The Cavitation Committee

Final Report and Recommendations to the 20th ITTC

1 MEMBERSHIP AND MEETINGS

The membership of the Cavitation Committee was:

- CPT. L. Accardo, Centro Esperienze Idrodyamiche, Ministrerio Difesa Marina, Rome, Italy. (Replaced by CDR. G. M. Bailo).
- Prof. G. Bark, SSPA Maritime Consulting AB and Chalmers University of Technology, Göteborg, Sweden.
- Dr. M. Billet (Secretary), Applied Research Laboratory, Penn State University, State College, Pennsylvania, U.S.A.
- Dr. B. Biskoup, Krylov Shipbuilding Research Institute, St. Petersburg, Russia.
- Prof. G. Kuiper (Chairman), MARIN, Wageningen and Delft University of Technology, The Netherlands.
- Dr. Jin-Tae Lee, Korean Research Institute of Ships and Ocean Engineering, Deaduk Science Town, Korea.
- Mr. Jaime Masip, Canal de Experiencias Hidrodinamicas, El Pardo, Madrid, Spain (Resigned).
- Dr. Y. Ukon, Ship Research Institute, Tokyo, Japan.
- Dr. M. Wilson, David Taylor Model Basin, Bethesda, Maryland, U.S.A.

Due to a change in his responsibilities in 1991, Mr. Masip was unable to continue his membership in the Cavitation Committee. CPT Accardo had his responsibilities changed, almost from the start, and was replaced by CDR Bailo from the same institute.

1.1 Meetings

Three formal meetings were held:

Rome, Italy, April 4 and 5, 1991, hosted by the Centre Esperienze Idrodinamiche. The original date of the meeting was delayed because of the Gulf War.

Memphis, Tenn., U.S.A., December 2 and 3, 1991, hosted by the David Taylor Model Basin. This meeting was held in conjunction with the ASME Winter Annual Meeting, December 4-6, 1991, Altanta, Georgia.

Seoul/Daejun, Korea, August 23 and 29, 1992, hosted by the Korean Research Institute of Ships. This meeting was held in conjunction with the 19th Symposium on Naval Hydrodynamics, August 23-28, 1992, Seoul, Korea.

An intermediate meeting was held in Hamburg, Germany, June 21-23, 1992, during the International Symposium on Propulsors and Cavitation, June 22-25, 1992, Hamburg, Germany.

2 RECOMMENDATIONS OF THE 19th ITTC

The following recommendations were made by the 19th ITTC Conference for the work of the Cavitation Committee of the 20th ITTC:

1. Hydrodynamic conditions for cloud cavitation formation should be clarified. The effect of cloud cavitation on material erosion and radiated noise should be reviewed.

2. Work should continue to evaluate the effect of nuclei and boundary layer characteristics on the scale effect of cavitation inception. Work should be initiated to relate nuclei size distribution measurements and cavitation susceptibility measurements with inception of various types of cavitation in cavitation facilities.

3. Work should continue to evaluate the mechanism and scale effect of vortex cavitation. Innovative concepts for delay of vortex cavitation should be monitored.

4. Progress regarding three-dimensional ship wake simulation in cavitation tunnels should be reviewed. Design features including the use of the centerbody and flow liner should be evaluated.

5. Work on measuring techniques for the model and full scale hull pressure fluctuations due to propeller cavitation should be monitored. Special attention should be given to the influence of the hull response to the pressure measurements.

3 INTRODUCTION

Cavitation remains a phenomenon which is difficult to describe theoretically. Even the precise physical phenomena are not properly understood, as noted in the discussion on cloud cavitation in this report. The most direct way to attack such a problem is to describe and analyse what is happening in the flow. This is done in chapter 4 on cloud cavitation. For that purpose, full scale observations have been collected. The idea of a comprehensive "atlas" of high quality cavitation observations is intended to stimulate the discussion on the phenomena and to put this discussion on a more factual basis.

It will be clear that the effects of cloud cavitation, of which erosion and noise are the more important ones, can only be described qualitatively. The parameters of the generating mechanism still have to be formulated adequately and quantitative experimental determination of erosion and noise is still very difficult.

The effect of nuclei on cavitation inception has been a long standing issue in cavitation research. Nuclei are very important, but for practical testing it is still not possible to recommend a nuclei density and size distribution for proper scaling. Tests in the French Cavitation Tunnel "GTH" in Val de Reuil have been conducted to address this question: If the nuclei content can be controlled, what nuclei distribution is recommendable to eliminate or minimize scale effects? The GTH has an unique nuclei control system and the opportunity given by the Bassin d' Essais des Carenes to use this facility has been greatly appreciated. A summary of the results is given in chapter 5.

Vortex cavitation remains very difficult to describe. Experimental work is difficult and the use of LDV equipment opens new possibilities to study vortices without disturbing the flow with the measuring equipment. These measurements are still very difficult, however, and are not part of a standard propeller test. The emphasis of this committee was on the phenomena of vortex cavitation, as reviewed in chapter 6, because this is the basis for innovative concepts that were also reviewed. Development and application of these concepts requires an increase in understanding of the basic phenomena.

The committee had to attack one of the major unsolved problems in model testing which is simulation of the ship wake in the vicinity of the propeller. Although important efforts are devoted to the proper scaling of the (unsteady) flow around the propeller, major problems remain. During the discussions, it was sometimes concluded that it is extremely important to scale the wake properly, but that it is nearly impossible to do so. Although this may be an overstatement, in practice every institution has to find its way through this problem using a lot of experience to compensate for a lack of control of the problem. The work of this Cavitation Committee focused on the

use of flow liners. Several members supplied extensive calculations to the committee to document the design technique of flow liners. The detailed calculations will be published elsewhere. The present report contains a summary and some conclusions in chapter 7.

The measurement of hull pressure fluctuations at model scale has in the recent past had little interest. The energy crisis in the seventies and early eighties reduced the amount of problems. The economical speed is increasing again, due to the stable and relatively low fuel prices. So these problems can be expected to come to the forefront. At the same time, the experimental and theoretical techniques to predict the risk of vibrations are still crude and further development is required. The techniques, in which the excitation forces are measured or calculated on one or a few locations at the model, prove to be insufficient for an accurate judgement of the expected hull response. More elaborate calculations are necessary to determine the effect of oscillatory forces on the vibrations of the ship hull. This effect makes it difficult to directly compare pressure fluctuations at model and full scale. The latest developments are reviewed in chapter 8. Efforts to assess the present test techniques have been continued on the tanker "St. Michelis". Comparative results from Japanese institutions are reported in the Appendix.

The Cavitation Committee also discussed the issues of validation and quality control with reference to cavitation. Any cavitation analysis not only requires an accurate determination of the fluid dynamics but also knowledge of the bubble mechanics. This makes the application of computational fluid dynamics very difficult and almost impossible at this time. Some thoughts are summarized in chapter 9.

4 CLOUD CAVITATION

The subject of cloud cavitation is, as most problems about cavitation, a rather old one. It was found in the early days of erosion studies that sometimes erosion was particulary intensive in areas where the cavitation collapsed from foamy structures. These structures were built up by numerous small bubbles, a cloud of cavities.

Due to the strong linkage to cavitation noise and erosion, interest in cloud cavitation has increased during recent years and theoretical models of the phenomen have been developed. Much of this was reviewed by the 19th ITTC and will not be repeated except where needed. This means that only a few references are made to the literature before 1990.

The Cavitation Committee emphasizes the importance of checking model observations, theoretical models and ideas against full scale observations. In the present report, an analysis of full scale observations is made that is intended to point out questions rather than to anwer them. A more scientific approach is left for further research. To specify a basis or a set of conceptions by which comparisons can be made, some present knowledge about cloud cavitation at model scale is reviewed in chapter 4. 1. Chapter 4. 2 contains the main point which is the discussion of full scale data. On the basis of mainly empirical knowledge, the structure of cloud cavitation is discussed from engineering and scientific points of view in chapter 4. 3.

4.1 Review of Some Properties of Cloud Cavitation as Observed from Model Experiments

This section begins with a description of the typical development of a sheet cavity on a conventional propeller operating in an inhomogenous wake or on an inclined shaft. Similar cavity dynamics are found on an oscillating hydrofoil. Although cloud cavitation can certainly occur in steady conditions, erosion and noise problems associated with cloud cavitation are significantly smaller for these conditions.

Considering a hydrofoil with increasing angle of attack, inception of sheet cavitation typically occurs as a few isolated "elementary" cavities occurring randomly from single nuclei or irregularities close to the leading edge (Bark, 1985). After some growth, these elementary cavities merge into a single sheet which is mainly glossy and transparent. Small bubbly distortions appear in the regions where the elementary cavities merge and protuding surface irregularities cause streaky distortions. Usually these distortions do not grow as they are convected downstream and do not influence significantly the development of cloud cavitation.

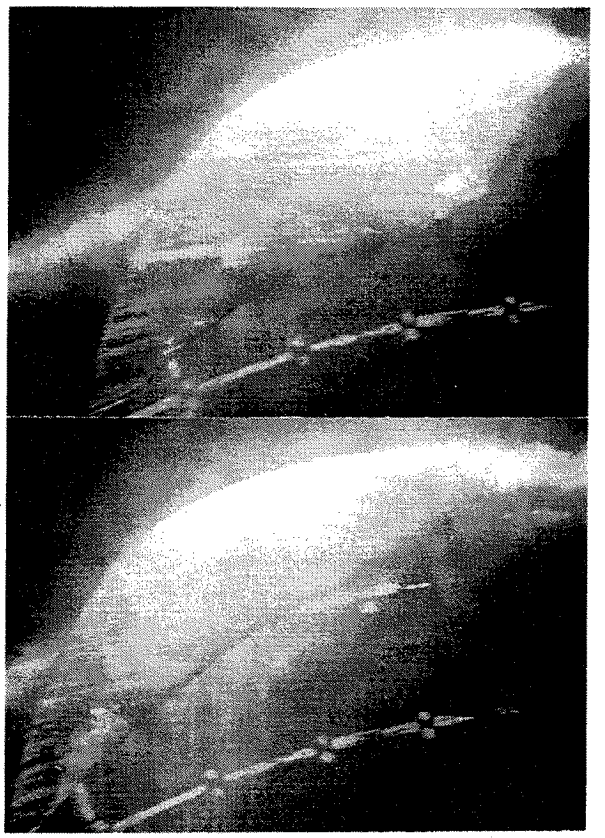


Figure 1: Full scale photograph of a sheet cavity with thick cloud formations and tendencies to break-off on a tanker propeller.

At increasing angles of attack, an irregular bubble distortion starts growing at the end of the cavity. When the sheet grows, the distortion typically spreads to a significant part of the cavity and is thereby transformed into thick irregular bubbly formations. These thick formations have a foamy appearence and are usually identified as cloud cavitation. It is not easy to determine precisely the internal structure or to estimate the void fraction. It is therefore difficult to apply a more exact definition of cloud cavitation.

Cloud cavitation disintegrates by breaking-off into a number of sub clouds, each of which can usually be expected to contain a large number of bubbles. These sub clouds are convected downstream into a region of higher pressure, where they collapse violently. Usually several collapse centers can be identified by high speed filming. It seems that the sub clouds often mutually interact. A series of sharp pressure pulses is often generated, some of them originating from rebounding cavities. There are two particularly important consequences of break-off: 1. it largely determines the initial conditions for the collapsing cavities and 2. it creates cavities of more spherical shapes, resulting in more violent collapse motions. This description corresponds mainly to the schematic behavior described by Bark (1985, 1986, 1988) and supported by Ito (1962), Bark (1978), Shen (1978, 1980), Kruppa (1982), and Kubota (1988).

The described behavior has been found to be particularly characteristic for sheets with their downstream edge being convex in the streamwise direction. Other types of distortions have also been observed to play a role, such as turbulence induced waviness of the cavity interface and bubble distortions generated upstream. It has also been observed that the upstream part of the sheet is not always smooth and transparent (Kuiper, 1978, 1981). Leading edge roughness or the number of nuclei can influence the cavity growth and structure of the sheet, but there seems not to be anysimple and universal relation to the development of cloud cavitation for these cases (Kuiper, 1978, Bark, 1985, Briançon-Marjollet et al, 1990).

A striking fact about the structure of cloud cavitation is that it can develop in at least two fundamentally different ways. First, the cavitation can grow as a cloud from isolated nuclei. This process occurs in acoustically induced cavitation if the low pressure region covers many nuclei (Moerch, 1989), and in hydrodynamically induced cavitation in a vortex. Alternatively, a cavity starting as a simply connected volume can transform into a cloud. An example of this type is shown by O'Hern (1990) for cavitation in vortices behind a plate perpendicular to the flow.

4.2 Cavitation on Full Scale Propellers

It is generally agreed that in many conditions, the existence and location of rather severe cavitation erosion can be reasonably well predicted by model experiments. However, the predictions sometimes fail when cloud cavitation is only weakly developed. Over-prediction of erosion also occurs because the classical paint test is very approximate with regard to the erosion intensity even when a global statistic "calibration" has been made

from correlations with full scale results. Despite some annoying failures, there are so many good predictions of the position and of he geometrical extent of the erosion that there is some support for the assumption that cloud cavitation often behaves fairly similar at model and full scale. It is important, however, to determine when scaling problems can occur, even if nothing can be done to improve the scaling. A more detailed and direct study of cloud processes at full scale is therefore needed, not only to determine the degree of similarity with model scale but also to evaluate the possibilities and limitations of prediction procedures, both experimental and theoretical.

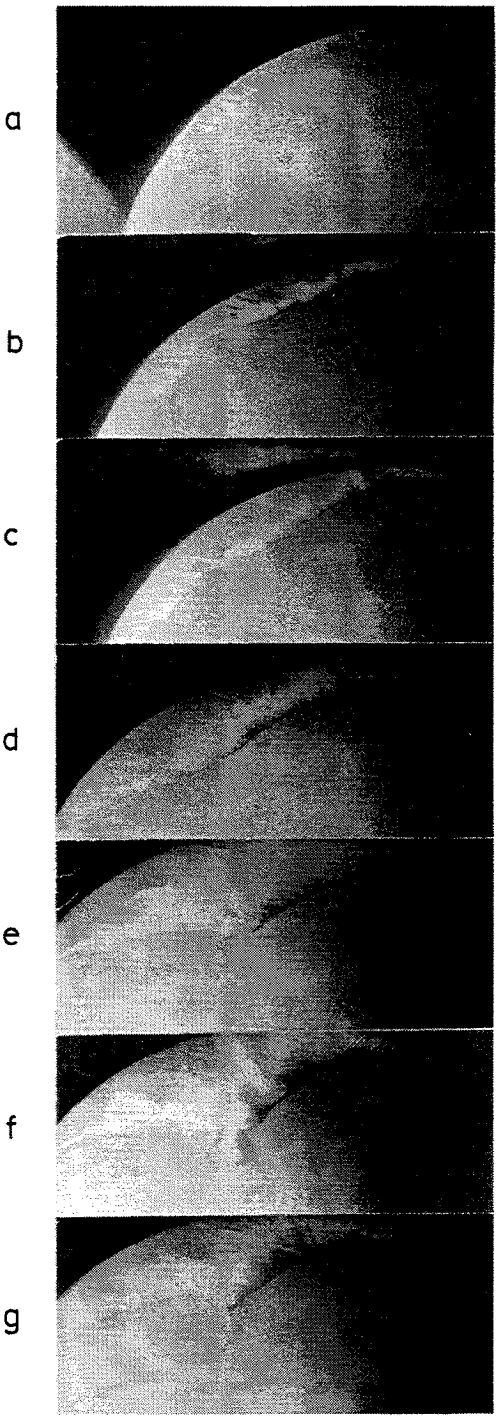


Figure 2: Full scale photograph of the development of thick cloud formations and break-off on a moderately cavitating propeller.

Some comparisons of model and full scale cavitation patterns are published, e.g., Lindgren (1972) and Weitendorf (1981), but they are usually not made to study cloud cavitation. As a first step to do this, the Cavitation Committee decided to collect a number of photographs of full scale cavitation to investigate the phenomena and to identify if a similar behavior occurs at model scale. To make publication of some of the material possible, it was also decided that no propeller data or photographs of corresponding model cavitation were required at this stage. In a limited request, photographs were then obtained from BMT, CEIMM, DTRC, HSVA, MARIN, SRI and SSPA. Some of these are shown in this section, and the main features of the cavities are discussed and compared with typical model behavior. This is expected to yield a first hint of tendencies, raise questions and indicate research areas. It is pointed out that the statements made below are based on more photographs than could be included in this report and also that some details visible in the original photographs may be lost in the reproduction process. A more scientific approach, desired for a research project of course, is an evaluation of high speed films or videos from corresponding model and full scale experiments.

The upstream part of the sheet cavity. In summary, the photographs indicate that the beginning of the sheet at full scale has about the same structure as at model scale. There are glossy and transparent sheets over a large part of the cavity interface, as shown in Figs. 1, 3, 4 and 5. The sheets usually contain some small bubbles, often occurring in streaks and starting from some surface irregularity close to the leading edge. This structure of the full scale cavity is fairly close to model cavities obtained when some surface roughness is applied to the propeller model. This general appearence was also found by Rutgersson (1982) in comparisons of model and full scale cavitation on a high speed propeller. In some cases, there is a tendency that the full scale

sheet contains more bubbles than a typical model cavity. The mechanisms partly explaining these cavitation pattern differences are discussed by Kuiper (1978, 1981). Although high speed films are needed for definite statements, there is no indication that small bubbles generated upstream in the sheet contribute to thick cloud formations downstream in the cavity.

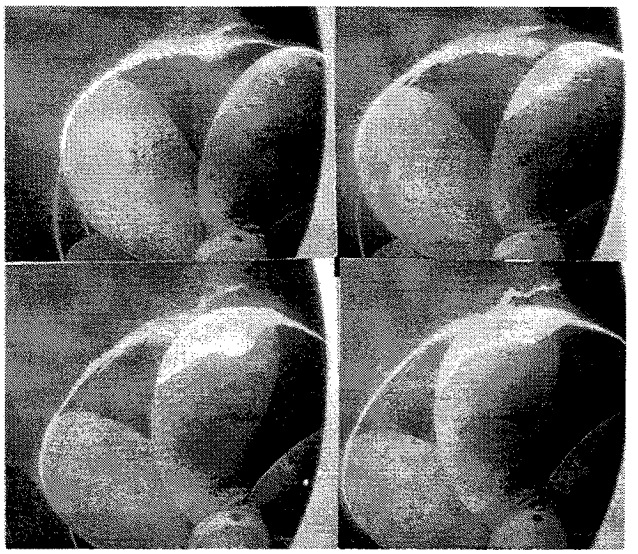


Figure 3: Full scale photograph of the development of thick cloud formations in the sheet cavities on the propeller of a containership.

Cloud cavitation. The most important conclusion, supported by Figs. 1-5, is that cloud cavitation at full scale develops mainly from distortions in the downstream part of the sheet. It is also noted that cloud formations protude significantly above the interface of the undistorted sheet, see for example, Fig. 1a, 2c-2g, 3 and possibly Fig. 5 (the lower blade). This is in agreement with model tests.

It is noted that at full scale, large voids do not always break-off from the main cavity in every blade passage. However a few break-offs in the sheets are observed. One example appears in Fig. 2f, in which a part of the cloud is breaking-off from the "corner" of the cavity. In Fig. 2g, below the "corner", a cloud can be seen which has separated from the main cavity far upstream and which has not yet collapsed.

A diffuse group of small clouds can be seen close to the trailing edge in the photograph shown in Fig. 2. This situation often results in erosion if the pressure increases steeply in this region. In Figs. 2c and 2d, thin streaks of cloud cavitation leaving the main cavity are also visible. This process, typical for a slowly growing cavity, can occur at model scale. In Fig. 2d, some streaks are present, possibly generated by surface irregularities close to the leading edge. This type of pattern also occurs at model scale.

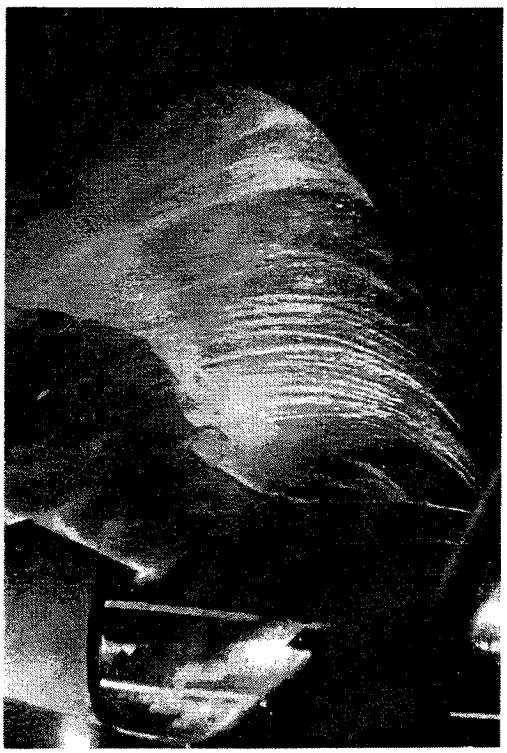


Figure 4: Full scale photograph of cloud formations and tiny break-off in the downstream part of a fairly glossy sheet cavity on a high speed propeller.

Although the cloud formations in Fig. 3 seem to be rather thick, no break-off is visible, except at one location. In Fig. 4, the first signs of a medium sized break-off are visible as narrow dark cracks in the downstream part of the white cloud (at about 20% of the blade span from the blade root). In Fig. 5, some detached clouds are visible close to the main sheet on the upper blade. Close to the blade root, there is a large patch of cloud cavitation, possibly generated by a "leading edge break-off".

In summary, the full scale photographs indicate phenomena which are rather similar at model and full scale. A subject of further re-

search is the shedding of cavitation from thick cloud formations. A few small broken-off clouds were observed at full scale. As will be discussed in the next sub-section, this also happens at model scale. An indication that thick cloud formations and break-off occurs more frequently in the sheet at model scale is obtained from the sketches of model and full scale observations of a tanker propeller presented by Lindgren et al (1972). The experimental procedures, however, have developed since 1972 and it is unknown if, for example, the stabilization of cavitation at model tests by proper selections of Reynolds number, surface roughness and gas content has any effect on break-off.

Cloud cavitation in the tip vortex. On modern propellers, the sheet cavity is often of small chordwise extent along a substantial part of the leading edge. Particularly on highly skewed propellers, this narrow sheet tends to be smoothly integrated with the tip vortex cavity, as can be seen in Fig. 5. In extreme cases, a large part of the downstream or inner edge of the sheet is almost parallel to the locus of a constant radius. This results in thick formations being convected along the inner edge of the cavity and into the tip vortex. This kinematical behavior was associated by Bark (1986) with "tip vortex cavity break-off" and it was assumed to be one of the more important mechanisms for noise generation, being effective also when no cloud cavitation breaks-off from the sheet. A reason for this is assumed to be the amplitude modulation of the diameter of the tip vortex cavity when the irregular clouds enter the tip vortex cavity. This modulation is assumed to result in a break-off of the tip vortex cavity into parts collapsing more violently than a connected long vortex cavity. Significant instabilities in the tip vortex are observed at full scale, Figs. 1b, 3 and 6.

In Fig. 5, the tip vortex cavities also contain thick cloud formations, but in this case, it looks as if at least the thickest formations are created within the tip vortex. It is interesting that there is a large amount of small bubbles in the region where the tip vortex appears to be modulated by clouds from the sheet, Figs. 3 and 6. A preliminary impression is that imploding vortex cavities at model scale have fewer and bigger bubbles compared to full scale.

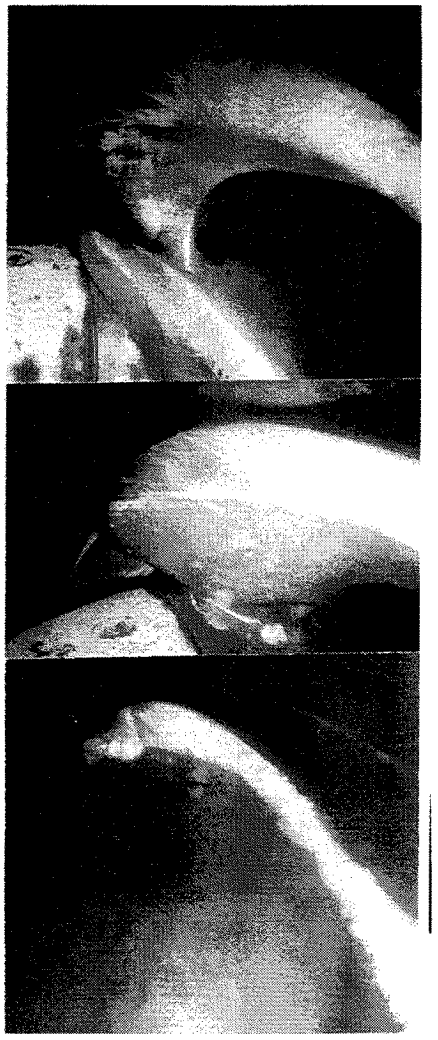


Figure 5: Full scale photograph of two propellers with the sheets gradually merging into tip vortex cavities. Some cloud formations are breaking off from the sheet and others are fed into the tip vortex. (Photographs a and b show a highly skewed propeller; propeller c is a less extreme design).

Other types of violent collapses. Fig. 7 shows heavy cavitation on a highly skewed propeller and is an example of the "leading edge break-off" discussed in chapter 4.1. The contrast of the prints is not very good, but in the original photograph it can be seen that the cavity detaches from the leading edge as is indicated in Fig. 7 by the dashed line. This type of cavity dynamics can result in very high volume accelerations and is different than cloud cavitation from a sheet (Bark, 1986).

4.3. Review of Some Recent Work on Engineering Predictions and Fundamentals of Cloud Cavitation

In this chapter, some recent research on engineering predictions and fundamentals of cloud cavitation are briefly sketched.

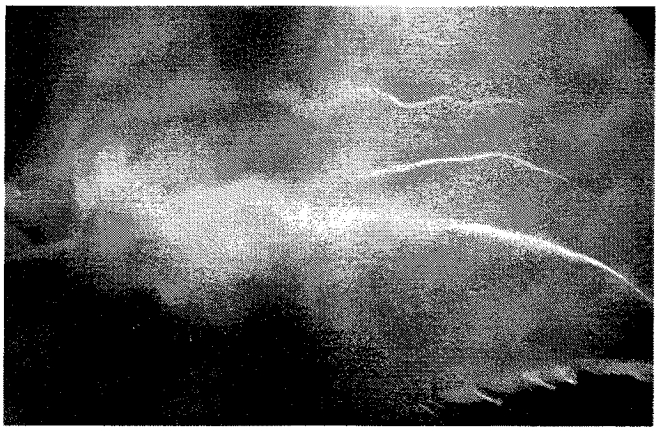


Figure 6: Full scale photograph of tip vortex cavities containing cloud formations.

Engineering predictions. Engineering applications in which cloud cavitation is crucial are prediction of erosion and noise. Cloud cavitation can also be expected to have some influence on the pressure pulses at blade rate frequency and multiples thereof. For the prediction of cavitation noise and pressure pulses one can use

a. model experiments,

b. primarily empirical methods,

c. theoretical methods with some empirical input about the cavitation, and

d. purely theoretical methods.

Methods a and possibly b have become more or less common practice, which does not mean, however, that all problems are solved. It is important that the experiment be conducted in such a manner that the crucial processes in the cloud cavitation are adequately simulated. This requires knowledge about the main mechanisms involved, their relative importance and possible scale effects. More quantitave answers are needed on the questions discussed in chapter 4.2 and by Baiter (1989, 1992) and Bark (1992).

Methods of type b depend upon some database combined with a scaling relationship. Cloud cavitation has to be considered in these methods or such methods will have a restricted validity or have to be updated continuously.

In reference to high frequency noise, there are a few methods of type c. Work in this category was presented by Matusiak (1992a, 1992b), who computes the cavitation extent using lifting surface theory with certain assumptions. The cloud cavitation from a sheet is taken into account on a partly empirical basis by a model describing the disintegration of the sheet into bubbles. The collapse of these bubbles, which are treated as a single bubble, are modelled by the Hickling equation and the noise in a wide frequency range is computed by applying linear acoustics. Some spectra are reasonably well predicted but significant problems still have to be solved before a sufficiently general and realistic model of the cloud cavitation is obtained. Modelling of cloud cavitation in the tip vortex is not undertaken. It should also be mentioned that Ligneul (1988) developed a theoretical method for noise from the tip vortex, but without simulation of possible cloud cavitation. Theoretical methods for computation of the low frequency pressure pulses have been on the market for many years but they still suffer from problems related to cavity dynamics as well as other simplifications, and they do not take cloud cavitation into account.

The problem of prediction of erosion was recently reviewed by Kato (1992). Significant research about processes in the fluid as well as in the solid is ongoing. It has been found that micro-jets, shock waves and interactions between these and bubbles are important. Recent experimental evidence shows that shock waves can in fact be the main mechanism when the cavity is close to the solid wall while micro-jets may dominate at slightly greater distances. Kato also discussed a simple scaling formula for erosion intensity of the cavitation formulated by Quang et al (1989) as well as other quantitative experimental methods. In such methods, the strength and number of pulses is determined, i. e. , quantities related to the behavior of the cloud cavitation. Kato finally suggests a research program for the development of more quantitative erosion prediction methods.

Figure 7: Full scale photograph of a sheet detaching from the leading edge ("leading edge break-off").

Fundamental problems. Considering the previous discussion, the following three main areas of research about cloud cavitation can be distinguished:

1. Mechanisms by which cloud cavitation develop from glossy sheet or vortex cavities.

2. The general structure and distribution of bubbles in cloud cavitation and how it develops in time, by coalescence, disintegration, etc. Development of break-off.

3. Collapse dynamics of cloud cavitation and the thereby generated pressure and momentum pulses responsible for noise and erosion. Of particular interest is the interaction between bubbles or clusters of bubbles and how these cavity configurations respond to external pressure fields.

Research in these areas is ongoing within several groups and several interesting results have been published since 1990. However, the final explanation or even description of the mechanisms involved in cloud cavitation is still missing.

For the time being, it seems reasonable to assume that cloud cavitation can be generated in more than one way. In a flow with strong vortices, it can be supposed to grow directly from cavitation nuclei, an assumption supported for example by the photographs taken by O'Hern (1990) of cavitation in separated vortices behind a plate. Several authors since Shen and Peterson (1978) have shown the vorticial motion of broken-off cloud cavitation on hydrofoils. It was numerically demonstrated by Kubota et al (1988, 1992) that a vortex in the upstream region can create a jet resulting in break-off. These large vortices can control the development and collapse of cavitation in the downstream region on a 2-D hydrofoil. A further study of vortex generation downstream of a sheet cavity was presented later by Yamaguchi (1991). A Navier-Stokes analysis, where the cavity is treated as a compressible bubbly liquid, was developed at the University of Tokyo for application to hydrofoils of finite span (Kato et al, 1992). The importance of vortices for the final development and position of collapse was also shown by Chiba (1992). He observed in model experiments with a propeller in a wake that the cloud cavitation typically was split into two parts, one collapsing into the tip vortex region and the other on the blade, close to trailing edge, thereby causing erosion. By use of a computer program based on a quasi-continous lifting surface theory, Chiba found that the collapse position on the blade coincided with the maximum strength of the free vortex. Although Chiba's approach in its present form does not model the structure of the cloud, it can possibly be developed into an engineering tool indicating in which region an existing distribution of cloud cavitation will collapse.

It is also noted that the numerical prediction of sheet cavitation developed by Stern (1989) shows significant oscillations of the cavity length for conditions at which cloud cavitation is experimentally observed. A closer study of the origin and physical interpretation of the instabilities reported by Stern is therefore of interest. The methods used by Stern and Chiba are directly applicable to propellers in non-uniform wakes, an important fact for the development of engineering knowledge about the hydrodynamic conditions connected with cloud cavitation. The latest

development in boundary element methods for cavitating flow by Kinnas and Fine (1992) is of interest for the calculation of cavity extent, which is important for cloud behavior.

In a study of hemispherical vapor cavities on a headform, Ceccio and Brennen (1991) observed that when cavities passed the region of turbulent reattachment, their underside became roughened and it seemed as if vapor was sheared-off from the underside of the cavity, leaving a trail of small bubbles.

Similar observations have also been reported much earlier by Holl and Carroll (1979) and van der Meulen (1980). Whether a similar mechanism of turbulent entrainment of vapor bubbles can contribute to the creation of cloud cavitation is unclear, but the observation anyhow indicates one way in which disturbances can start in cavity interfaces. Sometimes it is observed, for example in Figs. 2a - 2d, that sheets or narrow streaks at steady flow conditions are shedding bubbles or small clouds continously. Although this type of cloud cavitation is usually not the most violent, it can result in noise as well as erosion. When Ceccio and Brennen (1992) studied the dynamics of attached sheet cavitation on headforms in steady flow conditions, they found that the shedding of bubbles in the downstream end of the sheet corresponded to a Strouhal number, based on the cavity thickness, ranging from 0.002 to 0.02. This is about one tenth of the value associated with Kármán vortices, which was therefore omitted as a driving mechanism. Instead, the bubble shedding was assumed to be related to periodic entrainmentof vapor and small scale reentrant jets. A frothy mixture of vapor and liquid was also observed inside the cavities. The shedding processes were found to be similar on headforms, both with and without laminar separation, although the cavitation patterns developed slightly differently otherwise. A similar example of the coupling between certain flow properties and cloud behavior, as mentioned also by the 19th ITTC, is shown by Ihara et al (1989) who demonstrated experimentally how significant break-off of cloud cavitation on a hydrofoil was almost completely eliminated when the sweep angle was increased. This fact clearly shows that break-off is not simply related to the cavitation extent.

As to the general structure and distribution of bubbles in cloud cavitation, Matusiak (1992a, 1992b) developed a model for the size distribution of bubbles based on a paper by Agrestand and Kuznetsov (1974) and empirical knowledge. He investigated the sensivity of the noise for different assumptions in the bubble size distribution and selected the one yielding the best results.

A nonlinear effect which occurs when a size distribution of bubblesis excited by a harmonically varying pressure was analysed by Kumar and Brennen (1992). This effect was indicated as harmonic cascading. The authors show that a significant excitation of the cloud occurs at twice the excitation frequency if bubbles with this resonance frequency are present. The cascading was shown to occur only for bubbles having this resonance frequency. This fact implies that only very small bubbles would be involved when cavitation is mainly of the vaporous type. It was stated in chapter 4.1 that the dominating mechanism in the development of cloud cavitation seemed to be related to a distortion of the interface close to the downstream edge of the sheet. In some cases, however, it was also observed (Bark, 1986) that bubbles generated upstream in the sheet seemed to influence the development of cloud cavitation and they should therefore not be disregarded in the search for mechanisms. Maybe they can influence the size distribution of bubbles in a downstream cloud.

Generation of bubbles upstream in the sheet is often related to viscous effects and a few papers about this subject will be mentioned. In a study of the interaction between the boundary layer, travelling bubbles and the attached sheet on a stationary hydrofoil, Briançon-Marjollet et al (1990) found that traveling bubbles have some interference on the development of the sheet. Photographs indicated that many large bubbles in the sheet may influence the structure of the cavity, i. e., the bubble distribution in the upstream part of the region where transition to cloud cavitation occurs. Photographs with only small bubbles in the upstream part of the sheet do not, however, give the impression of a substantial influence. From their study, they also found even more arguments for a strong link between laminar separation and the detachment of the upstream edge of the sheet cavity. In an earlier study, Franc and Michel (1988) related the cavity behavior to, among other things, the turbulent area on an oscillating hydrofoil. Arndt et al

(1991) showed results which also indicated an influence of the turbulence downstream of a laminar separation on the structure of a sheet. The interaction between turbulence and a swarm of bubbles was studied by Lance et al (1991).

As to the collective behavior and interaction between cavities during growth and collapse, the theoretical research in this field was started by van Wijngaarden (1964) and was continued by Moerch (1980, 1989), Chahine (1982) and Fujikawa et al (1986). These papers, together with other main contributions, were reviewed by the 19th ITTC. A main finding is that mutual interaction of cavities during collapse can result in higher or lower collapse pulses affecting noise and erosion. Different numbers of cavities and cavities of different sizes and in different modes of growth and collapse can be involved in this collective behavior. Indications of such interaction in cavitation on a propeller blade are found by Arakeri and Shanmuganathan (1985) and Bark (1986).

Theoretical research about interacting cavities has been conducted by Chahine and coworkers. The latest progress in this research, Chahine et al (1992), is the development of a three-dimensional Boundary Element Method (BEM) for the interaction of a few closely spaced cavities placed in inhomogenous flow fields (in a vortex for example) and also close to solid boundaries. The development of this knowledge is described in earlier papers, as for example Chahine (1983, 1989, 1990, 1991), Chahine and Perdue (1988), Chahine and Duraiswami (1991), Rebut and Chahine (1992), Duraiswami and Chahine (1992) and Zhang, Duncan and Chahine (1992). Although some work remains with the three-dimensional boundary element method, the published calculation results indicate that this method is superior to the asymptotic approach (Chahine 1982) for cases of strongly interacting cavities. This method seems to have the potential for explaining and modelling processes being critical for the generation of erosion as well as noise. It was demonstrated that the detailed BEM-computations of certain cavity configurations indicated smaller collapse pulses than did the asymptotic method. Strong deformations of closely spaced cavities were predicted. Also the indicated disintegration of cavities interacting with inhomogenous flow fields are interesting. A problem with the BEM procedure is that it cannot simulate the reentrant jet after it hits the cavity surface. The development of the asymtotic method, for use in cases of weakly interacting cavities, as well as the BEM approach, is continuing.

A different approach to the interaction problem is taken by Tryggvasonet al (1992) in their study of two rising bubbles. They solve the full Navier-Stokes equations for the fluid both inside and outside the bubbles, thereby demonstrating how approaching bubbles can merge or bounce. They also investigate the problem of bubble coalescence. For cloud cavitation, it is reasonable to ask if it behaves in a chaotic way. Agrest et al (1974) and Matusiak (1992b) are investigating this subject in the modelling of disintegrating cavities. Peng et al (1992) demonstrate by numerical experiments that a single bubble can behave chaotically for certain excitations. In view of their assumptions, this analysis seems to be most relevant to gas bubbles or posssibly acoustically induced cavitation bubbles.

4.4 Conclusions

The following conclusions can be drawn:

1. Understanding the mechanisms of cloud cavitation is of crucial importance for the development of prediction methods. This is particularly important for the prediction of erosion and noise, and for pressure pulses at blade rate frequency and multiples.

2. Important knowledge about the generation as well as the development of cloud cavitation is still missing. One implication is that the requirements for model experiments or theoretical modelling are not known. High speed observations are necessary to determine the physical behavior of cloud cavitation.

3. Two mechanisms of importance for the intensity of the final collapse are the disintegration of the cloud by break-off and the interaction between separate bubbles during the collapse and growth.

4. Although reasonable predictions of the location of erosion can be made from model scale tests, detailed observations at full scale are necessary to derive proper scaling laws. Important questions about the mechanism of cloud cavitation remain to be answered before

scale effects including the break-off can be understood and properly treated.

5. Model tests can be used for fundamental research about cloud cavitation and mechanisms because the basic properties of cloud cavitation are the same at model and full scale. Much work remains, however, on the quantitative evaluation of the model results, particularly for erosion.

6. Progress has been made in the dynamics of bubble clusters as well as sheet cavities. A first generation of numerical methods for the prediction of cavitation noise has appeared, based on a simple model of the cloud cavitation. However, model experiments will still be the most important way to predict effects of cloud cavitation in the near future. For a real breakthrough of theoretical methods, it is neccessary to model cloud cavitation in a more fundamental way.

5 SCALE EFFECTS DUE TO NUCLEI

Progress continues to be made on the development of on-line measuring techniques since the comparative measurements reported by the 19th ITTC Cavitation Committee (1990). The most accurate method to measure microbubble distributions remains the direct observation made possible by holographic methods. However, the major problem is not only the analysis time required for a hologram but also the limited microbubble size and statistical data available.

The distribution of microbubbles in water tunnels is dynamic and it is this motivation that is driving improvements to the phase Doppler anemometer (PDA) and the cavitation susceptibility meter (CSM). Gindroz and Briançon-Marjollet (1992) conducted a study of nuclei measurement techniques comparing results from holography, phase Doppler anemometer (PDA) and the centerbody venturi (CSM) using a special installation designed to guarantee optimal optical and flow conditions. Liu and Brennen (1992) reported a program to measure nuclei and population dynamics in a water tunnel using a PDA. A key test in this program was the comparison of PDA measurements with standard holographic methods. Work has also continued at the Hamburg Ship Model Basin (Tanger et al

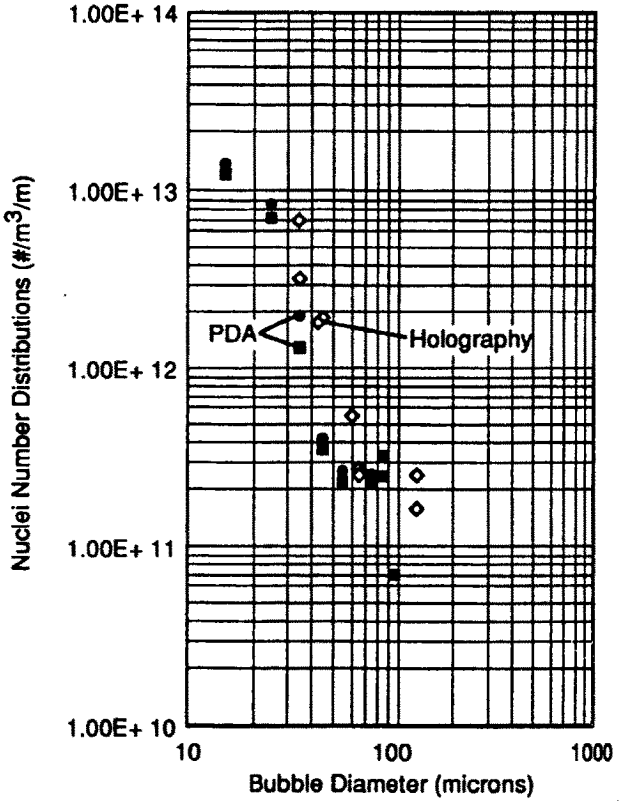


Figure 8. Comparison of microbubble distributions with the PDA and holography (Liu and Brennan)

1992) on the in-situ calibration of the PDA in the HSVA water tunnel.

It has been known for many years that microbubbles are very important to travelling bubble cavitation inception. A recent correlation between the nuclei distribution and the cavitation bubble distribution on a body has been reported by Meyer, Billet, and Holl (1992). Research at the Hamburg Ship Model Basin by Tanger et al (1992) clearly demonstrates an effect of microbubbles on propeller cavitation patterns and hence propeller excited pressure fluctuations. Many experiments reported by Avellan et al (1986) and Gindroz et al (1990, 1992), at the Institut de Machines Hydrauliques et de Mecanique des Fluides confirm a strong influence of microbubble content on the turbine efficiency and cavitation erosion rate of Francis turbines. In addition, a significant effect of microbubble distribution was found by Arndt (1992) on cavitation inception in a trailing vortex. Keller (1992) has attempted to correlate cavitation

In order to correlate nuclei distributions with the inception of various types of propeller cavitation, the 20th ITTC Cavitation Committee participated in tests conducted at the Grand Tunnel Hydrodynamique (GTH) of the Bassin d'Essais des Carenes. The GTH has a unique air control system including dissolved gas and microbubble control that offered an opportunity to correlate propeller cavitation inception with nuclei measured by several techniques. A summary of the microbubble control system and microbubble measuring techniques is presented, an experimental program is outlined, and comparisons of leading edge sheet, bubble and tip vortex cavitation inception on three different propellers to measured microbubble distributions and liquid tensions are then discussed.

5.1 Recent Comparisons of Cavitation Nuclei Measuring Techniques

The need to measure microbubble distributions/liquid tensions in order to scale cavitation results continues to be experimentally demonstrated. Gindroz et al (1990, 1992) from the Institut de Machines Hydrauliques et de Mecanique des Fluides have developed guidelines for performing Francis model cavitation tests that require injecting microbubbles into the water to obtain a specific saturation level. Significant progress has been made on cavitation nuclei measurements using the centerbody venturi (CSM) and the phase Doppler anemometer (PDA). Comparative measurements made at the Bassin d'Essais des Carenes, the California Institute of Technology, and the Hamburg Ship Model Basin have resulted in improvements.

Good agreement of microbubble distributions normalized by number count obtained by holography, phase Doppler anemometer and centerbody venturi has been shown by Gindroz and Briançon-Marjollet (1992). Measured distributions showed consistent trends with changes in microbubble size and number; however, results clearly show that a systematic calibration procedure is needed to determine the in-situ real measuring volume of the PDA for comparison of concentrations. These results were obtained in a special perspex flow tube with optical glass windows in which optimal conditions for each technique were taken into account. The measurements were made in-line with no significant change of nuclei between measurement points for the different systems. Precise calibrations were performed for each instrument in the flow tube.

For the case of the CSM, velocity measurements using a laser Doppler anemometer were made at several flow conditions to determine the pressure field where the flow is accelerated through a restricted section bounded by a central conical body and a cone diffuser. In this region, the pressure decreases. This promotes the explosive growth of microbubbles, characterizing them by a critical pressure. Special lenses with short focal lengths were required to measure correct velocity profiles across the throat. These elocity data were utilized in a mass flow calculation and compared to the measured flow rate to determine the measurement accuracy of the velocity data. The "controlled" lowest pressure value at the restricted section was then determined.

Precise relationships of phase difference to scatterer diameter were also defined for the PDA using latex particles in-situ. Several optical configurations and collecting angles were studied for microbubbles and latex particles. These particles are characterized by different scattering modes and surface irregularities on latex particles and produce a spread of the data. The main modes are reflection for microbubbles and refraction forlatex particles. A forward collecting scatter angle of 40 deg. was found to be an optimum for bubbles based on a unique relation of phase to diameter, a good visualization of signals, and a good signal-to-noise ratio. A PDA designed by Aerometrics was utilized in these experiments.

Liu and Brennen (1992) at the California Institute of Technology conducted calibration tests and comparisons of the PDA designed by DANTEC. After further developments of both hardware, software, and in-situ calibration for the PDA, very good comparisons of the PDA data with holography were obtained as shown in Figure 8.

Whereas the comparison measurements of Gindroz and Briançon-Marjollet (1992) were made at the Bassin d'Essais des Carenes in a pipe, the PDA and holography microbubble measurements were made at the same time and location on the center-line of the Low Turbulence Water Tunnel located at the California Institute of Technology. Liu and Brennen (1992) found the scattering angle to be critical to the phase Doppler technique, and it was de-

termined to be 86° for the DANTEC system only after a number of experimental tests and analytical evaluations. This system is currently being utilized to explore how the population distribution in a water tunnel changes with time, velocity, pressure, and air content. Initial results show that the microbubbles are dissolving in the water tunnel and the rate is similar to those observed by Gowing (1992) for flow in a large pipe.

The Hamburg Ship Model Basin has also continued the development of the PDA via extensive calibration procedure since its initial application by Saffman et al (1984). Tanger et al (1992) have shown that under ideal conditions, the PDA yields the correct size and concentration for single "frozen" bubbles in a rotating plexiglass disc. These tests with a rotating disc have been carried out both in air and in water. Nevertheless, the problem of the PDA amplification setting and the size of the control volume for measurements remains relevant. The control volume becomes larger with higher photomultiplier voltage and, therefore, influences the concentration. An in-situ calibration of the effective control volume is required.

5.2 Recent Correlations of Cavitation Nuclei and Cavitation

Tanger et al (1992) have continued to investigate the influence of cavitation nuclei on cavity extent and propeller-excited pressure fluctuations at the HSVA. Test results show that the recently built Hydrodynamics and Cavitation Tunnel (HYKAT) needs more nuclei seeding than the other HSVA tunnels to generate stable cavitation patterns on model propeller blades at approximately the same Reynolds number. This could be due to the wire mesh wake screens present in the small tunnels, creating upstream turbulence or microbubbles, and to the longer times that the bubbles are exposed to the higher static head which result in enhanced solution of microbubbles in the HYKAT. This facility has the capability to control both the dissolved gas with deaeration and the free gas by injecting microbubbles. Microbubble distributions are measured by a PDA of DANTEC.

It is also interesting to note from these tests that sheet cavitation on conventional propellers seems to show a higher degree of cavitation intermittency in the HYKAT due to a lower free air content of the water than observed in the medium-sized cavitation tunnel. This behavior and correlation to full-scale cavitation patterns was discussed by Weitendorf and Tanger (1992).

Calculations of the cavitation patterns were made for the model propeller using nuclei concentrations measured with the PDA system and blade pressure distributions that were calculated. The cavity length calculations were based on a bubble dynamics model developed by Chao (1978), Isay (1989), and Mills (1991). While this theory is based on single bubble dynamics, it includes compressibility and interaction effects between bubbles. Initial results show reasonable agreement between calculations and measurements. The calculations demonstrated analytically an influence of nuclei distribution on cavity extent.

The effects of microbubble distributions on travelling bubble cavitation inception have been examined by Meyer, Billet, and Holl (1992) on a Schiebe headform. A computer code statistically modelled cavitation inception, using a numerical solution to the Rayleigh-Plesset equation coupled to a set of trajectory equations. Bubble trajectories and growth were computed for an initial microbubble distribution using this code. A Monte Carlo cavitation simulation modeled a variety of random processes. Using microbubble distributions measured by holography, predictions of cavitation bubble distributions compare favorably with measured bubble distributions. Bubble cavitation inception was shown to be sensitive to nuclei distributions. Off-body pressure distribution was also found to be a significant factor in determining whether or not a microbubble would cavitate. The traditional definition of critical diameter based on the minimum pressure coefficient of the body or the equivalent measurement of liquid tension was found to be inadequate in defining cavitation inception because of off-body bubble trajectories. Thus cavitation inception was found to be dependent upon the distribution of the larger microbubbles.

Ceccio and Brennan (1991) have examined the interaction between individual travelling cavitation bubbles and the structure of the boundary layer and flow field in which the bubble is growing and collapsing. Results show that indidividual bubbles are often

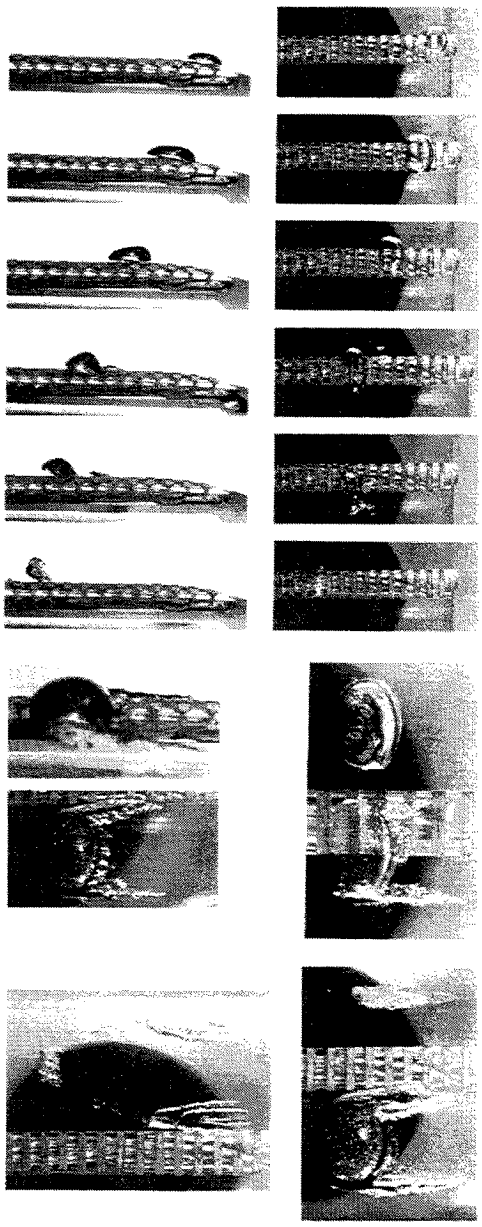


Figure 9. Photographs of cavitation bubbles on a headform (Ceccio and Brennan).

sheared by the fluid shear as shown in Figure 9. This figure shows such mocro-fluid mechnical phenomena as the hemispherical shape of individual cavitation bubbles, their thin film separating them from the surface, and the occasional production of attached streaks in the wake of the bubbles.

A recent series of tests were conducted by Kuhn de Chizelle et al (1992) in the Large Cavitation Channel of the David Taylor Model Basin on three geometric similar axisymmetric Schiebe headforms measuring 5.08 cm, 25.4 cm, and 50.8 cm in diameter over a range of speeds and dissolved oxygen contents. Surface electrodes detected the presence of cavitation bubble events. Inception was based on an arbitrarily chosen event rate of about 50 cavitation events per second and the results are summarized in Figure 10.

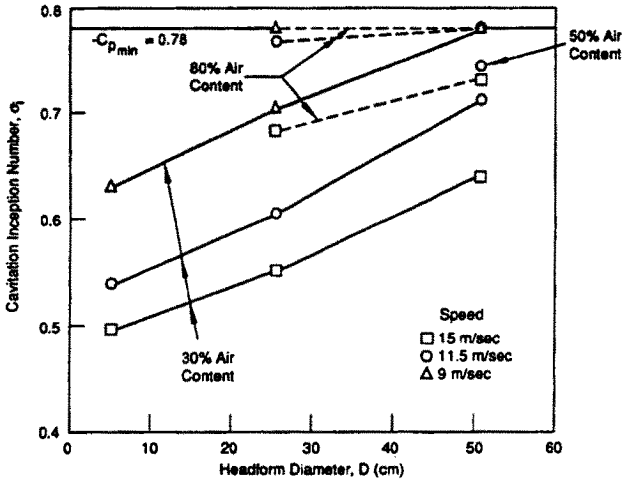


Figure 10: Cavitation inception on headforms (Ceccio and Brennen).

The data show that the cavitation inception number increases with increasing headform size and these data approach the magnitude of the minimum pressure coefficient and these trends are in agreement with many previous investigations. This headform size effect is simply a consequence that more nuclei of a reater number of being available for cavitation given a specific event rate.

Brennen and Kuhn de Chizelle (1992) have evaluated photographs/videotapes in an effort to demonstrate the connection between event rate (and by implication the cavitation inception index) and the nuclei number distribution. Using a simple synthesis of the cavitation event rate from the nuclei distribution, the variation of cavitation inception number for the headform size was predicted by an

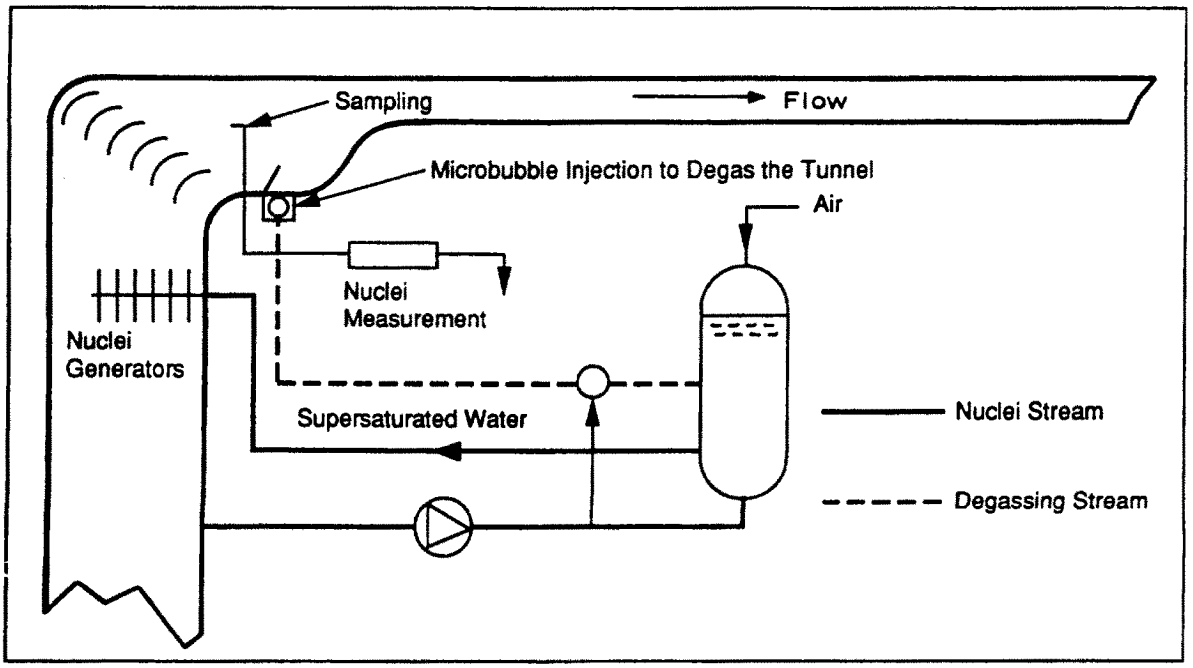


Figure 11: GTH seeding system.

analytical model. The effect of the air content is correlated with a change in event rate. However, two outstanding issues still remain. The observed event rates are at least one order of magnitude smaller than predictions based on the anticipated nuclei distributions. In addition, the variation of cavitation index with tunnel velocity could not be explained by the model.

Brennen and Kuhn de Chizelle proposed that the velocity effect may be a result of changes in the nuclei population with changes in the tunnel operating conditions that were not recorded. On-line monitoring of nuclei content and variations with operating conditions seem to be essential prerequisites for answering scaling questions. It seems clear that cavitation inception criteria are a natural consequence of the event rate variations.

Arndt and Keller (1992) conducted tip vortex cavitation studies with a hydrofoil having an elliptical planform, an aspect ratio of 3 and a modified NACA 662-415 profile. The dependency of cavitation inception on lift coefficient (C_L) was found to vary with the tensile strength of the water which was monitored by a vortex venturi device (Keller, 1987). Cavitation inception with water having little tension followed the C_L^2 relationship, whereas cavitation inception with high tension water varies as $C_L^{1.4}$.

5.3 Joint Bassin d'Essais des Carènes and Cavitation Committee Tests

Experimental Program. In an attempt to relate nuclei size distribution and liquid tension measurements with propeller cavitation inception, tests were conducted in the Grand Tunnel Hydrodynamique (GTH) of the Bassin d'Essais des Carènes located in Val-de-Reuil, France. Simultaneous measurements were made of cavitation inception on three different propellers and liquid tension/nuclei distribution. The GTH is a unique facility to do these tests because of a complete air control system including dissolved gas and microbubble control that enables the control of microbubbles in the test section. Details of this system are described by Lecoffre et al (1987).

The GTH was designed so that any bubble produced in the test section can be removed or dissolved after a trip around the tunnel circuit. The tunnel comprises a large downstream tank that acts as a high-speed separator where bubbles larger than 100μm are removed. All re-

maining bubbles are dissolved in the loop which has a large resorber.

The bubble distribution in the test section is controlled with seeding. Nuclei generators which utilize highly saturated water lie on a 600 x 600 mm grid on the upstream vertical tunnel leg from the contraction. They can produce either a homogeneous nuclei concentration in the test section or a distribution with an increased concentration along the axis at the center of the test section where the propeller is located.

The degree of saturation and pressure feeding the nozzle is automatically controlled so that the nuclei distribution can be produced over a range of test section static pressures. The system can supersaturate the water to the nozzles at a sufficient rate such that the entire system can operate indefinitely. A schematic of the seeding system is shown in Figure 11.

Cavitation inception data were obtained for four values of liquid tension/nuclei distribution at a dissolved oxygen level of 30%. These conditions were: 1. maximum tension with no nuclei injection, 2. medium tension with a low number of injected nuclei, 3. medium tension with a high number of injected nuclei, and 4. minimum tension with a very high number of injected nuclei. The liquid tensions of the water for Cases 2 and 3 were similar although the number of nuclei differed by an order of magnitude. For these water quality conditions, cavitation data were obtained on three 34 mm diameter propellers that were designed by Kuiper (1981). Each propeller was characterized by a different type of cavitation, i. e. , bubble, sheet, and tip vortex. Cavitation data were obtained at a constant Reynolds number for each propeller and for the varying water quality.

In parallel to the cavitation inception data and nuclei tension measurements, photographs, and videos were taken to allow post-test analysis of the cavitation inception point. Visual determination of the cavitation inception can depend strongly on the observers and their own criteria to quantify when cavitation inception begins. In addition, acoustic measurements were recorded over a range of conditions. The test conditions are summarized in Table 1 and a list of the participants for these tests is given in Table 2.

- Propeller Type
  - -- Bubble (B): J=0. 60, V=6m/sec.
  - -- Surface (S):J=0. 55, V=6 m/sec.
  - -- Tip Vortex (V):J=0. 55,V=4 m/sec.
- Measurements
  1. Cavitation inception/desinence (three data points each condition)
  2. Nuclei measurements with CSM, PDA and Holography.
  3. Acoustic measurements for several cavitation numbers.
  4. Photographs of cavitation inception.
  5. Video recording.
- Water Tension Conditions.
  1. Maximum tension (no microbubble injection, case 1)
  2. Minimum tension (low microbubble number, case 2)
  3. Medium tension (high microbubble number, case 3)
  4. Medium tension (large microbubble number, case 4)

Table 1: Propeller cavitation test conditions.

Organisation	Country	Participants	Role
ARL Penn State	USA	Dr. M. Billet	Cavitation Committee
DTMB	USA	Mr. S. Gowing Dr. M. Wilson	Nuclei Measurements Cavitation Committee
Bassin des Carenes	France	Dr. B. Gindroz	Organizer
Marin	Netherlands	Dr. G. Kuiper	Cavitation Committee
ONR	USA	Dr. E. Rood	Observer
ISL	France	Mr. Royer Miss Luquet	Holography
Aerometrics	France	Mr. Bauche	PDA

Table 2: List of participants.

Comparison of Results.

Microbubble/liquid tension measurements. Preliminary tests were conducted by the Bassin d'Essais des Carenes to not only calibrate the cavitation susceptibility meter (centerbody venturi), the phase Doppler anemometer from Aerometrics and holography but also to select appropriate microbubble distributions/liquid tensions for the propeller cavitation tests. The three measuring techniques were installed in-line along a by-pass to ensure each system sampled the same water and the length of the by-pass was chosen to correspond to the elapsed time from the intake of the sample tube to the test propeller. A schematic of the measurement configuration is shown in Figure 12.

The bypass flow for the nuclei measurements entered an intake placed in the center of the entrance plane of the contraction section upstream of the test section. A flexible hose then conveyed the flow through a double-S bend to prevent any concentration of larger bubbles via buoyancy to the top half of the flow. The PDA was placed the most upstream of the nuclei instruments to prevent any vertical migration of larger bubbles by buoyancy from skewing the PDA results. An initial se

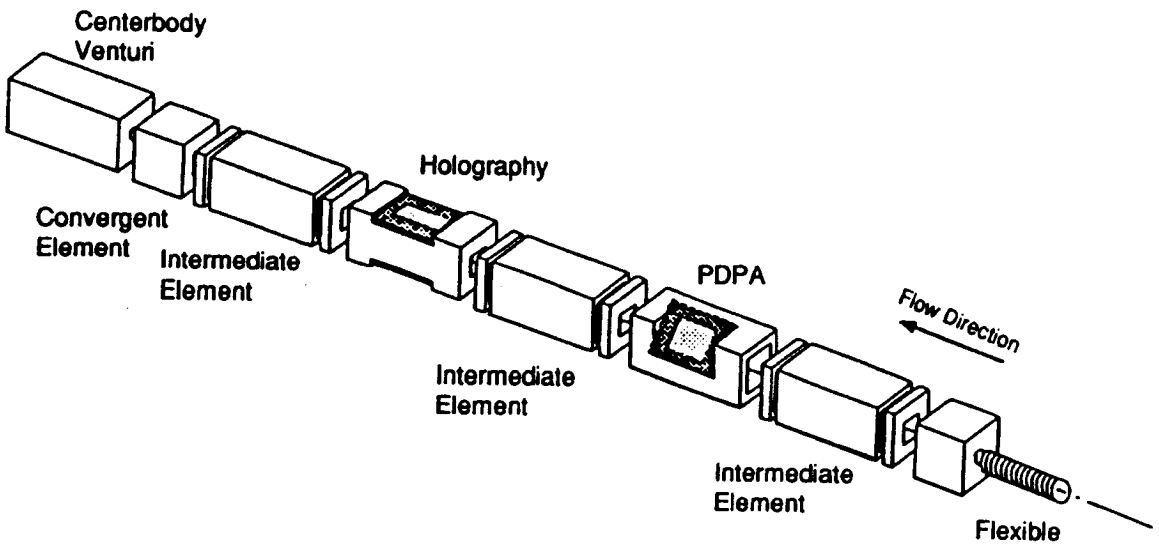


Figure 12. Schematic of in-line nuclei measurement system (Gindroz and Briançon-Marjollet).

ries of tests with different bypass flow speeds and hose lengths were run to determine effects of the pipe flow on the nuclei.

The PDA and CSM showed no effect off low velocity on the nuclei spectrum above a specific velocity, although variations of the hose length did show some dissolving effects on the nuclei because of longer elapsed times to the nuclei measuring points. The effects were manifested as a shift in the spectra along the size axis. The hose length which was used for the propeller tests created the same elapsed time from the intake to the nuclei instruments as from the intake to the propeller models.

Prior to these tests, an extensive calibration of the centerbody venturi was done in order to determine precisely the pressure distribution through the venturi and, more particularly, the minimum pressure that determines the tension corresponding to the smallest detected microbubble. Both computations and precise velocity distributions obtained with a laser Doppler anemometer were utilized to define the throat pressure. The minimum pressure in the throat is varied by changing the flow rate through the venturi. Its value can be determined from

$$p_{min} = C_p(min) \times \frac{\rho}{2}\left[\frac{Q}{S_{ref}}\right]^2 + P_{ref} \qquad (1)$$

where S_{ref} is the area upstream of the restricted area, P_{ref} is the static pressure at the reference area and is given from the calibrations.

All microbubbles with an internal critical pressure p_{cr} higher than the lowest value in the venturi (p_{min}) will cavitate. By varying the flow rate, it is possible to change the lowest pressure value in the venturi p_{min}. As the smallest detected nuclei depends on this minimum pressure, it is possible to determine the cumulative nuclei distribution as a function of the critical pressure on the critical radius. The relationship between the critical pressure and the critical radius comes from static equilibrium and is given by

$$R_{cr} = -\frac{3\Gamma - 1}{3\Gamma} \times \frac{2\gamma}{(p_{min} - p_v)_{cr}} \qquad (2)$$

where Γ is the ratio of the specific heat of gas, γ is the gas-liquid surface tension and p_v is the liquid vapor pressure. Each microbubble that cavitates generates a short shock wave at collapse. The number of activated microbubbles is determined by counting the pulses with a piezo-ceramic transducer associated with an appropriate system for signal treatment. Table 3 represents the magnitudes of water volumes analyzed by the different techniques typical for the propeller tests taken from Gindroz and Briançon-Marjollet (1992). The volume ratio represents the amount of water analyzed compared to the amount of water flowing through the by-pass pipe section. Because of the unique seeding arrangements, no dynamical variations of the distribution would be experienced. All measurements were made near the cavitation inception pressure for a particular type of propeller cavitation.

For the CSM, each measurement corresponds to a mean value based on a 10 second acquisition period or 100 detected bubbles. All measurements for the PDA were performed with the same photomultiplier voltage because preliminary tests showed it to have a significant influence on the number of small bubbles measured. At first it was planned to use an automatic system to analyze the holograms; however, all of the analyses were done manually due to the few bubbles present.

Figure 13 shows a representative comparison between distributions measured by the CSM, PDA, and holography. In every case, the PDA had a higher number of bubbles above 7 μm than holography, and holography had a higher number than the CSM. This trend can not be due to microbubbles changes

Measurement Technique	Analysing Time	Analyzed Volume	Total Volume Ratio
Centerbody Ventury (CSM)	10 min.	$2 \times 10^{-1} m^3$	0.5
PDA	10 min.	$2 \times 10^{-5} m^3$	4×10^{-5}
Holography	1 day	$2.5 \times 10^{-6} m^3$	1×10^{-2}

Table 3: Typical measurement times (Gindroz and Briançon-Marjollet).

along the pipe; however, this trend was very consistent for all measured distributions. Figure 14 compares the four microbubble cases used during the cavitation tests as measured by the CSM and holography during the propeller tests. The number and size distributions were significantly varied for microbubbles above 5 μm.

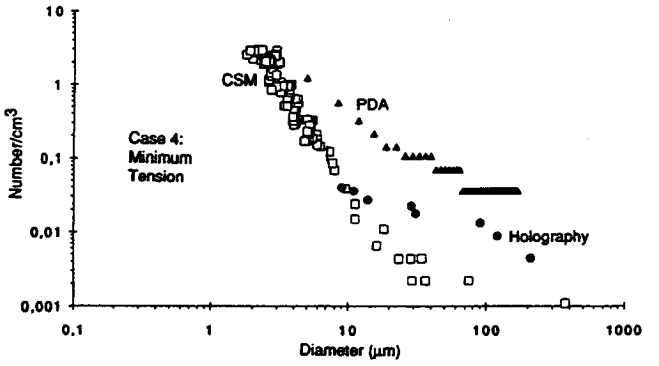


Figure 13: Nuclei distributions measured by CSM, PDA and holography for case 4 (minimum tension).

From these microbubble distributions, the critical liquid tension can be defined as

$$T = p_v - p_{cr} \quad (3)$$

where T is the liquid tension, p_v is the vapor pressure, and p_{cr} is the critical microbubble pressure of the largest microbubble. The minimum tension is used for comparison because it would correlate more closely with inception measurements. Table 4 gives a comparison of these tension and microbubble data. Again, the repeatability to obtain similar liquid tensions for each propeller test was very good in spite of different reference pressures in the test section. In all cases, each measurement technique predicted similar trends as the microbubble distributions were varied. Absolute comparisons of liquid tension and critical microbubble size between the CSM and holography are very good in most cases.

Tension Type	D_0(μm)								
	CSM			PDA			Holography		
	B	S	V	B	S	V	B	S	V
case 1 maximum tension	1.2	1.4	1.3	12	10	10	< 7	< 7	< 7
case 2 med. tension, low nuclei nr.	8	8	9	30	35	22	9	10	11
case 3 med. tension, high nuclei nr.	8	11	-	30	45	-	10	16	-
case 4 minimum tension	350	200	200	200	160	130	210	168	200

Tension Type	T(mbar)								
	CSM			PDA			Holography		
	B	S	V	B	S	V	B	S	V
case 1 maximum tension	1092	909	993	70	87	87	< 140	< 140	< 140
case 2 med. tension, low nuclei nr.	114	114	99	24	20	34	99	88	80
case 3 med. tension, high nuclei nr.	99	78	-	24	15	-	90	52	-
case 4 minimum tension	1.3	2.5	2.5	2.5	3.2	4.1	1.7	3.1	3.7

Table 4: Liquid tension comparisons for the conditions tested (Cavitation type: B=Bubble, V=tip vortex, S=sheet).

Tension Type	Tip Votex Cavitation (V)		
	inception	desinence	% diff.
case 1 (maximum tension)	0.41	0.42	0
case 2 (medium tension, low nuclei number)	0.60	0.89	48
case 3 (medium tension,. high nuclei number)	0.81	1.15	42
case 4 (minimum tension)	1.00	1.42	42

Tension Type	Bubble Cavitation (B)		
	inception	desinence	% diff.
case 1 (maximum tension)	0.24	0.24	0
case 2 (medium tension, low nuclei number)	0.86	0.93	8
case 3 (medium tension,. high nuclei number)	0.95	1.01	6
case 4 (minimum tension)	1.00	1.03	3

Tension Type	Surface Cavitation (S)		
	inception	desinence	% diff.
case 1 (maximum tension)	0.97	1.03	6
case 2 (medium tension, low nuclei number)	0.99	1.05	6
case 3 (medium tension,. high nuclei number)	-	-	-
case 4 (minimum tension)	1.00	1.06	6

Table 5: Cavitation inception results.

Tension Type	Tip Votex Cavitation (V)		
	σ/σ_i (case 4)	$\Delta(p_{0i} - p_{od})$ mbar	CSM mbar
case 1 (maximum tension)	0.41	1002	909
case 2 (medium tension, low nuclei number)	0.60	688	114
case 3 (medium tension,. high nuclei number)	0.81	323	78
case 4 (minimum tension)	1.00	0	2.5

Tension Type	Bubble Cavitation (B)		
	σ/σ_i (case 4)	$\Delta(p_{0i} - p_{od})$ mbar	CSM mbar
case 1 (maximum tension)	0.24	497.4	1092
case 2 (medium tension, low nuclei number)	0.86	93.6	114
case 3 (medium tension,. high nuclei number)	0.95	31.2	99
case 4 (minimum tension)	1.00	0	1.3

Tension Type	Surface Cavitation (S)		
	σ/σ_i (case 4)	$\Delta(p_{0i} - p_{od})$ mbar	CSM mbar
case 1 (maximum tension)	0.97	54	993
case 2 (medium tension, low nuclei number)	0.99	18	99
case 3 (medium tension,. high nuclei number)	-	-	-
case 4 (minimum tension)	1.00	0.0	2.5

Table 6: Liquid tension versus cavitation inception results.

Cavitation Inception Measurements. A summary of incipient/desinent cavitation data for the three propellers is given in Table 5. For each propeller, averaged cavitation data were normalized by the incipient cavitation number at minimum liquid tension. Desinent cavitation was approximately 6% higher than incipient cavitation for surface and bubble cavitation; however, differences as large as 40% higher were observed for tip vortex cavitation. The sensitivity of cavitation inception to liquid tension/nuclei distribution was found to be different for each type of propeller cavitation. Blade surface cavitation had a maximum of 3% reduction in cavitation index, tip vortex cavitation had a maximum of 59% reduction in cavitation index, and bubble cavitation had a maximum of 76% reduction in cavitation index for increasing liquid tension.

These different trends make it difficult to correlate with liquid tension; however, a comparison is shown in Table 6. In all cases, an increase in liquid tension as measured by the CSM resulted in a decrease in cavitation inception number. The difference in cavitation number between the minimum tension case and any other case represents another measurement of liquid tension for a particular flow. This value, given by $\Delta(p_{0i} - p_{0d})$, is also reported in Table 6. The value of liquid tension as measured by the CSM is higher than the values calculated from bubble and surface cases; however, for the tip vortex cases higher tensions are observed in the tip vortex.

Another way to try and correlate the inception results with the CSM data is to determine the critical bubble size from the nuclei spectra (as measured by the CSM) above which the cumulative number density of nuclei would produce a rate of cavitation events on the propeller that is comparable to the rate at inception. Static stability then predicts the tension required to make that critical bubble size cavitate and that tension appears as a reduction in the pressure at inception which results in lower cavitation numbers. An estimate of 0.002 nuclei/cc would be required for the tip vortex propeller to create one cavitation event per second which is assumed to be similar in magnitude to the observed incipient cavitation event rates. The spectra in Figure 14 show the nominal nuclei size at which that number density occurs for the different spectra tested. Using the static stability criterion, the tensions required to make those nuclei cavitate can be estimated. These tensions can then be compared to those measured in the CSM and the reductions in cavitation number can be compared to those measured. For the tip vortex propeller, the estimated reductions

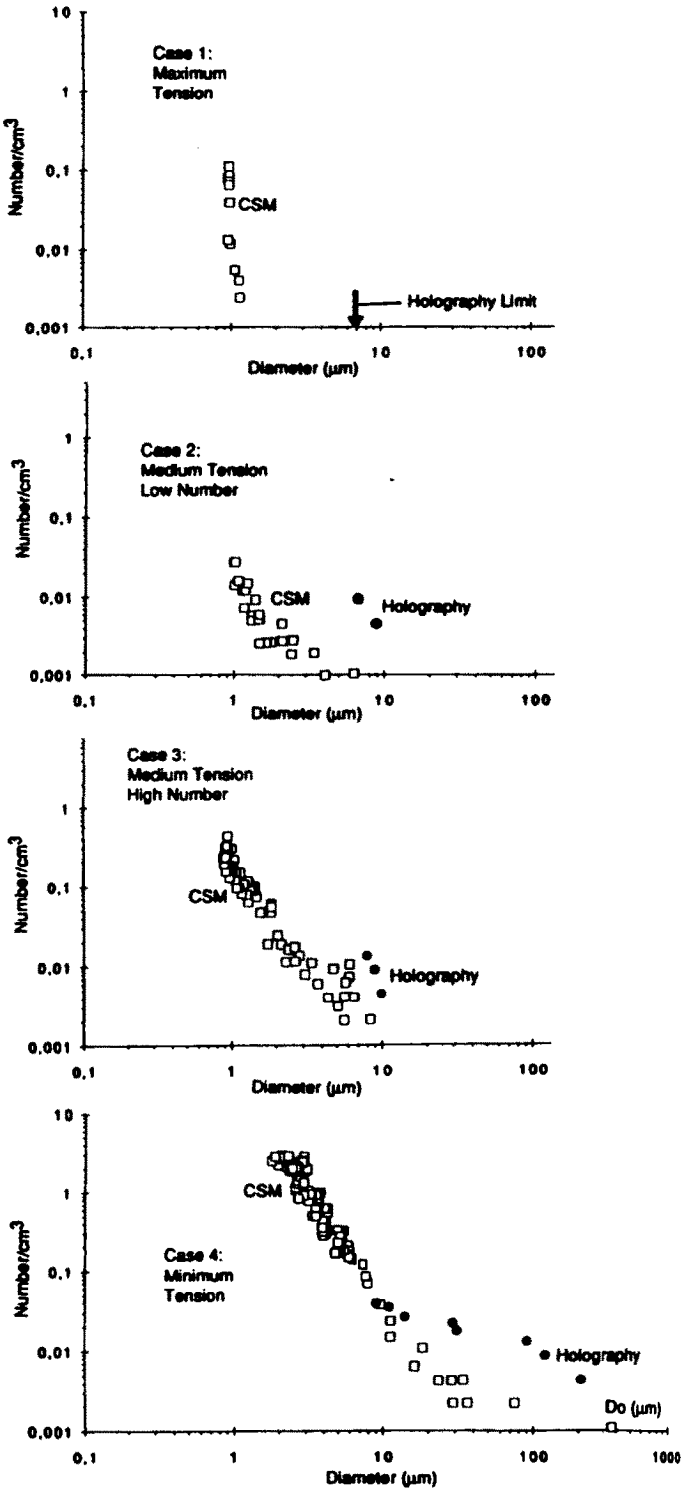


Figure 14. Nuclei distributions measured during tests with the B propeller (bubble cavitation).

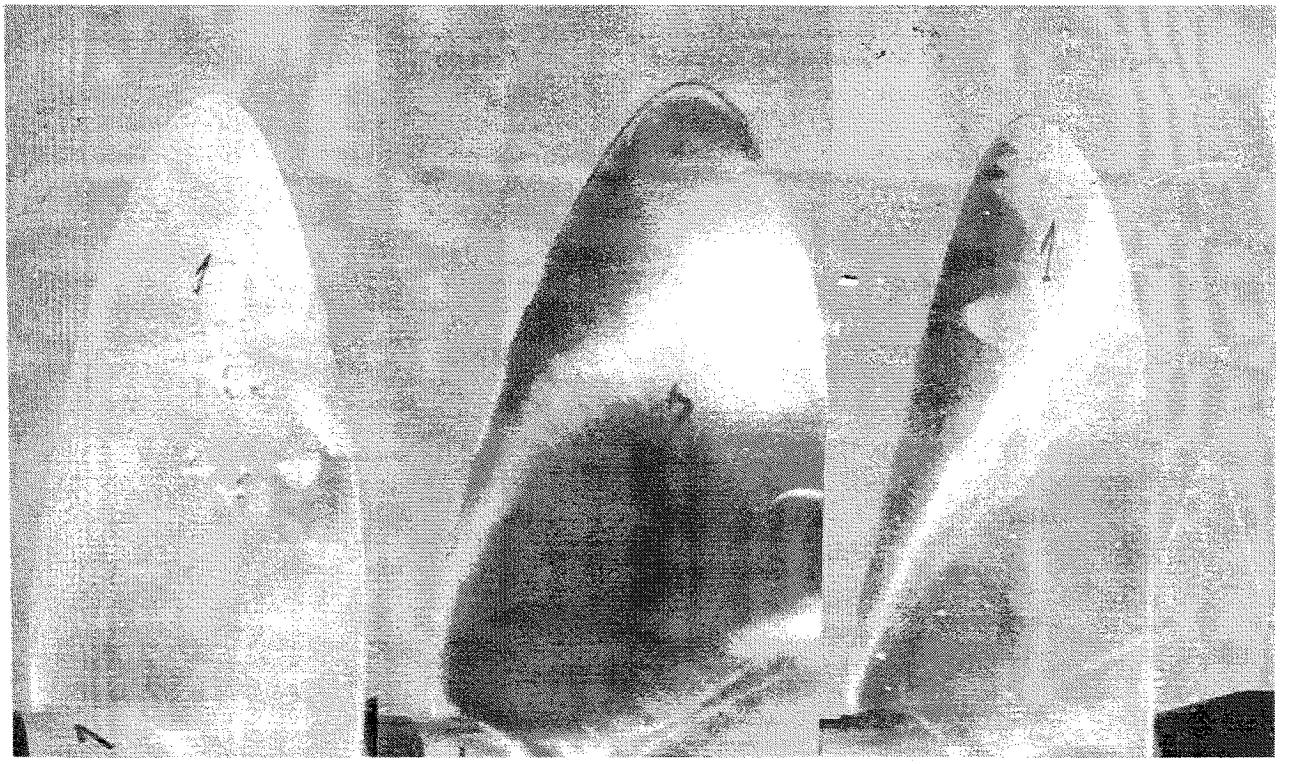


Figure 15: Photographs of cavitation inception for the three propellers.

in cavitation number ratio are 1.00, 0.92, 0.76, and 0.52, which can be compared to data of 1.00, 0.81, 0.60, and 0.41 for the four cases tested. Surface cavitation estimates do not compare and perhaps indicate another mechanism in the cavitation process.

Photographs showing incipient cavitation for the tip vortex, bubble and surface propellers are shown in Figure 15. The cavitation extent near inception is different for varying liquid tension/microbubble distribution. Cavitation inception was determined visually.

Finally, the size of microbubbles available near inception can be estimated by calculating the critical bubble size based on the CSM data and on the liquid tension as determined by the difference in cavitation number. The ratio of these two sizes for tip vortex, bubble and surface cavitation is presented in Table 7.

For the surface cavitation case, there is no apparent nuclei effect on the incipient/desinent cavitation characteristics which explains the large differences in the diameter ratios.

Summary of Results. These tests conducted at the GTH clearly demonstrate the influence of liquid tension/microbubble distributions on propeller cavitation. Little change in cavitation inception with a significant increase in liquid tension was found for blade surface cavitation; however, tip vortex cavitation inception decreased significantly for an increase in liquid tension. The measurement of liquid tension/nuclei distribution by either the CSM, PDA, or holography correlates the observed trends. At very high liquid tensions, the microbubbles involved in the process are apparently smaller than can be detected accurately by holography or the PDA. However, work remains to quantify this relationship.

5.4 Conclusions

The committee agrees that the measurement of liquid tension/nuclei distribution is very important to determine cavitation inception scale effects. Minimizing the liquid tension in a water tunnel or towing tank by some means will reduce these scale effects. Work on correlating liquid tension/nuclei distribution with a cavitation inception definition needs to be continued.

Tension Type	Tip Vortex Cavitation (V)		
	σ/σ_i (case 4)	CSM D_0, μm	$D_0(\delta p) / D_0$
case 1 (maximum tension)	0.41	1.4	0.91
case 2 (medium tension, low nuclei number)	0.60	8	0.17
case 3 (medium tension, high nuclei number)	0.81	11	0.24
case 4 (minimum tension)	1.00	200	-

Tension Type	Bubble Cavitation (B)		
	σ/σ_i (case 4)	CSM D_0, μm	$D_0(\delta p) / D_0$
case 1 (maximum tension)	0.24	1.2	2.21
case 2 (medium tension, low nuclei number)	0.86	8	1.22
case 3 (medium tension, high nuclei number)	0.95	9	3.17
case 4 (minimum tension)	1.00	350	-

Tension Type	Surface Cavitation (S)		
	σ/σ_i (case 4)	CSM D_0, μm	$D_0(\delta p) / D_0$
case 1 (maximum tension)	0.97	1.3	18.39
case 2 (medium tension, low nuclei number)	0.99	9	5.50
case 3 (medium tension, high nuclei number)	-	-	-
case 4 (minimum tension)	1.00	200	-

Table 7: Nuclei numbers/sizes versus cavitation inception.

Significant progress has been made for nuclei measurements with a CSM or PDA system. Comparisons with holographic data are in good agreement. However, the resolution of the control volume for the PDA in order to determine the nuclei concentration over a range of microbubble sizes needs to be defined more precisely.

6 TIP VOTEX CAVITATION

Tip vortex cavitation (TVC) is a distinctive and important feature of the flow past lifting surface blades of a marine propulsor. It is typically the earliest form of cavitation to appear on ship propellers, sometimes at an embarrassing low speed. It is an important source of hydroacoustic noise and can be responsible for erosion damage. It is a difficult problem area because presently it is not possible to make a reasonably accurate prediction of the tip vortex cavitation inception speed for a propeller design without a cavitation evaluation experiment.

A number of mainly experimental efforts have produced significant results in recent years for understanding trailing tip vortex flows and the development of cavitation. These have concentrated on:

1. tip vortex flow structure behind simple wings (lifting hydrofoils) with elliptical or rectangular planform shape,

2. the effects on cavitation inception of water quality as represented by bubble nuclei size and number, and

3. continuing exploration of Reynolds number scale effects.

Very simple wing geometries have been used for most of the detailed velocity mapping work, in order to try to obtain the basic features of the tip vortex flow.

This review covers features of the basic tip vortex flow structure in the near wake region important to cavitation inception, discussion of scaling issues, and a survey of concepts for the delay of tip vortex cavitation. On the general subject of trailing tip vortex wakes, there is a vast and growing literature, principally concerned with aircraft applications. Three survey articles are useful for outlining the older work: Donaldson and Bilanin (1975), Platzer and Souders (1979), and Bushnell and Donaldson (1990).

6.1 Tip Vortex Flow Structure and Cavitation

Formation of a trailing tip vortex near the tip end of a finite lifting surface occurs as the mechanism of relief of the differential of the pressures acting on the pressure side and suction side of the hydrofoil. Understanding tip vortex cavitation requires the understanding of the detailed flow structure of the rolling-up vortex. The real fluid flow characteristics of this flow are difficult and have been the subject of numerous investigations over many years.

The experimental studies have been most useful in illuminating the basic features of the flow. Some of the early detailed air flow measurements past wings include: Chigier and Corsiglia (1971, 1972) and Corsiglia et al (1973). More recent work containing measurements of flow velocity details, analysis and results, and addressing the phenomenon of tip vortex cavitation occuring on simple hydrofoil wings include: Arndt and Keller (1991), Arndt et al (1991), Arndt and Dugue (1992), Dugue et al (1989), Francis and Katz (1988), Fruman et al (1991), Fruman et al (1992), Green (1991), Green and Acosta (1991), Higuchi et al (1987), Higuchi et al (1989), Katz and Galdo (1989), Staufenbiel (1984), Stinebring et al (1989), and Stinebring et al (1991). In the work of Green (1991) and Green and Acosta (1991), the technique of double pulse holography was used to obtain spatial and temportal velocity detail using tailored microbubbles as Lagrangian flow markers. In all the other experiments, laser velocimetry (LV) was used, which provides an Eulerian view of the velocities at each point.

It is instructive to consider the general features of the tip vortex flow structure assembled into a composite picture from the recent work of Fruman et al (1992). Figure 16 shows LV-measured tangential velocities v_{tN} and v_{tS} and the axial velocity v_a at several axial stations obtained inside and near a shed tip vortex core. These results are a composite or collage put together from measurements form two different size hydrofoils with different section geometries obtained in different water tunnels, but both with an elliptic planform having the same aspect ratio of 3.82. Because of the way each hydrofoil was mounted in its facility, the tangential component measured for each was directed at 90 deg. to the other (see the sketch of Figure 16).

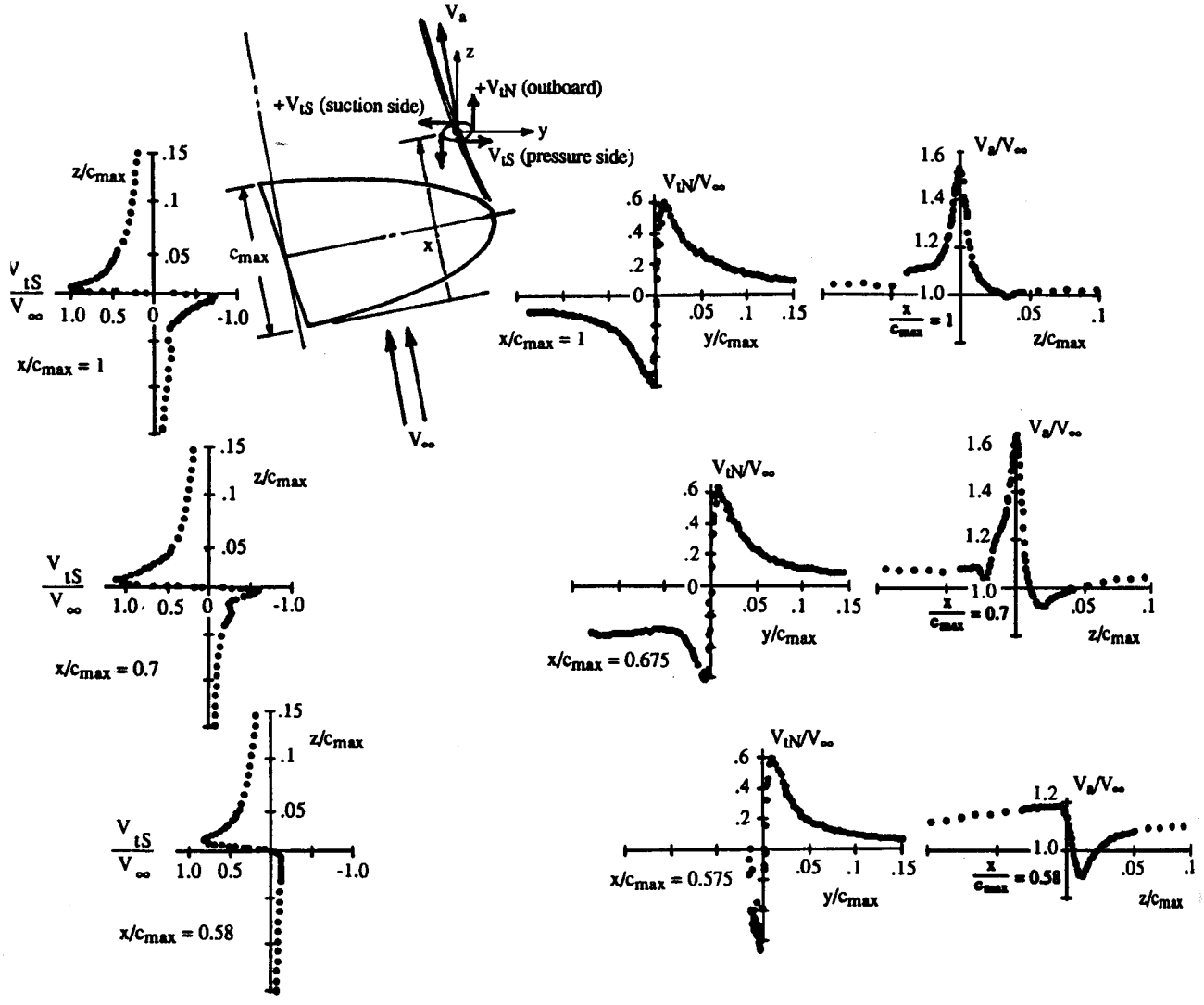
The diagrams for the tangential velocities show the expected flow features of a vortex: the solid body-type inner core flow, the sharply peaked v_t which defines the edge of the rotating viscous core, and the outer region (essentially inviscid) with v_t falling off proportional to the inverse radius raised to a fractional power (see Donaldson et al, 1974) and Hsu (1991). These distributions are at axial stations in the very near wake, where the x is measured from the leading edge line of the maximum chord (see sketch in Fig. 16). The tip vortex described here is captured in the process of rolling-up. It is noted that for each tangential velocity ratio v_{tN}/V_∞ and v_{tS}/V_∞, the maximum value v_{tmax}/V_∞ at the edge of the vortex core occurs downstream of the tip, somewhere in the range x/cmax = 0.6-0.7.

At first glance in Figure 16, it appears that the vortex cross section might be distinctly non-circular because, for example, at around

$$x/c_{max} = 0.7, \quad \begin{matrix} v_{tSmax}/V_\infty = 1.17 \\ v_{tNmax}/V_\infty = 0.67. \end{matrix}$$

Of course, the two velocity distributions come from completely separate experiments, but the differences in Reynolds number and lift coefficient provide the explanation. The tangential velocity distributions become properly similar in magnitude if the velocity ratios are scaled by factors suggested by Hsu's (1989) scaling analysis for tip vortex flow for an elliptic planform wing with elliptic loading, where R_n is the characteristic Reynolds number and C_L is the wing lift coefficient

$$\frac{v_t}{V_\infty C_L R_n^{1/4}} \qquad (4)$$



Spanwise Tangential Velocity
Foil Section NACA 0020
Re = 4.8 x 10^6, $\alpha = 10°$

Normal Tangential Velocity
Foil Section NACA 16020
Re = 1.1 x 10^6, $\alpha = 10°$

Axial Velocity
Foil Section NACA 0020
Re = 4.8 x 10^6, $\alpha = 10°$

Figure 16. Composite plot of tangential and axial velocity ratio distributions for trailing tip vortex from an elliptical planform wing. Two tangential velocity distributions have been obtained from completely separate experiments, described in Fruman, et al. (1992).

For the v_{tN} data (Figure 16) obtained in the ENCT water tunnel, we see that $R_n \approx 1.1 \times 10^6$, $\alpha = 10°$, so that from measurement results provided $C_L \approx 0.33$. For the v_{tS} data, obtained from the GTH water tunnel, $R_n \approx 4.8 \times 10^6$, $\alpha = 10°$ and since there were no lift data measured, the reasonable approximation $C_L \approx 0.48$ applies. Equal magnitudes of the peak values of the tangential distributions v_{tN} and v_{tS} are expected with rolled-up vortices as has been experimentally measured by Green and Acosta (1991), where it was determined that a trailing tip vortex is essentially axisymmetric to within experimental error.

In Figure 16, the plots of the axial flow velocity ratio in and near the tip vortex core show that at the center of the core there is a jet-like velocity excess that builds up to a maximum value of $v_a/V_\infty = 1.63$ at $x/cmax = 0.7$. Further downstream, the peak value of v_a/V_∞ decreases slowly but continues to

show a velocity excess out to several chord lengths. Just outside the tip vortex core, there are narrow valleys of axial velocity deficit ($v_a/V_\infty < 1$). This indicates that there is a weak counter-flow velocity sheath that encloses the suction side of the core jet for this case. In general, the axial flow characteristics of a tip vortex are very complex. The presence of a velocity excess anywhere in the tip vortex core can be linked to the relative magnitudes of wing induced drag and viscous drag components. Crudely, if the ratio of wing induced drag-to-viscous drag is sufficiently greater than one, there will be a jet-like axial core velocity excess. This is expected to occur for high lift because induced drag increases with lift squared. Otherwise, for relatively large viscous drag (which could be increased by flow separation effects), the velocity deficit trend will dominate. Thompson (1975) has described several cases of tip vortex axial flow based on towing basin experiments. He has pointed out that the details of the axial velocity depend on the wing section, Reynolds number, angle of attack, distance behind the wing, and especially the tip edge shape.

Cavitation occurs in a tip vortex when the minimum fluid pressure falls below a critical value p_{crit} which is usually close to the vapor pressure. The pressure coefficient

$$C_{p(crit)} = \frac{p - p_\infty}{\frac{1}{2}\rho V_\infty^2} \qquad (5)$$

characterizing the tip vortex flow usually ignores any effect of axial flow velocity because of the high levels of tangential velocities at the edge of the vortex core, so that approximately

$$C_p(x) = -2\int_0^\infty \frac{v_t^2(x)\,dr}{V_\infty^2 r} \qquad (6)$$

From the typical flow structure of the tip vortex seen in Figure 16, it is expected that the location of minimum fluid pressure in the flow over a lifting surface is likely to occur at the edge of the tip vortex core, somewhere downstream of the tip. A qualitative description of the development of tip vortex cavitation, then, follows three main stages (Souders and Platzer 1981).

• Detached cavity fingers appear first. These initial, intermittent cavity fingers have been observed to start at downstream locations measured from the leading edge of the wing (with tip chord length c_t) in the range of 1.07 c_t, 1.3 c_t to 3c_t and 1c_t according to Stinebring et al (1991), Green (1991), and Arndt and Dugue (1992) respectively. There are clearly many factors involved with such observations, not the least of which is a dependence on the facility.

• Vortex cavity is attached, thin, steady, and essentially circular cross section, with no growth orchange for many chord lengths downstream.

• At the advanced stage, the tip vortex cavity has thickened considerably, has a "twisted" or braided appearance, and may be joined with leading edge sheet cavitation.

Flow unsteadiness affects model experiments in terms of the measurement of tip vortex flow velocity magnitudes, vortex core location, and the condition of vortex cavitation inception itself. Inherent unsteadiness of the axial flow velocity right on the core centerline has been observed to be very high. Green and Acosta (1991) used a double pulsed holography method with tailored injected microbubbles and were able to measure instantaneous velocities for both axial and tangential flow velocity components within and near a tip vortex. They noted that the large observed scatter in the axial velocity was a real effect. For instance, for the high angle of attack case of a = 10°, the RMS fluctuating component of axial velocity on the vortex core centerline was found to be 0.2V∞. The vortex tangential velocity for the same high lift core also show some level of inherent unsteadiness, with a data spread of ±0.08 V∞, believed to be a real effect because the experimental error is ±0.01 V∞.

Vortex meandering or wandering of the vortex core is a familiar, observed feature of tip vortex flows. Especially at several chord lengths downstream, there is typically an erratic fluctuation of the vortex trajectory. This has been observed many times, for example by Corsiglia et al (1973) with measurements in air, by Baker et al (1974) with LV measurements in a water tunnel, and by Green and Acosta (1991) with measurements in a water tunnel. This phenomenon is most often at-

tributed to free stream turbulence in the test facility flow. The effect of vortex wandering is to broaden the velocity profiles and reduce the magnitude of the variations. Baker et al (1974) have investigated the magnitude of a correction to the $v_{t\ max}$ and the vortex core radius using observed RMS values of the displacements of a tip vortex.

For the downstream velocity field and details of trailing tip vortices behind propellers, Blaurock and Lammers (1988) have presented results from LV surveys which show the effects of skew. They found that increasing skew tended to reduce the magnitudes of the unsteady velocity components. Jessup (1989) conducted extensive LV velocity measurements of the flows both on the passing blades of model propellers and in the near field wake of the blades as well.

Vortex breakdown or vortex bursting (see Leibovich, 1978) is an extreme flow behavior that can occur with partially or fully rolled-up tip vortices trailing from lifting wings or propeller blades. The conditions for occurence of vortex breakdown are understood only in general, qualitative terms. It is known that the tendency for vortex breakdown in non-cavitating flow is promoted by an adverse pressure gradient along the vortex axis. This could occur in a decelerating external flow. A characteristic feature of vortex bursting is the disappearance or drastic reduction of the axial flow velocity in the vortex core. The phenomenon is usually observed in aging tip vortices where the core axial velocity has become very weak. It is not clear what trips the actual vortex breakdown. The effect of cavitation on the occurence of vortex bursting is even less understood. Interest here is in the possible occurence of bursting vortices at or very close downstream to the blade tips of a ship propeller operating adjacent to the hull boundary with blades passing through the nonuniform stern wake flow. English (1992) has recently suggested that successive vortex breakdown sites of the helical tip vortex system trailing from the propeller blades are "critical sites" or periodically occuring stagnation regions in the flow. These sites are thought to have a crucial role in the formation of cavitation propeller-hull vortex (PHV), first described by Huse (1972). It is suggested that each vortex breakdown site may be involved with the mechanism of transferring vorticity between the stationary PHV (extending from a point on the hull) to a fluctuating position in the flow on each of the passing cavitating tip vortices. Actually, it is not clear whether the vortex bursting helps create the conditions for the cavitating PHV to appear or whether the tendency for the hull-vortex to form causes the trailing tip vortex to burst in the relatively nearfield downstream trajectory of the tip vortex. (DeSiervi et al, 1982).

6.2 Scaling Issues

There are two main categories of scaling issues for tip vortex cavitation: Reynolds number and water quality. Physically, the regime of the influence of viscosity is confined to the core of the tip vortex flow field as the roll-up progresses. The important effect is the action of vorticity diffusion within and at the edge of the vortex core. At low Reynolds number, the action of viscous diffusion is relatively stronger than it is at higher Reynolds number. It is therefore expected that for a given magnitude and distribution of bound circulation (which governs the level of vorticity being fed into the tip vortex), the vortex core radius is relatively larger and the peak value of maximum tangential velocity at the edge of the core is relatively lower at low Reynolds numbers than at high Reynolds numbers.

Water quality in the present context refers to the presence of free air in the form of small bubbles and to the state of flow turbulence. There must be sufficient population of microbubbles in a test facility flow to function as nuclei or sites for the initiation of cavitation (or cold boiling) to occur. Both size and number density are important. The state of nuclei content can be related to the tensile strength of water. Qualitatively, if there are very few microbubbles present, it is possible to "pull a tension" in a water flow, wherein even if the minimum pressure falls below the vapor pressure, the water will not fracture or cavitate. Local pressure fluctuations due to turbulence or inherent flow unsteadiness can produce an instantaneous minimum pressure below the mean static pressure level. These two water quality features have opposing influences on the outcome of a cavitation inception experiment, and quantifying the details of their effects has been, and will continue to be, a challenge in this field.

Chandrashekhara (1976) showed that for hydrofoil wings, the inception cavitation num-

ber was dominated by the bound circulation strength squared

$$\sigma_i \propto [\Gamma/V_c]^2 \quad (7)$$

where Γ= bound circulation, c = characteristic chord, and V = free stream velocity, and he presented results of experiments for validation. He then showed how for propeller cavitation inception, the blade loading parameter can be recast as

$$\Gamma/V_c \sim C_L \sim \alpha_e \sim (\frac{P}{D} - J) \quad (8)$$

where C_L = lift coefficient, α_e = effective angle of attack, P/D = pitch-to-diameter ratio, J = V/nD = advance coefficient, n = rotational speed in revs/sec, and D = propeller diameter.

The experimental trends found in the original work of McCormick (1962) on this subject included the effect of scaling with Reynolds number. These trends were incorporated into empirical estimation formulas by Noordzij (1977) and Kuiper (1979) who suggested the estimation formula for propeller tip vortex cavitation inception

$$\sigma_{ni} \propto (\frac{P}{D} - J)^{1.4} R_n^{0.35} \quad (9)$$

where σ_{ni} is nondimensionalized by the factor $(1/2)\ \rho\ (nD)^2$, the propeller blade pitch ratio is taken at r/R = 0.9, and the Reynolds number R_n here is based on propeller tip speed. The Reynolds number exponent factor is m = 0.35.

While the direct use of this kind of formula has limitations for arbitrary propeller blade geometries, ratio of the expressions for ship-to-model leads to a familiar form for Reynolds number scaling the results of model scale cavitation inception

$$\frac{\sigma_{is}}{\sigma_{im}} = \left[\frac{R_{ns}}{R_{nm}}\right]^m \quad (10)$$

where subscripts s and m refer to ship and model, and where the exponent factor could be m = 0.35. The effect of circulation loading present in Equation 9 cancels out by taking the ratio, if the experiment is conducted using the thrust identity (or thrust loading similarity) and, kinematic similarity. In Equation 10, the form of cavitation number σ and the Reynolds number R_n are not important as long as they are used consistently for both ship and model values.

Use of the form of Equation 10 in the ITTC community is widespread. Basically, every laboratory group has its own preferred Reynolds number exponent factor m. Typical values in use range from m = 0.35 to 0.4. In fact, this factor should be treated as a correlation parameter, to be updated by continuing experience with full scale cavitation inception observations.

Hsu (1991) has carried out a "scaling analysis" of the trailing tip vortex flow generated by a lifting surface. The result provides a link between the Reynolds number exponent factor and the spanwise distribution of lift-producing circulation strength on the wing. The analysis uses the velocity distribution of a rolled-up vortex sheet from the Betz (1932) model developed by Moore and Saffman (1973) as an outer solution, together with a similarity solution for the axisymmetric, unsteady viscous flow velocity within the thin core of a vortex as an inner solution. In Hsu's interpretative analysis, the minimum pressure in the vortex core is ultimately connected with the circulation distribution through the action of viscous diffusion. With the assumption that cavitation inception occurs when the minimum pressure equals the vapor pressure, a result is given by Hsu (1991) for the inception cavitation number for a planar hydrofoil wing of the form

$$\sigma_i \propto C_L^2 R_n^m \quad (11)$$

with R_n = chord length Reynolds number, and where the Reynolds number exponent parameter m depends on the circulation distribution over the planform. For example, for elliptic loading an exponent of m = 0.5 is utilized. An approximate result for propellers is also given by Hsu (1991) for the inception cavitation number for tip vortex in the form

$$\sigma_i = \left[\frac{K_T}{ZJ^2} f_p(m, \frac{R}{c}, \frac{J_{des}}{J}, w_T, \Gamma_{des})\right]^2 R_n(0.7R)^m \quad (12)$$

where K_T = thrust coefficient, Z = number of blades, R = propeller blade radius, J_{des} = advance coefficient at design loading, w_T = wake

fraction, Γ_{des} = dimensionless design circulation distribution, and the Reynolds number is

$$R_n(0.7R) = \frac{v_A c_{0.7}}{\nu} \frac{1}{\sqrt{1 + (0.7\pi/J)^2}}$$

See Hsu (1991) and the 19th ITTC Cavitation Committee Report (1990) for the details of the function f_p inside the bracket in Equation 12.

The proper value for the parameter m must be solved iteratively, based on model test values for the inception cavitation number σ_i and all the other factors entering into the function f_p and Reynolds number (R_n). Once the parameter m is derived using propeller model results from sufficiently high Reynolds number tests, it is expected to apply to full scale cavitation inception as well. The scaling procedure follows, then, from Equation 10. Some examples of predictions based on the Hsu (1991) scaling procedure for tip vortex cavitation inception speeds for full scale propellers have been presented by Hsu and Remmers (1989). Generally favorable trends have been achieved. These results have been based on model cavitation tests run at Reynolds numbers in the range $R_n(0.7R) = 4 \times 10^6$ to 9×10^6.

From the recent extensive experimental results described by Fruman et al (1992), data are provided for desinence cavitation number for tip vortex cavitation formed on an elliptic planform wing. It is interesting to note how well the plots of σ_d versus Reynolds number can be fit with the exponent parameter $m = 0.5$ as indicated in Figure 17. Recall that the scaling analysis of Hsu (1991) shows that the expected Reynolds number exponent parameter for an elliptically loaded wing is $m = 0.5$.

An interesting form of the statement for inception of vaporous cavitation in tip vortex flow has been suggested by Higuchi et al (1989) and Arndt and Dugue (1992) which highlights the nature of scaling problems with respect to water quality. The condition for inception, that the minimum pressure in the flow fall below a critical value

$$P_{min} = P_{crit} \qquad (13)$$

can be expressed in terms of the inception cavitation number

$$\sigma_i = -C_p(min) + k_f \frac{p'}{\frac{1}{2}\rho V_\infty^2} - \frac{T}{\frac{1}{2}\rho V_\infty^2} \qquad (14)$$

with

$$\sigma_i = \frac{(p_\infty - p_v)}{\frac{1}{2}\rho V_\infty^2}, \text{ and}$$

$$C_p(min) = \frac{(\bar{p}_{min} - p_\infty)}{\frac{1}{2}\rho V_\infty^2}$$

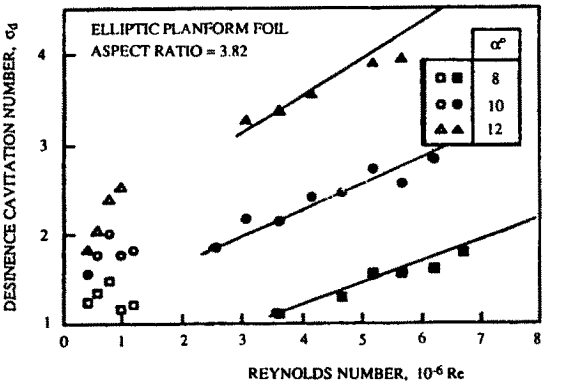


Figure 17: Example variation of desinence cavitation number with Reynolds number for tip vortex cavitation (Fruman et al 1992). Curve fits shown with Reynolds number exponent parameter m=0. 5.

The instantaneous minimum pressure can be less than the mean static pressure due to pressure fluctuations.

$$p_{min} = \bar{p}_{min} - k_f p' \qquad (15)$$

where k_f is a complicated factor involving the interaction of bubble nuclei and the fluctuating pressure. The critical pressure value can be less than the vapor pressure

$$p_{crit} = p_v - T \qquad (16)$$

where T is the "tension" or tensile stress that the fluid can sustain, which depends on the number and size distribution of bubble nuclei. In general, water with a high population of bubbles can sustain very little or no tension and is termed "weak". When devoid of any

bubbles larger than say 5 - 10 μm diameter, water can take a large tension (possibly up to 2 atmospheres), and is called "strong". Arndt and Dugue (1992) point out that the two "water quality terms" in Equation 14 are often of the same magnitude. So their effects could cancel out. It is also difficult to isolate or separate their influence.

Arndt and Dugue have offered some ideas on how to quantify these effects. If cavitation inception is measured in weak water (σ_{iw}) and in strong water (σ_{is}) and if the weak water result σ_{iw} can be corrected to zero tensile strength, then the third term of Equation 14 can be obtained

$$T = \frac{1}{2}\rho V_\infty^2 (\sigma_{iw} - \sigma_{is}) \qquad (17)$$

Unfortunately $C_p(min)$ is very difficult to measure directly, and its inference from detailed measurements of tangential velocities in the vortex (see Equation 6) cannot be regarded as a routine experiment free of complicating interference of real flow effects. However, if a clean value of $C_p(min)$ can be obtained, then the fluctuating pressure contribution can be estimated by

$$k_f \frac{p'}{\frac{1}{2}\rho V_\infty^2} = \sigma_{iw} + C_p(min) \qquad (18)$$

Under the most favorable conditions, these procedures for scaling water quality effects are qualitative because the tension and the turbulence factor k_f are both highly influenced by the bubble nuclei content in the flow. Discussions of related issues may be found in Stinebring et al (1991), Billet and Holl (1979), Green (1991), and Green and Acosta (1991).

6.3 Concepts for Delaying Tip Vortex Cavitation

Although our interest is in delaying tip vortex cavitation (TVC) associated with hydrodynamic lifting surfaces (especially propeller blades), we note that many useful concepts for tip vortex manipulation and control have come from the aerodynamic world. To delay TVC, the desired effect is to relieve the intensity of the trailing tip vortex. This objective is shared by both aerodynamic and hydrodynamic concerns. There are three main indicators: diminish the magnitude of the peak tangential velocities, increase the vortex core diameter (disperse or encourage the dissipation of the organized vortex), and raise the vortex core pressure.

Two themes are important in measuring success in aerodynamic applications. The first concerns the magnitude of reduction of induced drag, or lift increase on a given size planform, with an overall net increase of lift-to-drag ratio. The second involves the dispersement of the strong trailing vortex patterns that are produced by large aircraft during landing that can create a hazard for following aircraft. Especially this second category deals with the far vortex wake of a lifting surface which has little to do with the very near vortex wake important to the qualities of the tip vortex velocity pattern giving rise to vortex cavitation inception. Thus, a useful concept for alleviating tip vortex effects on aerodynamic lifting surface performance does not necessarily translate to a viable scheme for delaying the onset of tip vortex cavitation on propeller blades.

Concepts for tip vortex reduction can be organized under the main groupings: 1. Foil and Tip Geometry Treatments, 2. Mass Injection, and 3. Direct Vorticity Manipulation. For each concept, the mechanism of vortex control is described in terms of one or more of the following: (i) alter the character and/or magnitude of the bound circulation, (ii) accentuate diffusion (dissipation of vortex core vorticity over a larger region by reorganization and turbulence), (iii) introduce counter-vorticity for unwinding, cancellation, or weakening of the original vortex.

Foil and Tip Geometry Treatments.

1. Concept: Bulbous Tip.

A tip bulb is a rounded, local thickening of the tip end of the blade or wing. There are two important effects: 1. Flow over the bulb can introduce turbulence and thickened wake flow into the vortex core which acts to dissipate the vortex intensity, and 2. Flow around the bulb-shape helps interfere with the formation of strongly organized vortex. Key References: Crump (1948), Souders and Platzer (1981), Platzer and Souders (1980), Johnsson and Rutgersson (1991).

2. Concept: Ring Wing Tip, Tip Duct.

A hollow, duct-like shape is placed at the tip end of a wing or blade. It could extend part way or over the full length of the tip chord. It acts to alter the distribution and slope of the circulation near the tip. The net vorticity pattern shed into the tipvortex is distributed and therefore provides less concentrated and more weakly organized vorticity into the core. Key References: Green et al (1988), Duan et al (1992), Spencer et al (1966).

3. Concept: Endplates, Winglets, Tip Sails.

Various items within this general category have differing mechanisms for vortex control. Placement of endplates at the wing tip interferes with the vortex rollup process. Such plates will add turbulence and thickened wake flow into the vortex core. Endplates can be arranged at the tips of propeller blades (de Jong, 1992) in such a way to improve the lift efficiency of the blades. A wider distribution of shed vorticity has been observed (van Gent et al (1992)) in cavitation tests, but it is not clear whether there is an improvement in the overall tip vortex cavitation inception performance. Winglets (Whitcomb, 1976) are slender, high aspect ratio lifting appendages placed at a wing tip. They act to interfere with the tip vortex rollup process, and they are arranged to operate in the angled flow near the tip in order to provide extra wing lift. Tip Sails (Spillman (1978)) are also high aspect ratio and cambered lifting appendages placed at the wing tip, but are twisted and cambered so that they operate in the angled flow near the tip and are arranged in order to provide an extra force in the thrust direction. They also act to interfere and retard the tip vortex rollup. Key References: Hoerner (1965), de Jong (1992), van Gent et al (1992), Fornells and Gomez (1983), Whitcomb (1976), Flechner et al (1976), Spillman (1978).

4. Concept: Roughened Tip Region.

Roughness applied to small regions near the wing tip will act to increase the level of turbulence in the core of the tip vortex. This tends to increase the diffusion of vorticity at the edges of the core, thereby hastening the dissipation of the vortex. Selective roughening of a bulbous tip could increase the effectiveness of that concept as well. Key References: Katz and Galdo (1989), Platzer and Souders (1980), Souders and Platzer (1981), Johnsson and Rutgersson (1991).

5. Concept: Porous Tip.

Porosity of the wing tip can be created by putting holes or passages passing through the hydrofoil from the pressure side to the suction side. This will allow adiffused pressure equalization between the two hydrofoil surfaces and a local reduction of the circulation strength and slope, and therefore a weakening of the tip vortex intensity. The presence of the holes could also increase the level of turbulence feeding into the core with the resulting increase of core pressure and increased diffusion/dissipation of vortex intensity. Key References: Smith (1980), Spencer et al (1966).

6. Concept: Planform Shape.

Spanwise planform shaping could involve features such as skew and/or leading edge sweepback to alter the shape and especially the slope of the circulation distribution near the tip in order to reduce the intensity of vorticity feeding into the tip vortex. Swept tip planform shape can also influence the character of leading-edge separation-induced vortex flow in the planform tip region so as to produce favorable lift and moment features because of attached flow near the tips, even at high angles of attack. Key References: Boswell (1971), Cumming et al (1972), Holbrook et al (1985), Yamasaki et al (1982), Faller (1990), Rossow (1975), van Dam et al (1991).

7 Concept: Tip Region Pitch Reduction and Camber Unloading.

This involves simple approaches for tip unloading by changes of pitch and/or camber. These alter the magnitude and slope of the circulation distribution near the tip in order to reduce tip vortex intensity. Key References: Coon (1963), Glover et al (1979), Lover and Wills (1979).

Mass Injection.

1. Concept: Same Fluid Injection.

Same-fluid mass injection involves the active or possibly passive ejection of fluid out from the tip region. Axially-directed jets could be

aimed either upstream or downstream. Either way leads to a thickening of the vortex core, an increase of the core pressure, and increased dissipation of the vortex intensity. Transversely-directed jets could be aimed with a variety of angles, and serve to block, interfere with, and redirect the tip vortex rollup process. Key References: Jarvinen (1973), Lee et al (1989), Platzer and Souders (1980), Souders and Platzer (1981), Spencer et al (1966).

2. Concept: High Polymer Solution Injection.

This concept involves the selective injection of a highpolymer (drag-reducing) solution axially downstream into the vicinity of the vortex core. The viscoelastic behavior of jet-swelling acts to thicken the vortex core and increase the core pressure,with the resulting improvement of tip vortex cavitation inception speed. Key References: Chahine et al (1992), Fruman and Affalo (1990), Inge and Bork (1983), Hoyt (1978).

Direct Vorticity Manipulation

1. Concept: Contravanes, Twist Fence.

These concepts call for placement of a series of small vanes on each surface of a wing tip, or a short angled fence on the suction side. The angle of attack of the vanes and the curve pattern of the fence should be arranged to produce a local swirl velocity with rotation opposite to the tip vortex. The resulting unwound and weakened vorticity would diminish the intensity of the tip vortex. Key References: Marchman and Uzell (1972), Spencer et al (1966).

2. Concept: Wingtip Rotors.

There are two varieties of tip-mounted propellers or pump rotors envisioned for this concept. A turbine version would free-wheel and work to remove some of the rotational flow intensity at the tip, thereby weakening the vorticity feeding into the tip vortex rollup. A powered-rotor version could be driven (i) so as to inject mass (thrust) upstream with a resulting tip vortex dissipation effect; or it could be rotated (ii) so as to introduce a counter-rotation to the tip vortex. This would reduce the intensity of the net vorticity feeding into the tip vortex. Key References: O'Conner (1992), Snyder and Zumwalt (1969).

6.4 Conclusions

The present discussion has centered on tip vortex flows and trailing vortex cavitation issues because of the predominance of published work in that area. With regard to flow structure and mechanism, some conclusions include:

- There is considerable inherent unsteadiness of the velocities within the tip vortex core, especially the axial velocity component. Naturally occurring RMS velocity fluctuations of the axial and tangential components have been observed up to $\pm 0.2V_\infty$ and $\pm 0.8_\infty$ respectively.

- Axial core velocity unsteadiness is a good predictor of core pressure unsteadiness.

- A mechanism of tip vortex cavitation inception can definitely be related to bubbles cavitating in regions in the core in which the flow unsteadiness has caused local pressures to fall below the vapor pressure p_V, even though the mean core pressure is above p_V.

- There is no question that the inception cavitation number value is decreased dramatically when the air content is reduced, but the mechanisms and physical explanations are not clear.

- The details of the initiation of tip vortex roll-up are poorly understood. It is known that small changes in hydrofoil tip geometry can make large changes in the inception and character of cavitation at or near the tip. Also, any flow separation near the tip region can significantly alter tip vortex cavitation. The apparent wide variety of possible tip flow separation configurations on elliptic planform wings may be one reason why the cavitation inception results are difficult to correlate.

The Reynolds number scaling of tip vortex cavitation inception from the results of model testing continues to be based on correlation experience built up by each laboratory and is highly facility dependent. However, the basic form, suggested by McCormick (1962) is universally applied. There is a distinct need for an extended scaling law that incorporates the influence of nuclei size and content, which can

be related in some reasonable way to liquid tension measured in the facility flow.

Out of the large number of concepts suggested for relieving the intensity of a trailing tip vortex and thus delaying vortex cavitation inception, there are several categories that hold promise for practical applications to marine propulsors. These include: bulbous tip, tip duct, high polymer solution mass injection and planform shape.

7 WAKE SIMULATION IN CAVITATION TUNNELS

An accurate simulation of nonuniform wake distribution is crucial for the successful model tests of a propeller in a cavitation tunnel. However the target wake, which should be selected for the best correlation of model test results with full scale ones, can be different from one cavitation tunnel to another depending on previous experiences with model-full scale correlation. The method to generate the target wake also depends on available facilities of each cavitation tunnel.

The present situation on determining a target wake is confusing. Some organizations insist on using a model scale nominal wake as the target wake instead of simulating a predicted full scale wake, which inevitably contains scaling errors. Others use various scaling methods. Reliable full scale velocity data and corresponding full scale cavitation test results should be compiled for some time in order to determine the target wake on a firm physical background. Reliable methods are also needed to scale the nominal wake as measured in the towing tank.

Wakes in a cavitation tunnel are usually simulated by wire mesh grids, dummy models or ship models. Even though the importance of three-dimensional wake simulation is widely acknowledged, many organizations still use wire mesh grids with which only the axial component of wake is simulated. However effects of the cross flow components on cavitation test results can be considerable for certain types of ships, although uncertainties in extrapolating the test results to full scale sometimes conceal these effects.

When a complete ship model is used to simulate a three-dimensional wake distribution in a cavitation tunnel, the wake distribution may be quite different from that measured in a towing tank behind the same model due to the tunnel blockage effect. Flow control devices, such as flow liners, can be introduced in order to minimize these wall effects.

In this report, progress regarding wake simulations in cavitation tunnels is reviewed with emphasis on three-dimensional wake simulations and on flow control devices to reduce the tunnel wall effects.

7.1 Effects of Wake Simulation on Cavitation Test Results

Effects of Cross Flow Components. It is widely acknowledged that cross flow components of a wake simulated in a cavitation tunnel can play an important role in determining the cavitation performance of a propeller. Ball (1989) performed a series of cavitation experiments in systematically varied three-dimensional wake fields for a Navy propeller having an inclined shaft angle of 10 degrees. Direct influences of wake simulation on cavitation performances were confirmed by these experiments. The tangential velocity components were shown to be the chief influence on inception and extent for all forms of stable cavitation.

Lee (1992) calculated the unsteady loading and the cavitation performance of the "Sydney Express" propeller operating in the three-dimensional wake field using a lifting surface code, and compared the results with those of the propeller in the same axial wake but without the radial and tangential components. The comparison showed the direct influence of the cross flow components of the wake on the unsteady blade loading and cavitation. The calculated results also showed an increase of cavity extent on the starboard side for this right handed propeller due to the upward tangential velocity component.

In spite of the apparent influence of the cross flow components on cavitation performance, many facilities still use wire mesh grids with which only the axial component of wake is simulated. This is partly because of limitations of test facilities and partly because of confusion in determining a target wake. The target wake should be a three-dimensional full scale nominal wake, of which the prediction method is not well established. In order

to assess the importance of three-dimensional wake simulation, a more reliable prediction method of a full scale wake should be developed.

Prediction of Full Scale Wake. A number of investigators suggested full scale wake prediction methods (Hoekstra, 1975, Sasajima and Tanaka, 1966, Tanaka, 1979), but no reliable prediction method has appeared yet.

Sasajima and Tanaka (1966) suggested a simple method for the prediction of the full scale nominal wake from the measured model nominal wake. The basic assumption was that no appreciable separation occurs at the stern of a ship and that the velocity distributions at the stern of a model ship and a full scale ship are similar to each other. The result was that the velocity defect ratio is the same between the model and full scale ships and the width of the iso-axial wake is proportional to the frictional resistance coefficient. Considering wake patterns of modern VLCCs, where a pair of strong bilge vortices are intentionally generated to improve the wake uniformity to a propeller (Kim 1992), a more rigorous method to predict a full scale wake even for a separated flow should be developed.

Blake et al (1990) estimated a full scale wake after the sea trial of the "APL C-10" container ship in order to find a correlation between the model cavitation test results and the full scale ones. Model tests were performed, before the sea trial, in the model nominal wake simulated by wire mesh grids. The model tests over-predicted cavitation extents and fluctuating hull pressure values compared to the full scale ones. The full scale nominal wake distribution was then estimated by multiplying the model wake value at each location by a factor w_s / w_m, where w_s denotes the full scale Taylor wake fraction obtained from the torque identity method during the sea trial, and w_m denotes the nominal wake fraction of the model. Model tests were then repeated using this estimated full scale wake. The observed cavitation extent showed fair agreement with the full scale results, but the fluctuating pressure amplitudes were found to be lower than the full scale values.

Accuracy of the predicted full scale wake is ultimately evaluated by the correlation between model test results and full scale ones. In order to setup the correlation data base, full scale cavitation observation is encouraged. New methods for full scale cavitation observation should also be developed. MARIN developed a new technique to observe propeller cavitation of fast naval ships through a ball type perspex window (Kuiper 1992). The ball type window, inside which a CCD camera is installed, can be rotated to change the viewing angle. Early planning was made so that the windows for observations and illuminations of propeller cavity may be easily installed during the construction of a ship.

Analytical prediction of a ship's stern flow at full scale Reynolds number should be possible in the near future. CFD methods solving Reynolds Averaged Navier-Stokes (RANS) equations with a proper turbulent model seem promising (Ju, 1991, Larsson et al, 1991, Stern et al, 1988, 1991, 1992), even though calculation of the flow around a real ship geometry at full scale Reynolds number requires more efforts to tackle the currently involved problems, such as grid generation, near wall treatment of the turbulent flow near the hull surface, etc.

In order to establish the wake scaling procedure with a firm background, reliable full scale velocity measurements of ship's stern flow are indispensable.

Measurement of Full Scale Wake Distribution. Since the first full scale measurement (Kux, 1978) of a ship's stern flow, measurements of full scale flow velocity have been attempted mainly using Laser Doppler Velocimetry (LDV) (Kato and Ukon, 1990c, Kux, 1984, 1990, Norris, 1983, Tanibayashi, 1990). The measurements, however, require big installations and very precise arrangements of the optical system. The measuring locations are confined to the vicinities of the windows through which laser beams reach the flow field. Recently MARIN has successfully carried out LDV measurements at full scale (Kuiper, 1992).

Komura et al (1991) developed a tracer/multi TV camera system which can be used to measure a full scale three-dimensional velocity field with much less efforts. They used wooden balls as tracers. The tracers were ejected at the upstream of measuring zone. Positions of the tracers were traced by three CCD cameras, digitized and registered using mouse type digitizers. By differentiating the

positions of the tracers with respect to time, a three-dimensional velocity field was obtained. They claimed that the tracer/multi TV camera method is more convenient and more robust with regard to both installation and measurement than a LDV system. The measured velocity distribution of a training ship ("Seiunmaru") showed somewhat different values compared to that measured by a LDV system.

Since the total wake (velocity) is always measured in a full scale velocity measurement while a propeller is operating, the effective wake has to be found by subtracting the propeller induced velocities from the total wake. Since these induced velocities depend on the effective wake which is to be calculated, this can only be done in an approximate way. The full scale nominal wake, which should be simulated for the best model-full scale correlation, will be predicted by subtracting the propeller-hull interaction components from the calculated effective wake.

Simulation of Total Wake. A more accurate simulation of the inflow velocity to propeller blades would be provided by simulating the total wake distribution with a working propeller. As the measurements of the total wake (the velocity field in front of or just behind the working propeller in behind-condition) become popular both at model and at full scale, direct simulation of the total wake would become possible. Simulation of the total wake would enhance the accuracy of model tests and allow one to find direct correlations with full scale observations, because the propeller-wake interaction effects are taken account inherently (Kux, 1984).

The velocity measuring technique using a LDV system should also become less time consuming to be implemented in routine cavitation tests. Further development of the measuring technique is recommended for the method of total wake simulation to be tested and evaluated.

7.2 Flow Liners for the Control of Wake Distribution

Improvement of Wake Simulation Using Flow Liners. In some cavitation tunnels having larger working sections, a complete ship model or a dummy model is installed into the working section to simulate a three-dimensional wake into a propeller. However, the wake distribution can be quite different from that measured in a towing tank due to the tunnel blockage effects. In some cases, when using a complete ship model, the wake distribution becomes nonsymmetrical even though the ship is installed symmetrically. Fow liners can be introduced in order to overcome these wall effects. A typical arrangement of a pair of flow liners installed in a rectangular test section is shown in Figure 18.

Figure 18: Surface representation of the Sydney Express ship model with flow liners (Lee 1992c).

Flow liners can also be used to simulate the predicted full scale wake without modifying the ship model. Since the flow liner accelerates the flow near the ship's stern, the pressure gradient becomes more favorable compared to the situation without flow liner and accordingly the boundary layer thickness is reduced. The resulting wake distribution is assumed to resemble that of a full scale ship more closely. Ukon (1991) reported good correlations of fluctuating hull pressure between model and full scale for six selected ships, including two VLCCs, by adopting flow liners in order to simulate the estimated full scale wake.

Design Method Using Rankine Source Distributions. A Rankine source distribution can be used to design a flow liner at an early stage of development (Ukon and Kodama, 1992c). A potential flow is assumed and the flow around a ship model is approximated as axi-symmetric: the afterbody of a ship model is simplified to an equivalent ellipsoid having the same cross sectional area. The flow around the ellipsoid in an unbounded fluid can

simply be solved by distributing Rankine sources along the body center line. The location of the streamline surface which hits the tunnel wall boundary at the midship position is then calculated. The longitudinal sectional area of the flow liner is determined as the area between the tunnel wall and the calculated stream surface. Then local shape of the flow liner is determined empirically, considering the real geometry of the ship model and the tunnel wall.

Since the Rankine source method is based on a potential theory, the width of iso-velocity contour of the resulting wake distribution is narrower than that of the target one. The reason is the neglect of the boundary layer on the model and tunnel wall surfaces.

Analysis Using a Surface Panel Method. In order to estimate the tunnel wall effect and to obtain a general insight for the design of more realistic flow liners, a surface panel method was adopted for the calculation of the flow around a ship model installed in a rectangular test section of a cavitation tunnel (Lee 1992b,1992c). Sample calculations were performed for the "Sydney Express" ship model installed in a cavitation tunnel, as shown in Figure 18. The wake distribution of this model had been measured in the SRI cavitation tunnel with and without flow liners (Ukon, 1991).

In order to evaluate the tunnel blockage effect, pressure distributions on the hull surface in different sizes of test section were calculated (Lee, 1992c). As shown in Figure 19, the longitudinal adverse pressure gradient near the afterbody increases as the blockage increases, which would increase the possibility of flow separation. The increase of the pressure gradient is significant for those cases with more than 20% blockage of the test section, while it is negligible for the cases with less than 5% blockage. It implies that flow liners should be incorporated when the blockage is larger than 20%. For the wake simulation of a ship with blunt afterbody of which boundary layer can grow rapidly and separate easily, tunnel blockage effects can be significant even for a small blockage of 5%.

Pressure distributions on the ship surface for the cases of with and without flow liners are compared in Figure 20. The comparison shows that the flow liners accelerate the flow near the afterbody of the ship model, so that a more favorable pressure gradient and a narrower boundary layer thickness may result.

Even though the overall flow near the afterbody is accelerated due to the installation of the flow liners, the iso-axial velocity contour reproduced from the calculated wake distribution (non-dimensionalized by the maximum axial velocity on the propeller disk surface) does not change appreciably. Boundary layer corrections should be added in order to correlate the calculated velocity distribution to the measured one.

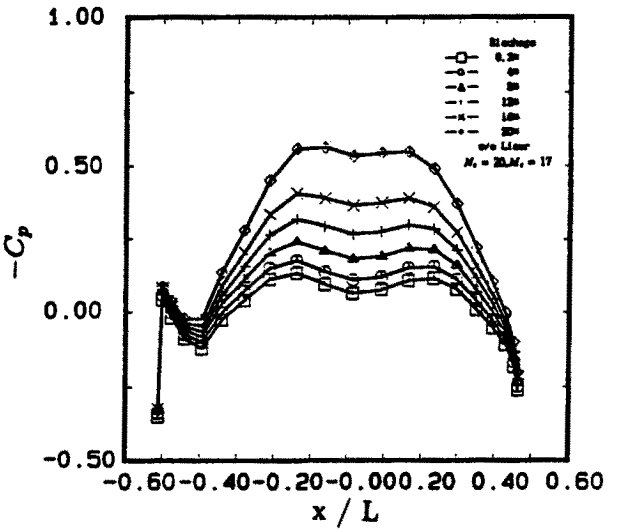


Figure 19: Pressure distributions along the longitudinal ship surface with varying tunnel blockages (Lee, 1992c).

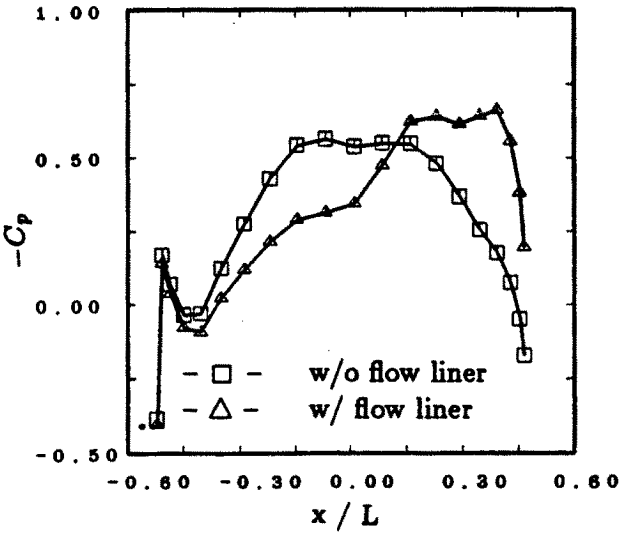


Figure 20: Pressure distributions along the longitudinal hull surface for the with- and without-flow-liner cases (Lee, 1992c).

7.3 Conclusions

A reliable prediction method of the full scale wake from the measured model wake has not appeared yet. The target wake and the wake simulation method can be different from one cavitation tunnel to another depending on previous experiences with model-full scale correlation and on available facilities.

Simulation of the total wake with a working propeller would enhance the accuracy of model tests and allow direct correlations with full scale observations. It would provide more accurate simulation of the flow to propeller blades because the propeller-wake interaction effects are taken account. Further development and evaluation of this wake simulation technique are recommended.

Generation of a three-dimensional wake distribution using a complete ship model in a cavitation tunnel may be difficult due to the tunnel blockage effect. Calculation of the flow field around a model ship in a cavitation tunnel by a surface panel method shows that the tunnel wall effect can be negligible for the blockage less than 5% and can be significant for the blockage more than 20% of the tunnel sectional area. Use of flow control devices, such as flow liners, can reduce the wall effects. Flow liners can also be used to simulate the predicted full scale wake without modifying the ship model when the complete model ship is used to simulate the wake.

8 MEASURING TECHNIQUES FOR HULL PRESSURE FLUCTUATION

Pressure fluctuation over the stern region of the hull induced by a cavitating propeller is one of the most dominant sources of ship hull vibration and inboard air/structure-borne noise. About 15 years ago, tremendous efforts were made to predict such pressure fluctuations induced by unsteady cavitation both by theory and by experiment. The 18th ITTC Cavitation Committee comparative measurement on the "Sydney Express" (ITTC, 1987) showed that accurate measurements of the pressure amplitudes and the experimental prediction on the vibration level from the model measurements are very difficult. The measured pressure amplitudes were seriously affected by the rotation rate of the model propeller used in the test. One reason for this was the existence of longitudinal standing waves in the cavitation tunnel (ITTC, 1987). Another suggested reason was the vibration of the measuring system (ITTC, 1990, Ukon, 1989b). In addition, it has been suggested that the pressure fluctuation measurement at full scale is also affected by the hull plate vibration (van Gent, 1989, 1990).

In the previous ITTC report, comparative measurements on the "Sydney Express" among Japanese establishments showed quite good correlations between the pressure fluctuations at model scale with full scale measurements. Some of the measurements, carried out behind wire mesh screens and with a flat plate above the propeller representing the hull, were affected by the rotation rate of the model propeller. However, reasonable measurements can be made by selecting an inherent frequency range determined by the propeller rotation rate and the stiffness of the measuring systems.

Recently a number of full scale measurements were performed, not only to examine the correlations between model and full scale (Blake, 1990, Friesch, 1986, 1987, 1992, Ukon, 1991a), but also to evaluate the design of the propeller (Blake, 1990, Kim, 1990, Vassipoulos, 1990). The present report monitors recent work on pressure fluctuations with special attention to the measuring technique of the hull pressure amplitudes. A further comparative measurement on pressure fluctuations on the "St. Michaelis" is described. In addition, recent investigations are described, which are related to the improvement of the theoretical prediction of the pressure amplitudes and cavitation.

8.1 Full Scale Measurements and Correlations with Model Tests

Measurements in Germany.

HSVA performed a number of full scale measurements on various kinds of ships (Blake et al, 1990, Friesch, 1986, 1987, 1992, Tanger et al, 1992, Weitendorf, 1973). Corresponding to each full scale measurement, model tests on ten ships were performed in the HSVA medium size cavitation tunnel. Some of the model measurements overpredicted the pressure amplitudes, while others underpredicted them. There were four cases for which a good correlation between

Key	A	B	C	D	E	F
Kind	Container	Training	Bulk	Tanker	Tanker	Tanker
Ms. No.	0449	0500	0496	0503	0531	0532
L_{pp}[m]	210	105	278	222	302	310
B[m]	30.5	16.0	46.0	42.0	58.0	58.0
D[m]	16.0	8.0	27.5	20.3	28.3	28.6
d[m]	11.0	5.8	17.0	12.2	18.8	18.8
$\nabla[m^3]$	43.457	5.639				
DW[ton]			166,000	80,000	240,000	240,000
DHP [PSS]	23,249					
BHP [PS]		3970	19,650	14,200	23,200	22,560
N[rpm]	105.1	176.0	65.0	103.0	70.0	56.0
V_S[kn]	22.3	16.0				
D_p[m]	7.00	3.60	8.90	7.20	10.6	10.2

Table 8: Principal dimensions of tested ships.

model and full scale were obtained (Blake et al, 1990).

Measurements in the USA.

APL C-9 Propeller. Extensive experiments were conducted and calculationswere made on an APL container ship with a newly designed skewed propeller (Blake et al, 1990). A comparison of the cavitation pattern between full scale and model was carried out, together with theoretical calculations. The model measurements at HSVA overpredicted both the cavitation extent and the amplitude of pressure fluctuations if the wake simulation was made based on the model wake. This was also the case with theoretical calculations based on the same wake distribution. When an estimated full scale wake was employed, the cavitation extent in the model test was smaller than that at full scale. The calculated cavitation patterns, however, were similar to the full scale ones using the full scale wake.

The model measurements of the pressure fluctuations with the full scale wake gave a better correlation with the measurements at full scale than those with the model wake, but they still underpredicted the amplitudes. The tendency of the model test results, with the model wake giving a larger extent of cavitation and higher pressure amplitudes than full scale results, has also been found in the comparative measurements on the "Sydney Express" when sufficient nuclei were supplied (Ukon, 1989b).

Measurements in Japan.

The Seiun-Maru Propellers. The "Seiun-Maru" originally was equipped with a conventional propeller. In 1982, a highly skewed propeller was installed. The principal particulars of the "Seiun-Maru" are shown in Table 8, Ship B.

Simultaneously the pressure fuctuations, cavitation pattern, cavity thickness (Kodama et al, 1983), cavitation noise and blade stresses near the propeller boss were measured on both propellers. Comparative measurements at SRI (Tokyo, Japan) in 1982 (Kurobe et al, 1983) did not show a good correlation possibly because of the simulated wake in the model test was wider than at full scale due to wall effects. Also, rough seas were experienced during the full scale measurements which could affect the results. Repeated model tests on cavitation patterns and pressure fluctuations were performed in 1990, using a new type of flow liner. Together with the cavitation experiments, new cavity profile measurements using a Laser-CCD method were made (Kudo, 1989, Ukon, 1991b). Better correlations on pressure fuctuations were found, but the correlations are still insufficient as shown in Fig. 21 (Ukon, 1991). In this model test, experimental data were obtained on the cavity volume variations for both propellers and these agreed with previous measurement (Kurobe et al, 1983). At full scale, the cavity thickness was measured again using a laser beam (Tanuibayashi et al, 1991). Recently, blade pressure measurements were performed on both propellers of the "Seiun-Maru", both at

model scale (Ukon, 1989, 1992) and at full scale (Ukon, 1990, 1991, 1992). Some interesting findings about the influence of the leading edge separation vortex in the pressure distribution were obtained and these data are invaluable for the evaluation of propeller theories at high Reynolds numbers.

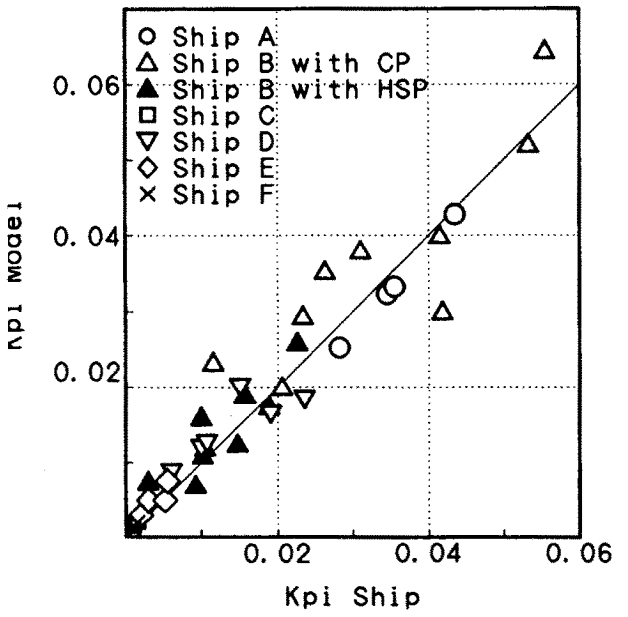


Figure 21: Correlation of pressure fluctuation amplitude between model and full scale ship.

Full Scale Propellers. Full scale measurements were conducted by seven major Japanese ship builders on four newly built ships (Ukon, 1991a). The principal particulars of the ships tested and of the models used in these measurements are given in Table 8, as ship C, D, E and F. Except for ships A and B in Table 8, the tested ships are full block ships. All the ship models tested were approximately 6 m long. To examine the correlation of cavitation extent and pressure fluctuations between full scale and model, the model tests were performed using a complete ship model with flow liners in the No. 2 working section of the SRI large cavitation tunnel. For these ships, a fairly good correlation of the pressure fluctuation amplitudes at the blade rate frequency was found, as shown in Figure 21.

8.2 20th ITTC Comparative Model Measurements

Measurements on "St. Michaelis". In the comparative measurements on the "Sydney Express", carried out by the 19th ITTC (Ship A in Table 8), a reasonable agreement in amplitudes of the pressure fluctuation was obtained among Japanese organizations (ITTC, 1990, Ukon, 1991a). One of the reasons for the agreement is that the tested ship is a fine ship, which makes simulation of the wake easier. For the 20th ITTC comparative measurement, a full block ship was selected, the German tanker "St. Michaelis".. The full scale measurements on this ship were conducted by HSVA (Friesch, 1986, Weitendorf, 1973). In the measurements at SRI, the complete ship model was employed with a flow liner. The wake simulation was performed by various kinds of combinations of the ship model and flow liners. For the final simulated wake distribution, using flow liner No. 3, cavitation observations and pressure fluctuations were made. The extent of cavitation on the propeller model behind the complete ship model was similar on the starboard side, but considerably smaller than that in the full scale, in spite of sufficient nuclei seeding. The cavitation patterns showed a distinctive difference between the full scale and the model in propeller tip vortex cavitation (TVC). Photographs indicated that the TVC at full scale (Friesch 1986) was extraordinarily thick for this ship, as shown in Fig. 22, while the TVC on the propeller model was relatively thinner. The measured amplitudes of the pressure fluctuations showed disappointing agreement between model and full scale, as shown in Fig. 23. It is expected that the difference in the cavitation patterns between model and full scale caused disagreement in the pressure fluctuation amplitudes. Little influence of the rotation rate was found on the model results. The rotation rate was varied from 18 to 33 rps. Leading edge roughness was applied in this case but it is not considered to cause this discrepancy.

In these comparative measurements by six organizations, an excellent agreement on cavitation extent and reasonable agreement for pressure fluctuations were obtained among the six cavitation tunnels. The correlation with full scale was still disappointing, however. From this it can be concluded that the cause of the discrepancy is not the model measurement

technique of the pressure fluctuations, but is a result of a poor estimate of the full scale wake and simulation of the TVC.

Measurements on the "Sydney Express". In the measurements at SRI, two kinds of target wake distributions were employed. One was the model nominal wake which was measured in a towing tank. In the tunnel, this wake was generated by the complete ship model without flow liners in the cavitation tunnel (Ukon, 1987, 1989, 1991). Another was the estimated full scale wake, calculated using Sasajima and Tanaka's method (Tanaka, 1979), which was simulated with the help of flow liners. The former wake was wider than the latter. The amplitudes of the measured pressure fluctuations induced by cavitating propellers working in the nominal wake were higher than those in the estimated full scale wake (Ukon, 1991a, Blake et al, 1990). The model measurements in the estimated full scale wake showed a reasonable agreement with the full scale measurements.

Figure 22: Tip vortex cavitation on "St. Michaelis", full scale propeller (Courtesy of HSVA).

8.3 Related Work on Pressure Fluctuations

Theoretical Predictions. For the theoretical prediction of the extent and volume of unsteady cavitation on propellers, the theoretical description of cavity flow is crucial. MIT (Cambridge, USA) has been active in this field. Uhlman developed a nonlinear cavity flow theory for a partially-cavitating and for a supercavitating two-dimensional hydrofoil based on the zero-order vortex panel method (Uhlman, 1987, 1989). Kinnas reformulated a linear cavity flow theory based on source and vorticity distribution methods, and introduced the leading edge correction (Kinnas, 1991) for partially-cavitating hydrofoils to remove the defect of the linearized theory. The leading edge correction was subsequently applied to the cavitating propeller problem (Kinnas, 1992). In his recent work, cavity shapes predicted from the linearized theory with or without the leading edge correction were compared to those predicted from a non-linear boundary element method (Kinnas, 1992). Lee developed a potential-based panel method for the analysis of a two-dimensional super- or partially-cavitating hydrofoil using normal dipoles and source distributions (Lee, 1991). In order to apply these non-linear cavity flow theories for a very thin hydrofoil, i. e., a supercavitating hydrofoil, a higher order-panel method was inevitable. Kudo developed a linear vortex panel method to treat two-dimensional supercavitating hydrofoils (Kudo, 1992). This trend in the calculation of cavity flows is expected to produce rapid progress. The modelling of the detachment of the cavity and of the closure of the cavity, however, is still a serious problem which needs to be overcome.

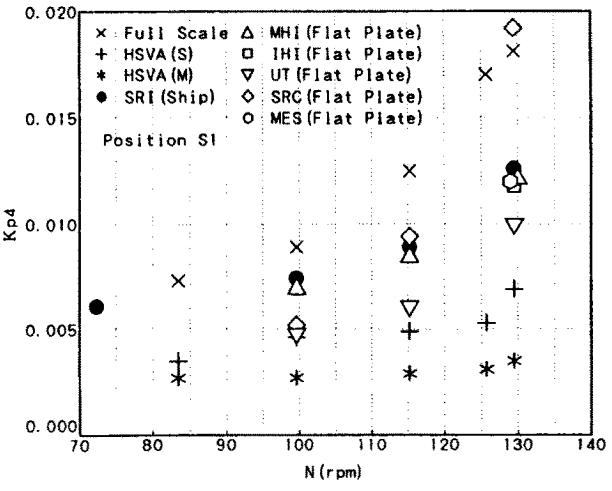


Figure 23: Correlation of pressure fluctuation amplitudes between model and full scale.

In addition to the prediction of the cavitation extent, attention must be given to the prediction of cavitation type. Szantyr developed an unsteady ducted propeller theory to analyze the impeller and duct performance and to predict the cavitation pattern and the pressure amplitudes (Szantyr, 1989). His calculation was compared with experiments and the correlation was not fully satisfactory. One of the reasons may be the neglect of laminar separation near the leading edge in his calculation. When the well known cavitation inception criteria (e. g., Ukon, 1980, Kuiper, 1981) are adopted, the cavitation pattern can be reasonably predicted including the type of the cavity (Ukon, 1987).

Propeller Design. With the progress of propeller theory and the publication of Eppler's program codes, new blade sections of marine propellers have been developed by several researchers. Yamaguchi proposed that a triangular pressure distribution on the back side could stabilize the unsteady cavitation behavior and reduce the pressure fluctuations (Yamaguchi, 1988). Lee (1991) applied a similar idea to the propeller design of a container ship. By adopting the new blade section in place of a conventional NACA-type blade section, a dramatic reduction of the global vibration level was achieved. The basic idea of these design methods is to manage the pressure distribution on non-cavitating propeller blades and thereby to control the unsteady behavior of cavitation. The next step should be a design method including cavitation.

Propeller Theory and Pressure Measurements. The interest in propeller theories seems to be shifting from (linearized) lifting surface theories to non-linear panel methods (Hoshino, 1989). The next step would be a finite difference method solving the Navier-Stokes equations. Improvements and extensions of a lifting surface theory have been made by Murakami et al (1991), Chao and Streckwall (1989), Streckwall (1991) and Ishii (1990).

For the development of a propeller theory, relevant experimental data to evaluate it are indispensible. However, the hydrodynamic characteristics of full scale propellers are generally not measured in detail. They are evaluated indirectly by measuring the thrust or power of a sea trial. Recently, however, pressure measurements on two types of propellers at full scale were performed successfully (Ukon, 1992). From the measurement results, some peculiar hydrodynamic phenomena were found. The blade pressure on the suction side at the trailing edge near the tip of the highly skewed propeller decreased stepwise and periodically. Such phenomena might be caused by a leading edge separation vortex. Similar but less pronounced phenomena were also observed on the conventional full scale propeller.

The full scale measurements suggest that significant viscous effects occur in the flow field around the propeller, not only at model scale, but also at full scale. The development of a new propeller theory including a leading edge separation vortex and a tip vortex separating from the blade is one of the most urgent tasks for propeller scientists to improve the prediction of cavitation extent and of pressure fluctuations. Ishii developed a new propeller lifting surface theory taking into account a tip vortex separating from the blade (Ishii, 1991, 1992). This theory is valuable as a first step to develop a more advanced and precise theory reflecting complicated viscous phenomena around the propeller blades. Viscous effects on the propeller blades play an important role on the hydrodynamic characteristics and CFD is one of the most promising tools to predict them. Uto developed his computational method to analyze incompressible viscous flow around a propeller (Uto, 1992). He calculated the pressure distributions on the conventional propeller blades of the "Seiun-Maru" for the case of $R_n = 5 \times 10^4$ and compared this with the model measurements (Ukon, 1992). A fairly good agreement was found for the pressure distribution, while some improvement of the correlation between thrust and torque is required. Recently Uto extended this theory to introduce a turbulence model for higher Reynolds numbers flow (1992).

8.4 Problems to be Solved

Wake Estimation. For the comparative measurements on the "St. Michaelis", one of the most serious problems was the estimation of the full scale wake. The LDV measurement obtained at full scale (Kux, 1990) showed an asymmetric wake on this ship. The wake data from the full scale measurement are not sufficient to be used for the estimation of the effective wake distribution. The measured wake distribution in front of the propeller, measured at full scale by LDV, was narrower than the

nominal model wake and similar to the target wake of the present comparative measurement. Disagreement of the cavitation extent was found between full scale and model tests. HSVA suggested that extensive separation of the flow occurring behind the stern hull has affected the full scale measurements of the pressure fluctuation amplitudes. More reliable total wake measurements close to the propeller disk are one of the most urgent tasks for the estimation of the propeller inflow. This should be done both at model and full scale. These total wake measurements and the development of new measuring techniques (Komura et al, 1991) should be encouraged from the view point of the prediction of the pressure fluctuations.

Cavitation Simulation. The present comparative measurements suggest that the complete simulation of cavitation patterns in the cavitation tunnel is still difficult due to the lack of a universal technique to estimate the wake distribution. Since Reynolds number effects are important for the thickness of the tip vortex, a new development for the simulation of the TVC is necessary for model tests in cavitation tunnels. The leading edge roughness application on the propeller model may weaken the TVC (Sato, 1990, Johnsson, 1991). On this point, nuclei seeding by electrolysis is more favorable for cavitation simulation in the cavitation tunnel (Kuiper, 1981).

Vibration effects on pressure measurements. When pressure gauges are mounted in the stern hull plating, the measured pressures are affected by vibrations of the plate, not only at full scale (van Gent, 1989, 1990) but also at model scale (Kurobe, 1985, Ukon, 1989). To check this, the pressure fluctuation measurements should be accompanied by measurements of the hull accelerations. To correct the measured hull pressures for the hull response, a separation into propeller induced and hull-vibration induced components of the measured pressures is necessary. Simplified corrections using the accelerations at the locations of the pressure pick-ups were formulated by Huse (1974), Sunnersjo (1982), and Kurobe and Yoshida (1985). In most of the full scale measurements, the acceleration was measured but it seems that this correction is not always made. The hull response over the whole stern influences the measured pressures above the propeller. To distinguish the propeller induced pressure from the hull-vibration induced pressure, additional measurements with a hydrodynamic monopole exciter were conducted by van Gent (1990). This was done to substitute the cavitating propeller by a calibrated artificial excitation, which made it possible to find transfer functions of the vibration induced pressures at the location of the pressure pick-ups. Phase information was found to be as important as amplitude information. Van Gent also performed full scale measurements of the pressure fluctuations induced by two kinds of propellers together with the accelerations. The measured pressures at full scale were corrected using the transfer functions and the measured accelerations at the pressure pick-ups. The correlation between model and full scale was considerably improved in this way. Simplifying the ship structure to an infinite thin flat elastic plate and the propeller cavitation to a monopole, van Gent evaluated numerically the equations for a fluid-loaded elastic plate by direct integration and indicated that the pressure on the plate surface was strongly reduced for practical values of plate thickness, monopole-to-plate distance and frequency (van Gent, 1989).

8.5 Conclusions

Development of a validated and acceptably accurate approach for the correct interpretation of propeller-induced unsteady hull pressures remains unsettled. To some extent, the ultimate goal of such research, which is to facilitate the use of model experiments for the prediction and assessment of ship vibrations and/or inboard noise, has been sidetracked. Such effort has been concentrated on the direct comparison of model and full scale coefficient values of the unsteady pressure amplitude (blade rate and higher harmonics), measured on the hull surface over the propeller. Even after the introduction of many corrective experimental techniques, such as the simulation of a full scale wake and the use of flow liners, the criterion of success has been to obtain agreement between model and full scale pressure amplitudes. This approach is not complete in some cases. Especially the dynamic response of the structure, both at model and full scale, and the reflection and transmission characteristics of the facility structures have received relatively little attention. It is felt that there needs to be activity in these areas, in model testing as well as in full scale testing and calibration. This may be one of the rea-

sons why on some full ships a good correlation of the pressure fluctuations at model and full scale could not be obtained, in spite of the fact that sufficient nuclei were provided and a tunnel calibration was carried out. There should be emphasis on the understanding of the transmission of pressure and vibrational energy though both model and full scale arrangements. It may be possible to incorporate some concepts or techniques of the "reciprocal method" to take advantage of the separation of the problem into the determination of the source strength of propeller cavitation and the transfer process of hydrodynamic pressure variations into the hull and appendages.

It has become clear that propeller induced pressures are very sensitive to the wake distribution, and one of the important reasons of a lack of consistency in model tests in various facilities is the simulation of the full scale wake. When this simulation is done consistently, the results are reproducible as discussed in the Appendix, which summarizes tests conducted in six different Japanese facilities. To obtain more knowledge about wake scaling, measurements of the total wake distribution close to the propeller plane with the propeller operating are recommended. These measurements can be conducted both at model and full scale, although at full scale, this is still very difficult. These measurements can give more insight in scaling and the results can serve as a basis for a scaling procedure. The measurement of total wake distributions is therefore encouraged.

The calculation of the full scale wake using Navier-Stokes solvers is becoming possible. The use and evaluation of these techniques is recommended.

The simulation of the effective wake in a cavitation tunnel is difficult. Not only the axial wake distribution, but also the tangential velocities should be properly simulated. The use of flow liners can improve the wake simulation. Further development of this technique is therefore recommended.

9 QUALITY CONTROL ACTIVITIES

9.1 Error analysis and scale effect

At present, the quality control activities of the Cavitation Committee are focused on the process of uncertainty analysis and on efforts to sort out several crucial scale effects. In general, the physics of real cavitation (such as inception) is difficult enough that it has not yet been successfully addressed by computational fluid dynamics methods. Therefore, the emphasis is not on validating CFD schemes, but on providing basic understanding and correlation with full scale results and observations, when feasible.

1. The Cavitation Committee has initiated a long term quality control effort to develop an approach to quantifying the uncertainty analysis for an important category of testing called the cavitation inception experiment for a marine propulsor. This experiment consists of plotting observed cavitation points in a diagram of cavitation number (σ) versus advance coefficient (J). Points for the same type of cavitation are connected to determine inception boundaries of each form of cavitation. The plan is to put together a sample analysis of errors to serve as a guide for interested investigators.

A preliminary outline of the main measurement parameters and issues of the problem is given below. The difficult task of a complete uncertainty analysis is to assign well founded error estimates for measurements that account for all the possible influences listed.

Flow Parameters

- Facility free stream velocity
- Facility pressure
- Facility water density
- Propulsor rotor RPM

Propulsor Geometric Accuracy

- Rotor diameter
- Blade thickness distribution
- P/D ratio distribution
- Angular spacing of blades
- Blade chord length
- Details of loading and trailing edges
- Details of application and affect of leading edge roughness for flow conditioning

Propulsor Operating Conditions

- Overall accuracy of open water test results for K_T and K_Q
- Accuracy of final (net) thrust and torque measurements, accounting for:
  - effect of tunnel pressure
  - flow velocity
  - correction for hub
  - correction for dynamometer internal resistance
- Possible Reynolds number scale effect on K_T and K_Q
- Correct inflow to propeller

Status of Facility Flow Turbulence Intensity

- Possible scale effects on different types of cavitation

Status of Bubble Nuclei Content

- Overall content of air as percent saturation
- Nuclei size distribution and liquid tension
- Scale effects on different types of cavitation

Detection of Cavitation Inception/Desinence

- Effects of visual detection, accounting for
  - tip vortex cavitation occurring detached or attached to blade tip
  - calling cavitation with premature inception on one blade
- Acoustic detection
  - works only for first occurring cavitation
  - variability of correlation with visual detection, difficult to apply full scale
- Reynolds number scale effects on the basic mechanics of the inception and desinence process.

It should be noted that in this list, there are critical issues of scale effects, both with the fluid dynamics and the bubble mechanics, that must be confronted directly in any attempt at estimating errors for a given experiment.

2. In order to make progress with one of the least understood categories of cavitation scale effect, the Cavitation Committee has completed an experimental investigation in co-operation with the Bassin d'Essais des Caränes on the effects of bubble nuclei size distribution and liquid tension on the cavitation inception of three main types of propeller blade cavitation: back (suction side) bubble, suction side sheet, and tip vortex. The experiment was conducted in the Grand Tunnel Hydrodynamique (GTH) and is described in detail in Section 5 of this report. In addition to providing some new information on the important influences of microbubble nuclei, this experiment also generated preliminary data for estimating bias type error in the detection of cavitation inception and desinence, both visually and acoustically.

9.2 Validation task

The Cavitation Committee has initiated planning of a comparative experiment for the model scale measurement of cavitation propeller - induced unsteady pressures on a nearby hull-type boundary, with the subject propeller operated in an easily reproduced wake. This will involve the simultaneous measurement of the fluctuating pressure amplitudes and phase angles (of blade rate harmonic components) at prescribed points on the boundary surface, the detailed vibration characteristics of the hull or mounting plate for the pressure gauges, and the complete calibration of low frequency acoustic response characteristics of the test section of the facility. There will be standardized requirements for the ranges of flow speeds and propeller RPM, the total air content, survey of nuclei size and liquid tension with a CSM, velocity surveys for the nominal wake, and careful records of the extent and appearance of blade cavitation.

The results of this experimental program conducted at participating facilities will be used (i) for comparison and first order validation of several computational schemes available for the calculation of propeller-induced unsteady pressure excitation and (ii) to highlight differences due to facility size and configuration, boundary vibration, possible acoustic resonance conditions, flow quality, and Reynolds number.

10 RECOMMENDATIONS TO THE CONFERENCE

• The analysis of cloud cavitation and the assessment of its effects requires insight in the dynamic behavior of the cloud, especially of the size of the clouds which are shedded and of the location and speed of collapse. This requires not only still photographs but also high speed observations. This type of data is also needed for development of theoretical methods for the prediction of erosion and noise radiation. Although this may be still too expensive for daily use, the exploration of such observation techniques is recommended.

• When hull pressure amplitudes measured at model scale are compared with full scale data, the hull response, both at model and full scale, should be taken into account. Model tests, conducted in a cavitation tunnel, should be conducted at a minimum of two rotation rates to certify that the results are independent of tunnel characteristics.

11 RECOMMENDATIONS FOR FUTURE WORK OF THE CAVITATION COMMITTEE

1. Attempt to establish a simplified comparative test with an easily reproducible wake, to determine the source of the scatter in hull pressure measurements between different facilities. Evaluate measurements and extrapolation techniques and compare with full scale data.

2. Continue to review the current research on cloud cavitation and expand the collection of photographs showing different types and stages both at full scale and at model scale. The development of prediction methods should be reviewed. The relationships between the flow field, the cavitation behavior and the effects in terms of erosion, noise radiation and low frequency pressure pulses should be quantified.

3. Work should continue to evaluate the mechanism and scale effects of vortex cavitation and concepts for delaying it. Work with new blade sections to delay inception of blade cavitation should be assessed.

4. Progress on developing computational efforts to predict cavitation inception and cavitation patterns on blades should be evaluated.

5. Work should be continued to evaluate the effects of nuclei on cavitation scale effects and to monitor progress on nuclei measurement techniques. Investigate nuclei distributions in various tunnels and tanks using a calibrated propeller model and determine if it is possible to classify the tunnel nuclei spectrum from photographs.

6. Work should continue on high speed phenomena, such as cavitation and ventilation, affecting the performance characteristics and safety of high speed vehicles (Transferred from the High Speed Marine Vehicles Committee).

7. Evalute methods of predicting cavitation extent and stability on propulsors operating in a spatially varying wake (Transferred from Propulsor Committee).

8. The Committee should develop standard procedures and codes of practice which conform to ISO 9000.

APPENDIX

COMPARATIVE MEASUREMENT OF PRESSURE FLUCTUATION ON THE "ST. MICHAELIS"

Five Japanese organizations--University of Tokyo (UT), Mitsubishi Heavy Industry (MHI), Ishikawajima Harima Industry (IHI), Ship Research Center (SRC) and Ship Research Institute (SRI)--conducted comparative measurements of pressure fluctuations on the "Sydney Express" propeller and significant progress on the measuring techniques was obtained (ITTC, 1990, Ukon, 1991). The "Sydney Express" has a low block coefficient and it is therefore expected that a good correlation between full scale and model scale can be easily obtained. For the 20th ITTC, a tanker, the "St. Michaelis",was employed for comparative measurements. Full scale measurement for this ship were conducted by HSVA (Friesch, 1986). In addition, HSVA performed model scale measurements in two cavitation tunnels (Kux, 1990); however, disappointing agreement was obtained between full scale and model scale results, not only for cavitation pat-

terns but also for the amplitudes of the pressure fluctuations. SRI also performed measurements using a complete ship model with a flow liner (Ukon, 1991). Finally, six Japanese organizations including Mitsui Engineering and Ship Building Co., Ltd. (MES) took part in the comparative measurements on this ship to investigate any problems on the measurements of pressure fluctuations in cavitation tunnels.

A.1 Experimental procedures

Test set-up. The tested ship is a small German tanker "St. Michaelis". The same propeller model used at SRI was also used at the other Japanese facilities. The scale ratio is 1/29 and the diameter of the propeller model is 196. 6 mm. The principal particulars of the ship and propeller are given in Table 9. The required measuring items were the wake, cavitation patterns, pressure fluctuations and accelerations.

Items	Hull	Items	Prop.
kind	tanker	kind	conv.
MS No.	0546	MP No.	300
L_{pp} [m]	174	D_p[m]	5.7
B [m]	32.2	x_b	0.163
D [m]	13.0	$P/D_p(0.7R)$	0.6905
d [m]	10.10	Skew	-
∇ [m^3]	52,033	a_B	0.62
DHP[kW]	6760	turning	Right
N [rpm]	130		
V_s	15.75		

Table 9: Particulars of the "St. Michaelis".

Experimental conditions. As the target wake, the wake estimated by the modified Sasajima's method was used from the wake measurement in the SRI 400 m towing tank. Both wake distributions are shown in Figure 24. Finally, the wake was the wake simulated by each organization using current techniques.

The experimental conditions were determined to be the same as the conditions in the HSVA model test. The cavitation number described here is based on the ITTC symbol and terminology:

SF6; $K_T = 0.160$; σ_n (0.8) = 1.994
SF4; $K_T = 0.157$; σ_n (0.8) = 2.517
SF3; $K_T = 0.164$; σ_n (0.8) = 3.366

The condition SF6 was the condition used by HSVA and the measurements were therefore performed mainly in this condition. The assigned air content ratio α/α_s was about 0.30. Leading edge roughness was applied to the propeller when sufficient nuclei could not be supplied. Cavitation observation were made at each 20 degrees.

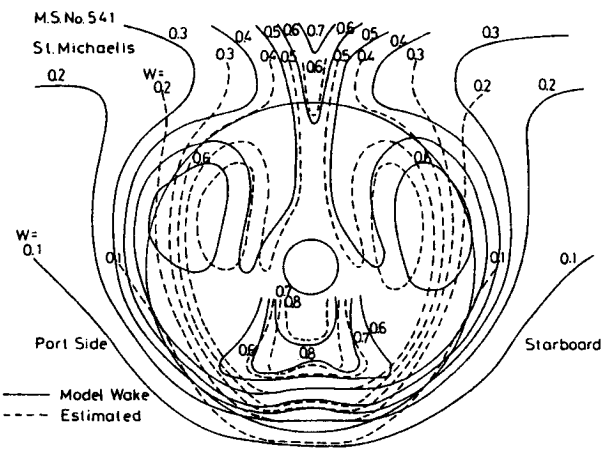


Figure 24: Wake measured in the towing tank and estimated wake.

For the pressure fluctuation measurements, pressure transducers were located mainly in the propeller disk plane. The most important pressure transducer (S1) was located in the propeller plane at 0.07 D to starboard. Some measurements in a position immediately above the propeller (C) will also be given (Friesch, 1986). The vertical tip clearance was 0.389 D. Measurements were obtained for at least two propeller rotation rates and the tunnel was calibrated as recommended by the 19th ITTC (1990). Additionally, accelerometers were mounted on the measuring flat plate and on the ship hull and tunnel wall. In some cases, accelerations were measured for different rotation rates of the propeller and these results are not described here.

A. 2 Measurement results

Full scale measurements. The obtained full-scale cavitation patterns (Friesch, 1986) are shown in Figure 25. From the photographs of the cavitation patterns, extremely thick

propeller tip vortex cavitation was observed at the starboard side at full scale.

Cloud cavitation was also observed. Pressure fluctuation amplitudes at blade rate frequency in the transverse and longitudinal directions are shown in Figures 26 and 27 respectively. At the most important pressure

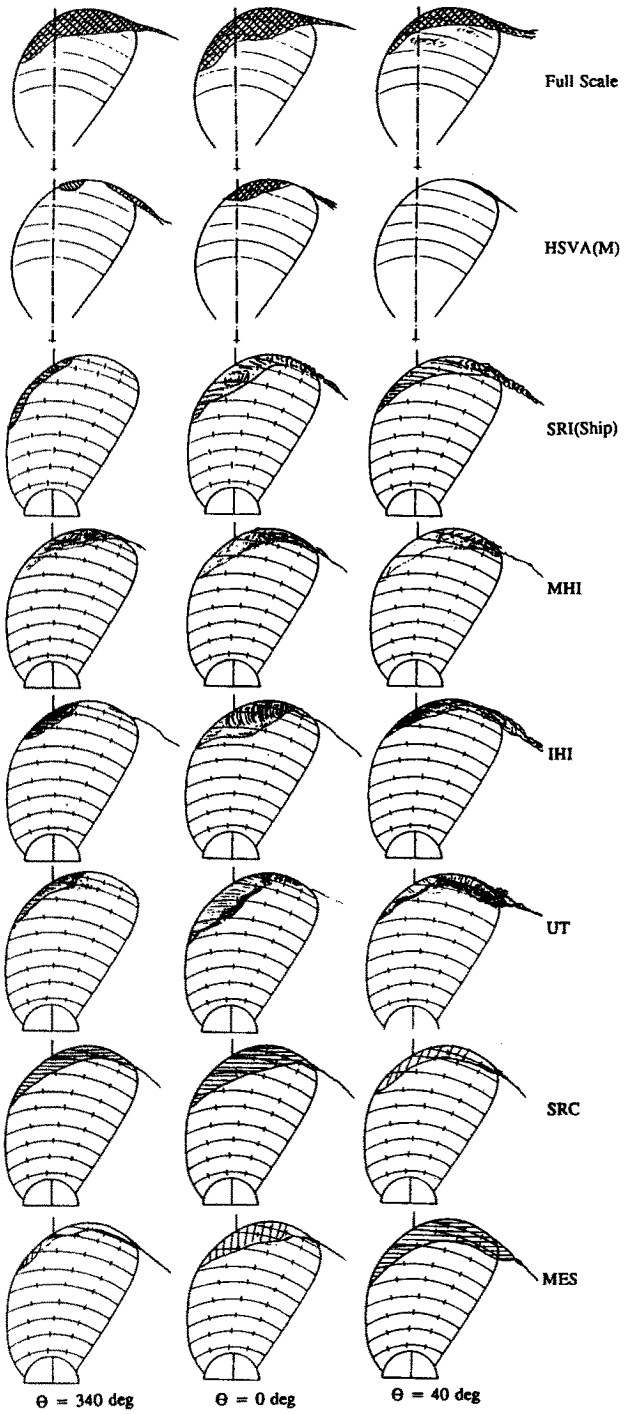


Figure 25: Cavitation patterns at full scale and in cavitation tunnels.

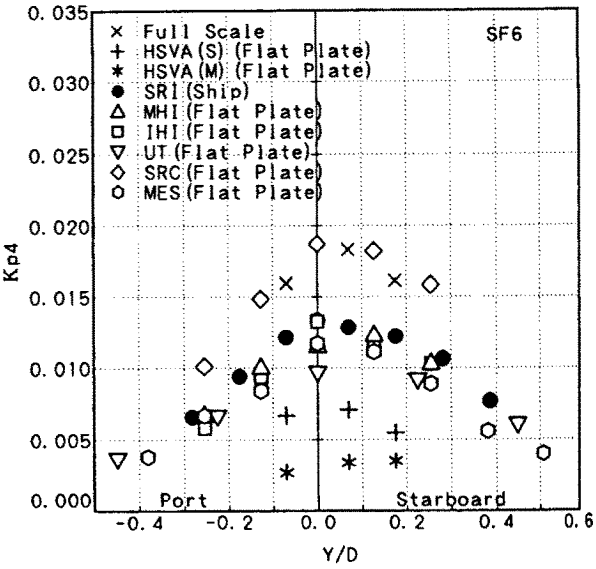


Figure 26: Pressure amplitudes in transverse direction.

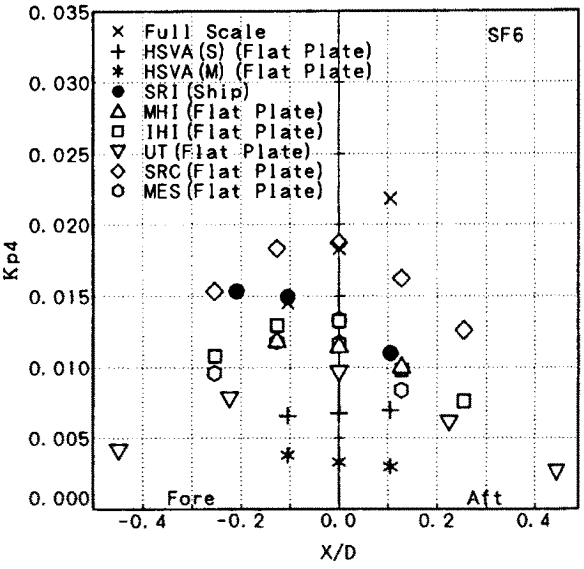


Figure 27: Pressure amplitudes in longitudinal direction.

point, the measured amplitudes at the first blade rate for each propeller revolution rate are shown in Figure 23 together with the model test results from each cavitation tunnel.

Measurements on the Flat Plate at HSVA. Measurements were performed at two cavitation tunnels of HSVA, i. e., the medium and the small tunnel. Cavitation extent for

each model test was considerably narrower than at full scale as shown in Figure 25. Cavitation patterns for the two model tests also differed from the full scale, especially the thickness of tip vortex cavitation and the presence of cloud cavitation. Consequently, the amplitudes of the pressure fluctuations at model scale were considerably lower than at full scale as shown in Figures 26, 27 and 23. The trend of the longitudinal distribution of the pressure amplitudes was completely opposite to that measured at full scale.

Measurements on the ship model at SRI. Before the cavitation tests, the wake distribution was measured in the SRI 400 m towing tank. The wake to be simulated was determined by the modified Sasajima-Tanaka method. In the SRI cavitation tunnel, the wake was simulated by using the complete ship model of the "St. Michaelis" and three different flow liners. The chosen wake distribution is slightly wider than the target wake and the full scale wake as measured by LDV (Kux, 1990)

Observed propeller cavitation patterns are shown in Figure 25. Better correlation of the cavitation extent between the model and the full scale was observed for the starboard side than for the port side of the propeller. The patterns at the port side and in the top position were considerably smaller than at full scale.

Measured pressure fluctuation amplitudes in the transverse and the longitudinal directions are given in Figures 26 and 27 respectively. They are smaller than the full scale measurements but a better correlation with full scale than from the model test results at HSVA was found. The longitudinal distribution was different from full scale, as was also found by HSVA. The peak of the longitudinal distribution at full scale was found behind the propeller disk. It can be stated that such a pressure amplitude distribution is an unusual one. The extraordinary thick TVC at full scale might cause such a peculiar phenomena. On the other hand, the TVC at model scale was observed to be very thin. The application of leading edge roughness cannot cause the difference of thickness of the TVC.

In order to check the tunnel effects, the pressure fluctuations were obtained for propeller rotation rates of 18 to 33 rps, as shown in Figures 28 and 29.

Measurements on the flat plate at Japanese Organizations. The wake distribution was simulated by wire-mesh screens in each cavitation tunnel. IHI performed pressure fluctuation measurements by using a flat plate with a heavy circular cylinder. The pressure transducers were mounted on the bottom of the cylinder and arranged in intervals of 25 mm. Cavitation patterns are shown in Figure 25. These patterns agree well with SRI model data; however, they are less than at full scale.

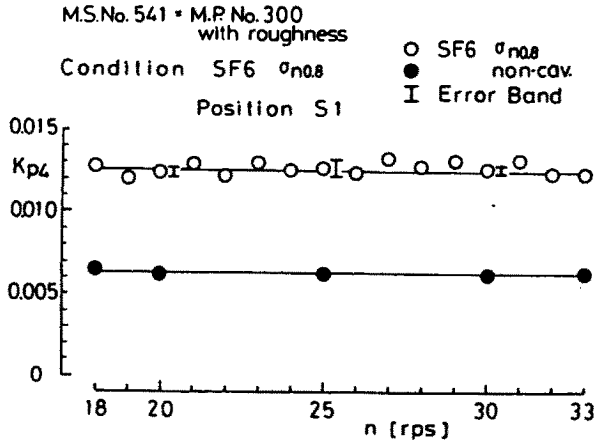


Figure 28: Effect of model propeller rotation rate on pressure amplitudes at position S1.

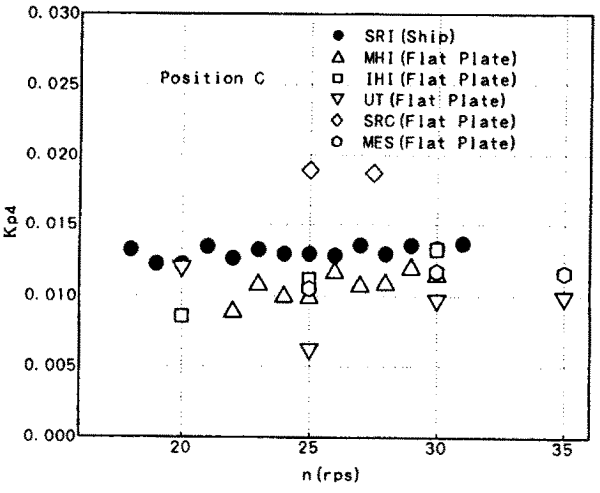


Figure 29: Effect of model propeller rotation rate on pressure amplitudes above the propeller at position C.

The pressure fluctuation amplitudes are plotted in Figures 26 and 27. These data in the trans-

verse direction also coincide with SRI model data, while the longitudinal distributions differ slightly from SRI's data. This difference is due to the geometrical arrangement of the pressure transducers.

IHI conducted pressure fluctuations using a flat plate. The pressure transducers were arranged in a similar manner as MHI. Cavitation patterns are shown in Figure 25. These patterns resemble full scale observations and are slightly greater than SRI and MHI data at some angular positions. The pressure fluctuation amplitudes are shown in Figures 26 and 27. The measurements in both directions agree well with those of SRI and MHI.

In the cavitation tunnel at the University of Tokyo, the pressure fluctuation amplitudes were measured on an acrylic flat plate. The arrangement of pressure transducers is shown in Fig. 5. The distances between the transducers was greater than that of the other tunnels. Cavitation patterns are shown in Figure 25. These patterns agree well with those at SRI, MHI and IHI. The measured amplitudes at blade rate frequency is shown in Figures 26 and 27, and are relatively smaller than those measured at SRI, MHI and IHI.

SRC also conducted pressure fluctuation measurements using a flat plate. The arrangement of the pressure transducers was the same as those at other organizations except SRI and UT. The observed cavitation extent was relatively larger than in any of the other facilities, however, the difference was not so large. Only these measurements, shown in Figures 26 and 27, agreed well with full scale measurements; however,the cavitation extent was still smaller than observed at full scale.

MES also participated in the present comparative measurements. The arrangement of the pressure transducers is the same at MHI, IHI and SRC. The cavitation patterns observed are shown in Figure 25 and closely resemble results at SRI. The measured amplitudes of the pressure fluctuations in the longitudinal and the transverse direction are shown in Figures 26 and 27, respectively, and are slightly smaller than those at SRI, MHI and IHI, but are larger than those at UT.

A.3 Discussion

The cavitation patterns obtained in the present comparative measurements are similar. In this respect, it appears that good agreement in the simulated wake between each tunnel was obtained. Only at SRI could the bilge vortex wake be simulated. A significant difference in cavitation patterns was not found except at an angular position of 60 degrees, where the cavitation disappeared.

In order to check the vibration effects on the measurements, the pressure fluctuations were measured at as many propeller rotation rates as possible. The measured results are shown in Figures 28 and 29. At SRI, no effect was found in non-cavitating conditions; however, in cavitating conditions, small differences were found. The effects of model propeller rotation rate on the measured pressure fluctuations are compared in Figure 29. The data of SRI and SRC are not affected by the propeller rotation rate, while data from MHI and MES increase slightly with increasing propeller rotation rate. Athough IHI and UT data vary with the propeller revolution rate, the measurements become constant at propeller rotation rates higher than approximately 30 rps.

A.4 Conclusions

From the present comparative measurements of the "St. Michaelis", the following conclusions can be drawn:

1. The correlation between full scale and the model results was not good in most of the cavitation tunnels.

2. Reasonable agreement was obtained among the model measurements, not only when the complete ship model was used, but also when a flat plate with wire mesh screens was used after tunnel calibration.

3. A lack of correlation between model and full scale result is assumed to be due to the incorrect simulation of the full scale wake.

4. A determination of the accuracy of the pressure fluctuation measurements is necessary at full scale.

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