ITTC Quality System Manual
Recommended Procedures and Guidelines

Cavitation Induced Erosion on Propellers and Rudders, Model Scale Experiments and Numerical Guidance.

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Abstract

The procedure provides guidelines in conducting propeller cavitation and rudder erosion model tests. Numerical simulation techniques are also included to assist with determining the risk of potential erosive damage. The model tests focus on the use of soft paint coatings to determine erosive events and highlights the importance of correlating visual observation of the cavitation dynamics with areas of paint removal.

Cavitation Induced Erosion on Propellers and Rudders, Model Scale Experiments and Numerical Guidance

1. PURPOSE OF PROCEDURE

The purpose of this procedure is to provide guidelines in conducting a propeller cavitation and rudder erosion test to identify the risk of potential erosive damage. Erosion test can be conducted with the propeller or rudder individually or together, but when looking at the rudder separately a propeller upstream must always be present.

The propeller and rudder erosion model tests described are assumed to be conducted in a cavitation tunnel. The procedure includes the application of the soft paint coating on the surfaces of the propeller or rudder, the undertaking of the tests and the interpretation of the results. The intent of applying soft paint is to provide a visual indication of where erosive cavitation occurs on the propeller blades. This is indicated by the removal of areas of paint during the tests.

The appearance of propeller cavitation types is not discussed in detail in this procedure but should be referred to in the ITTC Procedure 7.5-02-03-03-.2 dealing with the visual description and measurement of cavitation.

The main undertaking of an erosion test is in accordance with a standard cavitation test as detailed in the ITTC procedure 7.5-02-03-03.1.

This procedure solely concentrates on the use of a soft paint coating to determine erosive events and details the importance of correlating visual observation of the cavitation dynamics with areas of paint removal. In summary the following areas are of interest for the experiment:

- Identifying the expected location of the potential erosion zones on the propeller surface.
- Identifying the expected location of the potential erosion zones on the rudder surface.
- Does cavitation collapse occur on the surface giving an indication of potential erosion.
- Is the action of cavitation collapse sufficiently systematic and repeatable to provide a risk of erosion.

The procedure does not detail the required duration of the cavitation erosion incubation period. However, it gives an immediate answer if erosion is considered to be a potential risk. The incubation period and erosion risk are dependent on the facilities experience. To enhance the reliability of the experimental or numerical prediction procedures, it is required to perform frequent full-scale cavitation observations on both the rudder and propeller, and to study the correlation between the predicted and observed data.

A numerical approach for modelling propeller and rudder cavitation is also included in the document, although currently there is not a universally accepted method in the field of hydrodynamics to determine the risk of erosion. Hence, in practice, rudder designers can use indirect information - such as the pressure distribution on the surfaces - obtained from numerical methods as a modelling procedure that complements the experimental approach.

2. MODEL SCALE EXPERIMENTS

The undertaking of a cavitation test using a soft paint coating should complement the detailed visual observations of the cavitation on the propeller and rudder. These observations can be done visually under stroboscopic lighting, by time lapse video or by high-speed video observations.

It should be kept in mind that the aim of the experimental procedure for a cavitation erosion risk assessment is not limited to the occurrence that the soft paint coating has been damaged, but also to provide an explanation of the correlation of any paint removal damage with the occurrence of certain forms of cavitation, their dynamic behaviour and location with respect to the propeller surface.

2.1 Test Set-Up

2.1.1 Propeller Model Accuracy

The size of the model propeller should be determined within the capacity constraint of the test facilities and not exceed an acceptable extent of test-section blockage. It is recommended that the ratio of the maximum cross section area of the propeller and hull model to that of the tunnel working section is to be no greater than 20%, and to be as large as reasonable to achieve the highest possible Reynolds number. The propeller model must have sufficient and consistent geometry accuracy as detailed in ITTC Recommended procedure 7.5-01-02-02.

2.1.2 Rudder Model Accuracy

In conducting a model-scale test, one should use as large a model size as possible to achieve the highest possible Reynolds number, within the capacity constraint of the test facilities and within an acceptable range of test-section blockage. A large model size is especially important for the semi-spade rudders, where the gap between the horn and the blade at typical model scale is too narrow to represent flow through the gap. A larger part of a rudder can give better full-scale similarity of the cavitation pattern around the gap.

The model rudder must have sufficient and consistent geometry accuracy to study the characteristics of cavitating propeller tip and hub vortices interacting with the rudder surface.

Especially, for the test at non-zero angles of the rudder, the rotation axis of the rudder should be placed in the same position as the full-scale geometry.

For the rudder behind a propeller, the distance between the propeller and the rudder can have a large influence on the propeller loading. As a result, this distance can affect the cavitation characteristics on both the rudder and the propeller and should therefore reflect the full-scale situation.

2.1.2.1 Dummy Models

The main issue is to provide a realistically simulated wake velocity pattern which will also give the proper speed of advance at the propeller disk location. Usual practice is to use the nominal wake distribution (either for the model or scaled to full scale) as the target wake for the experiment.

For differently sized cavitation tunnels alternative model schemes are used.

In **small** water tunnels (in case of single screw ship):

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

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

- Inclined shaft with struts and bossing, mounted below a flat plate or bump-like dummy model hull (in case of twin screw ship with propeller operating outside the ship boundary layer)
- Dummy model ('after body model')

Large test sections may allow:

- Shortened, but otherwise scaled ship models
- Half complete or shortened ship model attached on a side wall (in case of twin screw ship)
- Completely scaled ship models

For all model configuration options, it is recommended to include as many of the stern appendages as possible, such as the rudder, in the correct location behind the propeller.

When using a dummy model, the simulated wake shall be documented to verify that the deviation from the target wake can be neglected (criteria for the dummy model wake acceptance Should be stated). Measurement of the wake can be performed by using any suitable velocimetry techniques. When using Pitot tube or laser Doppler Velocimetry, ITTC procedures can be adopted

2.1.3 Wake Field Simulation

The wake simulation adopted for the tests should be mutually established between the testing organization and the customer. More realistic wake simulations will produce representative cavitation, but often require larger facilities or more complicated test configurations. Facility experience is an important consideration, due to the often lengthy iterative procedures required to develop new wake generation techniques.

All wake field simulations shall comply with ITTC Recommended Procedures and Guidelines, 7.5-02-03-02.5: Experimental Scaling of a Wake to a Target Wake, which describes guidelines for experimental wake scaling and simulation. These simulations shall also be documented with wake survey procedures or verified to be similar to the towing tank wake or previously measured configurations. Nominal wake surveys are generally performed although determination of the effective wake, including the influence of the propeller is preferred, but difficult to determine.

Sometimes the full-scale wake can be used for erosion tests. This is mainly possible by use of shortened model sections or with flow liners. The estimated full-scale wake should then be based on flow calculations, but a universal law for the full-scale wake, which can be applied to all kinds of vessels, has not been developed yet.

2.1.4 Rudder Part Model Installations

For tests investigating the rudder only and focus on the improvement of rudder gap cavitation, one can install a partial model that is suitable to allow a larger scale - and thus larger gaps. Those tests normally do not allow the installation of a complete ship model, but the use of a model propeller upstream of the rudder must be advocated.

2.2 Calibrations

In the following the basic calibrations are listed that are to be performed as part of the preparation and set up of the cavitation test. It is recalled that all the sensors used for an experimental campaign have to be properly calibrated and linked to National Measurements Standards before and/or during the tests. A check of calibration is sometimes performed at the end of the test campaign to ensure that no drift happened during the tests.

Pressure gauges used to measure static and differential pressure should be calibrated to a recognised acceptable standard within an established time period prior to the test. Pressure gauge calibration checks during the test are recommended by varying the tunnel static pressure.

Thrust and torque dynamometer load response calibration should be carried out with applied loads that are traceable to a recognised acceptable standard. Calibrations should be performed within an established time period prior to the test. The long-term stability of the calibrated data needs to be confirmed.

Thrust and torque correction loads are to be measured for the bare hub operated at the pressure, rotational velocity, and flow velocity determined for each test condition.

Establish instrument zeros for the thrust and torque measurement accounting for "friction" effects of internal friction and gearing as the shaft rpm approaches zero.

The torsional or lateral vibrations of the propulsor shaft and housing may have an influence on the steadiness of the cavitation on blades, other parts of the propulsor and the said level of pressure fluctuation. Attention should be paid to the vibration level of the propulsor and shaft at each test condition. Propeller and shaft balancing is highly recommended to reduce excessive vibration.

2.3 Test Measurements

Measurements of the following are to be made during the cavitation test. Recording of the quantities below should be in a fashion that is consistent with the facility's specified uncertainty levels.

- Shaft thrust and torque
- Shaft rotational speed
- Facility flow reference velocity
- Static pressure
- Water Temperature
- Gas content
- Water quality measurement (dependant on facility)
- Rudder angle if moveable

As discussed previously, a complete description of general cavitation tests can be found in ITTC-Recommended Procedure 7.5-0.2-03-03.1. All the instrumentation for a visual description of the cavitation and for the measurements of cavitation events and inception are described in procedure 7.5-02-03-03.2.

2.4 Test Conditions

In a variable pressure water tunnel facility, the model test conditions should satisfy the same propeller working conditions as predicted for the full scale.

Three basic parameters of propeller working conditions are:

- Propeller loading condition,
- Realistic wake velocity pattern, and
- Corresponding pressure field.

(a) Propeller loading condition

The propeller loading through the kinematical condition for $J = V_A/(nD)$ needs to achieve the predicted full-scale K_T or K_Q (thrust or torque identity). Here V_A = propeller speed of advance (m/s), D = propeller diameter (m), n = rotational speed (rps), $K_T = T/(\rho n^2 D^4)$, and $K_Q = Q/(\rho n^2 D^5)$. Usual practice in water tunnel testing is to satisfy thrust identity, although there are circumstances where the torque identity approach is used.

(b) Realistic wake velocity pattern

Provide a realistically simulated wake velocity pattern which will also give the proper speed of advance at the propeller disk location. Usual practice is to use the nominal wake velocity distribution (either for the model or scaled to prototype size) as the target wake for the experiment.

(c) Corresponding pressure field

Set the facility pressure and flow velocity to obtain the correct full scale cavitation number $\sigma = (p_A - p_v)/(1/2\rho V_{ref}^2)$; where p_A = the representative static pressure at the propeller to match the full-scale cavitation number. The reference velocity V_{ref} is taken as V_A or nD., p_v is the vapour pressure corrected to the tunnel temperature. The reference submergence depth used in the calculation of cavitation number is usually taken at a point approximating the centre of expected cavitation extent in the upper part of the disk, such as 0.7R above the propeller centre line.

2.5 Air Content, Cavitation Nuclei and Stabilizing Model Cavitation

The effect of the water quality has been a subject of continuous discussion in the ITTC. The cavitation-nuclei concentrations in the water have a remarkable influence on the tensile strength of the water, and therefore the cavitation characteristics, especially inception characteristics, on the propeller blade. However, the modelling of the detailed nature of the cavitation nuclei is not necessary and it is not practical to represent the nuclei spectra of the seawater at full scale in a model test. However, it is very important to reduce the tensile strength of the water.

Generally, it is accepted that testing at relative high air content, modifies the nuclei, in a water tunnel facility and reduces the tensile strength and improves the correlation of model / full scale results. When there are insufficient concentrations of the nuclei, all forms of cavitation behave intermittently which may result in the lack of paint removal and thus provide misleading results. On the other hand, too high air content may introduce a cushioning effect to the cavitation collapse and will reduce its effects on the soft coating as well as providing unreliable results.

Hence, the optimum air content for a given cavitation facility should be determined by long established experience. To enhance the consistency of measured results, it is recommended that the tensile strength of the water in the facility should be checked periodically.

3. PAINT METHODOLOGY

3.1 Parameters Taken into Account

The test parameters that need to be considered performing propeller erosion tests are basically the same as described in Section 2 for cavitation tests and detailed in ITTC Procedure 7.5-02-03-03.1. This section describes the soft paint requirement for the erosion experiments.

3.2 Paint Test Method

The propeller and/or rudder model is covered by a single layer of soft paint and is subjected to the action of different types of cavitation in the behind condition in a cavitation tunnel for a pre-determined time. The evaluation of the results of the test consists in the examination of the state of the paint layer shortly after the removal of the propeller model from the tunnel test section.

Any damage of the paint connected with the action of collapsing cavities should be considered as a risk of erosion occurrences in full scale. Nevertheless, one has to assure that the cavitation appearance does not result from accidental, unwanted local surface irregularities and that it results exclusively from the thoroughly reproduced geometrical form of the model and testing conditions corresponding to the full scale.

The intent of applying soft paint is to provide a visual indication of where erosive cavitation occurs on the propeller blades. This is indicated by the removal of areas of paint during the tests.

It is recommended that erosive tests are undertaken at the usual operational condition design point. For CPP frequent off-design points should be considered, in particular low pitch settings when operating at constant shaft speeds.

3.2.1 Paint Used

A stencil ink is recommended to be used as the substance to cover the propeller model surface. As standard ink may be too dense therefore the paint should be a mixture of ink and an appropriate thinner. To make the evaluation of the test results easier and to obtain the most distinct traces of paint removal a black ink is normally recommended. A dark paint provides good contrast for the areas where the base propeller model material is visible when paint is removed. On dark substrates, a white or light paint should be used instead.

Stencil inks are either water-based thus water-soluble or solvent-based heavily pigmented paints. They can be used with a paint brush, paint roller, dipping or spray gun. However, chemical curing of water-soluble stencils can improve their resistance to water.

Solvent-based stencil ink serves as a waterproof, permanent and fast-drying paint, which can be applied either to any porous (e.g. paper, cloth, wood, cardboard cartons, etc.) or non-porous (e.g. metals, plastics or glass) surface. Solvent-based stencil ink can be based on petroleum, alcohol or glycol. It has to be emphasized that petroleum-based inks are usually intended for the application on porous materials and they may not dry on metal surfaces. The alcohol or glycol-based inks dry relatively quickly, i.e. from seconds to minutes on porous as well as on non-porous (including metal) surfaces. Usually, carbon black serves as the black stencil ink pigment therefore the ink has to be shaken well before use.

3.2.2 Paint Handling

In order to maintain the relatively short drying time and the appropriate thickness of the paint layer, the stencil ink may be mixed with an appropriate thinner. The ratio of the thinner and ink is dependent on the facilities experience to obtain good results. The thinner and the ink should be mixed the same for all tests and immediately prior to the application of the paint.

3.2.3 The Sequence of Activities

The first step of the procedure consists in the careful cleaning of the propeller or rudder model surface with a degreasing agent. After cleaning, the model should be thoroughly dried. Then the model should be covered with a single layer of paint, ensuring a consistent uniform coating. A typical thickness of 100 microns is suitable. If a spray gun is used it should be checked that the air compressor is equipped with the grease/oil separator and the paint layer is uniform. If there are any spots of dried paint drops on the model surface, then the surface should be cleaned and painted again. Before placing the model in the cavitation tunnel the paint should be dried and particular attention paid to the paint surface at the propeller blades' leading edges, which should be cleaned if required. For the rudder particular attention should be paid to the leading edge and gap areas. Usually, 30 minutes of drying in a well-ventilated room is sufficient. It is important that the drying time is kept consistent for each facility so that results are comparable between experiments.

The surface of the propeller model during the soft paint erosion test should be covered by a single, uniform layer of soft paint. Layer thickness can be monitored for test repeatability and reproducibility using for instance an ultrasonic thickness gauge. Deviations to the coating thickness may bring some differences in cavitation appearances compared to the unpainted surface. Deviations can also produce different results under the same cavitation conditions.

Touching the propeller model blades and rudder surface with bare fingers should be avoided. The state of the surface should be recorded before the model tests start. Any scratches or accidental paint damages should be documented, ideally with the use of photographs that can then be compared with post experiment results.

3.3 Experiment Methodology

3.3.1 Soft Paint Test

The required propeller operation condition in the tunnel test section should be achieved in the shortest possible time.

The recommended duration of the paint test should not exceed 120 minutes. During the entire period of the propeller and/or rudder model operation the state of the surface should be viewed (continuously when possible) visually in stroboscopic lighting to determine the initial moment of the paint's removal or with viewing photographs at regular intervals during the experiment.

Any removal of the paint not related to the action of cavitation (e.g. paint separation due to the lowered pressure) should be recorded. After completion of the test the model should be immediately removed from the test section of the cavitation tunnel. It is extremely important to avoid touching the painted surfaces as it can cause an unwanted damage of the soft paint layer. The state of the soft paint cover can be examined immediately after removal from the tunnel test section or after drying. The state of the paint cover should be compared with the original photos made before the tests. The picture of the surfaces should be recorded in the same way as before the test ensuring light conditions are similar allowing a high contrast between the paint and removed paint.

The soft paint test experiment should then be compared with the cavitation observations, obtained during a standard cavitation test of the propeller and rudder without soft paint applied. This ensures any predicted erosion is not purely an effect of the soft paint application as collapse is seen without the paint as well.

3.3.2 Additional recommendations for rudder cavitation tests.

The following recommendations are suggested for model testing of rudders behind highly loaded propellers.

The operation of the complete unit of the rudder and the propeller with the most realistic propeller inflow conditions is essential. Use of complete ship models for wake generation should be considered wherever possible.

The local Reynolds number at the rudder profile should be larger than 300,000 (based on tunnel water speed and rudder profile length) to avoid laminar flow effects. One should always use as high a Reynolds number as possible. One should ensure a constant water quality, at least a constant O_2-saturation level, according to facilities standard conditions, as discussed by the ITTC (2002b).

At model scale, one should investigate a much wider range of rudder angles than required for cavitation-erosion-free operation at full scale. Also, one should re-produce the off-design conditions of the propeller during the cavitation erosion test.

When investigating local gap cavitation phenomena or cavitation phenomena occurring in the vicinity of rudder geometric details like spoilers, one should use large-scale part models.

Using such large-scale part models without the upstream propeller gives an unrealistic uniform inflow and should be used only for judging the relative means of cavitation improvement - through spoilers, guide plates, etc. - during comparative testing.

Where full-scale cavitation behaviour of the rudder is known, one should use this information to calibrate the part rudder model test conditions. In practice, this means that one should vary the cavitation number and rudder angle until the problematic full-scale behaviour is reproduced. Then, one should use these conditions to investigate the means of cavitation improvement - through spoilers, guide plates, etc.

Full-scale rudder cavitation observations and the corresponding monitoring of rudder cavitation erosion damage are necessary to gather experience for visual assessment of rudder cavitation at model scale.

3.4 Cavitation Visual Observations

The propeller and/or rudder should be visually observed on both suction and pressure sides during the erosion tests so that potential erosive cavitation can be correlated with the areas of paint removal on the propeller. Full details of visual cavitation observation and methods of filming are provided in the ITTC Procedure 7.5-02-03-.2.

3.5 Evaluation of Results

3.5.1 Visual Observations

The main applications of the visual methods are:

1. Detection and assessment of the risk of erosive cavitation, undertaken by an experienced observer.
2. To supplement the soft paint tests by bringing additional information, which can be modified with the application of paint on the blade surface.
3. To analyse and gain understanding of the development towards erosive cavitation and its relation to the large-scale hydrodynamics in a way that can be applied in design for control of erosion.

Basic steps to analyse high-speed video recording should focus on:

- Detecting the existence of violent rebounds.
- Determining the strength of the propeller tip and hub vortex cavitation and its interaction with the downstream rudder.
- Estimating the location of any observed erosive cavitation.
- Observing the structure of the focusing cavity (glossy, cloudy or mixed). This gives information on the presence of re-entrant jets and contributes to the high-risk assessment.
- Estimating the acceleration and the distribution in time of the collapses' motion of the focusing cavity.

3.5.2 Evaluation of Paint Test

In a paint test method, a soft surface coating is applied on the propeller. It is assumed that this soft surface will be damaged by erosive cavitation. Therefore, the surface of the coated propeller needs to be investigated very carefully after the test and compared to the original appearance. By investigating the erosion damage on the coating (the form and the size) a prediction of the potential erosion damage can be made. If systematic correlation data exist between experimental and full-scale results it yields a possibility to predict the risk of erosion at full scale.

If damage is known to occur at full scale but has not been replicated at model scale the tests can be re-run with modification to the tunnel pressure until similar erosion is identified. This tunnel setting should be maintained when looking at new design options.

The surface damage should be documented as soon as possible - after taking the propeller or rudder out of the tunnel - because the paint itself can be weak.

All traces of paint removal should be checked documented and related to the observed cavitation phenomena. All spots where paint is removed in combination with observed cavity collapses, should be considered to have high potential to be erosive at full scale.

4. NUMERICAL SIMULATIONS

4.1 Methodology and guidance

Numerical methods can be used to study full scale propeller and rudder hydrodynamics and cavitation, which is hard to fully replicate at model scale due to the low Reynolds numbers and the complex interactions of the tip and hub vortices of the propeller with the rudder.

4.1.1 Potential-Flow Approach.

The potential-flow approach - such as a lifting-surface method or a boundary-element method (BEM) - is traditionally used in propeller and wing design, and it gives static-pressure information that can indicate the occurrence of cavitation on the surface of the propeller or rudder. Especially when a rudder is located just behind a propeller, one can consider the significant interaction between the propeller and the rudder by using the same numerical methodology. Of course, the calculation for the rudder alone with an appropriate inflow is also possible. It should be noted that BEM codes give more realistic and convincing results than the lifting-surface theory, primarily because the rudder is relatively thicker than the propeller blades.

However, potential-flow methods cannot predict the sole cavitation around the bottom edge of the rudder, without additional specific modelling. Also, for the semi-spade rudder, it is impossible to represent the gap between the rudder blade and the horn using the potential-flow approach. Potential flow methods can predict unsteady cavitation, but not the unsteadiness of cavitation. By ‘predicting unsteady cavitation’ we mean the variation of the cavity shape in a global sense as the blade enters wake regions with different flow velocities. By ‘unsteadiness of cavitation’ we mean the variations of the local cavity shape that can be present even in a foil under steady uniform flow in the form of unsteady cavity shedding

4.1.2 Viscous-Flow Approach.

The viscous flow approach can be categorized into single-phase solvers and multiphase solvers. A single-phase flow calculation can predict the flow pattern and static-pressure distribution around the rudder, which gives an indication of cavitation inception wherever the local static pressure becomes less than the vapour pressure. A multiphase flow calculation can give information on the unsteady behaviour of developed cavitation, and an indication of some erosive effects on propellers and hydrofoils such as time-history and time-derivatives of pressure on the surfaces. However, in practice few designers actually use multiphase flow calculations, because of high computational costs and the lack of universal acceptance of the cavitation-erosion models.

4.1.3 Consideration for Propeller and Rudder Inflow

The ship wake used as onset flow to the propeller can be computed directly, for instance by RANS methods. The most common procedure, however, is to use results of wake surveys from model experiments. The loading condition for the propeller, through the kinematical condition for $J = V_A/(nD)$ to achieve the predicted full-scale K_T or K_Q, can also be defined based on calculation only for full scale, but generally results of propulsion tests are used. Calculation of the effective wake, considering the interaction between the inflow vorticity and the propeller can be done by coupling a propeller panel method with a potential flow or RANS solver. Additional guidelines for numerical propeller modelling are given in ITTC-Recommended Procedure 7.5-02-03-03.4.

One major factor that affects the reliability of the numerical results for the rudder is how to consider the propeller action. The simple way is to assume the inflow and to calculate the flow around the rudder alone. The assumption of the inflow can be based on measurements in a model test or on numerical computations of the propeller. Conversely, one could compute the transient flow around the propeller and rudder simultaneously. While this method increases the computational costs it can be considered as fairly normal practice nowadays.

Alternatively, one could represent the propeller as a momentum actuator disk and treat the thrust and torque of the propeller as momentum sources - iteratively determined by the potential-flow codes for the propeller. However, this method has problems in properly capturing the tip and hub vortices generated from the propeller, potentially important factors for rudder cavitation.

4.1.4 Guidelines for Numerical Predictions

The aim of the propeller and rudder designs to minimize the cavitation erosion requires knowledge of the detailed unsteady flow and the cavitation dynamics occurring for the propeller within the flow region accelerated by the propeller. Because the universally accepted method to numerically predict the cavitation behaviour and subsequent erosion has not yet been developed, one must maximize the reliability of the available numerical methods. This reasoning leads to the following recommended guidelines for numerical modelling:

First of all, one must consider the propeller operation. Correct operation and conditions should be applied for the propeller. At the very least, for the rudder alone, one should use a rudder inflow based on measurements downstream of the propeller from a model-scale test or based on predictions using a numerical simulation of the propeller.

It is recommended that one should directly model the interactive flow between the propeller and the rudder using an unsteady numerical simulation, which would provide more realistic results.

Only for the sole cavitation on the rudder, when the bottom edge of the rudder is placed outboard of the propeller slipstream, can one obtain useful numerical calculations with a uniform rudder inflow. In this case, one can vary the incident angle to determine the sole cavitation performance.

The cavitation erosion is highly affected by the flow separation, local pressure gradient, dynamics of cavitation and interactions with the bulk flow. Therefore, one should use geometry that is exact as possible for the calculation.

Especially, for the cavitation around the gap of the semi-spade rudder, the pressure gradient and flow depend highly on the curvature of the corners and the size and location of the gap, so it is important that one models these geometric features with sufficient resolution of the flow through the gap.

Also, to predict the erosion induced by propeller tip or hub vortex flows, the numerical approach should model the propeller geometry or, at the very least, should use a model of the vortex flow. In the former case, care should be taken to ensure resolution of the unsteady vortical flow from the propeller to the rudder by using sufficient numerical grid density and appropriate methods. However, for the vortex behaviour around the rudder surface itself, one must be very careful and recognize that the results are highly dependent on the choice of the numerical methodology.

One should use a quality computational grid with an adequate number of grid points to minimize the numerical error. Also, one should concentrate the grid points in regions where flow variable gradients are expected to be high and where the occurrence of cavitation is suspected.

For the best predictions, one should conduct the numerical computation at the full-scale Reynolds number, especially for the gap and vortex cavitation.

At the moment, under the circumstance that the universal methodology for multiphase, viscous flow computations of cavitation has not yet been developed, the evaluation of the overall procedure is more useful than that of the detailed procedure (like the choice of the turbulence model or the grid topology) in practical design. Different models or indicators for prediction of erosion damage based on viscous-flow CFD solution are being developed and evaluated. However, likewise as in choice of appropriate cavitation mass-transfer or turbulence modelling method, there is currently no universally applicable model for erosion damage at each condition on all propellers and rudders. Therefore, in making the final prediction of rudder cavitation performance, one should only evaluate the numerical modelling results in comparison with full-scale or model-scale test data.

5. PARAMETERS LIST

5.1 Data Reduction Equations

Thrust coefficient

$$K_T = \frac{T}{\rho n^2 D^4}$$

Torque coefficient

$$K_Q = \frac{Q}{\rho n^2 D^5}$$

Advance coefficient

$$J = \frac{V_A}{nD}$$

Reynolds number at 0.7R

$$R_{0.7} = \frac{c_{0.7}\sqrt{V_A^2 + (0.7\pi nD)^2}}{\nu}$$

Vapour Cavitation number σ_v

$$\sigma_v = \frac{(p_a - p_v)}{\frac{1}{2}\rho V^2}$$

where, V = representative speed: V, V_A, nD, ωr, or $(V_A^2 + \omega^2 r^2)^{1/2}$

5.2 Definition of Variables

D	Propeller diameter	(m)

R	Propeller radius	(m)
$c_{0.7}$	Chord length at 0.7R	(m)
ρ	Mass density	(kg/m^3)
ν	Kinetic viscosity	(m^2/s)
T	Propeller thrust	(N)
Q	Propeller torque	(N·m)
n	Propeller speed	(Hz)
V_A	Propeller advance speed	(m/s)
σ	Vapour cavitation number	(1)
p_a	Ambient pressure (representative static pressure at point of interest)	(Pa)
p_v	Vapour pressure of water	(Pa)
t_W	Water temperature	(°C)
α	Gas content	(ppm)

6. VALIDATION

6.1 Uncertainty Analysis

The 20th ITTC (1993) mentioned critical issues concerning scale effects in cavitation testing. They were related to fluid effects (wake) and bubble dynamic effects. These must be taken into account when estimating errors of an experiment. Customers should be informed of the uncertainty assessment methodology used and which uncertainties can be expected for the tests. The uncertainty assessment methodology should inform about

- measurement systems,
- error sources considered, and
- all estimates for bias and precision limits and the methods used in their estimation (e.g., manufacturers specifications, comparisons against standards, experience, etc.).
- actual data uncertainty estimates.

The uncertainty analysis should be done in accordance with the following regulations/recommendations:

ISO, 1992, “Measurement Uncertainty,” ISO/TC 69/SC 6.

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8. KEYWORDS

ITTC, Guideline, Procedure, erosion, paint, cavitation, propeller, rudder, numerical simulation.