement of pressure transducers.

The transducers have to be mounted flush with the hull. Additionally, tri-axial accelerometers should be placed for example on the bridge, stern and main deck. At least two vertical axis accelerometers should be placed on the hull near the pressure transducers. Propeller shaft revolutions should be recorded with a one pulse per revolution tachometer.

<u>Instrumentation and Data Analysis.</u> Analysis methods of fluctuating pressure measurements have been discussed in 14th and 15th ITTC Propeller Committee reports (1975, 1978). Typical pressure pick-ups employed are strain-gauge transducers, rated, for example, at a maximum pressure of 50 psi (= 345 kPa) and suitable for a frequency range from zero to 6000 Hz (in water). Signal conditioning is performed by AC-carrier amplifiers. The carrier frequency is 1000 Hz, permitting the measurement of signals with a frequency range up to about 250 Hz. At this frequency the signal attenuation is about 1 %.

The pressure transducer signals, together with two pulse signals, are fed into the computer for further analysis. One of the channels contains one pulse per revolution, while the other displays, in most cases 120 equally spaced pulses per revolution, one of which appears simultaneously with the one pulse per revolution. The pulse signals are used for the periodic sampling of the pressure signals. Instead of 120 pulses per revolution, 60, 90, 180 or 360 pulses can be selected, the choice being made on the basis of requirements concerning aliasing (folding effect in sampling technique which can occur if sampling interval is too large) and data storage.

The results of all of these measurements should be recorded in the time domain on tape and spectrum analyzed. The most commonly used data treatment is harmonic analysis after averaging the measured values (18th ITTC Cavitation Committee report, 1987). From the frequency domain analysis, the signal amplitude can be determined for the first through fifteenth harmonic of blade frequency. Thus the amplitudes and the corresponding phase angles for the signals (with maximum, minimum, mean and the percent highest amplitudes) are determined. With the resulting blade rate harmonic components, the non-dimensional pressure amplitude coefficients are calculated as $(K_p)_{\mu Z} = (\Delta p_S)_{\mu Z} / \rho_S(n_S D_S)^2$, where $(\Delta p_S)_{\mu Z}$ is the μth blade rate harmonic component of the pressure amplitude, Z is the number of blades, and the subscript S means ship values. Narrow band spectral analysis and time series displays can be carried out for the pressures, vibration accelerations, and noise.

From the time domain recording, the overall behavior of the pressure signal, the energy content and broadband excitation can be found.

Influence of Hull Plate Vibration. Van der Kooij (1979) and Ligtelijn et al. (1992), were able to investigate the pressure scattering at full scale in a straight forward manner. The ship on which investigations have been carried out is a roll-on/roll-off container transport vessel built in 1978. In 1979 the first measurements were carried out. At that time a propeller of conventional shape was fitted. Later the propeller was replaced by another with high skew. In 1986 the second measurements were carried out. This time the measurements were extended with a series during which the ship was stopped at sea and a hydrophone was put in the vicinity of the propeller blade tip. In all three test situations pressures and accelerations have been measured with eight transducer pairs in the hull above the propeller. The transducer locations were in the centre of hull plate sections between frames and girders.

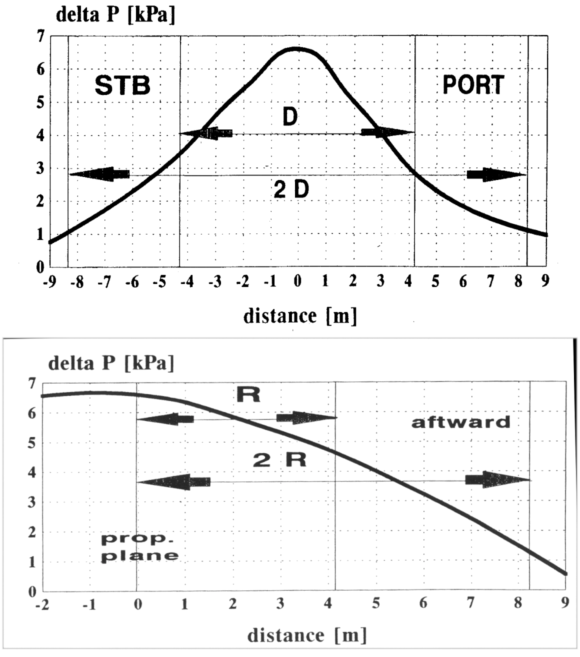

Figure 4. Presentation of results. Typical distribution of blade rate pressures, transversely and longitudinally.

The number of locations, the pairing of pressure and acceleration transducers and the variation in excitation (two different propellers and a pulsating source) provide for better conditions for judging the excitation level than the usual full scale trials. The three sets of experimental results are compared and conclusions are drawn about the way to correlate model and ship pressure levels (van Gent, 1990). But the problem is still complicated and the results are in some matters confusing. This means that we are still in a stage, where these influences are not fully understood and more work needs to be done to straighten out all the difficulties.

5.2.4 Presentation of Results

Principal ship and propeller data should be listed, together with information concerning ship speed, ship rpm and measured power.

The results of the pressure fluctuation measurements should be presented in form of tables and plots. The full scale dimensional values of the different harmonic components and the dimensionless K_P–values for all measuring points should be given together with narrow band spectra and time signals. The plots (see Fig. 4 as an example) should show the distribution of the pressures (blade rate and higher harmonics) in longitudinal and in transverse direction. Representative examples of RMS-signals are shown in Fig. 5. Figures like this can be used to demonstrate the influence of different propeller geometries on the pressures and to show differences between model and full scale data. The time signal of one or more transducers should be shown, to get an impression of the quality and character of the measured signal (Johannsen, 1998).

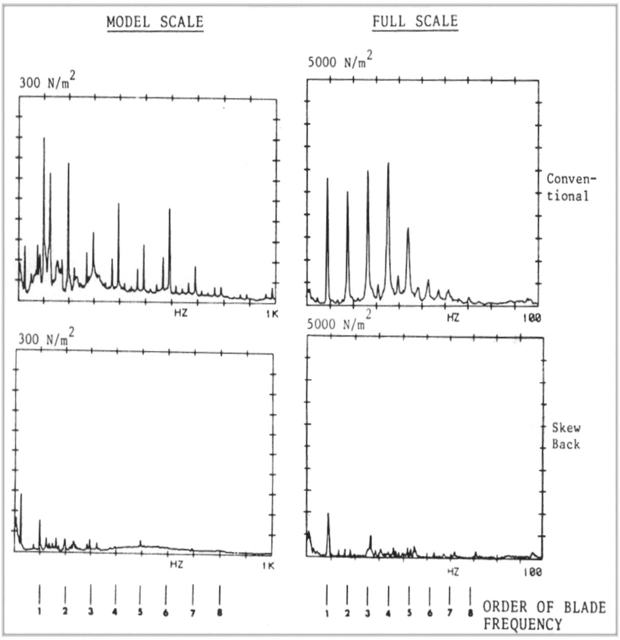

Figure 5. RMS-spectra of hull pressures induced by two different propellers in model and in full scale.

If cavitation observations have been performed, sketches, photographs and video recordings of the cavitation patterns in different blade positions should be added to the report.

5.2.5 List of Recommended Measurements

In the accompanying Table 1 a list of necessary and worthwhile / recommended data is shown, which should be measured to perform successful full scale measurements. The data listed under “absolutely necessary” are the minimum information that should be mentioned in the reports or papers dealing with the subject. These data are also the minimum input data to perform realistic and reliable model tests.

6. MODEL SCALE EXPERIMENTS ON PROPELLER INDUCED UNSTEADY PRESSURES

6.1 Introduction

This section provides a combined technical review and procedure for model experiments on cavitating propeller-induced hull pressure excitation. ITTC contributions to the art of model experimentation in this topic area may be found in either the Propeller Committee or Cavitation Committee reports in the ITTC proceedings going back to the 12th ITTC (1969).

The basic pressure fluctuation test consists of measuring transducer signals from flush-mounted pressure gauges located on a surface representing the ship hull shell, located adjacent to a propeller operating in a non-uniform inflow velocity field representing the flow behind the ship. Choice of the number and placement of pressure gauges should show the local peak of induced pressure amplitudes and the distributions of the pressures both laterally and longitudinally. The propeller cavitation patterns must be viewed and recorded. Example characteristic time series of pressure signals should be displayed. Model scale results must be analyzed for harmonic content and the pressure amplitudes scaled to ship scale for the prediction of dimensional unsteady hull surface pressures.

6.2 Procedure for Model Scale Experiments

<u>Test Set-Up.</u> (a) Propeller Model. Choice of model propeller size is a crucial step, because it affects the scale size of the entire experimental set-up. Within the size and capability constraints of the test facility, the model propeller should be made as large as reasonable to achieve the highest possible Reynolds number. The propeller model must have sufficient geometric accuracy and material strength for testing at high enough velocities and RPM to model desirable flow features. It is recommended to use numerical controlled machining if possible, as noted in the 20th ITTC (1993) Propeller Committee discussion of CAD/CAM for propulsor model design and manufacture. Model propeller blades are usually made of a strong aluminum alloy or brass. A thrust-to-disk area loading of around 70 kPa is a useful upper limit value for planning purposes.

(b) Setting Test Conditions. In a variable pressure water tunnel facility, the model test conditions should satisfy the same propeller loading and cavitation number as predicted for the full scale ship from towing basin powering test results. Three basic conditions are:

- Satisfy the propeller loading through the kinematic condition for $J = V_A/nD$ in order to achieve the predicted full scale K_T or K_Q (thrust or torque identity). Here V_A = speed of advance, D = propeller diameter, n = rotational speed (rps), $K_T = T/\rho n^2D^4$, and $K_Q = Q/\rho n^2D^5$. Usual practice in water tunnel testing is to satisfy the thrust identity, although there are circumstances where the torque identity approach is used.
- Provide a realistic simulated wake velocity pattern which will also give the proper speed of advance at the propeller disk location. Usual practice is to use the nominal wake velocity distribution (either for the model or scaled to prototype size) as the target wake for the experiment.
- Set the facility pressure and flow velocity to obtain the correct full scale cavitation number $\sigma = (p_0 - p_v)/\frac{1}{2}\rho V_{ref}^2$; where p_0 = total static pressure consisting of atmospheric pressure plus submergence depth pressure taken to a reference location on the propeller blade, and with the reference velocity V_{ref} taken as V_A or nD. The reference submergence depth used in the calculation of cavitation number is usually taken at a point approximating the center of expected cavitation extent in the upper part of the disk, such as 0.8R above the propeller centerline.

For Froude scaled cavitation testing in a facility with a free surface, such as a depressurized towing tank or a free surface circulating water channel, the standard results of a Froude scaled towing basin powering test may be used directly to set the propeller RPM and speed for the various operating conditions of the experiment. It is noted that the usual procedure for scaling model powering results to full scale is based on satisfying the thrust loading coefficient at full scale Reynolds number, which is equivalent to a thrust identity approach.

Within the general outline discussed above, some laboratories choose to calculate full scale cavitation evaluation test conditions by applying scaling modifications (such as the ITTC 78 scaling methodology) to model powering results derived from towing tank propulsion tests. Each laboratory's correlation experience should be used to decide on the details of this part of the procedure.

(c) Simulation of Wake and Hull Boundary. Discussions of model scale wake and ship hull simulation can be found starting in the proceeding of the 12th ITTC (1969). Test facilities for this type of experiment include: variable pressure water tunnel, depressurized towing tank, and circulating water channel with a free surface in the test section. For cavitation tunnel testing, alternative model schemes used in small water tunnel test sections include:

- Wire screen mesh placed perpendicular to the flow, in front of a flat plate 'hull'
- Parallel plate wake generator, in front of a flat plate 'hull'

For small to medium size test sections, the alternatives could include:

- Inclined shaft with struts and bossing, mounted below a flat plate or bump-like dummy model hull
- Dummy model ('afterbody model')

In large test sections:

- Shortened, but otherwise scaled ship models
- Complete scaled ship models

For all the model configuration types mentioned, it is recommended to include all the stern appendages such as the rudder in the correct location behind the propeller. The usual practice for testing in a free surface cavitation facility like a depressurized towing tank is to use complete scaled ship models run at Froude scaled speeds.

There are scaling issues connected with trying to satisfy the three governing similarity parameters: Reynolds number, Froude number, and cavitation number (Ligtelijn, 1992). Cavitation tunnel pressure fluctuation testing does not satisfy Froude or Reynolds number scaling, but is aimed at a relatively high value of Reynolds number. Testing in a free surface cavitation facility offers the possibility of matching Froude and cavitation number, but at a rather low Reynolds number.

When Froude similarity is not satisfied, the vertical distribution of static pressure is not scaled precisely as it should be. For cavitation tunnel testing run at higher flow speeds and RPM than dictated by Froude scaling, the correct cavitation number is exactly satisfied only at the blade reference point for scaled submergence depth pressure. This can be compensated for by simply adjusting the pressure head to the appropriate value for each of the blade positions of interest.

The low Reynolds number of model testing presents more complicated problems:

- Flows over typical model propeller blade chords are likely to have laminar or transitional boundary layer characteristics and this usually results in intermittent and unstable cavitation behavior. Concern with this has led to the use of sand grain roughness on the propeller model blade leading edges (Kuiper, 1981 and van der Kooij, 1979) for tripping turbulence in the boundary layer flow and improving the stability of blade cavities.
- Because of Reynolds number scale effect, the boundary layer thickness relative to hull length along a ship hull at full scale is smaller than at model scale. This will have the effect of producing wake velocity defect regions in the propeller disk that are narrower for full scale than for model scale. This means that the circumferential variation of local angle of attack on the blades could be affected by scale , and thus also the variability of cavitation. The magnitude of this influence depends greatly on the type of hull form. For very slim, open stern hull shapes, the net influence of hull boundary layer on the wake behind the ship will be small, and the Reynolds effect on wake could be ignored. For very bluff hull forms, the influence of hull boundary layer will be more noticeable. Wake scaling techniques such as the contraction methods by Sasajima & Tanaka (1966) and Hoekstra (1975) offer relatively simple methods for scaling a model wake to a target wake with full scale features. If Reynolds number wake scaling is to be applied, the practical recommendation is to target the three-dimensional full scale nominal wake.

The more difficult task is modifying a model configuration so that the measured wake reliably matches the target velocity profile. Some techniques that have been attempted include: the use of surface mounted patches of screen; shortened model hull length (Dyne, 1974 and Friesch, et al., 1992); wire mesh screens mounted perpendicular to the hull; slimmed afterbody dummy model shapes; and the use of flow liners in the corners of the test section to prevent flow separation on the aft end of a very bluff model.

Flow liners have been recommended (19th ITTC Cavitation Committee, 1990) when there is large blockage of the water tunnel test section. Information on the design and effectiveness of flow liners has been presented, for example by Ukon (1987) and in the 19th ITTC Cavitation Committee report (1990). However, currently there is no general use of flow liners in large cavitation tunnels, other than in the Ship Research Institute (SRI) large tunnel cavitation facility.

(d) Pattern of Pressure Measurement Locations. Guidelines for the arrangement of flush mounted pressure transducers on the hull surface of a full scale ship (discussed in Section 5 of this report) apply to the model scale as well.

(e) Propeller Cavitation Viewing. Adequate propeller viewing may be provided through the facility external viewing ports or windows; using cameras mounted on struts positioned inside a water tunnel test section or alongside the model hull in a depressurized towing tank; or using transparent viewing windows mounted in the model hull itself.

Other Essential Experimental Considerations. (a) Air Content, Cavitation Nuclei, and Stabilizing Model Cavitation. Providing for sufficient small bubble nuclei is very important for obtaining realistic results from scale model experiments. The specific problem for fluctuating pressure testing is that when there are insufficient concentrations of nuclei, all forms of cavitation behave intermittently and will therefore produce non-periodic pressure readings at the model scale. This can result in low averaged unsteady pressure amplitudes. Discussions in ITTC proceedings on this subject date back to the 15th ITTC (1978) Propeller Committee report and have continued through to the 21st ITTC (1996). Air content, as measured by means of a Van Slyke apparatus or by a Continuous Oxygen Analyzer gives the quantity of dissolved and free air in the water. It has been generally accepted that testing at relatively high air content (50 % saturation or higher) in a water tunnel facility will improve the correlation of model and full scale results. For testing in a depressurized towing tank, natural nuclei content is typically very low and intermittent blade cavitation can be a big problem. While addressing this problem, it was determined that an additional benefit of using sand grain roughness on the leading edges of model propeller blades was that small bubble nuclei were also produced; and used in conjunction with the generation of nuclei by electrolysis in the boundary layer flow past the hull, has contributed to the increased stabilization of the model scale blade cavities in the depressurized towing tank (Ligtelijn, 1992 and van der Kooij, 1979) and in a cavitation tunnel environment as well (Ukon, et al., 1998 and Ukon, et al., 1987). It is certain that operating at high Reynolds number and with high total air content, model blade cavitation behaves more realistically. Generally experience has shown that a water tunnel facility should have an air content as high as practical and still maintain adequate visibility, but the size of facility will have a large influence on what that highest practical air content can be. It is also noted that too high levels of air could introduce a damping effect on the measured unsteady pressure amplitudes. The optimum air content for a given cavitation facility should be determined by correlation experience.

Small bubble nuclei distributions have an especially marked effect on tip vortex cavitation inception, as has been demonstrated by the results and analysis of the joint ITTC-BEC experiment carried out in the GTH in 1992 (Gindroz & Billet, 1993; Gindroz & Billet, 1994a; and Gindroz & Billet, 1994b). Some idea of the extent of the effects of both liquid tension (size of nuclei) and the amount of dissolved air on the cavitation inception characteristics of a model propeller have been presented by Gindroz, et al. (1996).

(b) Facility Wall Effects. Measured pressure fluctuations caused by unsteady blade cavity volume variations can be altered by mirror image effects due to the walls of a water tunnel and cause errors in measured values. This was first discussed in ITTC literature in the proceeding of 14th ITTC (1975), and reviewed, for example in the 15th ITTC (1978) and 19th ITTC (1990) presentations. This effect can be a problem for very small water tunnels or in situations where the distance from propeller to pressure gauge location is unusually large.

An example of how tunnel size can influence the model measurement of unsteady pressure amplitudes is provided in a later section of this specialist committee report. Pressure data was obtained in the two different size test sections of the Hyundai Maritime Research Institute water tunnel (600 mm square and 850 mm square) with the same 250 mm diameter model propeller, positioned with the same tip clearance of 63.5 mm. Results for the measured K_p versus rotational speed are shown in Fig. 15 of this report. For the smaller test section results there is a greater variability of K_p with increasing propeller RPM than for the larger test section; and there are local peaks and valleys of K_p at certain n-values which may indicate the presence of some sort of resonance effect.

"Tunnel Resonance" is another problem related to the influence of facility boundaries. This refers to a condition where constructive interference of longitudinal standing pressure waves in the upper leg of a cavitation tunnel can produce interference unsteady pressures at the measurement locations of interest. This was first discussed in ITTC literature by Weitendorf (1981). The effect was identified by noting the unexpected variation in the magnitude of blade rate harmonic pressure coefficients with respect to propeller RPM, for cases measured at the same loading and cavitation number condition.

(c) Free Surface Effect. For unsteady pressure tests conducted in a depressurized towing tank or in a circulating water channel, free surface dynamic similarity will automatically be satisfied when the experiment is run at Froude scaled speed. For cavitation testing in a water tunnel facility, the operating cavitation number should be calculated including the static pressure head due to the wave height over the propeller location determined from a separate towing basin test.

(d) Effect of Induced Vibrations. With pressure gauges mounted in a hull surface, the measured pressure amplitudes will be affected by vibrations of the surface itself. It is known that hull vibrations can interfere with interpretation of full scale pressure measurements (van Gent, 1990 and Colombo & Chilo, 1984), and on the model scale as well (Kurobe, et al., 1988). There are simple correction estimates available, for example, from Sunnersjö (1982) and Kurobe & Yoshida (1985). The approach described by Kurobe & Yoshida (1985) assumes a simple vibration mode shape for a finite patch of the hull surface and computes the resulting pressure distribution and magnitude. An application of this approach was made by Wilson, et al. (1995). There it was shown that the measured vibration accelerations of the circular pressure gauge mounting plate imbedded in the hull surface 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 shown in the analysis by van Gent et al. (1989). He found that the net pressure exerted on the surface of an elastic plate excited by a monopole source nearby could be noticeably reduced for typical values of plate properties, frequency, and clearance distance.

Induced vibration of a simple pressure pulse measuring system, such as a flat plate used for mounting pressure gauges, can produce pressures acting on the plate that introduce errors into the measured values. This has been suggested by Ukon, et al (1989) as one of the causes of the variation of the blade rate pressure amplitude coefficient versus propeller RPM, as observed in the comparative unsteady pressure measurements on the Sydney Express propeller model presented at the 18th ITTC (1987).

(e) Higher Harmonics. The occurrence 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. Recent investigations of the subject of higher harmonics (Yamasaki, et al, 1994; Raestad, 1996; Friesch, 1998; and Johannsen, 1998) have identified unstable or excessive tip vortex cavitation as the cause of elevated unsteady pressures in a frequency range higher than blade rate. The physical mechanism usually blamed is 'vortex bursting,' or the sudden breakdown of blade tip vortex cavitation into cloud-like clumps, as discussed by English (1979). The use of time series display of the unsteady pressure time-varying signatures and narrow band spectral analysis have been key tools for the study of these problems. The experimental study by Chiba & Hoshino (1976) noted that there were large, narrow spikes (impulses) of pressure that could give rise to higher harmonic components associated with violent collapses of blade cavities into patchy clouds. Time series display of pressure signals was very important to understanding the role of cavitation in these results. The practical recommendation for model testing is to provide instrumentation and analysis capable of collecting and displaying pressure fluctuating signals out to perhaps 10-15 times blade rate.

Observations of Cavity Patterns. Propeller cavitation viewing and visual records of blade cavitation extent are essential parts of the overall procedure for unsteady pressure testing. The discussions and surveys of references on typical model blade cavitation patterns in the 18th ITTC (1987) and 19th ITTC (1990) proceedings deal mainly with categories of leading edge sheet cavitation. Cloud cavitation received extensive discussions in the 20th ITTC (1993) and 21st ITTC (1996) Cavitation Committee reviews. The latter reference also provides a recommended ITTC procedure for recording cavity extent and stability, concentrating on examples of vortex-like tip region sheet cavitation which typically occurs on highly skewed propellers.

Measurements and Instrumentation. The requirements for measurements and instrumentation for model pressure fluctuation testing fall into two main groupings. The following lists identify the measurement items and give any special notes about the instrumentation [in the brackets].

(a) Basic Test Measurements. 'Absolutely required' measurements include: facility flow velocity; facility static pressure; propeller thrust and torque; propeller rotational speed ; water temperature; air content as % saturation or % oxygen saturation [use Van Slyke Apparatus or Continuous Oxygen Analyzer]; wake velocity component(s) [most preferably use 5-hole pitot probes or Laser Velocimetry].

In the category of 'worthwhile to have' is the measurement of cavitation nuclei number and size distributions [use a cavitation susceptibility meter or Cavitation Nuclei Counter device].

(b) Unsteady Pressure and Cavitation Observation Measurements. 'Absolutely required' measurements include: unsteady pressure signals [use strain gauge diaphragm or piezoelectric type transducers]; control pulses per shaft rotation for data sampling [shaft encoder device with minimum number of pulses per rotation = 5*(highest BR harmonic)*(Z)]; data stream system [signal conditioners/amplifiers, A-to-D devices, link to computer and data storage]; viewing and photographic arrangements [windows, viewing pods or ports]; photographic and video records; stroboscopic lighting; and time series and narrow band spectra of pressure signals [spectrum analyzer machine].

In the category of 'worthwhile to have' are measurements of vibration acceleration [accelerometers placed near the pressure transducers]; sound pressure level of noise [hydrophones]; and time series and narrow band spectra for the accelerations and noise.

Data Collection and Analysis. Model scale blade cavitation behavior typically displays more variability or intermittence that the full scale. This shows up as random occurrences of a blade passing through the large velocity defect region of the wake without forming a fully developed cavity. The resulting weak pressure pulses scattered through the data can lead to lowered mean values of the amplitudes of the harmonic components when they are based on analysis of ensemble averages. Since the occurrence of such intermittence is made worse by low Reynolds number and low air content, the simplest approach is to test intentionally at high speeds and high air content, and just use the standard overall ensemble averages for the model results to be compared with similarly analyzed full scale results.

An approach developed for dealing with the problem of cavitation intermittence on model scale is to carry out separate Fourier analysis on each shaft rotation pressure signature. From the size-ordered list of amplitudes for each harmonic component, a mean is calculated from some percentage of the highest values (Johnsson, et al., 1976). The paper by Breslin, et al.(1982) presents a comparison study of full scale and model scale unsteady pressure pulse harmonics of the pressure coefficient that shows good correlation between the model mean of the highest 5% with the overall mean of the full scale result. The particular comparison shows reasonably good agreement between the model mean of the highest 5% and the full scale mean for all the harmonic components out to the fourth blade rate harmonic.

Another approach discussed by Friesch and Johannsen (1992) and in the 21st ITTC Cavitation Committee report is to use a preliminary culling procedure that identifies and excludes the smallest, insignificant pulses that are associated with noncavitating or weakly cavitating blade passages. Then ensemble averages are used to generate the various harmonic components. This has also lead to reasonably good agreement between model and full scale results.

With the resulting blade rate harmonic components, non-dimensional pressure amplitude coefficients are calculated as $(K_p)_{\mu Z} = (\Delta p_m)_{\mu Z} / \rho_m(n_m D_m)^2$, where $(\Delta p_m)_{\mu Z}$ is the μth blade rate harmonic component of model scale pressure amplitude, Z is the number of blades, and the subscript m denotes model scale values. Full scale pressure amplitudes are calculated on the basis of the same values of the non-dimensional pressure coefficient.

Reported results should include: time series displays of the pressure signatures and vibration accelerations; visual records (sketches, photographs, and video) of blade cavitation; principal particulars of ship and propeller geometry; listing of the model tested operating conditions; results for the full scale dimensional and non-dimensional component pressure amplitudes for all of the tested operating conditions; presentations of the longitudinal and transverse distributions of the pressure amplitudes; and displays of narrow band spectra for pressure and acceleration amplitudes.

7. METHODS FOR REDUCING PROPELLER EXCITATION

7.1 Dependence of Pressure Pulses Levels on Ship Afterbody Shape and Hull/Propeller Clearance

The most important factors influencing cavitating propeller induced pressure pulse amplitudes on a ship hull are the degree of the incoming flow non-uniformity at the propeller disk and the tip clearance between the propeller and the ship hull.

Flow Non-uniformity. Features of the non-uniform flow at propeller radius ratio $r/R > 0.6$ have the greatest effect on the pressure pulse amplitudes.

Growth of pressure pulse amplitudes excited by cavitating propellers operated in non-uniform flow is caused by the fact that the cavity volume varies intensively in unsteady flow around the propeller blade. Comparative results concerning measurements of pressure fluctuation pulses amplitudes in both uniform and non-uniform flows in a cavitation tunnel are presented in a paper by Weitendorf (1973).

Ship stern shape. The shape of the afterbody is of great importance. With the purpose to provide the minimum non-uniformity of the flow within the propeller's disk, the ship hull stern should be designed properly. Some recommendations on this problem are given in the 16th ITTC Report of the Propeller Committee (1981). Experimental results demonstrate that U-shaped hull stern sections lead to a more uniform wake flow and lower amplitudes of pressure pulses from the cavitating propeller compared to V-shaped sections (Lindgren & Johnsson, 1980, and Voevodskaya & Turbal, 1982). As it was shown by Lindgren & Bjärne (1980), both bulbous and open sterns positively influence the velocity field and pressure pulses amplitudes. The wake distribution of two-screw ships is usually more uniform that one of single-propeller ships. There are differing indications on how the direction of propeller rotation influences the pressure amplitudes. Outward turning direction is recommended by Voevodskaya & Turbal, 1982, inward turning direction was found to be better in some other cases (Friesch, 1998).

Clearance. It is obvious that smaller propeller/hull clearance will lead to higher excited pressure pulses on the hull. Comparative model tests show about a two-times local pressure fluctuation reduction when doubling the vertical blade tip clearance (Voevodskaya & Turbal, 1982, Lindgren & Johnsson, 1980). Some quantitative recommendations concerning optimum clearance values for both single-propeller and two-propeller ships were proposed by Voevodskaya & Turbal (1982).

7.2 Ship Stern Design Procedure

Ship hull vibration is a complex problem, cavitating propeller excitation being one of its sources. Some recommendation of how to design the ship stern providing acceptable hull vibration levels were made by Johannessen & Skaar (1980). At first, wake evaluation should be carried out by calculations or/and by model tests in a towing tank. In case of too wide wake variation, the afterbody shape should be redesigned and then tested again. In spite of the fact that increasing both vertical and horizontal clearances is a way to reduce pressure fluctuations amplitudes, alteration of afterbody lines is preferable. The installation of flow improving devices or of alternative propulsors or application of some other less commonly used approaches could be considered if there is no possibility to provide permissible propeller excitation levels by the two above mentioned methods. After evaluating pulsating pressure distribution over the propeller, hull vibration calculations should be performed.

7.3 Flow Improving Devices

For ships with given hull shape, propeller diameter and location, application of special appendages in front of propeller is a way to manage the flow into the propeller disk and to make it more uniform. These devices can serve as energy saving ones since some arrangements may increase the propeller efficiency by several per cent besides reducing propeller excited pressure fluctuations on the ship hull. Some information about flow improving devices was included in the 16th ITTC (1981) Report of the Propeller Committee.

Wake Equalizing Ducts (WED). The first information about WED was mentioned by Schmierschalski (1949). That WED was a nozzle ring, being not exactly circular, in front of the propeller. The ring has a diameter of about half of the propeller diameter and was arranged nearly concentrically to propeller shaft. Nowadays WED consists of two nozzle-shaped half ring ducts which are installed on both sides of the stern ahead of the propeller (Luthra, 1983, Stierman, 1987 and Friesch, 1992). WED diameter is also about half of propeller diameter and the chord length is between 0.5 to 0.8 of the duct diameter.

Fins. A large horizontal fin mounted above the propeller can be used to increase the water velocity in the upper part of the propeller disk region and thus partially reduce the wake peak at the propeller plane. Lindgren & Bjärne (1980) showed that some different fins arrangements fitted on a container ship hull provided improvements to the velocity field into the propeller disk and thus acted to reduce the pressure fluctuations significantly.

Two horizontal fins installed symmetrically ahead of the propeller help straighten the flow and equalize the velocity upper quadrants of the propeller's disk. These devices are often referred to aerofoil fins (Luthra, 1983). These fins with a downward incident angle are positioned ahead of the upper half of the propeller in vertically inclined wake. However, aerofoil fins have more vulnerability to slamming in heavy seas comparing to WED.

Vortex generating fins installed on a ship hull upstream the propeller can energize the boundary layer flow and prevent its separation, thus improving the wake in front of the propeller. Both single- and two-propeller ship models with the fins placed on the hull between stations 14 and 15 were tested in a towing tank at KSRI (Voevodskaya & Turbal, 1982). For the single-propeller ship model, the fins provided the reduced maximum deflection of the axial velocity from the radius averaged value by 30 per cent at the relative propeller radius $r/R = 0.7$ and by 10 per cent at $r/R = 0.9$. A more significant effect was obtained for a twin screw container ship model. The chord length of the wings was about $0.5R$ and its span was $0.3R$ approximately (R is the propeller radius). The wake flow non-uniformity was reduced by about 50 per cent. Additionally the shaft power was reduced by 4 per cent.

7.4 Alternative Propulsors

Ducted propellers. The application of ducted propellers instead of conventional ones may reduce the hull pressure fluctuations (Lindgren & Bjärne, 1980). However, the large pressure variations in the inner part of the duct may result in local vibrations of the duct. The report of the Propeller Committee of the 16th ITTC (1981) gives some probable reasons for the positive influence of the duct on the hull pressure pulses, the more uniform wake field being one of them. Propellers with non-axisymmetrical ducts specially designed for the wake improvement have been used with good results on several ships built in Russia (Turbal, 1973).

Pod Drives. Recently a new type of propulsor, namely AZIPOD is used on ships of different types. It permits rather uniform flow into the propeller disk and therefore provides low amplitudes of propeller induced pressure fluctuations on the ship hull as well as on both the pod and the strut. For example, AZIPOD propulsors designed at KSRI for 'Fantasy' and 'Eagle' passenger ships made it possible to reach the amplitudes of cavitating propeller excited pressure pulses of 1.35 kPa on the hull (Kaprantsev, et al., 1997).

Contrarotating propellers. The pressure fluctuation level was reduced somewhat by application of contrarotating propellers instead of the conventional one on a ship (Takekuma, et al., 1990). The vibration level and noise level in the engine room were also reduced.

Propeller with Vane Wheel. A distinct reduction of pressure fluctuations on the hull was observed in full scale and in model tests by use of a vane wheel (Friesch, 1992). In particular, the pressure fluctuations amplitudes both at the propeller blade rate and the twice blade rate were reduced by about 50 per cent by application of the vane wheel on a ship (Blaurock, 1989). An explanation for this effect may be that the cavitating propeller is being unloaded significantly by the vane wheel. Thus the propeller cavitation is less pronounced, which results in a reduction of the pressure amplitudes.

7.5 Application of Air to Reduce Propeller Induced Pressure Fluctuations

In the past, there have been many attempts to use air or gas supplied to the ship hull or to the propeller. The aim was to improve the acoustic or erosion characteristics of the propeller as well as the reduction of the ship hull resistance. Existing methods to reduce hull pulsating pressures by using air will be reviewed below.

Air bubbles layer. Air can be supplied from compressor through a system of nozzles on the ship hull upstream of the propeller. This results in a air bubble layer formed between the ship hull skin and the propeller, reducing propeller induced pressure fluctuations on the hull. Tests of ship stern model with operating propeller and with air nozzles were carried out in cavitation tunnel at KSRI. The unpublished results demonstrated the reduction of cavitating propeller induced pressure pulses at propeller blade rate. This method can be applied for almost any ship hull stern but the air flow rate to create the air bubble layer is rather high. Besides, the reduction becomes lower when increasing the disturbance frequency, i.e. the air bubbles layer reduces pressure fluctuations at higher blade rates less efficiently.

Honeycomb. A method to reduce pressure fluctuations by a honeycomb containing air located in cells over the propeller was studied theoretically and experimentally by Huse & Nielsen (1978). Pressure pulse reduction depends on cell dimensions, thickness of air layer and disturbance frequency (propeller blade rate and higher harmonics). Tests in a towing tank with a 7 m long ship model equipped with a honeycomb region 195 mm x 182 mm consisting of cells with 3.5 mm side lengths and with pressure wave generator simulating the propeller, demonstrated a reduction of pressure pulses amplitudes. With this arrangement higher reduction corresponds to thicker air layer in the cells.

Pressure release tanks. Pressure release tanks containing air in its upper part could be used at the ship stern to reduce propeller induced pressure fluctuations and the ship hull vibrations. This method is rather similar to the previous approach based on honeycomb application. Eight localized pressure release tanks each 61 cm in diameter and about 1.5 m height were installed onboard the Great Lakes bulk carrier MV ‘American Mariner’ (Reed & Bassett, 1989). Full scale measurements demonstrated significant pressure pulse reduction at the tank locations. However, pressure release tanks reduce pressure fluctuations only at the area of tanks and do not influence the pressure at the other parts of the ship hull skin.

Anti-vibration cave. Anti-vibration caves, consisting of watertight recesses sealed by elastometric membranes, were sited over each propeller to absorb the propeller-induced pressure pulse impacting on the underside of the hull of the 'Europatrol 250 Mk 1' ship, as reported in The Naval Architect (1995). Apparently these caves have a marked effect on noise levels and vibration throughout the speed range. This method can be applied for ships with arbitrary stern shape.The rate of air supplied to the cave is very small (practically zero) since the cave is bounded by the membrane below and by the ship hull skin above.

Air cavity on the ship hull. A method to reduce propeller induced pressure pulses by air cavity was recently studied at KSRI specially for the 22nd ITTC and was presented in a paper by Sadovnikov, et al. (1998).

With this scheme, an air cavity is formed covering a patch of the ship hull over the propeller. Air supplied by a compressor fills in a separation zone formed behind a cavitator, which is a small obstacle protruding into the flow (Figure 6). The cavitator initiating the cavity can be of two types: an inclined plate or a step. The air cavity reduces levels of propeller-induced pressure fluctuations by isolating a part of the ship hull skin from the surrounding water. Required compressor power is significantly less than 1 per cent of the ship main engine power.

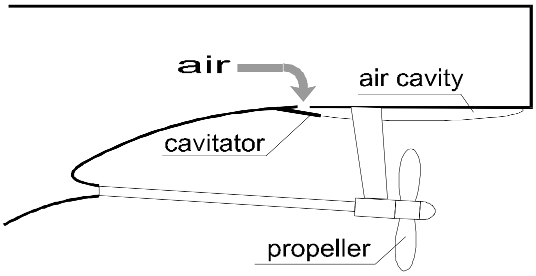

Figure 6. Scheme of the air cavity.

The air cavity is a homogeneous zone filled out with air, unlike the air bubble layer consisting of separated bubbles in the water. The cavity would damp pressure pulses efficiently from both non-cavitating and cavitating propellers if the resonant frequency of the cavity were lower than the frequency of fluctuations, i.e. propeller blade rate and higher harmonics. Theoretical evaluation shows that resonance frequency of the air cavity is lower than propeller blade rate in full scale but could be about the same in model scale.

A series of experiments was carried out in the Large Cavitation Tunnel (LCT) at KSRI. A representative model of a ship afterbody fitted with a 5-bladed propeller was installed in the working section of the LCT and tested in the range of flow speeds of 2.0 to 6.0 m/s. The air cavity was formed behind a triangular shaped wedge with openings for air supply distributed along the length of the wedge. Measurements of the propeller-induced hull pressures above the propeller were made with the propeller operating under both noncavitating and cavitating conditions. Results for the cavitating propeller showed that hull pressure amplitudes with the air cavity present were reduced compared with the no air cavity case for both the blade rate and twice blade rate harmonics.

A second experiment with the air cavity arrangement was carried out with a 6 m long twin crew ship model in a towing tank at KSRI, at speeds of 2.0 to 3.3 m/s. Air from a compressor was supplied to the region behind an inclined plate cavitator at several air flow rates and model speeds. Measurements of the hull pressure pulses over the propeller showed that the air cavity could provide reductions of unsteady pressure amplitudes. It was concluded that the air cavity scheme could be applied to some types of twin screw ships with near-horizontal stern shapes over the propellers and with V-strut shaft support arrangements.

Air supply to the propeller tip vortex. English (1998) carried out full scale trials of a ship with a vertical pipe supplying air past and slightly over the propeller. Injecting air led to a substantial reduction in vibration of the subject ship.

7.6 Vibration Neutralizers and Absorbers

Some non-hydrodynamic methods of reducing hull vibration by various ‘neutralizer’ and ‘absorber’ schemes have been reviewed by Hsueh (1998). Neutralizer devices function to transfer vibration energy of the ship hull to a mass-spring type of system with either a fixed or adjustable natural frequency.

Absorber devices generate an auxiliary force acting in opposite phase to the excitation either at a single frequency or possibly at several frequencies in order to reduce the net vibration response.

7.7 Propeller Design

Blade section. Wang et al. (1995) presented a new approach to the design of propeller and blade section, which combines the Eppler blade section design process with a lifting surface propeller design procedure. The effect of camber distribution, thickness distribution and pressure on the cavitation characteristics of the blade section and on the hull surface pressure fluctuations have been assessed. The following parameters have been considered: maximum camber location x_f, maximum thickness location x_t , pressure recovery location x_1. An application of the design methodology to a family of comparable propellers showed that both x_f and x_t have a significant effect on the amplitudes of the first harmonic, which are reduced as such parameters are shifted towards the trailing edge.

Praefke (1997) presented a propeller design procedure incorporating the design of new blade profile sections with the aim of optimizing the cavitation behavior and lowering the propeller induced vibration excitation. The procedure makes use of Eppler's method to obtain a profile contour for a given pressure distribution. Three different propeller designs have been evaluated by means of unsteady lifting surface theory. The propeller with the new camber line exhibited much less cavitation than the one with NACA a=0.8 camber line. The predicted propeller induced hull pressure fluctuations showed a reduction of 40% for the first blade rate harmonic. The predicted reduction has been confirmed by model test measurements.

Skew. Most of the literature agrees that skew has a favorable effect on cavitation inception, widens the region of cavitation free operation, and reduces the amplitudes of the hull pressure fluctuations. The major form of cavitation on highly skewed propellers is vortex-like spreading out along the span which often appears more sporadically compared to conventional propellers with less skew. This may influence the vibration and noise behavior at higher frequencies. For example Yamasaki et al. (1994) reported that large higher harmonics were encountered on a highly skewed propeller of a container ship with 2nd, 3rd, 4th and 5th harmonics larger than the 1st harmonic.

7.8 Propeller Material

A passive blade control (PBC) concept has been investigated by Dai et al. (1995). The basic idea is to delay the inception of tip vortex cavitation by making use of the elastic coupling properties of composite material systems in manipulating tip shape when the foil/propeller is subjected to off-design condition. The effectiveness of the concept was assessed initially via numerical simulation of a flexible foil characterized by an elliptical plan form, aspect ratio 2.55 NACA-66 thickness distribution and NACA a=0.8 camber distribution. According to the calculations, the rigid foil generates a much stronger tip vortex as compared with the twisted foil. Experimental results reported by Gowing, et al. (1998) have verified that special laminate construction technology can be used to fabricate lifting surfaces that are capable of deforming so as to produce a reduced angle of attack locally at the tip of a hydrofoil, in response to increased loads near the foil root. These deflections have been shown to delay cavitation inception index by up to 1/3 of the value for a stiff foil, but with the overall lift and drag characteristics remaining unchanged.

8. OUTLINE OF PROBLEMS AND SPECIAL DIFFICULTIES INCLUDING ROUND ROBIN TEST RESULTS

8.1 Introduction

Many experimental and theoretical studies on the hull pressure fluctuations due to propeller cavitation have been conducted, because this is one of principal sources of ship vibration and noise. Hence, the 19th and 20th ITTC Cavitation Committee (ITTC, 1990, 1993) reported the correlation of the pressure fluctuations between the results from model experiments and full-scale measurements. Also, the committee compared several sets of the measured data for the “Sydney Express” and the “St. Michaelis” propellers, so as to investigate measurement problems in a cavitation tunnel.

However, it was concluded that the agreement of pressure fluctuations between the model and the full scale results was not acceptable and that there existed scatter in the hull pressure measurements among different facilities.

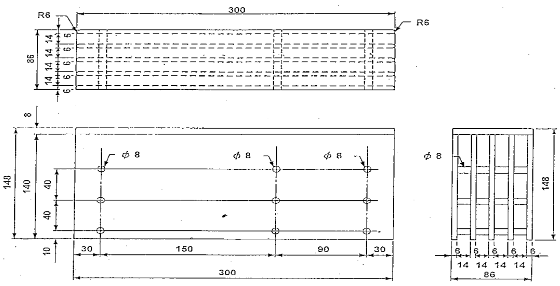

Figure 7. Schematics of wake generator with flat plates.

The 21st ITTC (ITTC, 1996) considered that one of the sources of the scatter might be the wake field simulated in each of the facilities, and carried out the comparative measurements of pressure fluctuations using a wake generator and the model propeller for the training ship “Seiun Maru”. The wake generator, as shown in Figure 7, consisted of flat plates to simplify wake field and to enhance the reproducibility (see 21st ITTC for the details of test arrangements and wake distributions). Figure 8 shows the location of pressure transducers used to measure the fluctuating signal on the flat plate above the propeller. The distance was constant at 63.5mm, so the tip clearance ratio with propeller diameter was 0.254 for all the results shown here.

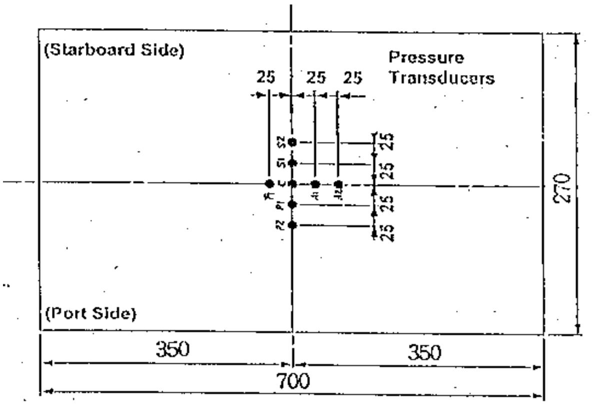

Figure 8. Location of pressure transducers on the flat plate above the propeller.

These comparative measurements involved five organizations in Japan: Mitsubishi Heavy Industries (MHI), Mitsui Engineering and Ship Building (MES), Ship Research Center (SRC), Ishikawajimaharima Heavy Industries (IHI) and Ship Research Institute (SRI). The principal particulars and operating condition of the propeller are shown in Table 2.

In spite of the similarities in the wake fields and the cavity patterns, however, the measurement results of the fluctuating pressure are scattered a lot (ITTC, 1996).

Table 2. Principal particulars and operating conditions of “Seiun Maru” propeller.

Diameter of Model [mm]	250.0
Pitch Ratio at 0.7R	0.944
Expanded Area Ratio	0.700
Boss Ratio	0.1972
Number of Blades	5
Skew Angle [Deg.]	45.0
Rake Angle [Deg.]	-3.03
Blade Section	Mod. SRI-B
Operating Condition	
Kt = $T / \rho n^2 D^4$	0.25
$(P_\infty - P_v) / \frac{1}{2} \rho n^2 D^2$	1.5

Hyundai Maritime Research Institute (HMRI) carried out the same comparative tests with its two different size test sections. HMRI also simulated the wake field by the wake generator and with a wire-mesh screen. In this report, the test results of six different organizations are compared, and an experimental study in order to clarify the source of this scatter is described.

8.2 Round Robin Tests

The test section sizes and shapes of the cavitation tunnels of six organizations are summarized in Table 3.

Figure 9 and 10 show the pressure fluctuations collected from this round robin test. Although the shape of axial and transverse distributions of pressure fluctuation on the flat plate agree well with each other, there is a large deviation of overall pressure amplitudes, especially at the low propeller revolution conditions. However, this deviation becomes smaller at the higher revolution conditions.

Table 3. Test sections of cavitation tunnel.

Organization	Test section size (Shape)
MHI	710 x 710 mm (Square)
MES	600 x 600 mm (Square)
SRC	600 x 600 mm (Square)
IHI	600 x 600 mm (Square)
SRI	750 mm (Circular)
HMRI	600 x 600 mm (Square)

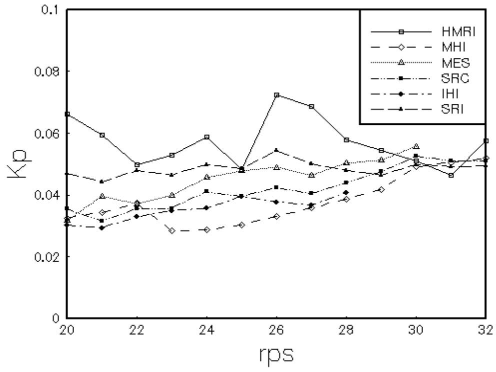

Figure 9. Propeller rotating speed effect on pressure fluctuation at plate center.

$(K_P = \Delta P / \rho n^2 D^2)$

Further, as shown in Figure 9, the variation of pressure fluctuation amplitudes versus the propeller revolution rate has peaks and valleys and tends to increase as the revolution rate is increased. HMRI results, especially, shows abrupt increase of the pressure amplitudes around the propeller rotation speed of 26 RPS. It was observed that the cavity pattern became very unstable and violent around this range of propeller rotation speed.

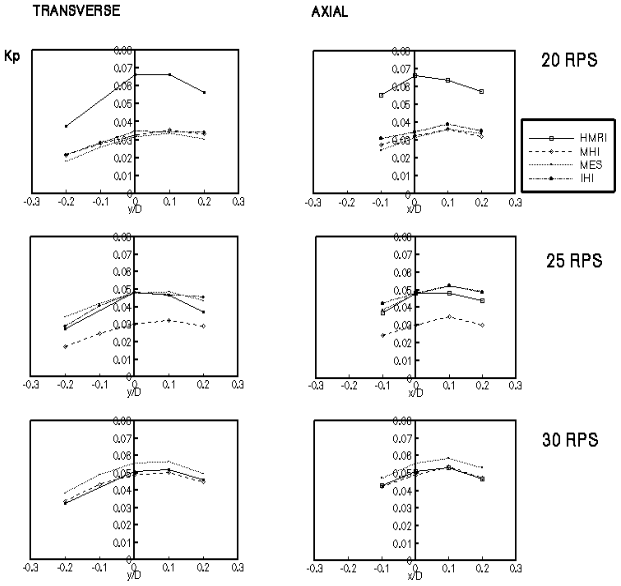

Figure 10. Transverse distributions of pressure fluctuation at the different RPM.

8.3 Effect of Test Section Size and Wake Simulation Method on the Fluctuating Pressure Measurements

HMRI experimentally studied on the effect of test-section size and wake simulation method on the pressure fluctuation, as shown in Table 4.

Table 4. Kinds of tests conducted in HMRI.

	Test Section	Wake Simulation Method
CASE 1	No. 1 (600 x 600 mm)	Wake Generator
CASE 2		Mesh Screen
CASE 3	No. 2 (850 x 850 mm)	Wake Generator
CASE 4		Mesh Screen

Figure 11 shows the wake pattern behind the wake generator at different inflow velocities in the two test sections. Also, in Figure 12, the wake simulated by the wire-mesh screen is shown. It is considered that the wake patterns for the wake generator and for the mesh screen are satisfactorily similar. Also differences in the tunnel inflow velocity do not significantly affect the wake pattern at the propeller plane.

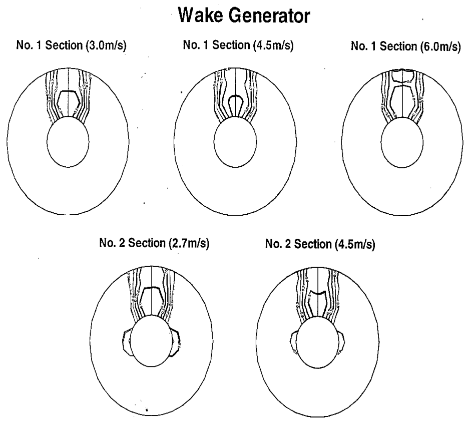

Figure 11. Wake patterns by wake generator.

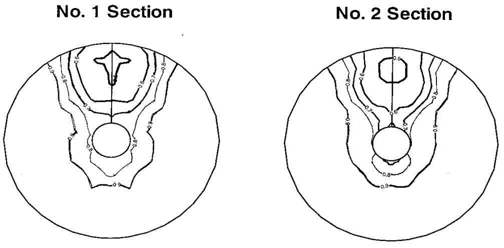

Figure 12. Wake patterns by wire-mesh screen (Vi=4.5m/s, Circle : propeller disk).

The cavitation patterns on the propeller blade, observed in HMRI, are shown in Figures 13 and 14. In general, the change of the cavitation area in different test sections is not significant. However, it is observed that the characteristics of cavitation patterns are much affected by the wake generation method.

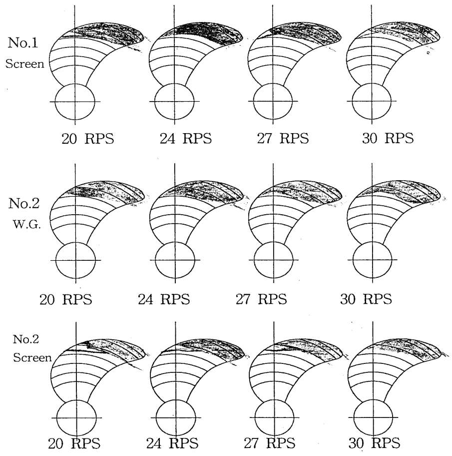

Figure 13. Cavitation patterns at three propeller Position in each test section.

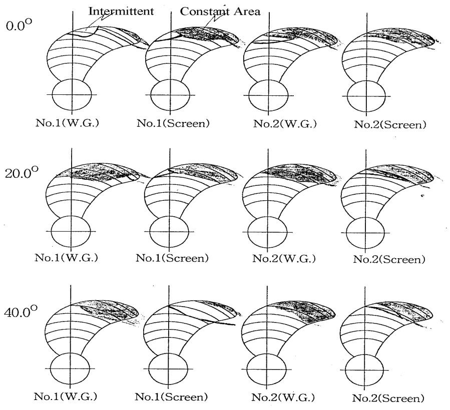

Figure 14. Change of cavitation patterns due to propeller revolution rate.

In general, the cavitation patterns on the blade behind the wake generator are observed to be very unstable and violent. Moreover, the volume of the cavitation is larger than that obtained with the wire-mesh screen. Also, the cavitation extent area is observed to be smaller in the smaller test section than in the larger section. These phenomena involve the interaction between the wake generator and the propeller and the wall effect.

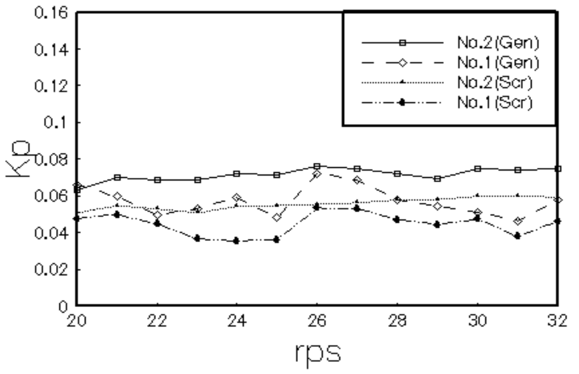

Figure 15. Variation of pressure amplitude at the plate center against propeller rotation speed.

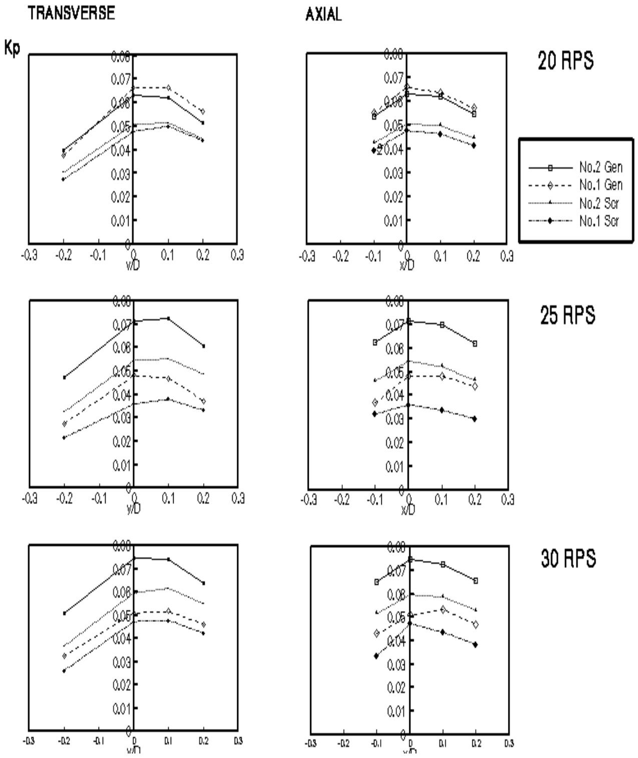

Figure 16. Axial and transverse distributions of the pressure fluctuations.

For the HMRI data the corresponding amplitudes of pressure fluctuations at the center of the plate are compared in Figure 15. The axial and transverse distributions of the pressure fluctuations are shown in Figure 16.

In the larger test section, the variation of the pressure fluctuation versus the propeller revolution rate is smoother than that in the smaller test section. The wake generator gives higher values of the pressure amplitudes than the wire-mesh screen throughout the propeller revolution range.

8.4 Conclusions and Recommendations

The experimental results collected in the present comparative experiments for the “Seiun Maru” propeller are still scattered and unsatisfactory, especially at the low propeller revolution rate, in spite of the similarities in the wake pattern and the cavitation area.

HMRI results clearly show that, when the flat plate set-up for hull boundary is used, the size of the test section and the method of wake simulation have a significant influence on the characteristics of cavitation patterns and the fluctuating pressure amplitudes due to the propeller cavitation. Especially, it seems that there exist strong interaction of the flow field between the wake generator and the propeller.

At this stage, it is recommended that the fluctuating pressure should be measured at the highest propeller rotating speed possible when the flat plate system is used. In addition, the characteristics of the cavitation tunnel such as the resonant frequency, the acoustic behavior, the set-up of the measuring device and the method of the wake simulation should be carefully examined in order to get consistent measurement results.

In this regard, it is further required to carry out systematic efforts to investigate the sources of these discrepancies in detail.

GENERAL TECHNICAL CONCLUSIONS

Measurement of unsteady hull pressures on full scale and model must be accompanied by propeller cavitation viewing and hull surface vibration measurements.

Results of propeller-excited hull pressure fluctuations are strongly influenced by intermittence of sheet cavitation and the dynamics of tip vortex cavitation.

Planning and execution of both full scale and model scale testing must include the capability of covering higher blade rate harmonics and broadband noise.

Propeller design procedures should be capable of handling problems with higher harmonic frequency excitation in addition to minimizing blade rate pressure fluctuations.

For improvement of excessive vibration problems on an existing ship, there are many possibilities involving schemes for modified geometries of either the hull or the propeller, or both.

Both experimental and numerical prediction procedures for propeller excitation need to be validated using results of sophisticated full scale investigations.

In model scale testing, the levels of unsteady pressure amplitudes can be seriously affected by the size of the facility test section, the method of wake simulation, and operation at very low Reynolds number. For a small facility it is especially necessary to test over a range of propeller RPM to check for undesirable facility-related variability of dimension-less pressure coefficient.

RECOMMENDATIONS TO THE CONFERENCE ON PROCEDURES

For full scale measurements of propeller-induced unsteady pressures, it is recommended that the Conference adopt *Section 5.2 Procedure for Full Scale Measurement*, outlined as follows:

- Requirement for propeller cavitation viewing along with hull pressure measurements.
- Guide for trial set-up, including the arrangement of pressure transducers and accelerometer locations.
- Monitor ship operating conditions and environmental parameters.
- Collection and analysis of data for hull pressures and accelerations.
- Presentation of data as time series, blade rate harmonic amplitudes, and the axial and lateral distributions of pressure amplitudes.

For model scale experiments on propeller-induced unsteady pressures, it is recommended that the Conference adopt *Section 6.2 Procedure for Model Scale Experiments,* outlined as follows:

- Include viewing of model propeller cavitation with the measurement of unsteady pressures.
- Guide for test set-up.
- Provide complete specification of operating conditions, facility flow parameters, and method of wake scaling (if any).
- Collection and analysis of hull pressure and acceleration data.
- Presentation of data in form of time series, results of blade rate harmonic decomposition, and the axial and lateral distributions of scaled pressure amplitudes.

RECOMMENDATIONS FOR FUTURE WORK

- Evaluate whether there are practical and reliable prediction methods for propeller cavitation volume time-variation and resulting unsteady hull pressures.
- Study the connection between improved cavitation inception and minimized cavitation extent (which often leads to improved overall propeller excitation) and possible increase of cavitation intermittence and elevated levels of higher harmonics and broadband noise excitation.
- Review how tip vortex flows and tip vortex

cavitation influence unsteady hull pressure excitation. Monitor all work on both numerical modeling and advance experimental observations of tip vortex flow phenomena and related cavitation development.
- Carry out an in-depth study of flow mechanisms and related physical descriptors or parameters that affect cavitation intermittence and cavitation instability. Include, for example, the effect of off-design operating conditions.
- Monitor new methods for reduction of propeller-induced unsteady hull pressures.
- Review the consequences of wake scaling and character of wake turbulence on propeller-induced unsteady pressures.

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The Specialist Committee on Cavitation Induced Pressure Fluctuations

Committee Chair: Dr. Michael B. Wilson (DTMB/NSWCCD)
Session Chair: Prof. Hiroharu Kato (Univ. of Tokyo)

The Specialist Committee on Cavitation Induced Pressure Fluctuations would like to enter the following table into the 22nd ITTC Proceedings as an addendum to Section 6 of the Committee Report.

Table: Recommended Measurements for Model Scale Pressure Fluctuation Testing

	Absolutely Necessary	**Worthwhile to Have**	Others
Ship Hull & Flow Data	• Type of hull form (section shape, etc.) • Draft • Aperture clearances • Height of shaft above baseline • Arrangement of any model-mounted view ports • Appendage arrangements	• 3D model wake velocity component distributions	• Model hull material
Propeller Data	• Type of propeller • Main particulars (D,Z. P, skew, A_E/A_0, etc.) • Propeller model material	• Propeller design conditions • Blade geometry Inspection	
Facility Data	• Water temperature • Range of total static pressure • Air content as % saturation or % oxygen saturation • Viewing and photo arrangements	• Water quality (nuclei size and number distributions)	• Pressure drop through test section • Turbulence
Test Conditions	• Pressure • Propeller RPM • Propeller thrust and torque • Pitch • Speed	• Test section flow speed and/or axial velocity next to model	
Instrumentation	• Type and capacity of pressure transducer • Type of amplifiers • Shaft encoder • Data stream schematic & storage medium • Type and capacity of stroboscopic lighting	• Accelerations measured next to pressure transducers • Type and capacity of hydrophones • Narrow band spectra of pressures and accelerations	
Evaluation of Test Data	• Measurement time • Number of points per revolution • Number of revolutions taken for harmonic analysis	• Time series	

I Discussions

Contribution to the Specialist Committee on Cavitation Induced Pressure Fluctuations

by Friedrich Mewis (HSVA)

The Committee report discusses pressure pulse measurements both for model scale and full scale with pressure transducers located only in a region of the ship's hull above the propeller.

My feeling is that the pressure pulses hit the rudder horn and that the rudder itself positioned in the slipstream of the propeller could experience very much higher unsteady pressures than the hull surface above the propeller. What is the reason that you have not mentioned this possibility in your report ? Or is my feeling wrong ?

by Tom van Terwisga (MARIN)

Intermittence of sheet cavitation is mentioned by the Committee as a cause for "artificial effects" in the distribution of pressure fluctuations over the blade rate harmonics.

Does the Committee know the reason for this intermittence (irregular) phenomenon ?

In case the intermittence would be caused by too low a Reynolds number, does the Committee expect to provide guidelines for minimal Reynolds number testing ?

by Tetsuji Hoshino, Nagasaki Experimental Tank, Nagasaki R&D Center, MHI, Japan

I would like to express my sincere appreciation to the members of the Cavitation Induced Pressure Fluctuations Committee for their effort to continue the round robin tests for the comparative pressure fluctuation measurements.

Figure 9 shows the variation of pressure fluctuation amplitudes versus the propeller revolution rate. Most of the results show the same tendency that the pressure amplitude gradually increases as the propeller rotating speed increases. Gradual increase of the pressure fluctuation would be due to the more stable cavitation in the higher rotating speed. On the other hand, the results of HMRI shows the peak around the propeller rotating speed of 26~27rps. This peak would be due to the resonance of the measuring flat plate with the propeller induced vibratory forces. I consider that this effect of resonance on the results of the pressure fluctuation measurement in HMRI should be checked more precisely.

by Stephare Cordier, Bassin d'Essais des Carenes, Val de Reuil, France

Title : Clarification of proposed procedure

The development of a test procedure for pressure pulse measurements is a difficult task and the Committee is to be congratulate for their work. This overview of the problems arising in the measurement of pressure pulses cats for some comments and request for clarification:

1) Vibration measurements are recommended could the Committee indicate the purpose of this measurement and how it should be used? Criteria for acceptance of the test, correction of the measurements, characterization of the structural response etc. It should be emphasized that pressure pulse themselves are not the issue is ship design, but it is the structural response which can be problematic. Hence the structural behaviors cannot be dissociated from the pressure purse excitation; for instance, it is very possible to have vibration problems with low pressure pulse peeves because of poor structural design.

2) II 6.3 discusses the model test parameters which should be respected to try to achieve similarity with full scale. This discussion sees not give clear guidance in selecting these parameters and their valves.

The particular, the reference velocity to be used for (V_a or n_D) is not identified. Furthermore it is not clearly indicated that thrust and (02) torture measurements must be performed in order to achieve K_t (02 K_Q) similarity. The Committee rightly pointed at the difficulties in abstaining a wake sinter to that at full scale for these tests. In this context it is felt that it is essential that me be taken as a reverenced vctocity for t and that the operating be set by K_t (02 K_Q) identity and not a valve of'S.

3) In the discussion of test parameters, the importance of tunnel velocity (on late of rotation) is not mentioned. Although it is impossible to dissociate Reynolds number effect from speed effects without performing test on gesture propellers (different speeds at the same Re), one has to recognize that cavitation and its dynamics are controlled by the pressure distribution (on P_a) on the blade surface Indeed studies performed or the effect of much emphasize the relationship between muctei diriensions and the absolute pressure level at attach they cavitate as they travel over the blade (pp 57-59 of 22nd ITTC report) accordingly, and despite the fact that it is difficult to identify speed effects from Re effects, speed has to be recognized as a parameter with full scale cavitation is to be achieved, respecting Mach number scaling (i.e. same flow velocity. At model and full scale) pressure distribution, and on particular the pressure gradients (in P_a) is the same as on the leaf ship.

In the procedure which has been developed at the Bassin d'Essais des carenes and validated with full scale measurement, the flow velocity is to be as close as possible to full scope speed-In these conditions. The cavitation patterns do not exhibit any intermittarcy and reliable measurements of pressure pulse can be made. Furthermore the use of Mach number similarity has the advantage that the pressure pulses measured need little extrapolation (just the density ratio).

Tests performed at lower speed with high dis solved gas content may be better from the standpoint of intermittarcy, however, they introduce significant differences in the dynamics of the cavitation and uncertainty in the pressure pulse measurements. Therefore it is our opinion that this technique should not be recommended.

Finally, it is clear that the use of Mach number similarity some consequences on the design of the test facility. Hence, although each institute has the responsibility to provide the best estimates with the tools they have, it should be recognized that it is not possible to get the same quality of data with facilities which do not have the same performance and which require different levels of investment.

4) As a general comment to the report of this Committee, it appears that many important information required to perform the pressure pulse tests are missing; for examples;

- Tolerance of propeller model accuracy.
- Turbulent flow: guidelines to ensure that transition is achieved.
- Pressure measurement instrumentation.
- Shaft speed encoder characteristics.
- Date analysis (ensemble averaging, shaft encoder time base, treatment of intermittance, etc).

In conclusion, and considering that this Committee will continue on the 23nd ITTC, we would strongly encourage this Committee to compile current practice and rational for their practice from member organizations priors to practicing their procedure.

II Committee Replies

Reply of ITTC Specialist Committee on Cavitation Induced Pressure Fluctuations to Friedrich Mewis

We agree with Mr. Mewis that taking into account the increase in power and ship speed especially for twin screw ships, the importance of excitation not only on the hull above the propeller but also on the rudder is important. The outline of a test procedure becomes difficult, because in many cases, the model rudders are so small, that the application of pressure transducers is not possible. If measurements can be performed, the question how to correlate such data to full-scale is not yet answered, because there are so few cases of full-scale data available. Therefore, also a guideline concerning acceptable values is missing.

Reply of ITTC Specialist Committee on Cavitation Induced Pressure Fluctuations to Tom van Terwisga

Reasons for the occurrence of fluctuating sheet cavitation on a model propeller can be too low rotational speeds (which means too low Reynolds numbers) and a lack of nuclei. If remarkable instability is observed, it should be checked if this is mainly because of scale effects or if it could be considered that it will be correctly translated to full scale. If such an instability is expected for the full-scale propeller, a cure should be sought, because this may lead to erosion or unwanted higher order pressure fluctuations. If scale effects seem to be responsible for the occurrence of such an instability, efforts should be undertaken to improve the behaviour in model scale. This could be done by increasing the free air content or by stimulating cavitation for example by roughening the blades.

Reply of ITTC Specialist Committee on Cavitation Induced Pressure Fluctuations to Dr. Hoshino

Thanks for Dr. Hoshino’s comments on the round robin test results.

HMRI also suspected that the unusual peaks around the propeller rotating speed of 26-27 rps in the Figure 9 might be due to the resonance of the measuring flat plate with the exciting forces. the natural frequencies of the flat plate are 77.5 Hz in air and 88.5 Hz in calm water, which are considerably lower than the tested propeller rotating speeds. The test results of the pressure fluctuation amplitudes in the larger measuring section (No. 2) did not show any unusual peaks and showed gradually increasing amplitudes.

As Dr. Hoshino pointed out, HMRI also thinks that the peaks in the smaller measuring section are mainly due to the resonance of the measuring flat plate with the propeller induced vibratory forces. HMRI is planning to clarify precisely the cause of these amplitude peaks in near future.

Reply of ITTC Specialist Committee on Cavitation Induced Pressure Fluctuations to S. Cordier

This reply addresses the four parts of Dr. Cordier's discussion.

(1.) The Committee believes that making measurements of local vibrations in connection with unsteady hull surface pressures is a good way to build experience as well as provide a minimal data base for possible later improved analysis. Presently, the use of this data seems to be limited to qualitative checks on the relative intensity of the acceleration levels among the locations tested and crude estimates of vibration-induced pressure. From our review of published work in this subject area, we have concluded that there is no agreed-upon approach for the proper analysis of such data.

It has been suggested that for full scale and for model testing that an accelerometer be placed close to every installed pressure gauge and that measurements of both pressure and acceleration be taken simultaneously. One idea is that when the local vibration amplitudes at certain locations reach excessive levels, the pressure data from that location may have to be disregarded or at least considered less reliable. Of course the problem is what criterion should be applied to make a judgment on what is 'excessive.'

The pressure correction approach suggested by Kurobe and Yoshida (1985) may be applied to a small, finite span of vibrating plating to estimate vibration-induced local pressure. This idea has been used by Wilson (1995) for an approximate check on the magnitude of interference pressures caused by vibration of a circular mounting plate for pressure gauges near a model propeller.

Van Gent (1990) has analyzed full scale hull pressure and local vibration data taken with co-located pressure gauges and accelerometers, with the aim of deriving the actual incident pressure characteristics from the measured data. He showed that local acceleration-correction techniques of the unsteady pressure measurements do *not* produce consistent pressure amplitude predictions for the desired incident pressure level. When another analysis approach was applied that accounted for the global effect of hull vibrations, a different type of troublesome inconsistency was found. Our interpretation of the current state of the art is that there are important unsettled issues which stand in the way of straight forward application of local vibration measurements for both scaling and evaluation purposes. However this a very important topic area for the work of the next specialist Committee.

(2.) The intent of the Committee's procedure was to provide a generic working outline which is broadly applicable to a variety of facility types and organizational testing practices. Therefore we felt that it was not appropriate to make detailed and very specific recommendations for the ranges of parameter values. Once the principal concepts are in place, as described in the Committee report, the operating conditions derived from the important ship speed cases, the powering test results, and the scale ratio of the model are sufficient to determine the model test conditions.

There is no need to specify a choice for reference velocity between advance velocity V_A or rotational speed nD since they are both linked to the basic kinematic similarity parameter --- the advance coefficient J determined by powering tests and using open water propulsion characteristics.

It is standard and recommended procedure that model thrust and torque measurements be made during an unsteady pressure evaluation test. This is noted in the enclosed table "Recommended Measurements for Model Scale Pressure Fluctuation Testing." Although in our discussion we have mentioned the possibility of setting the model test conditions using the torque identity in some circumstances, we definitely favor the idea of matching the thrust coefficient (thrust identity) because that achieves the identical thrust loading coefficient for model and full scale. In a water tunnel or free surface channel facility where there are wall boundary effects on the facility velocity, it is most desirable to set the model propeller operating conditions on the basis of the advance velocity as noted by the discussion write-up.

(3.) It is agreed that a truly complete list of similarity parameters relevant to the fluid mechanics of cavitating propeller-induced unsteady hull pressure excitation should include, for example, the absolute value of flow velocity (or in some sense the 'Mach number' defined as the free stream velocity in a ratio with respect to a reference velocity). We feel that the Committee was directed to cover the main practical problems of fluctuating pressure testing in the wide variety of sizes and types of facilities of the ITTC member organizations, and to provide a reasonable prescription for this category of evaluation experiments. This does not necessarily cover an exhaustive study of all scientific issues.

Dr. Cordier asserts that to achieve proper cavitation dynamic similarity at model scale, the full scale flow velocity should be used. The Committee thinks that there is no convincing evidence to show that a 'Mach number ' effect exists to a degree that would justify the choice of a model test speed of this magnitude. Of course, there are compressibility effects that enter into cavity collapse dynamics and the resulting radiated hydroacoustic pressure pulse associated with the collapse. However this influence occurs at much higher frequencies than are of concern here. Also we believe that any Mach number effect is less important than the phase angle shift due to the finite pressure wave velocity in water causing a relative difference (model to full scale) in the arrival time of a pressure pulse at a point on the hull. This also can be shown to have only a slightly noticeable influence at high blade rate frequencies (above 3*BRf) where many other inaccuracies come into play anyway.

There are important *practical* problems with the choice of a large value of model test speed that involve the size and power of the model drive motor and the capability of thrust and torque dynamometry. Some numbers from a realistic example can be helpful here. Consider the case of a model simulation of a 28 knot full scale ship with a 6.71 m diameter propeller. With a scale ratio of 25, the model propeller would have a diameter of 268 mm. From model powering experiments the wake fraction factor $(1 - w_T) = 0.886$, and with the choice of a model scale advance velocity $V_A = 7.62$ m/s the test conditions would require a model propeller rotational speed = 2340 RPM, model thrust = 1.43 kN, model torque = 65 N-m, and model drive motor power = 15.9 kW. If instead, the model advance speed is chosen to be the same as full scale $V_A = 12.8$ m/s, the test conditions would require a model rotational speed = 3920 RPM, model thrust of 4.01 kN, model torque = 182 N-m, and model drive motor power = 74.7 kW. For the latter case, the range of model thrust, torque, and RPM may exceed the capability of typical available dynamometry equipment of most water tunnel test facilities. The more difficult problem would be to provide a sufficiently powerful but small enough sized motor to be able to be fitted inside a surface ship model of either a full proportional length or partial length type. Providing a practical arrangement for a twin screw surface ship model would be still more difficult.

The Committee agrees that it would probably be advantageous to be able to test at full scale ship speeds, but we disagree that this should be the recommended approach for model testing in the Committee's outlined procedure. This should not be substituted for the practical prescription of testing at lower speeds and with appropriately high nuclei content. It should be noted that there is ample evidence from years of testing experience in several types of facilities that the outlined procedure can provide many examples of rather good correlation between model and full scale unsteady hull pressure results using the standard scaling laws provided.

(4.) Certainly there are areas of testing technique and practice that should and will receive attention by the continuing Specialist Committee of the 23rd ITTC. It is not clear just how much intricate detail on specific instrumentation and analysis should be spelled out by an ITTC procedure, when the assigned objective appears to be to outline the principle ideas and provide the key references from the published literature. We thank Stephane Cordier for outlining his points of concern.