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Prediction of Cavitation Erosion Damage for Unconventional Rudders or Rudders behind Highly-Loaded Propellers

1 PURPOSE OF PROCEDURE

The purpose of this procedure is to provide guidelines and to ensure reliable experimental and numerical approaches for predicting the cavitation and erosion damage on "unconventional" rudders and on rudders behind highly-loaded propellers.

The considered procedure of the erosion prediction is intended to be conducted in a cavitation tunnel, sometimes in combination with numerical simulation. Therefore, the model test for the erosion risk assessment of the rudders should be conducted to meet the reliable procedures of the standard propeller cavitation test recommended by the ITTC (2002a) and the experimental procedure for cavitation erosion on propellers, rudders, and appendages recommended by the ITTC (2005a).

A numerical approach for the cavitation erosion, universally accepted in the field of hydrodynamics, has not yet been developed. Hence, in practice, rudder designers can use indirect information - such as the pressure distribution on the rudder surface - obtained from numerical methods as a modelling procedure that complements the experimental approach.

To enhance the reliability of the experimental or numerical prediction procedures, it is required to perform frequent full-scale rudder cavitation observations and to study the correlation between the predicted and observed data.

For additional information and background on the cavitation for unconventional rudders or for rudders behind highly-loaded propellers, the reader can refer to the report by the Specialist Committee on Cavitation for the 25th ITTC. In addition, based on full-scale experience, Friesch (2003) and Bark et al. (2004) have further expressed the importance of this cavitation issue.

2 MODEL-SCALE EXPERIMENTS

The prediction of cavitation erosion on rudders almost always involves experimental testing of a model-scale rudder. This section includes a number of important considerations for this type of testing.

2.1 Test Set-Up

The test engineer must be careful in setting up model-scale cavitation experiments-since the model geometry, the arrangement of the model parts, the size of the model parts, the flow conditions, and the instrumentation will all influence the test results and impact the final cavitation prediction.

2.1.1 Model Size and Manufacture.

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.

Also, both the model propeller and 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.

2.1.2 Arrangement.

For the rudder behind a propeller, the distance between the propeller and the rudder can have a remarkable 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.

2.1.3 Wake Field Simulation.

The flow around the rudder is affected by the propeller loading, which is governed by the inflow to the propeller. To represent the cavitation on the rudder, the propeller inflow should be realistically simulated. In normal practice, one uses the nominal wake distribution (either for the model or scaled to full scale) as the target wake for the experiment.

For all model configuration options, it is recommended to include as many as possible of the stern appendages. In the case where the propeller has an inclined shaft with shaft brackets, one can use an oblique inflow and an arrangement of the shaft brackets. Wherever possible, one should conduct the cavitation test with the complete ship model—including propeller(s), rudder(s), and all other appendages.

Some investigators have discussed the use of the full-scale wake for erosion tests, taking the estimated full-scale wake from flow calculations. However, the universal law for the full-scale wake, which can be applied to all kinds of vessels, has not yet been developed.

2.1.4 Rudder Part Model Installations.

For tests that 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.

2.1.5 Test Conditions.

In a cavitation tunnel the model test conditions should satisfy the same propeller working conditions as predicted for full scale.

For a cavitation erosion test procedure, the ITTC (2005a) recommended three basic parameters of propeller working conditions:

- Propeller Loading Condition,
- Realistic Wake Velocity Pattern, and
- Corresponding Pressure Field

The best possible full-scale similarity of cavitation phenomena requires the highest possible Reynolds number during the test. This requirement is in conflict with maintaining the full-scale Froude number. Consequently, the similarity of the cavitation number between model test and reality can only be achieved in one horizontal plane at the same time. Thus, the pressure inside the cavitation tunnel has to be adjusted to meet the full-scale cavitation number at that horizontal plane, at which the cavitation phenomenon under consideration occurs.

2.1.6 Calibration.

For a successful erosion test, one must properly simulate, not only the cavitation pattern on the rudder, but also the cavitation generated from the propeller. As part of the preparation and set-up of the test, one must calibrate:

- Thrust and Torque of the Dynamometer,
- Correction of the Thrust and Torque on the bare Hub,
- Rudder Angle, and
- Balancer for the Rudder (if applied).

2.2 Consideration for Rudder Cavitation Tests

In addition to the test set-up, one must strongly consider the effects of propeller loading and scaling on the model tests and final cavitation prediction.

2.2.1 Propeller Loading.

Since the rudder is located in flow accelerated by the propeller, and since this acceleration directly depends on the propeller loading, the propeller coefficient C_{Th} is of importance for the rudder cavitation behaviour. Measurement of an equivalent to the advance velocity of a propeller behind a ship, however, is difficult in a cavitation tunnel due to the hindered slipstream contraction and the blockage effect. For this reason, it is recommended to adjust the proper thrust coefficient, K_T, in the tunnel instead of C_{Th}. In practice, the use of K_T means that the tunnel water speed should be adjusted at constant propeller rpm until the proper K_T value is reached.

2.2.2 Scale Effect.

Even more importantly than when performing model tests for propeller cavitation, one must account for scale effects when performing model tests for rudder cavitation. This effect especially holds when performing rudder cavitation tests for unconventional rudders. Most full-scale experience shows that for almost all rudder cavitation phenomena (gap, sheet, and vortex cavitation) - including cavitation inception - the rudder angle when cavitation occurs is under-predicted from the model test.

Regarding gap cavitation scale effects, another focus is the viscosity effect within those gaps. The flow through those gaps is highly viscous and suffers extremely from a Reynolds number that is too low at model scale. Boundary layers are too thick at model scale, hindering any fast flow through the rudder gaps and delaying gap cavitation.

Vortex cavitation is also not free from scale effects. For predicting the inception of the vortex cavitation at full scale from model tests, one should use the equation presented by McCormick (1962),

$$\left(\frac{\sigma_{i,\text{full scale}}}{\sigma_{i,\text{model scale}}}\right) = \left(\frac{Re_{\text{full scale}}}{Re_{\text{model scale}}}\right)^m \qquad (2.1)$$

where a typical value of the exponent m is 0.4. However, investigators should determine their own value based on different arrangements, conditions, and special properties of the cavitation testing facility - such as the gas content.

3 TEST METHODS

To assess the possibility of cavitation erosion on unconventional rudders and on rudders behind highly-loaded propellers, one should apply the following methods:

- Paint Test and
- Cavitation Observation Using Time-Lapse Video or High-Speed Video.

It is important that the test techniques be optimized for the specific test set-up. For improved results, one must consider not only the charge-coupled device (CCD) cameras, the lamps, the lenses, and the type of paint, but one must also consider the basic equipment such as the test-section windows, the prisms, the windows inside the ship models, and the fitting of the ship models with internal cameras and lamps. The ITTC (2005a) provided the recommended details for these types of tests.

3.1 Assessment of Erosiveness

The traditional method to assess the erosiveness is to observe and assess the cavitation at model scale. Even if the fundamental physical mechanism is still not clear, this method represents a sufficient basis for assessment, as long as observation and judgment are conducted by a hydrodynamically-experienced observer.

The lack of such experience can lead to problems in high-speed video observations of cavitation at model scale. Cavitation simply looks different using this tool, and experience needs to be acquired to judge it correctly.

One important, but time-consuming means to gather the missing experience requires the observer to perform frequent full-scale rudder cavitation observations and to study the correlation between the model- and full-scale data. As long as this experience is lacking, high-speed video should be applied as an addition.

3.2 Recommendations for Unconventional Rudder Cavitation Tests

The following recommendations are suggested for model testing of unconventional rudders or 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.

In the case when 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.

All of these recommendations especially apply for high-speed video observations.

4 NUMERICAL METHOD

In spite of much effort, a universally-acceptable numerical method for predicting cavitation erosion has not yet been developed, primarily because the physical mechanism for cavitation erosion has not been fully clarified. Hence, in practice, to evaluate the possibility of the occurrence of cavitation erosion on rudders, a designer without access to model-scale test data must rely on indirect numerical modelling - to obtain, for instance, the static-pressure distribution on the rudder surface - or on empirical approaches based on the designer's experience.

4.1 Numerical Methodologies

The numerical methods can be divided into potential-flow and viscous-flow approaches.

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 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, 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.

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. 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.

4.2 Consideration for the Rudder Inflow

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 flow around the propeller and rudder simultaneously. However, this method increases the computational costs.

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.

4.3 Guidelines for Numerical Predictions

The aim of the rudder design to minimize the cavitation erosion requires knowledge of the detailed unsteady flow and the cavitation dynamics occurring 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. At the very least, 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.

If possible, 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, 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 and local pressure gradient. 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.

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. 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.

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.

Parameter Type	Absolutely Required	Worthwhile to Have
General Information (Ship and Propeller Operating Conditions)	Type of Ship Engine Power and rpm Propeller/Rudder Main Particulars Shaft Immersion Tip Clearance Rudder Geometry Details Drawing of the Stern Shape, Including the Arrangement of Appendages	Ship Main Particulars Propeller Geometry Data (Blade Section Distributions of Pitch, Chord, *etc.*) Propeller Design Conditions Range of the concerned propeller off-design conditions
Model Propeller/Rudder Operating Conditions	Propeller/Rudder Model Material Flow Velocity, Including the Wake Distributions Static Pressure Propeller Thrust and Torque Propeller rpm Rudder Angle	Detailed Inspection of the Blade Geometry Pressure Drop through the Test Section Level of Turbulence Upstream of the Propeller Rudder Forces and Moments
Water Quality	Water Temperature Air Content (as % Saturation or % Oxygen Saturation)	Tensile Strength of the Water Nuclei Distribution Number and Size
Instrumentation	Type of Video Camera Type and Method of Illumination Type of High-Speed Video System Number of Frames Per Second	
Paint	Type of Paint Method of Model Painting Number of Paint Layers Duration of the Paint Test	Type of Thinner Mixture of Paint/Thinner Preparation of the Propeller model before Painting

Table 5.1 Key parameters for predicting cavitation erosion damage

Basic Measured Data		Derived Parameters	
Representative Static Pressure at the Position of Cavitation Occurrence	p	Cavitation Number	$\sigma = \dfrac{p_{\text{Tunnel}} - p_{\text{V}}}{\frac{1}{2}\rho_{\text{Tunnel}}(\pi n_{\text{M}} D_{\text{M}})^2}$
Rate of Revolutions (*rps*)	N	Torque Coefficient	K_Q
Tunnel Speed (m/s)	V_{Tunnel}	Thrust Coefficient	K_T
Propeller Thrust (N)	T	Advance Coefficient	J_{A}
Propeller Torque (Nm)	Q	Vapor Pressure	p_{V}
Rudder Angle (degrees)		Water Density	ρ_{Water}
Water Temperature (°C)	t		
Air Content / Oxygen Content	$\forall / \forall_{\text{S}}$		

Table 5.2 Checklist of basic variables and derived parameters

Parameter	Recommended Values	Comments/References
Pressure Adjustment to	0.8 *R*, 0.0 *R*, -0.8 *R*	According to the Position of Cavitation Occurrence on the Rudder
Blockage	Less Than 20% of Test Section Size	
Number of Revolutions of the Model Propeller	As High as Possible in Accordance with the Tunnel Speed	ITTC (1996)
Air Content / Nuclei Distribution	High Enough to Avoid Delay of Cavitation Inception	ITTC (1984), ITTC (2005b)
Reproducibility	At Least Two Different Rotations	ITTC (1993)

Table 5.3 ITTC recommendations for certain parameters

5 KEY PARAMETERS

The key parameters that one must consider in predicting cavitation and erosion damage for unconventional rudders and for rudders behind highly-loaded propellers are basically the same parameters recommended by the ITTC Procedure 7.5-02-02-03.5 (2005) for propellers and conventional rudders. Additionally, one should collect information on the position and loading of the rudder in order to assess the rudder cavitation.

These key parameters can be categorized into absolutely necessary data and data that is worthwhile to have (but not necessary). This worthwhile, but not necessary, data will considerably help to improve the reliability and quality of the measurements.

Table 5.1 lists the key parameters for predicting cavitation and erosion damage. Then, Table 5.2 provides one with a checklist of the basic variables and the derived parameters. Finally, Table 5.3 provides some ITTC recommendations for certain parameters.

6 VALIDATION

Improvement in predicting cavitation and erosion damage for unconventional rudders or rudders behind highly-loaded propellers requires the continuing validation of the modelling methodology. For numerical models, validation is the assessment of the accuracy of the computational simulation by comparison with experimental data. Thus, validation implies that one has quantified the uncertainty of the experimental data, and this section describes the required uncertainty analysis. In addition, this section lists some key benchmark tests that one can use to help validate their models.

6.1 Uncertainty Analysis

The ITTC (1993) mentioned critical issues concerning scale effects in cavitation testing. Customers should be informed of the uncertainty assessment methodology used and which uncertainties can be expected for the tests.

As a result of the questionnaire conducted by the ITTC (2008) on cavitation modelling, the extent of rudder cavitation phenomena seems to be rather under-predicted from model tests, and the rudder angle corresponding to cavitation inception seems to be larger at model scale than at full scale. This discrepancy might be due to the previously discussed scale effects, especially when testing with a low Reynolds number, which can result in an unrealistically hindered flow through the rudder gaps, for example. Model basins should be aware of this discrepancy and should inform their customers that the model test results have a tendency to show an optimistic picture of the full-scale situation. It is an important task for the future, however, to overcome this uncertainty.

For computational fluid dynamics (CFD), the ITTC (1999) discussed uncertainty analysis. Also, the ITTC (2002) included this topic in their Quality Manual (Section 7.5-03-01-01 – 7.5-03-01-04). Stern and his colleagues (2001) proposed a verification and validation procedure for CFD simulations. More recently, Oberkampf, Trucano, and Hirsch (2004) provided a very objective and extensive description of verification, validation, and the predictive capability of all types of computational models. However, no universally-accepted procedure exists for the verification and validation of CFD simulations.

For the uncertainty analysis of measurements, one should follow the regulations and recommendations from the ITTC (1990) and the ISO (1992, 1993a, 1993b) - as well as the practices discussed by Coleman and Steele (1999).

6.2 Benchmark Tests

The ITTC (1969, 1981, 1984) has conducted several benchmark cavitation tests for standard screw propellers, for comparative tests using the soft-surface technique, and for extensive comparative erosion tests. The results of these benchmark tests should prove quite useful for validating numerical modelling.

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