The Specialist Committee on Cavitation Erosion on Propellers and Appendages on High Powered/High Speed Ships

Final Report and Recommendations to the 24th ITTC

1. INTRODUCTION

1.1 Membership

The Membership of the Specialist Committee on Cavitation Erosion on Propellers and Appendages on High Powered/High Speed Ships was:

- Dr. Michael L. Billet (Chairman).
  ARL, The Pennsylvania State University, U.S.A.
- Dr. Stephen R. Turnock (Secretary).
  University of Southampton, UK.
- Dr. Laurence Briançon-Marjollet.
  Bassin d'Essais des Carenes, France.
- Dr. Bong Jun Chang.
  Hyundai Heavy Industries Co. Ltd., Korea.
- Mr. Jürgen Friesch.
  Hamburgische Schiffbau-Versuchsanstalt, GmbH, Germany.
- Dr. Leszek Wilczyński.
  Ship Design and Research Centre, Poland.

1.2 Meetings

Four meetings of the Specialist Committee on Cavitation Erosion on Propellers and Appendages on High Powered/High Speed Ships were held as follows:

- ARL of the Pennsylvania State University, U.S.A., January 2003.
- Ship Design and Research Center, Poland, October 2003.
- Bassin d'Essais des Carenes, France, May 2004.
- School of Engineering Sciences of the University of Southampton, United Kingdom, February 2005.

2. RECOMMENDATIONS OF THE 23rd ITTC

1. Develop procedure(s) for methods and scaling models of cavitation erosion on propellers and appendages.
2. Develop guidelines for prevention of erosion.
3. Develop a procedure for cavitation induced erosion tests.

3. LITERATURE REVIEW

The destructive action caused by cavitation has been a practical problem for ships for over 100 years. Erosion of ship propellers and appendages can cause a loss in performance which leads to eventual costly maintenance or replacement of the damaged part. The damage is caused by the collapse of small vaporous cavities as they enter a high-pressure flow region. Upon collapse, enormous pressures occur on a material surface and material damage can occur. Although much is known about the bubble dynamics and material response, the problem of the prediction of prototype cavitation damage remains unsolved. Figure 3.1 summarizes the issues of the design and scaling aspects of the ship erosion problem. The state-of-understanding of cavitation erosion has been documented previously in the ITTC (1975, 1981, 1984, 1987, 1990).

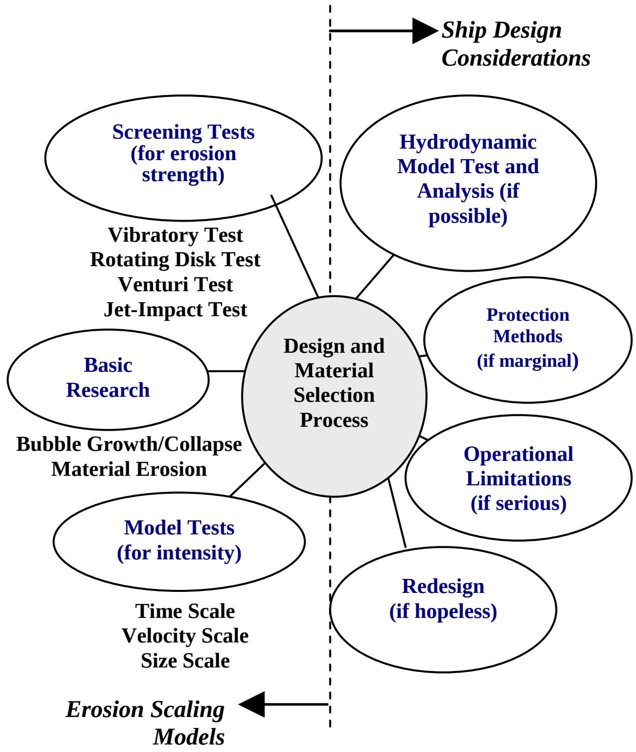


Figure 3.1- Design and scaling aspects of cavitation erosion for propellers, appendages and rudders.

The importance of cavitation erosion prevention is accented with the new generation of large and fast, sometimes very fast, container ships, ferries, and ROPAX-vessels. The shipping market has demonstrated a strong industrial advantage for very large container ships with higher speeds as shown in Fig. 3.2. This results in the propeller operating at reduced cavitation indices with an increase in blade loading while the maximum draft of the ship remains nearly constant. The maximum power for single screw ships that dominate the merchant fleet has grown from 30 to more than 70MW over the last two decades. The hydrodynamic challenges for these ships are discussed by Mewis and Klug (2004). Thiruvengadam (1971a) predicts that the erosion rate varies as the 6th power of velocity. Thus, if the ship speed is increased by 25% while maintaining the same propeller advance speeds, and let us assume the same cavitation intensity, the erosion rate would increase by a factor of approximately four! Examples of cavitation erosion observed on ship propeller blade tips are shown in Fig. 3.3 and on the rudders in Fig. 3.4.

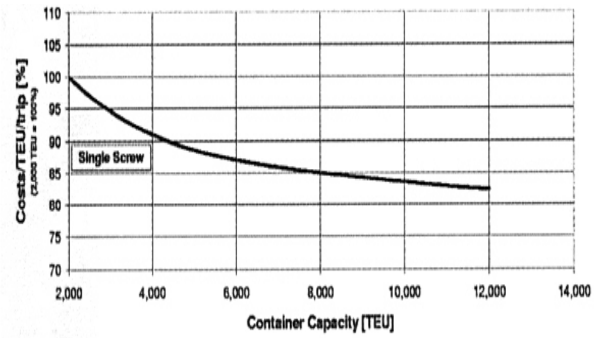


Figure 3.2- Economy of scale, relative cost per TEU (Twenty Feet Equivalent Unit) (Stopford, 2002).

Figure 3.3- Damaged propeller blade tips (Courtesy of HSVA).

The prediction of cavitation damage on rudders is very difficult. Cavitation damage can occur not only due to local cavitation on the rudder but also due to the cavitation produced by the propeller then collapses on the rudder. At model scale, this ship wake/propeller/rudder interaction is difficult to produce due to the low Reynolds number relative to the rudder. Figure 3.5 shows observed cavitation patterns on a semi-balanced rudder during a water tunnel test.

Figure 3.4- Rudder damage (Courtesy of HSVA).

Figure 3.5- Cavitation patterns on a semi-balanced rudder (Courtesy of HSVA).

An accurate prediction of cavitation damage at full scale remains a very difficult task although significant progress in modelling the physics has been made. This is because any type of cavitation has the potential to cause damage; but, only those flow conditions where bubbles collapse very near the surface actually result in damage. As an example, Knapp (1955) reported that for tests with soft aluminium only 1 in 30,000 bubbles resulted in an indentation of the surface. The collapse of this bubble occurs over a very small area (on the order of hundredths of a square millimetre) and in a very short time interval (measured in microseconds). The message is that very small changes in flow conditions on local flow geometry can result in very significant changes in cavitation erosion.

A literature survey was conducted for publications and conference proceedings on the subject of cavitation erosion. Over the last ten years there have been numerous studies in this area; however, most of these efforts have been on material characterization and on the physics of cavitation bubble collapse. Several important papers in these research areas are in the seminar proceedings of the International Cavitation Erosion Test (2000) and the Fifth International Symposium on Cavitation (2003).

The most recent study that is directly related to ship cavitation erosion issues is EROCAV (Friesch 2003, 2004). EROCAV was a cooperative program to develop a practical tool to assess the risk of erosion on ship propellers and rudders in the design stage. This program included full-scale investigations, mechanisms of cavitation induced erosion, prediction tools and comparative model tests with the goals of providing guidelines. From a study on a full-scale propellers, seven different types of cavitation were identified where erosion occurred and are: (1) fluctuating/travelling sheet cavitation, (2) cloudy tip vortex, (3) severe/unstable mid-chord cavitation developing into clouds, (4) vortices originating from the leading edge on the tip, ending cloudy, (5) foaming root cavitation, root vortex cavitation, ending cloudy, (6) foaming sheet close to trailing edge, and (7) sheet cavitation along the leading edge of the face side, breaking up into clouds. Full-scale observations for large container ships showed that cloudy face-side cavitation did not automatically result in cavitation erosion damage. An executive summary of the EROCAV project is given in Appendix A.

A workshop sponsored by the Bassin d'Essais des Carenes was held on 27-28 May 2004 for the ITTC Committee. The purpose of this workshop was to invite cavitation erosion experts to identify the state-of-the-art and address cavitation erosion scaling. This was very well attended and the list of presentations is given in Appendix B. Some of these results are discussed in Section 4 that summarizes scaling procedures.

It is well established that erosion is caused by collapse of a cavitation volume that is very near the solid surface. This collapse is characterized in some cases by a jet which is formed at the side of the cavitation volume farthest from the surface and is directed toward the wall (Plesset and Chapman, 1970). In other cases, collapse is associated with transient cavitation vortices downstream of cavities (Karimi and Avellan, 1986). Also, the collapse energy of cavities in a cloud can be forced toward a surface (Mørch, 1981). A recent study by Berchiche, Grekula, and Bark (2003) suggests that the collapse of "glassy cavities" also has a focusing effect on the collapse energy.

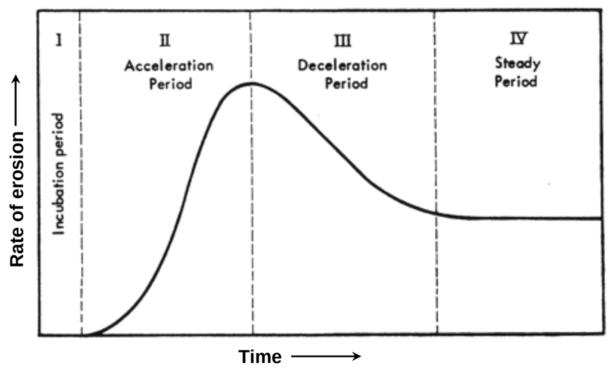
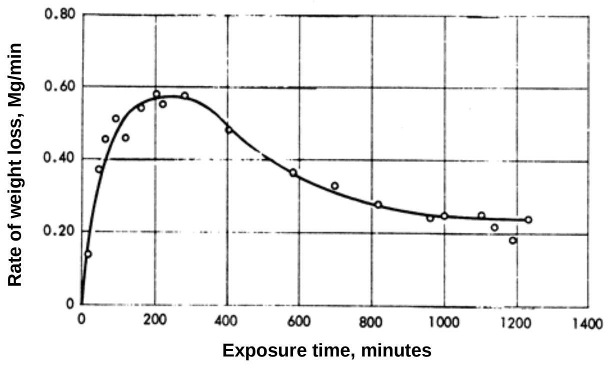


Figure 3.6- Classification of erosion periods.

It is well established that the rate of erosion is a function of the exposure period. The rate of erosion increases from negligible values, reaches a maximum, then decreases and levels off to a steady value. Thus, cavitation erosion history of a material can be divided into four periods as shown in Fig. 3.6.

(1) Incubation Period,
(2) Acceleration Period,
(3) Deceleration Period, and
(4) Steady Period.

Material: Tobin Bronze
Frequency: 14.2 kcs
Amplitude: 1.91 x 10^{-3} cm
Liquid: Distilled Water
Specimen Diameter: 1.59 cm



Material: 316 Stainless Steel
Frequency: 14.2 kcs
Amplitude: 1.91 x 10^{-3} cm
Liquid: Distilled Water at 75˚F
Specimen Diameter: 1.59 cm

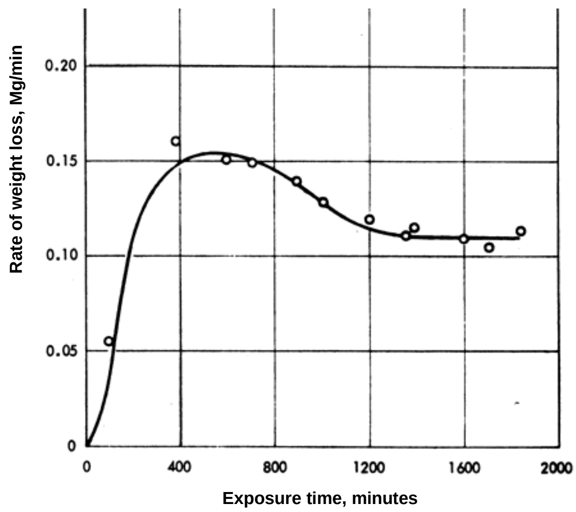


Figure 3.7- Relationship between exposure time and cavitation rate (Thiruvengadam, 1971a).

In the incubation period each material indentation is produced by a single event, and thereby many researchers such as Stinebring

(1997) relate the volume of the indentation to a collapse energy. Choffat et al. (2003) have developed a new procedure to control the exposure time during the incubation period to prevent overlapping of pits. As the exposure time increases, pit overlapping will occur which then leads to material weight loss in the acceleration period.

The transition from the different periods will be different for each material. Figure 3.7 is an example for bronze and 316 stainless steel tested in a vibratory device (Thiruvengadam, 1971b).

The relative resistance of many materials has been catalogued using one of several screening tests. Some of these include vibratory tests, rotating disk tests, jet impact tests, venturi tests, and water tunnels. Basic research combined with screening tests has led to several protection techniques and material scaling relationships. One recent study has been reported by Steller (1999). Wilczynski (2003) has attempted to model the cavitation induced erosion as the consequence of unreversible, resonant absorption by solid body material of the energy released during collapse.

Limited experience with composite structures for propellers and rudders at sea indicate a low resistance to cavitation erosion. Thus, a cavitation damage resistant coating may be required.

The cavitation damage resistance of coating materials is very difficult to define. In some cases a coating will be able to absorb and dissipate energy and show no damage. However, if the rate of absorption exceeds a critical threshold at that condition the coating will fail catastrophically. ARL Penn State has evaluated the resistance of coatings in the ultra high-speed water tunnel. In this facility a sample is placed in a region where the collapse of a sheet cavity occurs. Figures 3.8 and 3.9 show results from one coating. Figure 3.10 shows results for an aluminium sample for comparison. The test conditions for any samples were the same. As can be noted, the coating response to cavitation is unpredictable.

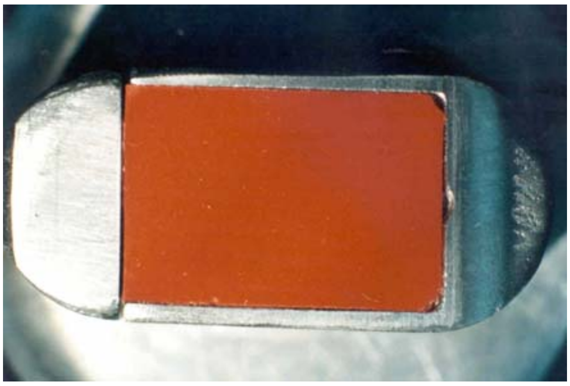


Figure 3.8- Coating after exposure time of 1200 minutes (Courtesy of Stinebring)

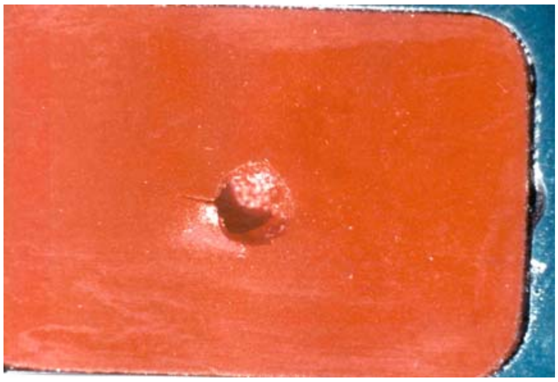


Figure 3.9- Coating failure after exposure time of less than one minute (Courtesy of Stinebring)

Figure 3.10- Erosion on aluminium sample after 150 minutes (Courtesy of Stinebring)

The initial scaling relationships for cavitation erosion as proposed by Knapp (1955) was based on material testing to determine erosion power. These results indicate that it is possible to model erosion and to predict prototype performance. However, it must be recognized that cavitation erosion is a complex problem involving cavitation type, its unsteadiness, and the response of the material to this energy.

This initial effort has led to the developments of models that identify the energy associated with a specific form of cavitation and the frequency of cavitation by many investigators. Estimating this energy and frequency and applying this to known material response is the basis of erosion predictions. Some recent models are discussed in Section 4. A general expression for damage rate is:

$$D = F\left(V^N, \sigma/\sigma_i, \Delta\sigma(t)...\right)G(M, HT,...)H\left(t/t_0\right) \quad (3.1)$$

where:
F = energy distribution associated with a type and structure of cavitation over time
G = material response
H = time associated with the erosion process.

It is very important to realize that the energy associated with the collapse of a bubble or a vortical structure will be different, and will influence the cavitation aggressiveness.

The design of a propeller or rudder to reduce cavitation erosion or the choice of material to resist damage relies on information as outlined in Fig. 3.1. Basic research on bubble collapse, material characterization, and energy models gives much needed fundamental knowledge to develop scaling relationships. It appears that it is possible to conduct model propeller tests over a shorter time using paints, weaker materials, etc. to identify potential erosion damage. Also, new computation fluid dynamics tools are being developed that predict cavitation performance. However, it is important to note that similar cavitation patterns, types of unsteadiness, etc. that occur full scale need to be modelled correctly. Also, the selection of material depends upon several factors such as corrosion, strength, reproducibility of results, and the techniques employed in the model application. A procedure is presented in Section 5 for model scale testing.

It is very important for propeller/appendage designers to determine if cavitation erosion is an issue before testing. Thus, it then could be possible to modify the design geometry, flowfield, or choose different materials that could be more erosion resistant. A review of mitigation techniques and resulting guidelines is given in Section 6.

4. SCALING LAW SUMMARY

In this section, we focus on the scaling laws found in the literature concerning the prediction of cavitation erosion damage. However, it is obvious that the first stage in this process is to have geometric and flow similarity between model and full scale. This can be stated as follows:

- model geometry,
- ship wake (viscous effects, shaft inclination),
- cavitation pattern,
- pressure gradient,
- frequency of cavitating structures (bubbles, clouds, vortices, etc.) capable of imploding (Strouhal), and
- pressure wave generated by cavitating structures.

Computations can be also used to give us better knowledge of the flow conditions at full scale, for example, the wake structure (Bull, et. al. 2002).

4.1 Development of Scaling Laws on Cavitation Erosion Based on Experiments

Scaling laws on cavitation erosion damage are always studied during the incubation period. However, even in that period, it appears that there are some difficulties to achieve good results because the tests duration is important to eliminate pit overlapping. It is also difficult to measure with a great accuracy surface deformations to obtain number, location and volume of pits.

Most efforts to determine scaling concentrate on pitting damage rate and volume damage rate on controlled samples. Almost all the authors used the incubation period of the material to analyze flow and to study the effect of the following parameters on pitting damage rate and volume damage rate:

- scale effects,
- flow velocity effect,
- change of fluid, and
- change of material.

Stinebring et al. (1977) used samples of pure aluminium during the incubation period to study the effect of velocity, air content and length of the cavity on the pitting damage rate which is defined by the number of pits per unit area and exposure time.

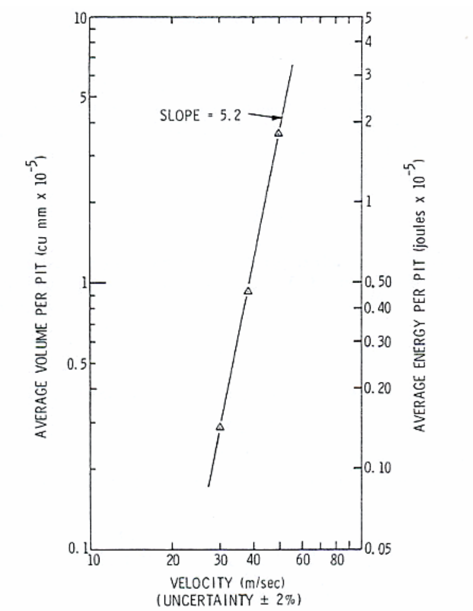


Figure 4.1- Scaling with Velocity (Stinebring, 1977).

They used the *dynamic hardness* (surface hardness of a material at a high strain rate) to obtain a relation between the volume of the pits and the necessary energy to create a pit. The pit volume is calculated with the radius and depth of the pit which are measured with a microscope.

The pitting damage rate was found to be proportional to V^6 (Fig. 4.1) where V is the local reference velocity. The mean volume of the pit increase as V^5 (Fig. 4.2) and as the number of the pit increase as V^6, the total energy of collapsing bubbles per unit surface area increase as V^{11}.

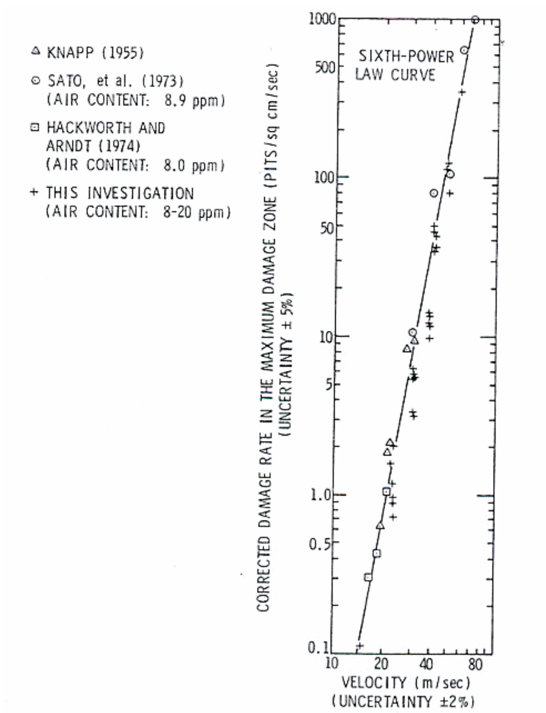


Figure 4.2- Damage rate scaling with velocity (Stinebring, 1977).

The study of air content effect on the pitting rate shows that the pitting rate increases when the air content decrease and that the volume of the pits increases when the air content decrease. The tests have been conducted for three air contents (7, 10 and 20 ppm). When air content is doubled, the pitting rate is divided by two. This is due to the fact that ρc (fluid density times the speed of sound) changes. Also, the non-condensable gas in the cavitation bubble affects the rebound and the bubble dynamics.

Stinebring et al. (1980) began to develop the energetic analysis of the cavitation erosion phenomena. They proposed that the total energy (E_T) is a sum of three energies:

$$E_T = E_A+E_E+E_R \tag{4.1}$$

where:
E_A = absorbed collapse energy,
E_E = elastic energy due to the recovery of the surfaces after the collapses, and
E_R = energy remaining in the bubble after the initial collapse.

The E_A energy is calculated from measurements of the pits, the E_R energy is neglected. The distribution of bubbles collapse energy found from experiments is shown for three test velocities in Fig. 4.3.

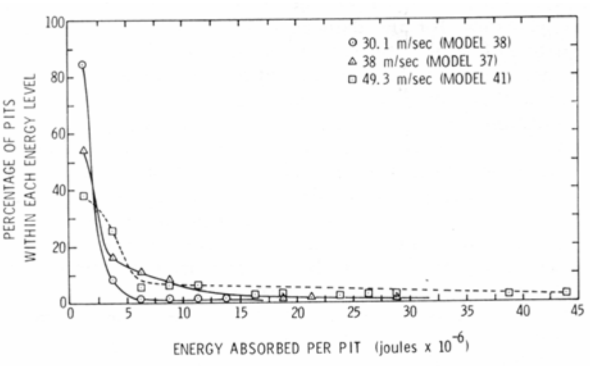


Figure 4.3- Distribution of collapse energy (Stinebring et al., 1980).

The energy E_E is calculated from the pits to be within the range of 4 to 30% of the total energy associated with a bubble.

The authors use only the incubation period in their analysis because the energies could be estimated during this period. However, this investigation can not predict the mass loss at full scale but it accounts for hydrodynamic scale effects, F, in Eq. 3.1.

Pereira et al. (1998) measured the volume and the frequency of the cavitating structures. The potential energy E_c of a structure is expressed by:

$$E_c = \Delta p \, Vol \cong \Delta p \lambda^3 \tag{4.2}$$

where,
Δp is the difference between the minimum and the maximum pressure in the flow and Vol is the volume of the structure. Fluid energy spectrum of the structures is expressed as a function of flow global parameters. The comparison between the fluid energy spectrum and the material deformation energy spectrum showed a proportionality relationship defined by the collapse efficiency. This is a macroscopic efficiency that integrates the generation process and the energy cascade. This efficiency was found in the range 10^{-5} to 10^{-4}.

Escaler et al. (2003) had conducted tests of mass loss in cavitation tunnel, vortex cavitation generator and vibratory device with two types of materials. They found that the classification of material linked to hardness is different between a cavitation tunnel and a vibratory device. Hence, the aggressiveness of the flow is found to be higher in a cavitation tunnel.

The scaling approach developed by Lecoffre (1995) is based on few rules:

- The number of bubbles emitted by two cavities with geometrical and cavitation similitude follows the Strouhal law.
- The pressure intensity *(I)* generated by the collapsing bubbles can be estimated by $\rho c V_j$ (where ρ and c are respectively the fluid density and the speed of sound and V_j is the bubble jet velocity).
- Concerning the material, there is a threshold in energy above which a pit can be created.

Then putting the hydrodynamic and the material response in regard, the following schematic curves (Figs. 4.4 and 4.5) are obtained from Lecoffre during the incubation period.

The velocity effect on pit histogram for the same material is shown in Fig. 4.4. When changing the material, the threshold will change as shown in Fig. 4.5.

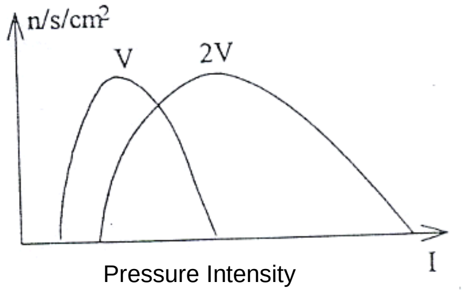


Figure 4.4- Effect of a doubling of the velocity (Lecoffre, 1995).

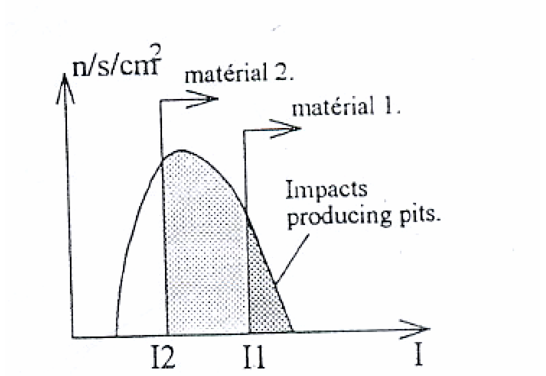


Figure 4.5- Material as a high pass filter (Lecoffre, 1995).

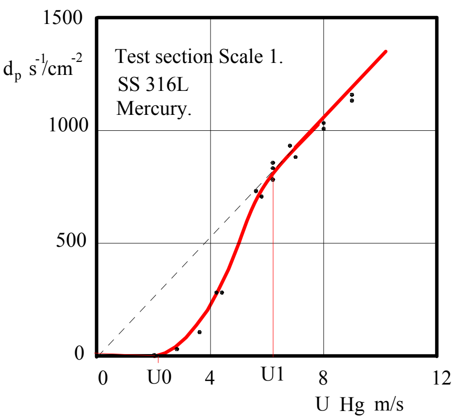


Figure 4.6- Velocity scaling in Mercury (Lecoffre, 1995).

Initially, the number of pits per unit time and area increase with velocity with an exponent *n*. Then when each bubble or cavitating structures had enough energy to create a pit, the number of pits per unit-time increase linearly as *V*, as shown in Fig. 4.6. The exponential region is similar to that observed by Stinebring and others in water.

When changing the scale λ (same material, same velocity, and same fluid), the number of pits per unit time and area is proportional to λ^3, as shown in Fig. 4.7. This implies the influence of Strouhal number ($St = f{\cdot}L/V$) and the surface area over which the cavitation is related to λ where one characteristic dimension L is related to λ and the density is proportional to λ^{-3}.

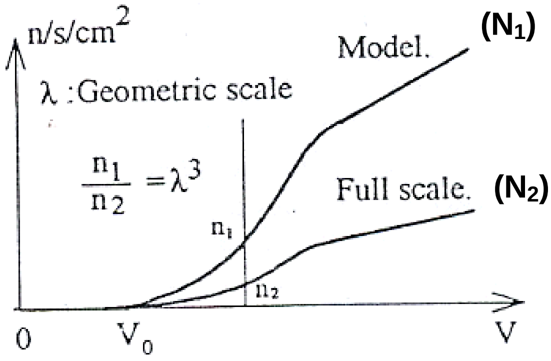


Figure 4.7- Influence of velocity, same material, same fluid (Lecoffre, 1995).

However, the resulting damage rate also depends upon the energy associated with the cavitation structures which increases with scale. The net result is that at large scales the damage rate is increased; however, it is important to realize that the events per area and time decrease.

Lecoffre uses experimental results to validate these extrapolation laws.

4.2 An Approach Coupling Fluid and Material: Numerical Method and Experiments

Fortes-Patella and Reboud (1998a) describe the dynamic response of various materials exposed to liquid jet and pressure wave impacts by a simulation making use of an elasto-plastic solid model. Calculated pit profiles were compared to experimental ones produced in test materials by cavitation in various fluids. Two types of pressure loading were calculated: micro jet impact or pressure wave impact. The best agreement between experiments and calculations has been found for pressure wave emission.

The couple (*P,L*) (Pressure, applied at the surface distance to the solid boundary) was found to be unique for each pit (characterised by h (depth) and $R_{10\%h}$ (radius)) for a given material and a given wave passage time. This allows the calculation of the 3D histogram of flow pressure pulse using the histogram of measured pits.

The authors show that there is no effect of material on histogram of flow pressure pulse.

The number of pits normalized by area and time was found experimentally proportional to $\lambda^{2.7}$. This is close to usual λ^3 law noted by Lecoffre. The volume damage rate does not change measurably with the scale. The number of pits normalized by area and time was found experimentally to increase as the power 5 of the velocity. The pit depth does not vary with the velocity. However, the pit volume normalized by area and time increase as V^7.

The calculations assume an elasto-plastic solid model and pressure wave emission, and showed no effect of material on the histogram of flow pressure pulse as expected. On average, the maximum surface pressure P for the two scales at the same velocity distance, but the distance to the solid boundary is smaller for the model scale. This implies that the energy emitted by the collapse of the structures is higher for the larger scale.

Then always using the elastoplastic solid model, Fortes-Patella and Reboud (1998b) calculate an efficiency η between the fluid energy (acoustic energy) and the plastic deformation energy of the material. The calculated efficiency values (m) are 8% for aluminium, 2% for copper and 1% for stainless steel.

This allows the definition of an extrapolation procedure for different materials exposed to the same flow. Hence,

$$\forall_{copper} = (\alpha/\eta)_{alu} \times (\eta/\alpha)_{copper} \times \forall_{alu} \tag{4.3}$$

where,
$\forall$ = volume of pit,
η = efficiency, and
α = a constant for the material.

This methodology allows the prediction for both aluminium, copper, and stainless steel. However, for aluminium and stainless steel, this approach overestimates the volume by a decade. One explanation is that during the test with stainless steel, the test time is large and then the risk of pit overlapping is high. So, the number of pit rate and their volume is underestimated.

Fortes-Patella et al., 2000 and Choffat et al., 2003 used a 3D laser profilometer developed by EDF to study the effect of test duration and to analyze cut-off parameters on the evaluation of the volume damage rate and the pit number rate. They found that for soft materials (such as copper, pure aluminium) the pit number rate and the volume damage rate are very time dependant, Fig. 4.8.

This is due to pit overlapping during the test. It can explain the discrepancy between different results found in the literature as it is illustrated in Table 4.1.

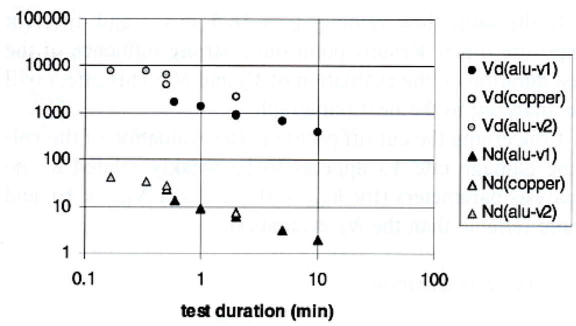


Figure 4.8- Volume damage rate *Vd* and pit number rate *Nd* as a function of test duration for copper (υ = 38.5 ms^{-1}) and aluminium samples (υ_1 = 20ms^{-1} – room temperature, υ_2 = 32 ms^{-1} – 30ºC). *Vd* (µm^3 mm^{-2}s^{-1}) and *Nd* (x10-2pits mm^{-2}s^{-1}).

Table 4.1- This table summarizes results obtained by many authors considering the influence of the flow velocity on the evaluation of pit number rate N_d and volumetric damage rate $V_d{}^a$ (Fortes-Patella et al., 2000)

Technique	Effect of Flow Velocity	Test material/ Fluid
Interference Method	$N_d \sim \upsilon^6$	Stainless steel/Hg
	$N_d \sim \upsilon^4$	Stainless steel/water
	$V_d \sim \upsilon^3$	Copper/water
	$V_d \sim \upsilon^8$	Stainless steel/water
2D optical techniques	$N_d \sim \upsilon^6$; $\underline{\underline{V}} \sim \upsilon^5$	Aluminum/water
	$N_d \sim \upsilon^5$	Indium/water
3D roughness meter	$N_d \sim \upsilon^7$	Stainless steel/water
3D laser profilometry	$N_d \sim \upsilon^{3.5}$;$V_d \sim \upsilon^5$	Aluminum/water
	$N_d \sim \upsilon^4$;$V_d \sim \upsilon^5$	Copper/water
	$N_d \sim \upsilon^{5.5}$;$V_d \sim \upsilon^7$	Stainless steel/water
	$N_d \sim \upsilon^5$;$V_d \sim \upsilon^7$	Stainless steel/water
	$V_d \sim \upsilon^5$	Copper, aluminum, stainless steel/water

[a] $\underline{\underline{V}}$ is the average volume per pit

4.3 How to Apply to an Erosion Problem?

Lecoffre (1995) and Masip (1998) described a process to predict full scale erosion based on similarity laws. Briefly, the process is shown in Figs. 4.9 and 4.10 and can be summarized as follow:

- The first stage is to apply similarity laws to quantify the flow aggressiveness. In the ITTC 1966, this was identified as necessary in order to quantify cavitation damage. The use of a soft material as a sensor in connection with the use of paint tests to indicate only the location of damage risks.
- The second stage is to apply similarity laws to model data to obtain the predicted full scale impact histogram.
- Third, is to reproduce the full scale pit histogram in a fast erosion apparatus (such as “veine tourbillon” or high-speed tunnel) and to measure the erosion rate for a material.
- Finally, use of similarity laws on material to predict full scale erosion.

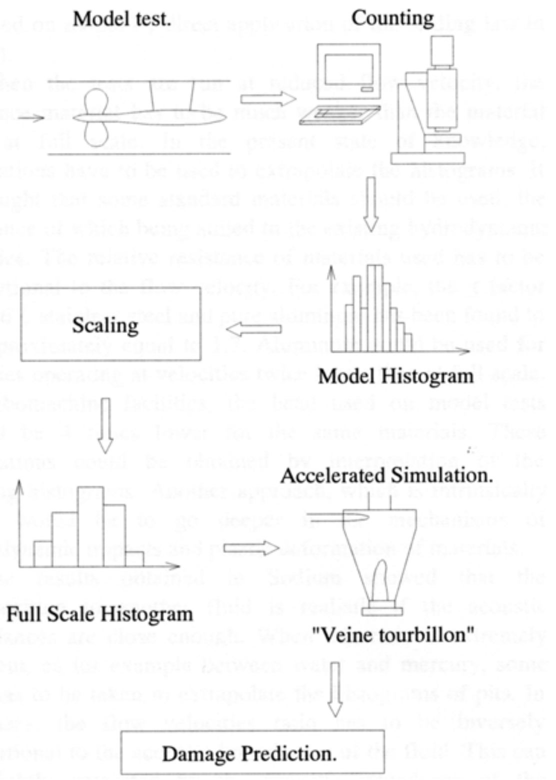


Figure 4.9- Methodology to predict cavitation damage (Lecoffre, 1995).

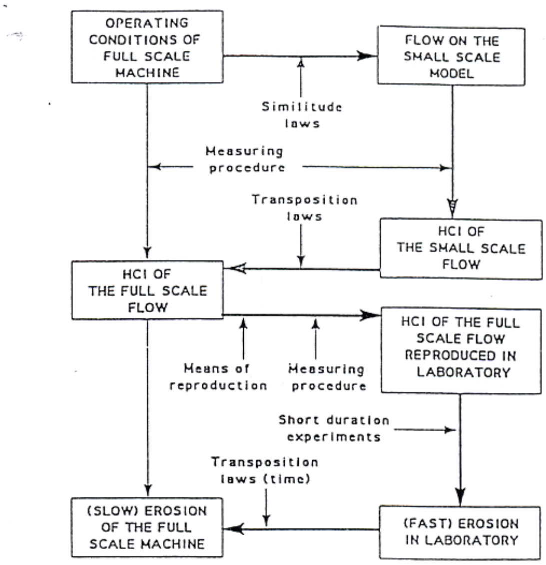


Figure 4.10- Application of the prediction erosion methodology (Masip, 1998).

When this process is not possible, a more global method can be applied. Hence, Turbomachinery Society of Japan (2003) produced a guideline presenting the prediction and the evaluation of the cavitation erosion on the rotodynamic pumps based on the experiences accumulated in university and pump manufacturers. In this work, different predictions can be found based either on flow conditions or on measurement of acceleration due to vibration of the pump or CFD. This was presented at the workshop.

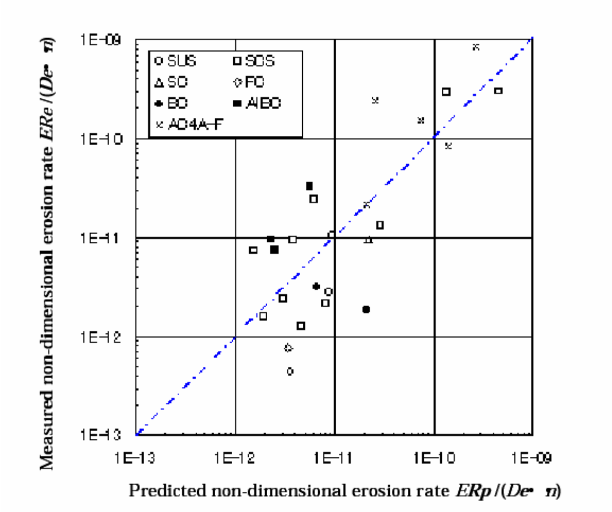


Figure 4.11- Relationship between predicted erosion rate and measured rate (TSJ Guidelines, 2003).

Figure 4.11 illustrates the prediction accuracy of one of the equation, presented in the guideline, involving discharge, NPSH, specific speed, tensile strength of the material, speed of rotation and hub diameter of the impeller.

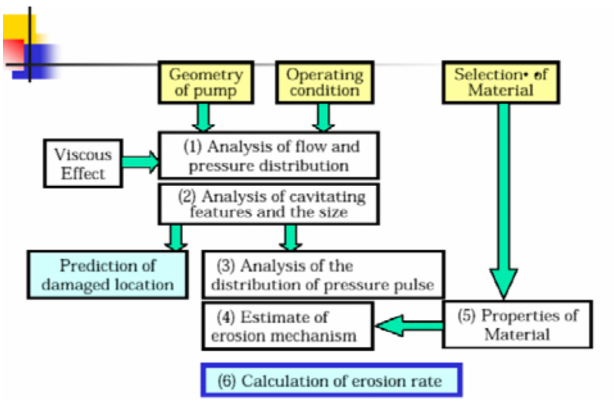


Figure 4.12- Predicting method of cavitation erosion.

Also, two processes are described hereafter, one useful when the physical flow is known as shown in Fig. 4.12 and the other one when just CFD is available as shown in Fig. 4.13.

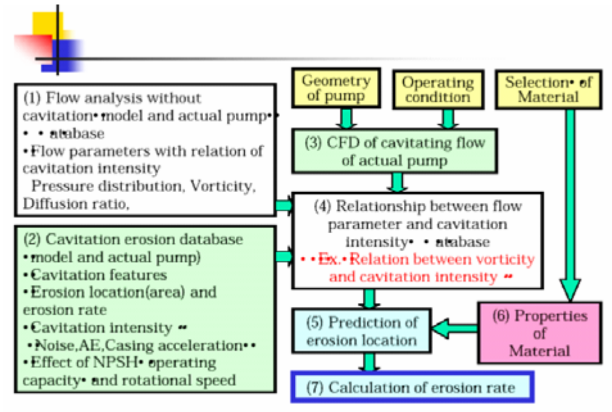


Figure 4.13- Prediction method of cavitation erosion based on the flow analysis without cavitation and erosion database.

5. TEST PROCEDURE

5.1 Questionnaire

As a first step toward developing a procedure, this Committee developed a questionnaire for assessing current practices in use by various organizations for predicting cavitation-induced erosion damage. The questionnaire was sent to approximately 100 organizations comprised mostly of ITTC Member Organizations, along with industry and academia involved in cavitation research.

The questionnaire was divided into four major areas: (1) Facilities, (2) model, instrumentation set-up, and test conditions, (3) test procedures (paint test), and (4) analysis of the results.

<u>Summary of the Responses.</u> Of the organizations contacted, 16 organizations from 11 countries responded with answers, and 5 organizations from 5 countries responded with no answers primarily because they are not involved in cavitation-related activities.

The 11 countries which responded with answers are as follows, with the number of responding organizations specified in parentheses: Canada (1), People's Republic of China (1), Finland (1), France (1), Germany (1), Japan (4), South Korea (2), The Netherlands (1), Poland (1), Sweden (1), and USA (2).

Analysis of the Responses. The questions were organized to gather information in the following areas:

- Test facility involved in erosion tests;
- Propeller and ship models, instrumentation set-up, procedures;
- Adopted test conditions; and
- Analysis and presentation of results.

Test Facility and Wake Simulation. The responses to the questionnaire have been analyzed in various ways and some of them are presented in graphical form. The types of cavitation tunnels used vary from open-jet (1), closed-jet (14), free-surface cavitation tunnels (1) to a large depressurized towing tank (1). The typical reference velocity used during erosion testing is shown in Fig. 5.1.

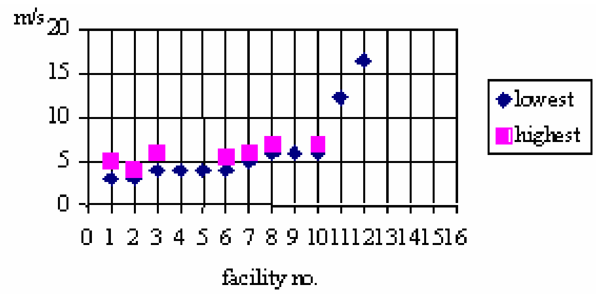


Figure 5.1- Tunnel speed during erosion test.

Wake simulation is critical when performing erosion tests because of its impact on the resultant cavitation patterns. Analysis of the responses indicated that tunnel velocity measurements and quality checking of the simulated wake in the facilities are common procedures when performing these tests. Although most facilities are still using pitot tubes, LDV is becoming popular for measuring the time-averaged velocity field.

The survey of the wake simulation adopted (wire screen, dummy model, and full model) for performing erosion tests showed, with some exceptions, that smaller facilities implement wake simulation by wire screen. Larger tunnels use more sophisticated wake simulation methods.

Dummy models are widely used for medium-size facilities, while full-ship models are adopted for tunnel cross section larger than 1 m^2. One organization uses a combination of full-hull model and flow liners.

Propeller and Ship Model, Instrumentation. A typical propeller diameter used for erosion tests is in the range of 150-250 mm. Some large facilities use propellers with diameters up to 400 mm. Popular propeller materials are brass and high-strength aluminium alloy. Typical manufacturing accuracy is in the range of 0.01-0.05 mm. Only some of the respondents use carborundum turbulence stimulation on propeller blades. Normally for the dummy model set-up, brackets and rudder are also mounted. When using full-ship models, wood or fibreglass is used for construction and all the appendages are mounted. Shaft rotational speed is measured using a multiple-pulse encoder mounted on the propeller shaft, on the dynamometer or on the motor.

Test Conditions. In general, test conditions are based on towing tank propulsion test results. In some cases, the designer specifies test conditions. In both cases, K_T identity is widely used compared to K_Q or J identity. There is no standard definition of the cavitation number σ for erosion tests among the organizations. Static pressure is defined variously at the shaft centreline at 0.7R or the propeller tip at 12 o'clock angular position. The dynamic pressure is calculated with the propeller rotational speed or with the vector sum of the propeller rotational speed and the advance velocity.

During the test, water quality is monitored by all of the organizations. Oxygen content or total air content is measured during tests performed below 7 m/s with a propeller rotational speed in the range of 15 - 45 rps. Most of the organizations observe cavitation using stroboscopic light with video or digital still cameras. A few organizations also use high speed video to observe cavitation.

Data Acquisition, Processing and Presentation. Most of the facilities mentioned that observation methods should be combined with soft surface techniques. Most of the facilities focus on observations by eye, time lapse video and high speed video, combined with the paint test method.

Figure 5.2 shows the percentages of the different methods used in judging the danger of cavitation induced erosion. Observations are made by eye, time lapse videos and sometimes high speed video observations. No organizations mentioned routinely using other measuring techniques such as acoustic noise or impact methods.

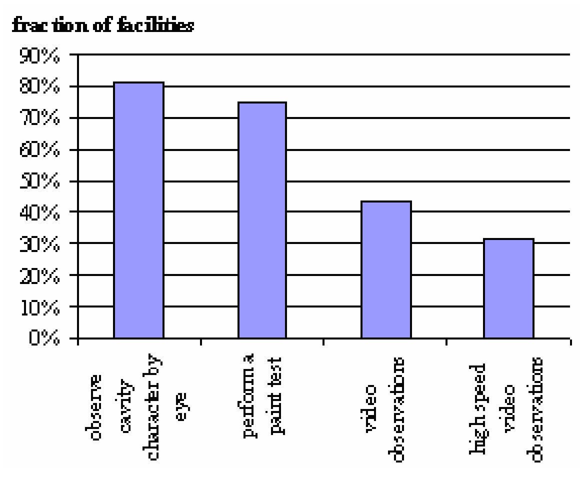


Figure 5.2- Methods to judge the danger of erosion for propellers.

Cloudy, bubbly and fluctuating sheet cavitation are mentioned as cavitation phenomena being responsible for erosive damage (see Fig. 5.3).

The soft surface technique used in nearly all facilities is the paint test method, which is in most of the cases used in combination with different observation methods. Most of the institutions spray the paint on the propeller blades (see Fig. 5.5) and the duration of the paint test varies between 0.5 and 3 hours (Fig. 5.4). In most of the cases one layer of paint ink is used.

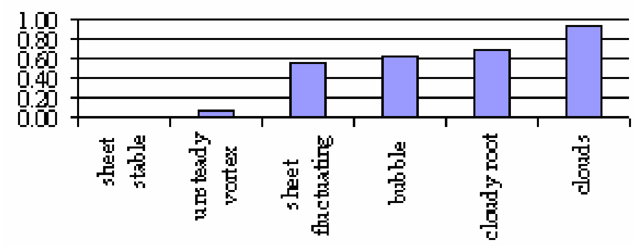


Figure 5.3- Assessment of erosiveness of particular cavitation forms (1 - most erosive, 0 – non-erosive).

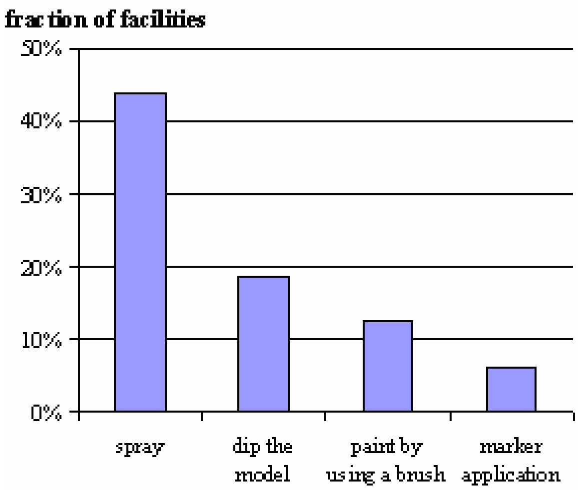


Figure 5.4- Ways of paint application.

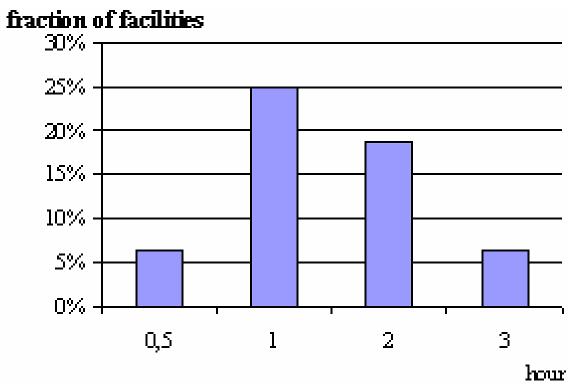


Figure 5.5- Duration of the erosion soft paint model test.

Summary. Questionnaire results indicate that many organizations perform erosion tests when a cavitation tunnel is available. The wake simulation used varies with the facility type. In some facilities, limitations due to blockage or to low propeller Reynolds number are apparent. Nonetheless, the information obtained is valuable data for a ship designer. Larger facilities offer more-advanced testing capabilities and a range of wake simulations (dummy models, full model, shortened model, flow liners, etc.).

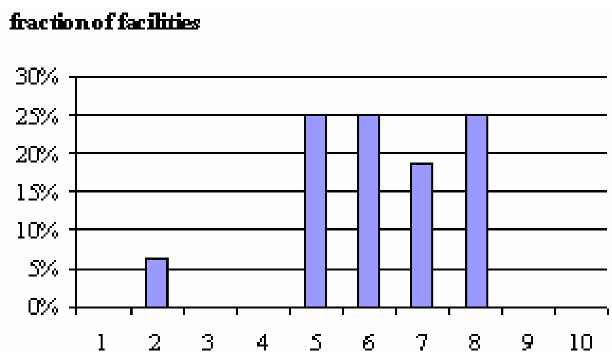


Figure 5.6- Confidence in the quality of propeller erosion model test results (x scale 1-10: 1 very uncertain, 10 very confident).

All the organizations perform data acquisition and analysis in a similar way – mainly observation of the cavitation phenomena by different methods and relate it to experience from full scale; but, only a few use high speed video techniques to analyze the cavitation time history. Paint tests with different paint mixtures are the mostly used additional test methods.

Figure 5.6 shows the confidence of the different institutes in the test methods used.

5.2 Development of the Procedure

This Specialist Committee developed a procedure for predicting cavitation-induced erosion damage on propellers, rudders and appendages. This recommended procedure is included in the ITTC – Quality manual as Procedure 7.5-03.

The basis of each erosion test is a cavitation test according to ITTC-Procedure 7.5-02.

Comments on the Procedure. The Committee was assigned to develop a procedure for the prediction of cavitation induced erosion damage on the basis of model-scale experiments. The procedure provides guidelines to ensure the most accurate data possible from the tests. The procedure discusses the paint test and observation techniques, mainly the high-speed video technique. Details related to cavitation tests are described in the Cavitation Test Procedure 7.5-02.

All parameters used in an erosion test should be kept the same as for the cavitation test. An erosion test is a cavitation test with one or more blades treated with a soft surface; however, the observations are performed in more detail and over a longer time. Enhanced observation techniques are described within the procedure. Also, emphasis is given to the high speed video observation technique because this technique provides more insight into the cavitation dynamics involved in the erosion process.

The required results of cavitation propeller/rudder model experiments including cavitation dynamics observations and the soft paint test are:

- The estimation of the full scale erosion risk
- Information on the possible location and extent of the erosion zone with respect to the propeller/rudder surface
- The explanation of the physical background of particular soft paint damage from the point of view of observed cavitation dynamics

Therefore it has to be constantly kept in mind that the soft paint (or any other soft coating) test should be considered as a complementary one to the cavitation observations. The interpretation of the potentially erosive character of the cavitation dynamics is always based on observations. The soft paint test serves only as the best possible verification of the conclusions arising from the detailed cavitation observations. Thus the primary aim of the paint test is to confirm the suspicion of the erosive character of the cavitation appearance. The pattern of the removed paint can be understood only as the result of the cavitation observation, during which the origin of the frame of reference is shifted directly onto the propeller/rudder surface.

The soft paint test as any other model test is connected with scaling of the examined phenomena. As the cavitation erosion time history is usually nonlinear and consists of several characteristic periods, the problem of the time scaling arises. It is believed that the soft paint test enables shortening or even skipping the erosion incubation period. This feature of the soft paint test brings obvious disadvantage of neglecting the propeller/rudder material erosion resistance. However the soft paint removed by the cavitation collapse induced array is usually considered as the high risk area.

Scaling Issues. In this part of the report, some physical phenomena and information on the test techniques recommended in the procedure are documented. These play an important role when performing erosion tests in a cavitation test facility, but which can neither be put in a direct law nor can specific values be given.

Hydrodynamic Scale Effects. With regard to the propeller hydrodynamics including the ship wake and cavitation, an elaborate procedure usually results in adequate simulation of the cavitation dynamics. This is achieved primarily by requiring similarity of the cavitation number and a pressure coefficient reflecting the flow field on the blades (with appropriate ship's wake and advance coefficient). Although important, these similarity conditions are not the only ones and they are usually only approximately fulfilled. A corresponding level of accuracy for the boundary conditions influencing the cavitation dynamics can however be even more difficult to achieve. An important problem appears when full-scale measurements have to be compared with model measurements or numerical predictions. Such comparisons are very important for establishing correlations between predictions and "true" full-scale data. However full-scale data can be even more difficult to interpret than model data. This fact is one reason why the effects of boundary conditions have to be taken seriously. In an experiment the following boundary conditions need to be considered:

- The presence of representative wake field.
- The presence of appropriate cavitation behaviour.
- The presence of other bounding surfaces as tunnel walls, etc.

In theory these points appear as boundary conditions for the hydrodynamic or possibly acoustic equations describing the behaviour of the cavitation dynamics. More details on the influence of physical boundary conditions on the cavitation behaviour can be found in the report of the Specialist Committee on Cavitation Induced Pressure Fluctuations of the 23rd ITTC (2002).

The main assumption in scaling of model results is that the model and full-scale processes are similar and most important, are measured and analyzed in ways preserving this similarity. Due to the fact that all similarity requirements cannot all be fulfilled in a model experiment, the cavitation behaviour at model and full scale will be different; i.e. scale effects will occur. For example, scale effects in the extent and dynamics of the cavitation will influence the behaviour concerning erosion damage. The dynamic behaviour will additionally be influenced by the thickness of the paint, the roughness of the paint surface and the treatment of the paint. All these parameters will additionally influence the surface tension of the paint and hence influence the reaction of the paint on the observed cavitation behaviour. Therefore it is very important to observe the cavitation dynamics.

High Speed Video Observations. To follow the true development of a particular cavity is only possible with a high-speed camera based on traditional film or the digital video technique. With a high-speed video you can make a test photograph to make the first evaluation of the cavitation phenomena and if necessary make another one, close up or from a different angle etc., until you have the data you need. Because of the short recording time, one or a few seconds, there is, however, some risk that you do not notice intermittency or long term variations but with repeated recordings that problem can be eliminated. It may also be time consuming to cover a sufficient number of views to feel safe that nothing is missed.

In a cavitation tunnel without permanent installation of the hardware, the procedure usually starts with observations in stroboscopic light. (If you have the permanent installations referred to above you may have use of some of the following steps as well). The aim of the preliminary observation is:

- To get a first estimate of the risk of erosion.
- If there is a risk, the aim is to decide if additional tests such as paint tests or high speed video are needed or if it immediately can be concluded how to reduce the problem.
- Particularly if high-speed video or film is considered the preliminary test is used for a first planning of that recording.

The following guidelines for high-speed video recordings are applicable. The frame rate, the exposure time of an individual frame and the duration of the total recording are the primary parameters that have to be selected. The exposure time is partly related to the frame rate. The requirements on these parameters are related to the water velocity, the propeller rate of revolutions and the image scale. In a typical propeller experiment with advance velocity up to approximately 10 m/s exposure times from 1/10000 sec or shorter is usually sufficient to avoid motion blur. A lower limit for the frame rate may be around 3000 frames/sec but a value between 5000 and 7000 is significantly more useful. As low as 1000 frames/sec is usually found to be inadequate for analysis. A value of 10000 frames/sec as an upper limit, and still with rather good geometrical resolution, seems to cover most requirements that can be expected in commercial testing. At this frame rate however, problems can occur to get enough light. It is still also an open question if some small scale processes in propeller tip cavitation in fact require still higher frame rates to be adequately followed at a useful image scale. A recording length of 1 or possibly up to 2 seconds is usually sufficient. Usually a number of recordings have to be made, at different scales, exposures and lightings. As for standard video small lens apertures are required for sufficient reduction of aberrations degrading the sharpness and for obtaining a sufficient depth of focus. The most effective way to control aberrations and depth of focus is to select the best camera position and to have enough of light. Optical elements such as prisms and correction lenses can to some extent also be used. Although the subject of resolution is a very important issue for a visual analysis method it cannot be treated in detail here.

Water Quality. The effect of water quality has been a subject of continuous discussion in the ITTC (1996). The cavitation nuclei concentration in the water has a significant influence on the tensile strength of the water, and therefore on propeller cavitation characteristics, especially inception and intermittence. However, the detailed effects of cavitation nuclei are now better understood. The ultimate solution will not involve reproducing the seawater nuclei full-scale spectra in model tests.

Minimizing the liquid tension and maximizing the number of nuclei is one method to reduce scale effects; however, in many facilities, this is not always practical. The “natural” nuclei spectrum of any cavitation facility depends on the history of the fluid as it circulates through the facility. This means that the nuclei spectrum will depend on conditions such as dissolved air content, pressure level, velocity, and the transit time through the different parts of the circuit, i.e. the main pump, vanes, resorber, etc. Consequently, the "natural" spectrum is different in each cavitation test facility. Each facility has its own unique relationship between air content and nuclei distribution for a given operating condition. It must, therefore, be observed that too high a level of air content creating too many air bubbles could introduce a damping effect on cavitation dynamics.

It is certain that operating at high Reynolds numbers will reduce water-quality scale effects on model blade cavitation. To minimize these scale effects, the experiments should be run at high Reynolds number and high flow velocity with high nuclei content, which is often reached by increasing the dissolved air content.

Model – full scale correlation plays an important role for both the testing community and their customers. Therefore comparisons like those described within the EROCAV project play an important role in the daily work of testing institutes and comparable data should be available at these institutes. Obtaining and analyzing full scale data is itself a major challenge substantially different from model scale testing and should be done very carefully. A detailed discussion on full scale measurements is given in the 22nd ITTC report (1999).

Scale Effects Specific for Paint Tests. The following scaling problems are important when conducting erosion tests:

- Scaling of the erosion time history including the incubation period and the erosion time rate,
- the location of the erosion zone, and
- the extent of the erosion zone.

The soft paint method of erosion risk assessment provides limited information concerning scaling of the phenomenon. Neither the full scale incubation period nor the full scale erosion rate can be estimated from the soft paint test. Moreover, as mentioned above one of the intended features of the method is to neglect the characteristic incubation period of the erosion. Therefore the duration of the soft paint test is set arbitrarily basing on the empirical knowledge concerning the response of the soft paint towards the direct action of the cavitation collapse. The questionnaire revealed that the duration of the soft paint erosion test does not exceed 2 hours. As it has been already emphasized the state of the soft paint should be controlled constantly during the entire duration of the paint test. The differences in the moments of the first occurrence of the paint damage may bring some insight into the level of the action of the cavitation collapse on the propeller/rudder model surface. The soft paint does not allow for scaling the material response towards the action of the cavitation collapse. The paint removed confirms the risk of exceeding threshold level for the cavitation collapse intensity.

The only information on the scaling of the erosion concerns the location and size of the erosion zone. However conclusions about the extent of the erosion zone must be preceded with the analysis of the possible scale effect concerning the cavitation appearance and dynamics.

6. DESIGN GUIDANCE

6.1 Introduction

Methods to control cavitation on moderately loaded propellers and thereby prevent erosion are well known (Carlton, 1994). The principles used to control cavitation still apply to the higher powers and speeds considered in this report. However, all aspects of the propeller and all the structures and appendages that are within the propeller race will be much more vulnerable and greater care must be taken in their design. Advice on design to avoid or manage cavitation within previous ITTC proceedings is limited to lower loadings/speeds (ITTC 1975, 1981, 1984, 1987, 1990, 1996, 1999).

Cavitation occurs when the locally accelerated flow lowers the pressure below a critical threshold. Cavitation damage occurs when cavitation structures enter a pressure region which is above a critical threshold. Any downstream structure is potentially vulnerable. These include active devices such as rudders in their numerous forms, support struts and even parts of the ship hull itself.

The designer requires knowledge of the detailed unsteady flow and the cavitation dynamics occurring within that flow region. It is often the case that prediction of the downstream track of the tip vortex and associated cavity system is very difficult and as a result cannot be easily considered in the design process.

Recent developments in high speed vessel design has resulted in the use of more heavily loaded propellers. Cavitation inception is based on cavitation number where the maximum allowable pressure coefficient is proportional to the square of local velocity. Both the more heavily loaded conditions and the higher vessel speed conditions will by necessity imply that regions where the flow accelerates above the vessel speed need to be carefully controlled. This applies both to local surface stream wise curvature changes and off body flow features such as tip or hub vortices.

The physical mechanisms whereby cavities are created, convected and are ultimately destroyed with any resultant damage do not change from those for more lightly loaded or slower ships. However, far greater care needs to be taken for all appendages and structures downstream of cavitation sources. The necessary guidance for design therefore re-iterates the standard procedures and approaches but with far greater emphasis on attention to detailed hydrodynamic design. As always, early design changes are far cheaper than retrofitting of whole new sub-systems or components.

6.2 Flow Regime Downstream of Propeller

It is the increase of fluid momentum by a working propeller where the risk of cavitation inception is greatest. However, once the propeller has accelerated and swirled the flow this high momentum fluid will travel downstream and increase the risk of cavitation on appendages and struts placed in way of the race.

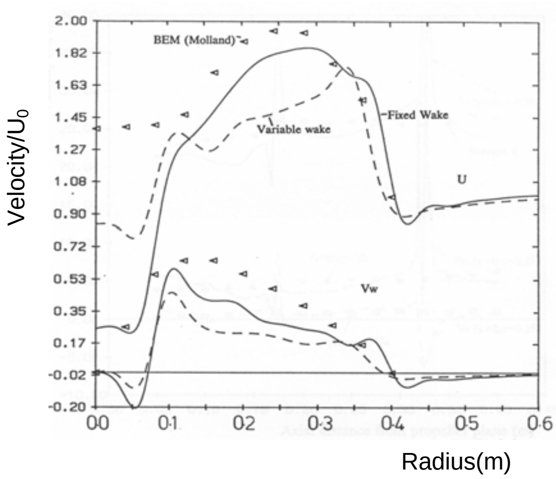


Figure 6.1- Calculations of the circumferential averaged axial and swirl velocities at a typical rudder stock position downstream of a propeller of radius 0.4 m (Turnock, 1993).

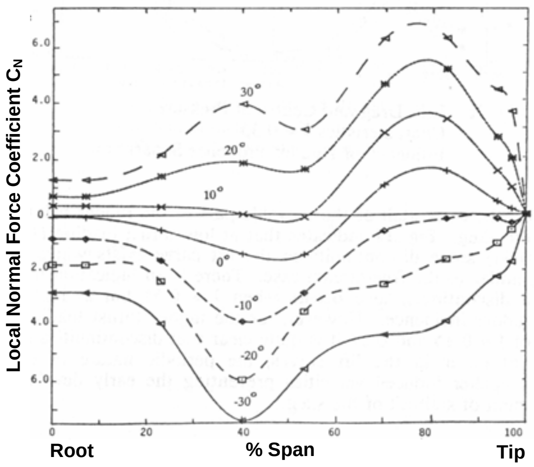


Figure 6.2- Measured span-wise variation of local normal force for a typical all-movable ship rudder (Molland and Turnock, 1993).

The curves in Fig. 6.1 illustrate for a propeller thrust loading condition that the mean axial speed can be double that of the freestream. Also important is the magnitude of the swirl velocity component and its influence on the effective angle of incidence seen by downstream sections.

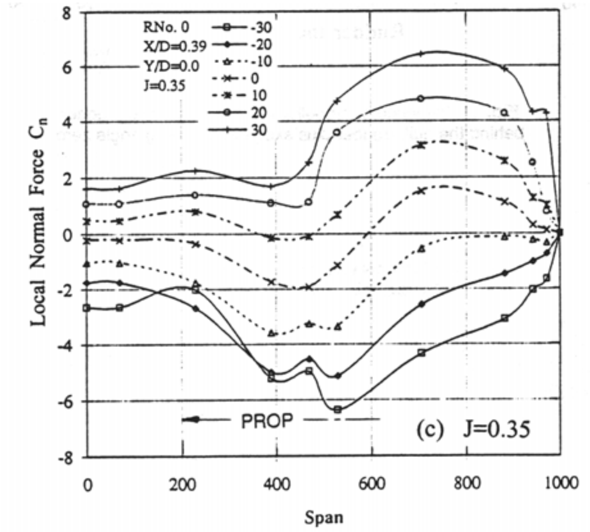


Figure 6.3- Measured span-wise variation of local normal force for a typical semi-balanced skeg rudder (Molland et al., 2000).

Figures 6.2 and 6.3 show how the local side force at a given span varies with rudder incidence for a high propeller thrust loading for an all-movable (spade) and semi-balanced skeg rudder respectively. The variation in local normal force coefficient closely follows the change in effective section onset incidence. For high rudder angles stall occurs earlier at some span positions than others. Also the magnitude of the sectional force is controlled by the accelerated axial speed at that span induced by the propeller. It is apparent that large variations in section incidence occur causing a corresponding reduction in local surface pressure Cp and increased risk of cavitation. Such effects have led to the development of twisted rudders Löhmer (2004), Shen et al. (1997).

A rudder will always have a variation in circulation across the span. Changes in the rudder incidence for course keeping will increase the variation in circulation across the span and can result in an increase in cavitation and possible cavitation damage.

If the time varying flow field is examined the local flow is even more extreme especially in the vicinity the tip vortex. The location of the impact of this tip vortex varies in time. For instance if a vortex impacts on discontinuity such as a gap or a hub vortex impacting in the vicinity of the gap between the horn and all-movable component are likely to be vulnerable to cavitation damage.

Another important influence is that of the upstream influence of a rudder on propeller cross-flow. This may become significant at large rudder angles where a cross-flow is induced at the propeller plane.

6.3 Examples of Cavitation Damage

Typical examples of recent problems on heavily loaded/high speed vessels have been examined by the EROCAV consortium and reported in the following papers. These provide valuable references to typical problems on these vessel types and for a limited number of cases information at model and full scale (Bart et al. (2004), Friesch et al. (2004), see Appendix A).

Carlton and Fitzsimmons (2004), present details of complex cavitation structures observed at full scale and make limited comparisons with corresponding model scale results. Details of complex behaviour including vortex bursting to form potentially erosive clouds are given. A useful discussion of available methods for full scale observations is also presented.

Tukker and Kuiper (2004) present the key considerations as to whether cavity collapse for erosion is important:

- If it occurs on or close to a propeller surface (or by implication a downstream appendage),
- If the velocity of collapse is high, and
- If the area of collapse is small.

High speed video observations at model scale are used to enhance the understanding of the erosive process. The dynamics of cavitation are better identified through video rather than time lapse photography and it can be used to identify the three erosive risk factors.

Complementary papers from Bark et al. (2004) and Friesch (2004) examined the risk of erosion on propellers and rudders, and how it can be predicted from calculations and/or appropriate model tests with comparisons from full scale observations. This work is based on the EROCAV research program that developed practical tools based on improved understanding of the process of erosive cavitation. One of the important contributions has been the compilation of a handbook of observations, Bark, Berchiche, and Grekula (2004), to provide a framework for assessing the risk of erosion from model or full scale observations.

Ligteliyn and Dang (2004), presented some good quality full scale studies of erosive behaviour on propellers and suggestions on how to deal with these.

6.4 Possible Practical Solutions

In the circumstances where the cavitation process is not fully understood, practical solutions to minimize the cavitation erosion have to be based on experience. In practice, these solutions can be categorized into two approaches: 1. Control the hydrodynamic characteristics by altering the flows and/or shapes and 2. Increase the material resistance against the erosion without any change of hydrodynamic characteristics. Sometimes these solutions can be applied concurrently.

Recently, through the full-scale inspection conducted by ship owners, classification societies and research organizations, cavitation erosion damage on propellers and appendages is reported more frequently due to the increase of capacity and speed of ships. The typical characteristics of damage on these parts and the practical solutions against the damage can be summarized as follows:

Propeller. The cavitation erosion can occur at any part of propeller blades, but it most usually occurs in the following locations:

- blade tip,
- middle of chord, especially at the higher radius,
- blade root and boss cap,
- around the leading edge of blade face side, and
- at the anti-singing edge treatment.

The blade tip where the rotational speed is highest has a relatively high curvature, and therefore the pressure gradient across the blade tip is very strong. As a result, the erosion near the tip is regarded to be mostly due to the abrupt collapse of the strong tip vortex cavitation. In the design of the propeller, the loading around the blade tip can be adjusted to minimize the erosion damage based on the designer's experience. Practically, when the erosion occurs at the blade tip, a change in curvature at the tip can be made to avoid the damage, without a significant change of propeller performance.

Normally, the region near 0.8 radius of the propeller generates the larger loads and mostly affects the propeller performance. Typically higher camber is used to increase the propeller efficiency which can result in the occurrence of the cloud cavitation and thus erosion damage is highly probable. The appropriate camber to each type of propeller should be chosen from the results of numerical tools and design experiences.

Near the blade root and boss cap, the pressure gradient along the streamline is relatively large, due to the thick blade roots and interaction between the blades. Hence, unsteady bubble or cloud cavitation could occur. When erosion is expected at this region, a decrease of blade root thickness and camber can be considered which will result in an increase of the blade chord length.

Sometimes, erosion on the leading edge of the blade face can occur. In the severe gradient of wake field, the excessive reduction of the pitch may induce the cavitation on the face side of the blade. The unsteadiness at the closure region of this cavitation can lead to erosion damage.

At times, the erosion can be observed along the anti-singing edge treatment, due to the chord-wise discontinuity at the beginning of the edge treatment. If erosion occurs, increase in the length of the anti-singing edge treatment can be made without invoking the singing phenomena.

When erosion damage occurs on the surface of existing propellers, the modification of blade shape may have an influence on the propeller performance, except the small amount for the edges. Hence, the application of geometrical changes to prevent damages is not practical in many cases.

Due to the high rotational speed of the blade and the increase of surface roughness, the use of coatings is still rare. Instead of increasing the material strength, laser beam re-melting or epoxy repairing techniques for the damaged surface can be considered (Junglewitz, 2003).

Rudder. Recently, erosion damage on the rudder has been a focus with the appearance of the high speed Ultra Large Container Carrier (ULCC). The strong cavitation generated from the highly loaded propeller may not only collapse on the rudder, but also the accelerated flow may lead to cavitation on the rudder itself.

Especially, for the horn type rudder, the erosion around the gap between the horn and the rudder blade is more severe than that in full spade rudder, due to the discontinuity of the surface and flow through the gap. From full scale inspections, the erosion damage is reported to usually occur in the areas shown in Fig. 6.4.

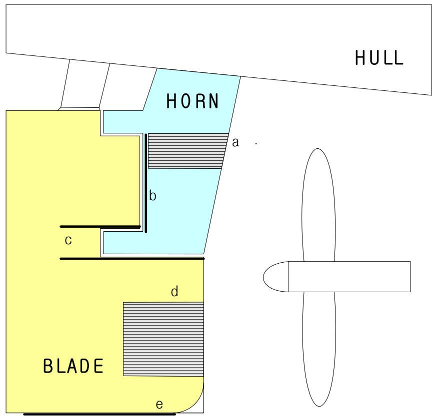


Figure 6.4- Typical erosion areas for the horn type rudders (a, b, c, d, and e).

On the upper part of the horn (Region a), erosion damage is due to the collapse of the vortex cavitation generated from the propeller tip and typically occurs along the chord. The surface discontinuity and flow through the gap between the horn and the blade (Region b and c) induce the cavitation and results in the severe damage reported on these regions. Sometimes, the erosion damage may occur behind the leading edge of the rudder blade (Region d), due to the rotational flow induced by the propeller. Also, the vortex cavitation at the bottom edge of the blade (Region e) so called the sole cavitation, may induce the erosion damage.

Practical solutions have been well developed, because these solutions can be applied without changes to propulsion performance. First, in Regions a and d an increase of material resistance should be applied. For example, a SUS and mild steel plate overlay or plastic coating would be effective. However, minimization of the corrosion damage, especially in the use of the SUS must be considered.

For erosion damage around the gap between the horn and rudder, a strip to prevent the flow through the gap would be attached at the centre of the gap. The sacrificial strips at the edge of the horn or rudder could be effective to minimize the erosion damage on the rudder body. Also, a sacrificial plate is applied in the gap.

To minimize sole cavitation, the curvature of the bottom of the rudder blade is necessary. Sometimes a horizontal sacrificial plate can be attached.

Recently, the full-spade rudder whose upper and lower sections are twisted in opposite directions has been applied to high speed container carriers. Due to the lack of full scale observations, it is expected to overcome the drawback of erosion around the gap for the horn rudder. However, the discontinuity of the blade located coaxially with the propeller shaft center, may aggravate the hub vortex cavitation and resultant erosion. Hence, the detailed study on the unsteady characteristics of the hub vortex cavitation around the discontinuity is recommended before application. In addition when the angle of the full spade rudder is not small, the cavitation in the upper region is strong while in typical horn-rudders the cavitation on the horn is independent of the blade angle.

Struts or Other Appendages. The erosion damage on the surface of struts in conjunction with the inclined propeller open shaft can occur. To reduce this damage, the strut should be aligned with the flow stream, based on the data from model test and numerical tools, for example, Laurens and Cordier (2003).

Recent work by Frolova et al. (2004), Han et al. (2004) and Dang (2004) also suggest a variety of additional cavitation control techniques which may be of use.

6.5 Guidelines to Minimize Cavitation Erosion

Concept/Early Design.

Propeller: Define loading condition of propeller and decide if erosion issues are to be considered.

Analyze propeller from the perspective of erosion risk (e.g., possible types of cavitation, dynamics of cavitation processes).

Avoid too much tip unloading (The cavitation on the suction side becomes more unstable and fluctuates the more the tip loading is reduced).

Unload the tip only to the extent that is really necessary to maintain hull-pressure fluctuations or noise levels within acceptable limits.

Design for stable developed sheet cavitation.

Design will need to balance requirements concerning efficiency, pressure fluctuations and erosion damage.

Where possible design both rudder and propeller as a unit from the start of the design process. The same care should be taken when designing and manufacturing the rudder as used when designing and manufacturing a propeller.

Rudder and Appendages: Identify all appendages and external hull features and analyze the likelihood of cavitation erosion. This should include possible influences of hull yaw and rudder incidence deflecting propeller race.

For each appendage or hull feature likely to be in way of propeller race ensure that its hydrodynamic shape has a minimal influence on the flow without sacrificing function. If possible, remove regions that cause rapid changes in flow velocity or allow formation of strong vortex systems.

For those appendages/struts where there is scope to move them to avoid or reduce the interaction with the race examine the effect of an alternative location.

Use appropriate profile shape and thickness. This may well require use of appropriate two-dimensional CFD analysis.

An appropriately shaped large leading edge radius should be chosen in order to widen the cavitation bucket and to be able to cope with changes to the incoming flow incidence.

Above a service speed of 22 knots ALL sharp edges, corners etc., should be avoided.

Use a profile with a sufficiently small absolute value for C_p at moderate angles of attack (typically maximum thickness should be 35% behind leading edge and with a smooth pressure distribution).

A round curvature (fillet) should be applied at the rudder sole (tip).

Final Design.

Propeller: Perform detailed model tests with the final design by using High-Speed-Video and the paint test technique.

Look at off design conditions (Especially during off-design service, cavitation erosion may occur). In particular, make sure that test process is conditioned by enough knowledge about the actual design point, possible off-design conditions and their duration.

Sudden changes of the shape or volume of a cavity should be avoided.

Bubble cavitation is potentially erosive and should be avoided as long as no specific information is available to the contrary. This requires that the safety margin against bubble cavitation is sufficient.

The chord-wise extent of a leading edge sheet cavity should increase with increasing radius. An exception could be made, if the cavity is still connected and is not isolated.

A stable cavitation sheet on the suction side usually helps to avoid erosion. However, avoid any cavities that separate from each other, for example, shedding of leading edge vortices at radii lower than the location of the main tip- or leading edge vortex.

If the model tests show a focusing cavity close to the tip and the tip vortex bursts, and the resulting cloud moves back onto the blade, there will be a need to apply more loading onto the tip so that the cloud will move downstream.

Rudder and Appendages: Make tests with either a whole model or partial larger model.

Tip and hub vortices from the propeller, and sometimes cavitation sheet shedding from the propeller produce cavities in the onset flow to the rudder. This may cause additional cavitation on the rudder surface and also an implosion of the cavities accompanied by erosion.

Avoid any gap or flap moving mechanism in the slipstream of hub and tip vortex; especially tip vortices tend to move upwards. This needs to be taken into account or possibly checked by CFD calculations or model tests.

The mounting of the rudder stock must not lead to a local expansion of the rudder profile. It is essential to make sure that the mounted rudder stock fits within the local profile thickness. If this is not the case use another more appropriate (higher *t/c* or longer chord) profile.

Any gap flow is often associated with erosion. Assure that the flow through the gap is at a lower velocity. Check for separated flow regions through use of CFD essential for all semi-balanced rudders.

Construction/Manufacture.

Propeller: A high-quality propeller manufacture process is required. On high powered small craft attention to detail is required for such features as rope cutters and for controllable pitch systems the method of blade attachment and hub shape.

Rudder and Appendages: The size and shape of cathodic protection mounted on a control surface that is in the propeller race will require attention to placement and fitting.

The local alignment and shaping of upstream support struts is critical, as well as prevent generation of lift to minimize induced drag also need to avoid large values *–Cp*. Rather than use of simple section shapes, cavitation insensitive forms and possibly larger chords will be required.

Grind and polish all welds.

No welds to be located in areas where cavitation may occur.

Round (fillet) all edges.

Minimize size of all gaps.

In Service.

Propeller: Assure that no changes will be made to the ship and propeller geometry after the model tests.

If a propeller blade is eroded, the position of the damage is known, but which cavity caused the erosion is not. Consequently:

- the first step should be an observation in full scale with high-speed video; simultaneously re-analysis of model test videos (if available) should be conducted
- after that new cavitation observation tests with a special focus on the damage and at conditions such that the full-scale cavitation is simulated should be carried out; simultaneously such analysis can be done with validated software

An alternative, but less fundamental measure could be to improve the blade resistance against erosion. A method, developed by the University of Bochum, University of Rostock and the SLV Rostock could be applied for bronze propellers. This is a Laser heat treatment consisting of a re-melting of a thin surface layer and could be concentrated on critical areas. It has not yet applied to full scale propellers.

More general countermeasures comprise improving the inflow to the propeller. This is an indirect countermeasure that needs considerable experience to apply successfully. Possible methods are: Schneekluth ducts, vortex generators, air injection or others.

If the blade tip is eroded due to the tip vortex, a practical measure can be to cut off the damaged part and modify the leading edge radius, or camber in order to stabilise the cavitation pattern (increase tip loading). This will at least reduce the erosion rate, and possibly solve the problem.

If the erosion is at mid-chord/mid-blade position, grinding down to sound material and leaving as it is could be a possible solution, as long as the remaining blade thickness is sufficient. Since the flow upstream is not changed the implosion could take place at the same old position, but is now further away from the blade surface and consequently it will not have such a strong damage impact.

Restoring the surface by welding or any liquid metal could only be a temporary solution, because the reason for erosion remains unchanged.

Rudder and Appendages: Put guide plates at the different positions where erosion will occur.

On the bottom plate if erosion occurs due to sharp edges then these edges should be smoothed with a larger radii.

A number of single weak erosion markings, especially in the first third of the rudder chord indicate that the erosion is probably due to tip and hub vortex or bubble cavitation. As long as the erosion is weak, a simple cover could improve the situation. Hard covers such as ice breaker hull paint (mostly epoxy based) as well as soft covers (neoprene) can be used.

If other countermeasures are not applicable, a plating with high tensile steel could be applied. Special care has to be paid to the welding procedure, as the connection of mild and austenitic/martensitic steel will need attention.

If erosion still occurs around the gap of semi balanced rudders then further geometry optimisation from analysing the flow through the gap using of CFD is recommended.

7. CONCLUSIONS

Cavitation erosion has become a significant problem with high powered/high speed ships and needs to be addressed in the design stage.

The propeller/rudder/appendages must be designed as a unit with the same design effort in order to reduce the potential of cavitation erosion.

Off-design ship operating conditions are important and need to be considered to reduce the risk of cavitation erosion.

Hydrodynamic and material specifications must be followed more carefully in manufacturing to reduce possible cavitation erosion.

It is recommended to do more documentation of the observed full-scale cavitation erosion patterns not only to improve correlations to model scale tests and predictions but also for the improvement of design methodology to reduce potential cavitation erosion.

The recommended guidelines to reduce cavitation erosion are only qualitative and more research into the physics of cavitation structures/material interactions is required before damage rates at full-scale can be quantified.

8. RECOMMENDATIONS

Adopt the new Procedure: 7.5-03: Propulsion; Cavitation; Cavitation Induced Erosion on Propellers, Rudders and Appendages; Model Scale Experiments.

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9.2 Nomenclature

CAV	International Symposium on Cavitation
FAST	International Conference of Fast Sea Transportation
PRADS	International Symposium on Practical Design on Ships and Other Floating Structures

APPENDIX A: EXECUTIVE SUMMARY OF THE EROCAV PROJECT

A.1 Introduction

The purpose of the EROCAV Project was to develop a practical tool to assess the risk of erosion on ship propellers and rudders in an early design stage. The maximum power for single screw ships has grown from 30 to more than 70 MW over the last two decades. Parallel the speed of the ships, and therefore the loading on the propeller increased. Together with the increase in ships speed and propeller loading, the inhomogeneous inflow to the propeller leads to an increased danger of cavitation on the propeller and the appendages (rudder and struts). Cavitation can cause erosion resulting in severe material damage with a number of negative consequences such as damage to rudders, appendages, and propellers (propulsor) which may result in a total loss of propeller blades, excessive vibrations, and loss of efficiency which will increase the impact of emissions on atmospheric pollution. This results in higher costs for the owner. Although ships have been model tested for decades, there exist no good prediction methods for cavitation erosion. The risk of erosion on a ship propeller or rudder depends on the impact strength of the cavity implosions and on the resistance against erosion of the propeller or rudder material. Therefore, within the EROCAV Project a systematic analysis of possible erosion mechanisms and the related cavitation patterns was performed, scaling effects were addressed, bubble collapse impact correlation by use of acoustical measures were investigated, and the role of cloud cavitation for the occurrence of erosion damage was checked. The main focus of the work was on the identification and the understanding of global, as well as more detailed hydrodynamic mechanisms generating erosion. Such knowledge is the key to understand the possibilities to simulate erosive cavitation processes by model experiments or by computational methods. Finally, this information forms the basis for the formulation of guidelines for the design of propellers and rudders. The combination of fundamental studies and well controlled experiments in model, as well as full scale result in a unique knowledge base concerning the hydrodynamic mechanisms involved.

The main tasks of the research:

- To gather data on cases in which erosion was encountered at full scale and to collect the corresponding data from model tests;
- To select ships with erosion damage for the full-scale tests and perform the full-scale measurements;
- To develop a knowledge base about the mechanisms of cavitation induced erosion;
- To extend the existing methodology to predict erosion in full scale by modelling the involved mechanisms;
- To develop improved experimental test procedures for the reliable prediction of cavitation induced erosion;
- To reproduce in model scale the eroded zones on the propeller blades and rudders observed in full scale;
- To develop a practical estimation procedure based on main propeller parameters;
- To improve the design procedures for rudders and propellers.

A.2 Project Results Summary

The existing database of the project partners have been checked, and the main types for erosive cavitation on propellers have been localized as (1) fluctuating sheet and vortex cavitation, (2) cloudy tip vortices, and (3) irregular/unstable mid-chord cavitation. Also collapsing cavitation, merging into foaming cavitation (small bubbles or clouds) is regarded as being erosive in some cases.

The full-scale work has been carried out very successfully, and the cooperation with the owners was very good. Instead of the planned three ships, four ships have been investigated. Additionally one owner was so enthusiastic about the results that he requested similar observations on another ship outside the project. These results have also been made available for the EROCAV consortium, so that the database in EROCAV consists basically of five ships! The results available are a set of fully documented cavitation observations and erosion data. This is more or less unique. The results show a variety of mechanism causing erosion on propeller and rudder. Apart from the regular mechanism of cloud cavitation behind a sheet, observations have shown that slight cloudy streaks near the tip can also cause propeller erosion. In particular, cavitating vortex structures originating from the propeller leading edge appear to be potentially erosive. Rudder erosion was expected to be caused by tip vortices, but the mechanism seems to be more complicated in that erosion is especially caused when there is breaking up of the cavitating tip vortex upstream of the rudder. The mechanism involving the existence of a cloud of cavitation and the subsequent implosion on the rudder have to be investigated further. The observations have shown that there are indeed erosion mechanisms which have not been considered in detail until now. It was found that some types of cavitation which were believed to be harmful might not always be as harmful as expected thus allowing more space for optimization of propellers from the efficiency point of view. For example, some pressure side cavitation on propellers was occurring frequently without causing erosion damages. Since this type of cavitation has always been considered to be very erosive, more investigations are necessary. The cooperation in EROCAV has already led to a cooperative investigation at full scale by four ex-EROCAV members to investigate this phenomenon further.

The work on the review and implementation of models concerning the mechanism of cavitation induced erosion covers more than what is traditionally meant by “mechanisms”. Examples of classical hydrodynamic mechanisms are the formation of a micro-jet at the collapse of a spherical cavity close to a solid body and the formation of a small group or cloud of sub-cavities. This micro-jet and the shock wave emitted at the collapse of the clouds are supposed to be the main mechanisms of cavitation erosion. It has been the aim of the research in EROCAV to start from these and look for more large scale mechanisms related to erosion that create links between the small scale mechanisms mentioned above and the behaviours observable in ordinary model tests to judge propeller and rudder designs. Therefore, the principle of energy focusing by a collapsing cavity is generalized and formulated for practical applications. A conceptual model for the hydrodynamics of erosion is introduced and a handbook for observation and analysis of eroding cavitation was written. This handbook has been elaborated with clear definitions, a categorization of different cavitation types was made, and a guideline to judge a certain observed cavitation behaviour concerning the danger of erosion was formulated. Due to the wide scope of the project, this handbook has been tested against simplified model tests with a straight wing, model tests with a propeller behind a ship model, and the respective full-scale observation.

Another main objective of the research work was to develop and improve erosion prediction methods based on model tests. Three different test techniques have been investigated in detail; the work went well for the paint test technique and the High Speed Video observations. The work related to the acoustic impact method shows, however, even if the application seems promising, the interpretation of the signals, both in the fluid and/or the material is so complicated that only an initial application could be obtained. Further research efforts will be necessary to make this method a practical tool for every day work. It must be stated that model experiments are and will continue to be the only reasonable way to make predictions, concerning the influence of cavitation on the occurrence of erosion. Besides the detailed observation of the cavitation phenomena, high speed video observation and paint tests are the most reliable tools at the moment. Unfortunately the paint test method up to now does not give reliable results for the prediction of cavitation induced rudder cavitation. Further research is needed to develop an adequate paint. Therefore, the only way to judge the danger of erosion on rudders is to observe the cavitation phenomena very carefully.

The results of the full-scale measurements and the new developed test techniques have been used in an extensive series of model tests in the different test facilities of the partners. Both methods, the paint test method and high speed video observations were used to compare the model test results with the full-scale data. The analysis of the physical behaviour of the observed cavities was made, using the rules given in the handbook. The results show that cavitation patterns on propellers can be reproduced quite well in cavitation test facilities mainly behind whole ship models, but also dummy models give quite reliable results. The risk of erosion on the back side of the propellers was reproduced quite satisfactory in all facilities using the paint test technique. High speed video observations appear to be a powerful tool to detect erosive types of cavitation and to improve the knowledge concerning the structures of the cavities further, and should therefore be used routinely. The prediction of face side cavitation and its influence on erosion seems to lack sufficient accuracy and needs to be investigated further. The prediction of erosive cavitation on rudders based on model tests is much more difficult, mainly because of very low Reynolds numbers involved and the interaction between vortex structures and the different types of flow across and around the rudder, especially at different angles of attack. The paint test technique does not always give reliable results, and therefore detailed observations are the only way to judge the danger of erosion on rudder models. It is suggested to perform additionally detailed investigations with large models in a separate test set-up.

One of the objectives of the project was to develop guidelines based on the results of the work performed and make them available to others. In these guidelines the accumulated knowledge was applied in a practical way and split into three main parts. The first part is related to the design stage before model test results are available, the second part deals with improvements on designs after model test results are available, and the third part is related to improvements of existing hardware when damages have been found after some time of operation of the ship. In all three parts, the problems related to propellers and rudders are treated separately.

A.3 Objective and Strategic Aspects

The main objective of the project was the improvement of the prediction methods for cavitation induced erosion. The development of new test techniques and new theoretical numerical tools was the main aim of this research program. The technical and scientific objectives include improved accuracy of the full-scale prognosis based on improved test techniques. The realization of the new test methods and the new software tools will strongly enhance the capacity of model basins, and consequently of propeller designers, ship yards, and ship owners.

The fall out on the economic side is evident: better propeller and rudder designs from the cavitation point of view, and therefore better efficiency and less fuel. The cavitation erosion database and the new developed handbook are a useful background both for engineering and scientific discussions and consulting. The bench mark tests with the full-scale data obtained are the fundamentals for all the comparisons. The results available are a unique set of documented full-scale cavitation observations and related erosion data correlated/validated in detailed model tests. Paint test technique and high speed video technique are the new or improved powerful tools in model testing.

APPENDIX B: WORKSHOP ON CAVITATION EROSION – BASSIN D'ESSAIS DES CARENES, VAL DE REUIL, FRANCE

Thursday, May 27th, 2004

"A Theoretical Approach to an Extended View of the Development Towards Erosive Collapses," by G. Bark, N. Berchiche, and M. Grekula

"Experimental and Numerical Study of Cavitation Erosion on Single Hydrofoil Configurations; Part 1: Three-dimensional Unsteady Cavitation Effects on a Single Hydrofoil," R. Bachert, B. Stoffel, M. Dular, and B. Sirok

"Experimental and Numerical Study of Cavitation Erosion on Single Hydrofoil Configurations; Part 2: Pit - Count Erosion Study and Numerical Simulation of Cavitating Flow," M. Dular, B. Stoffel, R. Bachert, and B. Sirok

"A Phenomenological and Numerical Model for Scaling the Flow Aggressiveness in Cavitation Erosion," R. Fortes-Patella, J. L. Reboud, and L. Briancon-Marjollet

"Experimental Investigations Concerning the Influence of Flow Velocity on Erosive Aggressiveness of Cavitation," B. Bachert, B. Stoffel, and S. Baumgarten

"Preventing Cavitation Erosion on Propeller Blades – New Phenomena and Practices in Design," J. Ligtelign and J. Dang (Wartsila Propulsion Netherlands BV)

"Prediction of Erosive Effects of Cavitating Flows in Injection Equipment," D. Greif, R. Tatschl, U. Iben, M. Vo∃, and A. Morozov

"EROCAV Project: Model – Full Scale Correlation in Different Cavitation Test Facilities," J. Friesch (HSVA), G. Kuiper (MARIN), L. Briancon (BEC), D. Q. Lee (SSPA), and L. Wilczynski (CTO)

"Cavitation Erosion at ARL Penn State," M. L. Billet and D. R. Stinebring

"Scaling Rules, Methods, Instruments and Facilities to Forecast Cavitation Damage," Y. Lecoffre

"Presentation d'un Nouveau Moyen d'Essais d'Erosion de Cavitation Dans les Pompes," B. LeFur

Friday, May 28th , 2004

A Procedure to Account for Overlapping in Pitting Tests," T. Choffat, R. Fortes-Patella, J. P. Franc, and A. Archer

"On the Vibratory Approach for Cavitation Monitoring in Hydraulic Turbines," M. Farhat and X. Escaler

"Acoustic Emissions: Measurements of Sound Attenuation on a Rudder and Propeller," A. Boorsma

"Wear Kinetic Laws for Cavitation Erosion Downstream Simple Holes, Multi Holes Orifices and Butterfly Valves," A. Archer

"Guideline for Prediction and Evaluation of Cavitation Erosion in Pumps," K. Uranishi, T. Ikohagi, H. Kato, S. Saito, T. Okamura, S. Kawasaki, K. Kobayashi, and T. Kawabe

"Twisted Leading Edge Technology Combined with the Well Established King Support Rudder from Becker, in Order to Avoid Rudder Cavitation Erosion Induced by the Rudder Itself," C. Löhmer.