ITTC Quality System Manual
Recommended Procedures and Guidelines

Cavitation-Induced Pressure Fluctuations: Numerical Prediction Methods

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7.5	Process Control
7.5-02	Testing and Extrapolation Methods
7.5-02-03	Propulsion
7.5-02-03-03	Cavitation
7.5-02-03-03.4	Cavitation-Induced Pressure Fluctuations: Numerical Prediction Methods

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Table of Contents

Abstract:

This guideline describes the procedure to ensure accurate, and reliable full-scale calculations of cavitation-induced pressure fluctuations using numerical methods. It discusses the different numerical approaches and provides a common method for presentation of the results.

Cavitation-Induced Pressure Fluctuations: Numerical Prediction Methods

1. PURPOSE OF PROCEDURE

The purpose of this procedure is to ensure accurate, consistent, and reliable full-scale predictions of cavitation-induced pressure fluctuations using numerical methods.

The primary background document for this procedure is the report of the 23rd ITTC Specialist Committee on Cavitation Induced Pressure Fluctuations. References are given for typical methods. However, cited references do not supersede other, similar methods not cited.

2. NUMERICAL PREDICTION OF CAVITATION-INDUCED PRESSURE FLUCTUATIONS

This section is written to provide guidance to naval architects in shipyards, owners, and consultancies, including model basins, on how to use available methods.

Methods for calculation of cavitation-induced pressures generally fall into two categories: one that is based on empiricism, relying heavily on model test results, and one that is based on solving the flow problems by first principles. The two types of method will be treated separately here.

For both types of method, sometimes a code user cannot access or revise the mathematical formulation content. This limits useful application, since theoretical or numerical inadequacies may not be apparent to a user or may not be addressable via his own modifications to the code.

2.1 Empirical Methods

Empirical methods are based on analysis of measured data, typically model test results. The analyses are usually statistical (e.g., Holden et al., 1980), but methods using neural networks (Koushan et al., 2000) are also used. For successful analysis, a large number of tests should be included. However, the many parameters describing ship and propeller geometries and cavitation test conditions, as well as the constant development of ships and propellers, make it difficult to collect a sufficient amount of data. With these reservations in mind, empirical methods should be used in the early stage of design, particularly for a relatively traditional ship and propulsion arrangement.

Cavitation induced noise of marine propeller can also be predicted by semi-empirical techniques using a potential flow-based solver. Namely, Tip Vortex Index (TVI) and Tip Vortex Contribution (TVCo) proposed by Kim et al. (2016). Based on experiments data, Lafeber et al. (2015) used the Empirical Tip Vortex (ETV) model to predict the tip vortex cavitation noise while authors (Zhang & Zhi, 2019) established an empirical mode decomposition of ship hull pressure fluctuation induced by a cavitating propeller. Bosschers (2017) improved a semi-empirical formula to predict the hull pressure fluctuations and underwater radiated noise due to the tip vortex cavitation. Results of above-mentionedtechniques indicated that the presented formulation can easily be used for propeller noise estimation in design process. However, the correlation between the propeller cavitation phenomenon and hull pressure fluctuation is not well covered.

Generally, the user of an empirical method should make sure that the ship and propeller under consideration are covered by the cases upon which the method was built. For this purpose, it is most helpful if thorough documentation is available, including correlation with both model and full-scale measurements.

The wake distribution is very difficult to predict with sufficient accuracy at the early stage of design. It can be done on a statistical basis for the type of ships under consideration, or by using a simplified description of the ship hull form. Usually, the mean wake and the wake peak are needed.

The propeller geometry is usually described with a few overall parameters, including diameter, number of blades, pitch, blade area ratio, skew, and thickness. Tip unloading can be indicated by a reduction in pitch near the tip. It is important that the basic of the method comprises the specific characteristics of the propeller in question. Therefore, the usage of the method depending on the availability of supporting documentation, respective scale factor and representative cavitation behaviour.

Prediction of details of cavitation such as type (sheet, bubble, tip vortex etc.), extent and dynamics, are not necessarily included in empirical methods. This generality of course requires that the cavitation performance of the propeller under investigation is similar to that of the propellers that are the basis of the method. If the cavitation is represented for instance by a simple formula for sheet cavitation, it should be evaluated whether this type is representative for the cavitation of the propeller being investigated. Therefore, a direct link for each cavitation type to its specific numerical implementation is essential.

Pressures are usually predicted at a few points or maybe at a single, representative point on the hull surface. Usually, only pressures at blade frequency are predicted, but pressures at twice blade frequency may be calculated. The accuracy of those pressures is rather limited. If forces are required, pressure fluctuations should be predicted at several points, with phases.

2.2 Numerical Methods

Ideally it ought to be possible to make a complete numerical calculation of cavitation-induced hull pressures given the hull, propeller geometry and operating conditions. Adequate methods can be fully resolved by multiple body motion using: (DDES) Delayed Detached Eddy Simulation (e.g., Long et al., 2022); Unsteady Reynolds-Averaged Navier−Stokes (URANS) equations (e.g., Ji et al., 2012); or a combination of a steady viscous CFD method (RANS) for the ship flow and an unsteady potential-flow method (BEM) for the propeller loading (e.g., Perali et al., 2016). In every case the propeller geometry should be part of the method and should be acceptable provided that the geometry is not amended significantly.

However, most methods rely to some extent on model test results, in particular the onset flow to the propeller, i.e., the ship wake field, and the loading condition. Moreover, for the most part only sheet cavitation can be predicted with reliability whereas it is somewhat more difficult (difficulties in resolving vapour structures, complex numerical grid resolution and most notably, modelling chosen for turbulence), to treat the other types of cavitation relying on the current state of numerical cavitation models development. For field methods (viscous CFD), other important aspects in accuracy of cavitating flow simulations are numerical grid resolution and especially the chosen modelling method for turbulence, i.e., URANS or hybrid RANS-LES, for instance.

Even though numerical methods have been confirmed as a potential prediction of propeller cavitation induced pressure fluctuations, for instance by RANS methods (Hasuike N. et al., 2015; Sato K. et al., 2009), its results are yet subject to sea trials and/or model test validation, as it offers a well-controlled physical measured value at a real scale loading condition.

2.2.1 Ship Wake Field

The ship wake used as onset flow to the propeller can be computed directly, for instance by RANS methods (Larsson et al., 2000). The most common procedure, however, is to use results of wake surveys from model experiments. Many organizations scale those data to full scale and to effective wake. However, comparable ship's hull stern form within an acceptable threshold difference should be used for model experiments. On the assumption that all calculations deal with the full-scale flow, both corrections should in principle be applied.

The loading condition, through the kinematical condition for $J = V_A/(nD)$ in order 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. Those results should be corrected to full scale, along with the wake distributions, to ensure the best description of the full-scale case.

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 Euler or RANS solver (Choi, 2000; Choi & Kinnas, 2000a, 2000b, 2001; Rijpkema et al., 2013; Krasilnikov, 2013; Sánchez-Caja et al., 2014). Additional improvement for the validation/calibration of those methods are still required.

2.3 Calculations for Non - Cavitating Propeller

Calculation of the flow over a propeller in the non-cavitating condition can be considered as the first step in the total computation. This calculation should generally be done by lifting-surface (vortex-lattice) or boundary-element (panel) methods that best and most reliably describe the flow (22nd ITTC, 1999). Also, RANS methods for propellers in the flow abaft a ship hull have been largely developed (e.g., Tran Ngoc et al., 2019). When considering both hull and propeller combined calculation, a coupling RANS-BEM approach could be an alternative (e.g., Calcagni et al., 2021) to significantly reduce required computational resources compared to fully RANS calculation.

2.4 Cavitation Prediction

The prediction of cavitation serves dual purposes. First, it provides the basis for assessment of the detailed cavitation performance of a propeller with a view to modification if in a design situation. Secondly, it gives the cavity geometry, including its history, i.e., the time variation of the cavity volume. This variation is necessary for most hull surface-pressure calculation methods.

This committee has found it impossible to recommend one particular method for predicting cavitation. The general recommendation is to use the most-advanced and most-complete procedure available. The user should be aware of the limitations of the method used, both in the theory and found in comparisons with experiments. In the following paragraphs, recommendations, where possible, are given for prediction of the various types of cavitation.

Sheet cavitation is the most common and easiest type of cavitation to deal with theoretically. Most numerical procedures address this type. Some methods use 2-D cavitating profile techniques along with lifting-surface and boundary-element procedures for non - cavitating propellers. The most-advanced methods treat cavitation as an integral part of the procedure, with the non - cavitating analysis as a first step of an iterative procedure. Methods that can address partial as well as supercavitation should be used (Kinnas & Fine, 1994). Face (sheet) cavitation should be included, in particular, if off-design conditions or controllable-pitch propellers are treated. RANS or other CFD analysis has had success in modelling such as critical cases.

Even though, sheet cavitation still become dominant in “high skew propeller”, tip vortex cavitation is an important type when the amount of blade sheet cavitation is small. Tip vortex cavitation plays an influential role in fluctuating pressures. Only a few methods have been presented that address this type of cavitation (Szantyr, 2000; Sezen & Bal, 2019). Yet some progress on replicating vortex cavitation by using RANS (e.g., Gaggero et al., 2013), those techniques still need dedicate effort to capture the phenomenon properly. Tip vortex cavitation modelling requires a direct simulation of the larger, energy-containing turbulent scales. Large-eddy simulation (LES) has become a more mature method to model these important turbulent scales, but the computational costs remain prohibitively large. However, methods like detached-eddy simulation (DES) allow one to compute these important turbulent scales only in the areas of interest, reverting to a RANS simulation elsewhere. These types of methods are beginning to make the numerical modelling of vortex cavitation inception possible, but they remain primarily a research topic.

For cloud, bubble, root, and hub vortex cavitation, only a few methods have been published and are in use. For bubble cavitation, a method (Szantyr, 2000) for assessment relies on the dynamics of a test nucleus in the pressure field on the blade. For cloud cavitation there appears to be no reliable means of prediction. A multi-scale multiphase modelling method, such as Eulerian-Eulerian (e.g., Li & Carrica, 2021; Viitanen & Peltola, 2021) or Eulerian-Lagrangian (e.g., Wang et al., 2021; Lidtke et al., 2016) flow description, is likely needed for a complete representation of various cavitation types. These currently remain as research topics.

RANS and two-phase flow methods are promising for the problem of a propeller in an inhomogeneous inflow with unsteady cavitation (e.g., Paik et al., 2013), though at present, its simulation accuracy (for sheet cavitation) still depends on many aspects, such as grid density, discretization scheme, turbulence model, and cavitation model, etc. (Salvatore, et al. 2009). It is pertinent to first improve the cavitation numerical model implementation along with the calibration and the validation process of the RANS methods against available experimental data.

As stated by the 22nd ITTC Specialist Committee on Cavitation Induced Pressure Fluctuations (22nd ITTC, 1999 pp. 555), “the key for the accurate prediction of unsteady hull pressures is accurate prediction of time variation of cavity volume.” Assuming that this has been achieved in the earlier step of the calculation, the pressure in an unbounded fluid can be computed by the unsteady Bernoulli equation. Alternatively, the acoustic wave propagation equation can be used (e.g., Bloor & Kinns, 2000), but this is hardly worthwhile for points close to the propeller. It is more difficult to include the effects of the hull and the free surface. Many organizations use solid hull boundary factors. Such factors should consider the shape of the hull and the position of the points where the pressure is calculated. A more accurate, but also more complicated, approach is to include the actual hull shape. Here an additional boundary-value problem must be solved with no water penetrating the ship surface (Neumann condition) and usually a high-frequency condition on the free surface. For example, by regarding the unsteady sheet cavity as a modification to blade surface shape, the boundary-value problem for the hull with such a propeller having time-varying geometry can be solved by the surface panel method (Kanemaru and Ando, 2011). However, it remains unknown that, even if the time variation of cavity volume is accurately simulated, how much error would be introduced by solving the hull-propeller problem with a potential flow method.

2.5 Presentation of Results

Results should be presented in terms of pressure amplitudes, phases, and time series up to typically third blade rate. It is unrealistic that higher-order amplitudes can be predicted with sufficient reliability. Results of cavitation calculations should also be presented (ITTC 7.5-02-03-03.2), stating which cavity model was used and which types of cavitation were treated.

3. PARAMETERS

3.1 Parameter to be Taken into Account

The main parameters that need to be considered during pressure fluctuation computations are presented below. If we include the parameters “worthwhile to have”, the computational accuracy could be improved.

General Information:

- Type of ship
- Engine power *P* and propeller rate of revolution *N*
- Propeller main particulars (diameter *D*, blade number *Z*)
- Shaft immersion h_0
- Tip clearance d_D
- Ship main particulars (worthwhile to have)
- Propeller design conditions (worthwhile to have)

Propeller Operating Conditions:

- Onset flow axial velocity (ship wake V_i) distribution.
- Propeller rate of revolution *N*, thrust *T* or torque *Q*.
- Onset flow tangential U_T and radial U_R velocity distribution (worthwhile to have)
- Stern wave height H_W (worthwhile to have)

Propeller Geometry:

- Detailed geometry (radial distributions of pitch *φ*, chord *c*, skew c_S, rake i_G, and thickness *t*; chordwise thickness and camber shapes *f*).

Hull Geometry:

- Drawing of stern shape including arrangement of appendages to construct either calculation grid or hull boundary factors.
- Offsets of ship stern and appendages (worthwhile to have).

4. VALIDATION

4.1 Uncertainty Analysis

The trend of increasing reliance on numerical predictions in the shipbuilding community motivates a better understanding of the uncertainty of these predictions. A rigorous Verification and Validation (V&V) procedure has been proposed for CFD simulations (Stern, et al., 2001; 22nd ITTC 1999, pp. 213-218 (Uncertainty Analysis for CFD); ITTC Quality Manual Section 4.9-04-01-0l). However, there is no universally accepted V&V procedure for CFD especially for full-scale conditions. The overall methodology is to examine comparison errors in the results. This is to demonstrate the accuracy of numerical codes so that they may be used with confidence.

While uncertainty assessment is well established in experimental fluid dynamics (EFD), it is still controversial in CFD (Larsson et al., 2000). It is nonetheless stated that the baseline for the V&V procedure would be the availability of experimental data. The numerical modules are to be calibrated against accessible model test or sea trials data. Then credibility is obtained by demonstrating acceptable levels of uncertainty.

4.2 Benchmark Tests

The following selected ITTC reports presented experimental results of fluctuating pressures on hull. Since detailed data on neither propeller nor ship were presented, it is still not possible to do any comparative calculations based on the information in these reports alone.

(1) Comparative Noise Measurements with the Sydney Express Propeller Model (16th 1981, vol. 1 pp.447-453)

(2) Comparison of Hull Pressure Amplitudes for Sydney Express Propeller (17th 1984, vol. 1, pp.248-252)

(3) Comparison of Propeller-Induced Hull Pressure Measurements for the "SYDNEY EXPRESS" Propeller Models (18th 1987, vol. 1, pp.209-210)

(4) Propeller-Induced Hull Pressures (19th 1990, vol. 1, pp.182-187)

(5) Further Measurement of Pressure Fluctuation on 'SYDNEY EXPRESS' Propeller (19th 1990, vol. 1, pp.213-219)

(6) Comparative Measurements on German Tanker "St. Michaelis" and the "Sydney Express" (20th 1993, vol. 1, pp.230-231)

(7) Comparative Measurement of Pressure Fluctuation on the "St Michaelis" (20th 1993, vol. 1, pp.236-240)

(8) Measurements of Hull Pressure Fluctuation (21st 1996, pp.65-69)

(9) Measurement of Hull Pressure Fluctuation, Round Robin Tests (22nd 1999, vol. 2, pp.547-585)

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6. KEYWORDS

ITTC; procedure; guideline; Numerical methods; Cavitation; Pressure-Fluctuation; Full-scale.