ITTC Quality System Manual
Recommended Procedures and Guidelines

Model – Scale Cavitation Test

Alves Pereira F., Boucheron R., Boucetta D., Fetherstonhaugh C., Krol P., Pang Y., Park C., Sato K., Straka W. A., Viitanen V.

7.5	Process Control
7.5-02	Testing and Extrapolation Methods
7.5-02-03	Propulsion
7.5-02-03-03	Cavitation
7.5-02-03-03.1	Model – Scale Cavitation Test

Disclaimer

Updated / Edited by	Approved
Specialist Committee on Cavitation and Noise of the 30th ITTC	30th ITTC 2024
Date: 05/2024	Date 09/2024
© 2024 ITTC.A Switzerland	DOI:

Table of Contents

Abstract

A standard procedure for model scale cavitation test is presented to ensure consistency, reliability and comparability amongst ITTC organizations. This document provides best practice for cavitation test including model accuracy, wake simulation, calibration and reporting.

Model - Scale Cavitation Test

1. PURPOSE OF PROCEDURE

To ensure consistent, reliable model-scale cavitation test results, comparable amongst ITTC organizations.

2. MODEL-SCALE CAVITATION TESTS

2.1 Introduction

Model scale cavitation tests are routinely conducted in conventional cavitation tunnels, some with free surface simulation. A few member organisations operate depressurised towing tanks. The goal of all these facilities is to operate the propulsor within the simulated propeller velocity and static pressure field. Exact simulation is not achievable due to insufficient knowledge of the actual full-scale flow field and simulation approximations due to Reynolds Number, Froude Number, and non-geosim hull representations.

All tests are intended to achieve geometric similitude of the propulsor. Therefore, the propeller model must have sufficient material strength and geometric accuracy at the specified test conditions to ensure sufficiently accurate results.

2.2 Propeller Operating Conditions

The propeller operating conditions investigated should be mutually established between the testing organization and the customer. The customer specifies the ship operating conditions of interest for the cavitation investigation. Some example conditions are:

- full (design) displacement, full power,
- full displacement, 80% full power (endurance speed),
- ballast displacement, full power, or
- towing load,
- trial and service condition.

The detailed test parameters required for setting test conditions are taken from the results of model powering tests, scaled to the ship self-propelled powering points. These are typically obtained from towing basin powering experiments. The propeller is tested at a prescribed set of parameters: cavitation number, σ, propeller advance ratio, J, and thrust coefficient, K_T. At a particular propulsion operating point, the procedure for setting the tunnel flow conditions to achieve a model simulation of this operating point is usually made on the basis of the “thrust identity.” In the absence of thrust data or by special request, a cavitation test will be run at a “torque identity” condition, satisfying a target full-scale torque coefficient value. When testing in a depressurized towing tank, conditions can be set based on propeller rpm and tow speed, from a previously conducted powering test performed with a geosim model.

The size of the propeller should be such that the highest possible Reynolds Number is achieved within an acceptable level of test-section blockage and within the capacity constraint of the test facility. For the level of blockage, as typical guidance, it is recommended that the ratio of the maximum cross section area of the propulsor/hull model to that of the measuring section of the testing facility should not be greater than 0.2. However, as the blockage effect or acceptable maximum cross section area depends on the hull shape and test setup, assessment of blockage effect using CFD or other numerical simulation could be conducted. Also blockage correction method of velocity, pressure and other derived parameters could be considered. (e.g. correction for thrust can be found in Wood and Harris (1920) and Werle (2011)).

The choice of propeller angular velocity and tunnel speed should result in sufficiently high blade Reynolds Number as to avoid adverse effects of blade laminar flow on cavitation. Typical propeller Reynolds number at 0.7R ($Re_{0.7}$) is 5×10^5 to 1×10^6 similar with propeller open water test, but it depends on propeller type and facility. If low blade Reynolds numbers cannot be avoided, such as when following Froude scaling in a depressurized towing tank, then artificial leading-edge roughness can be utilized to ensure turbulent flow over the propeller blades. The size of roughness will relate to model size and other practices in each facility, and it's still under discussion. Care must be taken to account for effects of artificial roughness on propeller thrust and torque. Alternatively, tests can be conducted at model speeds higher than Froude scale.

To compensate for the deficiency in number of cavitation nuclei in a cavitation tunnel, and especially in a depressurized towing tank, injection of nuclei or cloud of tiny gas bubbles can be adopted. One of typical way is using electrolysis of the tank water. In this system, a cathode and an anode are glued to the ship model in the form of metal strips of 0.5 mm thickness and 3.5 mm wide. There are other ways to generate nuclei, e.g. using cavitation system etc., and they can also be adopted to this purpose.

2.3 Propeller Model Accuracy

The geometry of the propeller model is to be inspected prior to testing. This should include a visual inspection for nicks and local damage and subsequent repair. Manufacturing accuracy should be verified to ensure the geometry is within prescribed manufacturing tolerances. For the case of a controllable pitch propeller the selected pitch must be carefully verified. Effort should be made to ensure the propeller model does not deform under test operating conditions beyond what would be expected to occur full-scale.

Blade surface global tolerance of ±0.05 mm for a typical 250 mm diameter propeller is considered acceptable. Leading edges and tip edges require a higher level of accuracy, which is very difficult to manufacture and inspect. A tolerance within 0.05mm is recommended for the edge sectional shape (leading, trailing and tip edge geometry).

More details can be found in ITTC Recommended Procedures and Guidelines, 7.5-01-02-02 "Propeller Model Accuracy".

2.4 Wake Simulation

The wake simulation adopted for the tests should be mutually established between the testing organization and the customer. 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. More realistic wake simulations will produce more 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. Wake simulations shall be documented with wake survey procedures or verified to be similar to the towing tank wake or to previously measured configurations especially when a dummy model is used to simulate the propeller inflow. Nominal wake surveys are generally performed, although determination of the effective wake, including the influence of the propeller is preferred, though difficult to determine. Measurement of the wake can be performed by using any suitable velocimetry techniques. When using Pitot tube, laser Doppler Velocimetry or PIV, ITTC Recommended Procedures and Guidelines should be adopted (7.5-02-03-02.3, 7.5-02-03-02.4 or 7.5-02-01-04 respectively). The degree of difficulty in achieving a sufficiently representative wake flow depends in part on the type of ship hull involved. Approvable discrepancy between simulated and target wake depends on individual wake and each facility, and no general criteria have been established. But one of the important points in wake simulation is angle of attack of propeller blade and its variation. Regarding this point, not only wake peak value but also average wake which affect propeller operating condition should be paid attention to. In addition, not only axial but tangential velocity components may also affect to angle of attack and should be paid attention to, especially in case with inclined shaft ship.

2.4.1 Open Shaft and Strut Configurations

Wakes for combatant hulls with open shaft and struts are relatively simple to simulate if the propeller operates outside the hull boundary layer. In that case, the wake is dominated by the flow inclination angle to the shaft line. Inclined shaft tunnel set-ups with geosim shaft and strut configurations create a reasonably good wake simulation. The wake is predominately a variation in the tangential inflow. This velocity distribution can only be approximated with wake screens, which produce axial wake variation. An appropriate propeller unsteady performance analysis can be used to match the unsteady blade loading for the specified inclined flow wake. If part of the propeller operates in the hull boundary layer the resulting axial wake deficits may contribute to cavitation. Prior to testing, wake survey data can be used to assess its importance. Significant wake complexity may require a full hull model to properly simulate the flow, however this wake would be at model scale and not corrected for higher *Re* or full scale.

2.4.2 Single Screw Configurations

Wakes of propellers operating well inside the hull boundary layer, such as single screw ships, often have deep velocity deficit contours, and also often have complexities present in the tangential and radial velocity component distributions that influence propeller cavitation. Options for model wake simulations for these types of hull forms are:

- parallel plate wake generator,
- variable density screen wake generator,
- foreshortened hull model,
- full-length, complete hull model.

Three-dimensional wake simulations are preferred over two-dimensional screen type wake generators.

2.5 Calibrations

The following is a list of the basic calibrations that are to be performed as part of the preparation and set up of the cavitation test.

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 static tunnel pressure.

Thrust and torque dynamometer load response calibration. It 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.

Thrust and torque correction loads are to be measured for the bare hub operated at the pressure, angular 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 model propeller shaft may have an influence on the steadiness of the cavitation on blades and the level of the pressure fluctuation. Attention should be paid to the vibration level of the shaft at each test condition. Propeller and shaft balancing is recommended to reduce excessive vibration.

The sensor for measuring water temperature should have an accuracy less than ±0.1° C.

2.6 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.

- Propeller thrust (T) and torque (Q). The definition of thrust and torque (i.e. accounted components like blade, boss, etc.) should be specified.
- Propeller frequency of revolution (n)
- Facility flow reference velocity(V)
- Ambient pressure (p_A)
- Temperature (t_w)
- Gas content ratio (α_s), or other water quality measurement

2.7 Propeller Model Markings

Marking is made on certain model components to facilitate the interpretation of cavitation extent and location as follows:

- Paint or mark blade numbering on each side of each blade
- Paint or mark along constant radius lines at selected r/R values, suction side (SS) and pressure side (PS), typically at 0.5, 0.7, and 0.9 radius
- Paint or mark the mid chord line and/or the reference line, SS and PS
- Mark the hub and bossing to help determine a blade position angle.
- Blade position angle

Great care must be exercised to use very thin painted or marking pen lines to avoid providing artificial sites for initiation of sheet, bubble or streak cavitation.

2.8 Water Quality

An important part of the test set-up phase is to know the water quality of the test facility. This includes some knowledge of the nuclei size distribution/liquid tension as well as dissolved gas content. Previous measured nuclei distributions/liquid tension data can be correlated to online gas content in most facilities to estimate water quality during cavitation testing. Systematic procedures must be implemented to consistently achieve a given water quality before testing.

More detail can be found in ITTC Recommended Procedures and Guidelines 7.5-02-03-03.2 “Visual description and measurement of cavitation events”, and 7.5-02-03-03.9 “Model-Scale Propeller Cavitation Noise Measurements”.

2.9 Water Temperature

Cavitation testing requires a measurement of the water temperature using a resistance temperature device or some other means primarily to determine the water density, viscosity, and vapour pressure. Continuous measurements during the test are recommended to keep track of eventual water heating, especially in smaller testing loops.

2.10 Cavitation Viewing and Lighting

Visualization can be done through viewing ports in the tunnel walls, unless the test section is equipped with large transparent windows. When testing a propeller behind a hull, such as in a large cavitation tunnel or a towing tank, video or high-speed cameras can be installed in watertight, pressurized housings positioned beside the hull, or through ports in the hull located close to or over the propulsor.

For more detail, ITTC Recommended Procedures and Guidelines 7.5-02-03-03.2 "Visual description and measurements of cavitation events" should be referred.

2.11 Setting Static Pressure at Propeller

The representative static pressure at the propeller, p, is selected to match the full-scale cavitation number. The full-scale static pressure at the propeller is typically determined from the still water submergence depth. In some cases, when a large stern wave occurs at the propeller location, this additional hydrostatic head is considered.

When operating at Froude scaled speeds, as occurs in a depressurized towing tank, the selected static pressure results in equivalent full scale cavitation numbers at all water depths.

In water tunnel testing, generally, Froude numbers are not satisfied, preferring to operate propellers at as high a Reynolds number as possible. Consequently, full scale cavitation numbers are only matched at one depth. If cavitation predominately occurs at a vertical location other than shaft depth, then another vertical location can be selected. As the cavitation often occurs near the blade tip, at the top of the disk, a location of such as 0.8 to 0.9R at the top of the propeller disk would be selected to match model and full scale cavitation number. The location in the propeller disk at which the representative static pressure is satisfied is not limited to 0.8 to 0.9R, but should be clearly stated in the test report.

2.12 Selecting Representative Velocity, V_0, for Computing Cavitation Number

A number of options are used to define the representative velocity, V_0, used in the computation of the cavitation number. Typical velocities are V, V_A, nD, ωr, and $\sqrt{(V_\mathrm{A}^2 + \omega^2 r^2)}$ where r is propeller blade section radius. Propeller angular speed is often used for controllable pitch propellers. The representative velocity should be clearly stated in the cavitation test report.

2.13 Cavitation Inception Test

Cavitation inception tests consist of plotting observed cavitation points in a diagram of cavitation number (σ) versus propeller advance ratio (J_A) or thrust coefficient, K_T. Points for the same type of cavitation are connected to determine inception boundaries of each form of cavitation.

For more detail, ITTC Recommended Procedures and Guidelines 7.5-02-03-03.2 "Visual description and measurement of cavitation events" should be referred.

2.14 Scaling Method of Tip Vortex Cavitation

In order to accurately prediction of cavitation inception and radiated noise, it is important that the cavitation extents and dynamics in the model-scale test are similar to those at full-scale. Regarding this similarity, scaling method should be discussed especially in tip vortex cavitation.

For more detail, ITTC Recommended Procedures and Guidelines 7.5-02-03-03.9 "Model-Scale Propeller Cavitation Noise Measurements" should be referred.

2.15 Reporting Cavitation Patterns

Adequate reporting of model cavitation patterns should include some or all of the following:

a. display of still photographs or sketches of cavitation.
b. notes as to the character of the fluctuations and unsteadiness associated with the above patterns.
c. video presentation of cavitation. If available, high-speed recordings are recommended to document the cavitation dynamics.
d. display of any special cavitation regions.
e. discussion and interpretation of each cavitation type encountered and range of accuracy.

For more detail, ITTC Recommended Procedures and Guidelines 7.5-02-03-03.2 "Visual description and measurement of cavitation events" should be referred.

3. PARAMETERS

3.1 Basic Measurement Quantities

D	propeller diameter	(m)
n	propeller frequency of revolution	(1/s)
ω	propeller frequency of revolution	(rad/s)
p_A	ambient pressure (representative static pressure at the point of interest) (Sec. 2.11)	(Pa)
Q	propeller torque	(Nm)
r	blade section radius	(m)
T	propeller thrust	(N)
t	water temperature	(°C)
V_T	tunnel velocity	(m/s)
α_s	gas content ratio	(%)

3.2 Derived Parameters

J propeller advance coefficient (-)

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

K_Q torque coefficient (-)

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

K_T thrust coefficient (-)

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

p_v vapour pressure of water (Pa)

$Re_{0.7}$ propeller Reynolds number at 0.7R (-)

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

V	ship speed	(m/s)
V_A	advance speed of propeller	(m/s)
V_0	representative speed: V, V_A, nD, ωr, or $(V_A^2 + \omega^2 r^2)^{1/2}$ (Sec 2.12)	(m/s)
σ_v	vapor cavitation number	(-)

$$\sigma_v = (p_A - p_v)/((1/2)\,\rho(V_0^2))$$

3.3 Recommendations of ITTC for Parameters

ITTC recommendations for the various parameters above are contained within the body of this procedure, section 2.

4. VALIDATION

4.1 Uncertainty Analysis

The 20th ITTC (1993) presented a list of the critical issues of scale effects, both with the fluid dynamics and the bubble mechanics that must be confronted directly in any attempt at estimating errors for a given experiment.

4.2 Benchmark Tests

1) Comparative Propeller Tests (7th l955 pp.129-216)

- The Completion of the Full Programme of Tests in One Tunnel

- The Tests of At Least One Model Propeller in Each of the Eight Tunnels

- The Completion of the Open-Water Tests of All the Model Propellers In Ship Tanks

- Measurement of All the Model Propeller, Including Surface Finish Propeller Models from 8 to 18 Inches Diameter at Reynolds' Number from 1.5 to 7.5 million

2) Cavitation Tunnel Tests of Series 1 Propellers (7th l955 pp.131-135) Parent Model AEW/C2 (Diameter 9-12-15-18)

3) Cavitation Tunnel Tests of Series 2 Propellers (7th l955 pp.135-168)
3-Bladed Propeller; The Developed Blade Area Ratio 0.655,
The Pitch Diameter Ratio 1.333 Constant Ogival Sections with Sharp Leading Edges
The Design Advance Coefficient J=0.925

4) Cavitation Tunnel Tests of Series I 12 Inch Propellers and Series III 12 inch Propellers (7th 1955 pp.169 - 189)
Series I: 12 Inch Propeller in All Tunnels
Series III: 12 Inch Propeller in Tunnels
Tunnel Wall Effect: less than 0.14

5) Open Water Tests of Model Propellers (7th l955 pp.190 -199)
Series I: Tested in No.2 Ship Tank Haslar
Series II: Tested at Carderock
Series III: Tested at Gothenburg

6) Tolerance and Surface Finish of Model Propellers (7th l955 pp.200-216)

7) Cavitation Inception on Head Forms Comparative Experiments (11th l966 pp.170, 219-232)

- Cavitation Number for Cavitation Inception on the Body

- Cavitation Number when Bubbles are Clearly Visible in the Test Section in Front of the Body i.e. when the Resorption Power of the Tunnel is No Longer Sufficient.

8) ITTC Standard Screw Cavitation Tunnel Tests at Brodarski Institute (12th l969 pp. 523-525) 228.6 mm Diameter

9) Comparative Hydrofoil Experiments and Development of a Standard Cavitator (14th 1975 Vol.2 pp.76-93)

- Results of Tests with Three-Dimensional 19-012 and 16-1512 Hydrofoils in Different Cavitation Facilities

- Progress in the Development of a 'STANDARD CAVITATOR’

10) Appendix A (Hydrofoils) (15th 1978 pp.340-347)

Foil F: Symmetrical Profiles NACA 19-012

Foil G: Cambered Profiles NACA 19-1512

11) Comparative Tests with the Foil-Head form Combination (16th l981 pp.420-424)

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

13) Comparative Tests on Soft Surface Techniques (16th 1981 pp.436-444)

-The SSPA Stencil Ink Method, Modified by SRI-MHI Test Procedure

14) Comparative Tests with Foil-Headform Combination (17th 1984 pp.245-248)

15) Comparison of Hull Pressure Amplitudes for Sydney Express Propeller (17th 1984 pp.248-252)

16) Comparative Erosion Tests with Propeller Model (17th 1984 pp. 252-255)

17) Comparative Noise Measurement with Sydney Express Propeller Model (17th 1984 pp.255-256)

18) Comparative Cavitation Observations on Propeller with and without Leading Edge Roughness (18th 1987 pp.207 -208)

- Model Propeller; NSMB Model 6091, as the '18th ITTC Propeller'

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

20) Comparative Noise Measurements with "SYDNEY EXPRESS" Propeller Models (18th 1987 pp.210~-211)

21) Cavitation Nuclei Measurements (19th 1990 pp.166-175)

22) Propeller-Induced Hull Pressures (19th 1990 pp.182-187)

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

24) Joint Bassin d'Essais des Carènes and Cavitation Committee Tests (20th 1993 pp.206-214)

- Measurement of Liquid/Nuclei Distribut ion Determination of Cavitation Inception Scale Effects.

- Minimizing the Liquid Tension in a Water Tunnel or Towing Tank.

25) 20th ITTC Comparative Model Measurements (20th 1993 pp.230-231)

- Measurements on German Tanker "St. Michaelis" and the "Sydney Express"

26) Comparative Measurement of Pressure Fluctuation on "St Michaelis" (20th 1993 pp.236-240)

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

5. REFERENCES

ITTC Recommended Procedures and Guidelines, 7.5-01-02-02 “Propeller Model Accuracy”

ITTC Recommended Procedures and Guidelines, 7.5-02-01-04 “Guideline on Best Practices for the Applications of PIV/SPIV in Towing Tank and Cavitation Tunnels”

ITTC Recommended Procedures and Guidelines 7.5-02-03-03.2 “Visual description and measurement of cavitation events”

ITTC Recommended Procedures and Guidelines, 7.5-02-03-02.3 “Nominal Wake Measurement by LDV, Model Scale Experiments”

ITTC Recommended Procedures and Guidelines, 7.5-02-03-02.4 “Nominal Wake Measurement by a 5-Hole Pitot Tube”

ITTC Recommended Procedures and Guidelines, 7.5-02-03-02.5 “Experimental Scaling of a Wake to a Target Wake”

ITTC Recommended Procedures and Guidelines 7.5-02-03-03.9 “Model-Scale Propeller Cavitation Noise Measurements”

The Cavitation Committee on 20th ITTC, 1993, “Final Report and Recommendations to the 20th ITTC”, 20th ITTC

Werle, M. J., 2011, “Propeller Wall-Blockage Performance Corrections”, Journal of Propulsion and Power, Vol. 27, No.2, March-April 2011

Wood, R. Mck. and Harris, R. G., 1920, “Some notes on the theory of an airscrew working in a sind channel”, Advisory Committee for Aeronautics, Reports and Memoranda, No. 662

6. KEYWORDS

ITTC; Guideline; Procedure; Experiment; Model scale; Model test; Cavitation; Propeller

Appendix A. CHECKLIST OF PARAMETERS

Table 1: Checklist of parameters

Basic measured data		**Derived parameters**		
	Symbol, unit		Symbol, unit	Relation
chord length at r/R=0.7	$c_{0.7}$ [m]	propeller advance coefficient	J [-]	$J = \frac{V_A}{nD}$
propeller diameter	D [m]	torque coefficient	K_Q [-]	$K_Q = \frac{Q}{\rho n^2 D^5}$
propeller frequency of rotation, propeller rotational velocity	n [1/s] ω [rad/s]	thrust coefficient	K_T [-]	$K_T = \frac{T}{\rho n^2 D^4}$
ambient pressure	p_A [Pa]	vapour pressure of water	p_v [-]	
propeller torque	Q [Nm]	propeller Reynolds number at 0.7R	$Re_{0.7}$ [-]	$Re_{0.7} = \frac{c_{0.7}\sqrt{{V_A}^2 + (0.7\pi nD)^2}}{\nu}$
blade section radius	r [m]	ship speed	V [m/s]	
propeller thrust	T [N]	advance speed of propeller	V_A [m/s]	
water temperature	t [°C]	representative speed	V_0 [m/s]	V, V_A, nD, ωr, or $(V_A^2 + \omega^2 r^2)^{1/2}$
tunnel velocity	V_T [m/s]	vapor cavitation number	σ_v [-]	$\sigma_v = (p_A - p_v)/((1/2)\rho(V_0^2))$
gas content ratio	α_s [%]	kinematic viscosity	ν [m^2/s]	