ITTC Quality System Manual
Recommended Procedures and Guidelines

Cavitation Induced Pressure Fluctuations Model Scale Experiments

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

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Abstract

Abstract: The procedure provides guidelines to ensure the most accurate test results when conducting ship propeller cavitation-induced pressure fluctuations measurements at model scale.

Cavitation Induced Pressure Fluctuations Model Scale Experiments

1. PURPOSE OF THE PROCEDURE

To provide guidelines and to ensure a best possible quality of test results in terms of accurate data on the performance characteristics of ship propellers concerning cavitation induced pressure fluctuations.

2. MODEL SCALE EXPERIMENTS ON PROPELLER INDUCED UNSTEADY PRESSURES

The basic pressure fluctuation test consists of measuring transducer signals from flush-mounted pressure gauges located on a surface representing the ship hull shell, located adjacent to a propeller operating in a non-uniform inflow velocity field representing the flow behind the ship. Choice of number and placement of pressure gauges should cover the local peak of induced pressure amplitudes and the distributions of pressures both laterally and longitudinally. Example characteristic time series of pressure signals should be displayed. The model scale results must be analysed for harmonic content and the pressure amplitudes scaled to ship scale for the prediction of dimensional unsteady hull surface pressures.

Test facilities for this type of experiment are: variable pressure water tunnel, depressurised towing tank, and circulating water channel with a free surface in the test section.

2.1 Test Set-Up

2.1.1 Propeller Model

The size of model propeller should be determined, within the capacity constraint of the test facilities and within an acceptable range of test-section blockage (with the model and propeller being less than 20%), to achieve the highest possible Reynolds number. 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”.

Model propeller blades are traditionally made of strong aluminium alloys or brass. Whether the surface of the model is hydrophobic or hydrophilic might have an influence on the cavitation characteristics and hull-pressure measurements. A thrust to disc area loading of about 70 kPa is a useful upper limit value for strength considerations.

2.1.2 Wake Simulation

2.1.2.1 Global Information

The main task is to provide a realistic simulated wake velocity pattern which will also give the correct 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.

There are scaling issues connected with trying to satisfy the three governing similarity parameters: Reynolds number, Froude number, and cavitation number. Cavitation tunnel pressure fluctuation testing does not satisfy Froude or Reynolds number scaling but is aimed at a relatively high value of Reynolds number. Testing in a free surface cavitation facility offers the possibility of matching Froude and cavitation number, but at a rather low Reynolds number.

When Froude similarity is not satisfied, the correct cavitation number is exactly satisfied only at the blade reference point for scaled submergence depth pressure. This can be compensated for by simply adjusting the pressure head to the appropriate value for each of the blade positions of interest.

The low Reynolds number of model testing presents more complicated problems. Because of Reynolds number scale effects, the boundary layer thickness relative to hull length along a ship model in the cavitation tunnel is relatively wide. The magnitude of this influence depends greatly on the type of hull form. Wake scaling techniques such as the contraction methods offer relatively simple methods for scaling a model wake to a target wake with full scale features. If Reynolds number wake scaling is to be applied, the practical recommendation is to target the three-dimensional full scale nominal wake. In any case, 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.

2.1.2.2 Dummy model

The main issue is to provide a simulated wake flow to the propeller by using partial ship model or flow devices.

Alternative model schemes are used depending on type of ship and facility size:

In **small** water tunnel **test sections** include (in case of a single screw ship):

- Wire mesh screen placed perpendicular to the flow, in front of a flat plate simulating the 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')

In large test sections:

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

For all the model configuration types mentioned, it is recommended to include as much of the stern appendages, such as the rudder, in the correct location behind the propeller.

A difficult task is modifying a model configuration so that the measured wake reliably matches the target velocity profile by surface mounted patches of screen, shortened model hull length, wire mesh screens mounted perpendicular to the hull, slimmed after body dummy model shapes and flow liners in the corners of the test section to prevent flow separation. All these configurations strongly depend on the skill of the model basin and on existing correlation data between model and full scale.

When using dummy model, the simulated wake shall be documented to verify that the deviation from the target wake can be neglected. 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.

2.1.2.3 Simulation by a Ship Model

The full ship model for cavitation induced pressure pulse tests normally comes from previous resistance and self-propulsion tests performed in a towing tank. Normally the specification of the model construction shall comply with the ITTC 7.5-01-01-01 Quality manual procedure regarding model construction. Furthermore, it shall comply with the low-pressure environment and the higher velocity encountered in the cavitation test facility.

The ship model shall be completed with all the required appendages, fin stabilizer, rudder and turbulence stimulators, that can influence the propeller inflow.

High quality mechanical components shall be adopted for the transmissions with respect to self-propulsion tests in order to reduce the level of vibration and noise generated by the motor, gearbox or any rotating device used in the transmission mechanism. An accelerometer shall be installed on the ship model to monitor the levels and the frequency distribution of the induced hull vibrations.

The alignment of the shaft and joints shall be accurate in order to reduce propeller rotational speed variation during the revolution. Propeller rotational velocity fluctuation shall be maintained within 1%. In order to check the rotational speed of the propeller the mounting of a multi-pulse encoder (at least 1000 pulses per revolution) on the propeller shaft shall be preferred.

For the above reasons in case of twin screw ships two motors configuration (one for each propeller) shall be preferred because this reduces the number of mechanical components required in the transmission and hence the induced hull vibration. Furthermore, a two motors configuration allows the possibility to investigate the effect of different phase rotational angles between the propellers for reducing the hull excitation induced by cavitation.

In the case of cavitation observation where windows are required for camera installation on the model the windows should not affect the propeller inflow.

In case that electrolysis is used for cavitation stabilization, electrodes could be mounted on the ship model at least 1 meter upstream of the propeller plane.

2.1.3 Pressure Transducers

Rugged miniature, high sensitivity, flush mounted pressure transducers of suitable range shall be used for pressure fluctuation measurements. There are mainly two types of pressure transducers being used: piezoelectric and piezoresistive. Today, both types are working well, and the choice depends on the i/o hardware used in the facility. Transducer range depends on the facility velocity and static pressure and could be absolute or differential. Band pass frequency response of the transducer shall be at least 1000 Hz and the measuring range shall not exceed 4-5 times the maximum measured pressure in order to limit the measurement errors. Pressure transducers shall be periodically calibrated with respect to a standard calibration reference. If possible, a minimum of 5 transducers shall be installed on the ship model hull. If force calculations shall be performed the number of pressure transducers shall be at least 20 located over an equi-spaced grid. Normally pressure pick-ups can be located at 0.8D ahead of the propeller disc to 0.6D behind the propeller disc (D = propeller diameter). The maximum extension to port and to starboard amounts to about 0.6D to 0.8D, depending on the section shape. The distances between the transducers are in the range of 0.15D and 0.35D.

2.2 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 ships.

The two basic parameters of propeller working conditions are:

- Propeller loading
- Corresponding pressure field

2.2.1 Propeller Loading Condition

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

2.2.2 Corresponding Pressure Field

Set the facility pressure and flow velocity to obtain the correct full scale cavitation number $\sigma = (p_0 - p_V)/(1/2 \rho V_0^2)$; Where p_0 = total static pressure consisting of atmospheric pressure plus submergence depth pressure taken to a reference location on the propel1er blade, and with the representative speed V_0 taken as V_A, nD or πnD. The reference submergence depth used in the calculation of the cavitation number is usually taken at a point approximating the centre of the expected cavitation extent in the upper part of the disk, such as 0.8.R above the propeller centreline.

Inclusion of the effect of stern wave heights can be determined based on experience of the model basin.

For Froude scaled cavitation testing in a facility with a free surface, such as a depressurized towing tank or a free surface circulating water channel, the standard results of a Froude scaled towing basin powering test may be used directly to set the propeller RPM and speed for the various operating conditions of the experiment. It is noted that the usual procedure for scaling model powering results to full scale is based on satisfying the thrust loading coefficient at full scale Reynolds number, which is equivalent to a thrust identity approach.

2.3 Measurements and Instrumentation

The requirements for measurements and instrumentation for model pressure fluctuation testing can be divided into two main groupings. The following lists identify the quantities measured items and give special notes about the instrumentation [in brackets].

A) Basic Test Measurements

Measurements ‘**Absolutely required**’ include:

- facility flow velocity;
- facility static pressure;
- propeller thrust and torque;
- propeller rotational speed;
- water temperature,
- gas content as % saturation or % oxygen saturation [use Van Slyke Apparatus or Continuous Oxygen Analyzer],
- wake velocity component(s) [most preferably use 5-hole pitot probes or Laser Velocimetry].
- In the category of ‘**worthwhile to have**’ is
- the measurement of cavitation nuclei number and size distributions [use a cavitation susceptibility meter or Cavitation Nuclei Counter device].

B) Unsteady Pressure and Cavitation Observation Measurements

Measurements ‘**Absolutely required**’ include:

- unsteady pressure signals [use strain gauge diaphragm or piezoelectric type transducers];
- control pulses per shaft rotation for data sampling [shaft encoder device with minimum number of pulses per rotation = 5*(highest BR harmonic)*(Z)];
- data stream system [signal conditioners/amplifiers, A-to-D devices, link to computer and data storage];
- viewing and photographic arrangements [windows, viewing pods or ports];
- photographic and video records; stroboscopic lighting; and time series and narrow band spectra of pressure signals [spectrum analyzer machine].

In the category of ‘**worthwhile to have**’ are

- measurements of vibration acceleration [accelerometers placed near the pressure transducers]. These measurements can be used as a help to analyse and interpret the pressure signals;
- sound pressure level of noise [hydrophones];
- time series and narrow band spectra for the accelerations and noise.

2.4 Calibration

For a successful hull-pressure measurement, the cavitation pattern on the propeller blade must be simulated properly, according to procedure ITTC 7.5-02.03-03.1. As part of the preparation and set-up of the test, the following calibration should be performed:

- The torsional or lateral vibrations of the model propeller shaft may have an influence on the steadiness of the cavitation on the blades and the level of the pressure fluctuation. Attention should be paid to the vibration level of the shaft at each test condition.
- Pressure gauges to measure static and differential pressure should be calibrated within an established time period prior to the test.
- In order to enhance the reliability of the measurements, it is recommended that the calibration data of the pressure gauges be confirmed, simply by the change of the static pressure inside tunnels before the measurement.

2.5 Data Collection and Analysis

We must distinguish two types of analysis:

1. harmonic analysis or blade angular position domain analysis
2. time domain analysis

The harmonic analysis is dedicated to provide the pressure amplitude at blade rate or blade rate frequency. This analysis has to deal with pressure as function of blade angular position changing with time: $p(\theta) = p(\omega t)$. To get rid of the potential fluctuation of the shaft revolution rate that might come to be a problem when focusing at the high harmonics, it is always better to use an encoder on the shaft to sample the pressure as a function of the blade angular position. It is helpful to use an encoder with a number of pulses which a power of 2 $N = 2^p$, so that the Fast Fourier Transform might be used to speed up the calculation of the harmonic decomposition of the signal.

If the shaft revolution rate is stable enough, the harmonic decomposition can be performed in the time domain.

On the contrary the blade angular position domain analysis is not useful when looking at the broadband level of the pressure pulse signal. Because the broadband level is generally related to the non-stationary cavitation, the fluctuations are not only related to the blade angular position of the blade but also to the physics of cavitation itself. This means that the broad band level cannot be estimated in the blade angular position but in the time domain.

2.5.1 Global Data Collecting and Presentation of Results

The following types of data can be of interest to be presented in the report:

- Sequences of the unfiltered pressure signal p(t). A sufficient number of propeller revolutions have to be covered to yield a realistic impression of variations over time, as intermittency etc. To get an overview of the characteristic of the pressure signal the frequency content of the signal should be at least up to 10 blade frequency multiples but 20 or higher is preferable. The amplitude scale has to be dimensionless as Kp (definition see section 3.1) or in Pascal. The plot of p(t) can be very informative and should always be included in the report. As an important complement at least one type of the spectra listed below should be appended.
- A table showing amplitudes and phase angles (mean values) for the first 5 harmonics. This is in principle a pure line spectrum[1] (Kp or amplitude in Pa).
- A plotted mean value spectrum, including the continuous part, for the first 5 harmonics (Kp or amplitude in Pa).
- A plotted spectrum showing the mean values of the X% highest blade passage pulses, including the continuous part, for the first 5 harmonics. X can be for example 50 or any value which according to full scale correlation has been proven to correspond to full scale data. The idea here is to exclude the smallest pulses which in model testing may be a result of excessively intermittent cavitation because of lack of nuclei or other scale effects. Other types of pulse statistics can give equivalent information. Sequences should be sampled during several minutes. Good complements are also video recordings showing variations over some time.
- A plotted mean value spectrum, including the continuous part, up to 15th or 20th harmonics. Because of its relevance for higher frequencies excitation and the dominance of the continuous spectrum at these frequencies this spectrum can be presented in 1/3-octave

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[1] Pressure pulse and noise spectra are usually a mix of two types of spectra: Broadband noise having a continuous spectrum and tones/sinusoidal components having a a spectrum containing line components at discrete frequencies. See e.g. Beranek (1988) or Urick (1983).

bandwidths, which simplifies the scaling (Kp or amplitude in Pa).
- Additionally, a plot showing the arrangement of the different pressure transducers should be given.

First harmonic or blade rate means the blade frequency i.e. the number of propeller blades multiplied by the rate of revolutions of the propeller shaft.

The presentation of continuous spectra in the same graph as discrete spectral lines is problematic in the sense that these spectra have to be scaled to full scale in slightly different ways. Only for spectra of the constant percentage type, as the 1/3 octave, the same scaling can be applied to lines as well as the continuous part. This problem can be managed in different ways: Avoid plotting of mixed spectra in the same graph, recalculate the scaled and modified spectrum or write out the Pa or K_p scaled amplitudes at the spectral lines only. Since the continuous spectrum contains information about the cavitation as well as the energy exciting the ship it is important to include it in the report. Above the 5th to 10th harmonics the continuous part can be dominating.

2.5.2 Higher Harmonic Components

The present meaning of higher harmonics covers a frequency range from 5 up to 10 or possibly 20 multiples of the blade frequency. In practice these frequencies cause high frequency vibrations and what on passenger ships would be called low or medium frequency noise. The experience of prediction at these frequencies is limited and no standard or praxis has been developed.

In a standard test for pressure fluctuations the first two or three, possibly up to five harmonics are usually considered. The limit is set by the number of harmonics that can be clearly distinguished above the continuous spectrum and be predicted by some accuracy. Full scale correlations usually indicate that the discrepancy between model and full-scale increases at higher harmonics. The first two are typically reasonably close to full scale while the values of the higher harmonics are sometimes too low by model tests.

The number of harmonics is strongly related to the shape of the pulses. Two main behaviours can be distinguished. For sheet cavitation on the blade the pulse shape is related to the gradient of the wake - the higher the gradient of the wake the more harmonics. For tip vortex cavitation the higher harmonics are typically generated during pulsations of the cavity behind the blade, due to mechanisms not fully known.

Two main reasons for too low values predicted for higher harmonics can be identified: Spreading of energy from the harmonic spectral lines by phase modulation or a less steep wake in model scale.

Excessive modulation can be avoided by using a high Reynolds number, high nuclei content and by minimizing the unsteady wake by use of flow liners to avoid separation.

A fundamental lack of high harmonics due to wrong pulse shape can be cured by simulating the proper wake as much as possible.

When excessive modulation exists, its effect can be reduced by measuring/analysing in wider bandwidths, or afterwards by integration of the spectrum in some interval around the harmonics. There is no standard for this type of analysis, and therefore the analysis is strongly related to the correlation experience of the model basin.

From the 5th harmonic it typically happens that the energy of the continuous part of the spectrum dominates over the energy in the lines so obviously the continuous spectrum has to be considered.

Considering these facts a practical way is to analyse the first spectral lines, having levels 5-10 dB above the continuous spectrum, in the traditional way by a line spectrum. The entire spectrum can however also be shown as a 1/3-octave band plot (scaled according to the K_p -formula) being particularly adequate at frequencies at which the continuous spectrum dominates. This data presentation also corresponds to the mode characteristics of the hull at higher frequencies.

2.5.3 Uncertainty Consideration

Measurement of pressure pulses requires skill and insight into the physics of cavitation, but it is a straightforward process not resulting in any extraordinary difficulties. Usually, the main error sources appear because of hydrodynamic problems introduced by the approximations made in a model test. The hydrodynamic problems result in lack of similarity between model and full-scale cavitation and pressure signals, a fact implying that analysis and interpretation of model results become complex and can result in errors difficult to quantify.

Adding up all errors in the most pessimistic way in such a complex process may result in error estimates larger than the measured quantity. An estimate based on experience and full-scale correlation can be less conservative but usually more realistic.

Obviously, all sources of error have to be estimated and weighed in some way. Among the standard errors related to instrumentation are those emanating from transducers, selections of sampling frequency and duration, pulse and phase deformation due to filters, amplifiers etc. Errors from these sources are reduced simply by giving priority to a professional selection and operation of modern measuring systems. The unavoidable errors from the measurement chain have then to be added to the errors emanating from the hydrodynamic approximations. Examples of the latter are:

- Error in the specification of the loading condition (cavitation number and advance coefficient). The source of this error is the propulsion test or an equivalent for the determination of the loading condition.
- Error in the realization of the loading condition at the cavitation test. In this error are included deviations in controlling the tunnel setting (to properly fulfill K_T-identity etc.). Also possible effects of use of approximate similarity conditions are included in this group of errors. Ignoring the Froude number effect on the cavitation number (often considered to be small).
- Deviations in hull or dummy geometry
- Deviations in propeller geometry

The importance of these error sources can vary, not only between different facilities but also between different projects. If the wake is extremely bad a small and local error in blade geometry of a heavily loaded propeller will make a small difference while the same error on a high-speed ship can be significant. It is very important therefore to analyse the error sources individually, in every project.

An engineering way to handle the hydrodynamically based errors which are often difficult to derive or estimate, is to consider key input data, loading conditions etc., not as exact numbers but the nominal numbers +/- 5 or 10%, as a guess. Performing then the tests also at +/- 5 or 10% variation of the cavitation number and/or advance coefficient will produce a plot from which the sensitivity of the results for input errors can be estimated. With later assumptions about the input error also the output error can be estimated and the risk that a certain design fails due to a realistic but unknown error can be evaluated.

2.6 Other Essential Experimental Conditions

This section deals with a lot of items that need to be considered when performing pressure fluctuation measurements but cannot be put into a direct rule neither specific values can be given. The points mentioned should be considered when discussing the results, depending on the experience with the specific test facility and the correlation achieved there.

2.6.1 Gas Contents, Cavitation Nuclei and Stabilizing Model Cavitation

It is generally accepted that testing at relatively high gas content, as a kind of nuclei, in a water tunnel facility reduces the tensile strength and improves the correlation of model and full-scale results. When there are insufficient concentrations of nuclei, all forms of cavitation behave intermittently and will therefore produce non-periodic pressure readings at model scale.

When testing in a depressurized towing tank, the generation of the nuclei by the sand grain roughness on the leading edges of the model propeller blades or electrolysis in the boundary layer flow past the hull stabilizes the cavitation on the model propeller blade.

However, too high levels of air may deteriorate the visibility inside the tunnel and introduce a damping effect on the measured unsteady pressure amplitudes.

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

1.1.1 Influence of Wake Simulation

One of the most critical problems when performing pressure fluctuation measurements is the correct simulation of the wake of the full-scale ship. When performing such type of measurements, the following limitations regarding the wake simulation shall be always kept in mind.

- Full ship models provide three-dimensional inflow at the propeller discs which is correctly simulating the full-scale propeller inflow for twin-screw hulls provided that the propeller discs are outside the ship boundary layer. In case of a single-screw hull, where the propeller is working in the ship boundary layer, the large difference of the model and ship Reynolds numbers produces a wider wake and a different flow to the propeller in model scale.
- Shortened full ship models proposed to reduce the differences between the boundary layer thickness between model and full-scale ship can be adopted but particular attention shall be applied when shortening the model in order to avoid possible separation of the flow at the fore-body that will definitively deteriorate the propeller inflow simulation. Prior to testing, oil paint or tuft visualization is suggested for verification.
- Wire screens are a suitable and practical means to reproduce the full-scale ship wake when the axial velocity distribution is the objective of the simulation. They are not effective in simulating the tangential and the radial velocity distribution.
- Dummy after-body model can be used to simulate the full-scale propeller inflow, but

it requires a time-consuming iterative process of model modifications and wake measurements to achieve the target propeller inflow.

2.6.2 Facility Wall Effects

The wall effect has been a subject of continuous discussion in the ITTC. The Round-Robin tests in the 22nd ITTC report show that different levels of pressure fluctuations have been measured in different test section areas in spite of similarity of wake field and cavity pattern. However, the effect of the blockage on the pressure measurement is not clarified quantitatively because the measured results include the effects of different sources like tunnel vibration, Reynolds numbers etc.

Hence, systematic studies on this effect will be needed, and it is recommended that each facility gains experience by comparing at least the results for two different sized propellers.

2.6.3 Effect of Induced Vibration

If a pressure transducer is mounted in a vibrating surface a pressure can be induced by the vibration. This pressure adds, with the component of its phase angle, to the pressure that would have been measured without the vibration. The vibration can be excited by the propeller or by uncorrelated sources. They can be global, including the complete hull girder, or local plate vibrations.

Although the problem has been much discussed there are only a few studies published and according to a few full-scale examples the influence of vibrations at lower frequencies seems for most cases and transducer positions to be modest. This, however, does not mean that severe influence cannot occur, for example at transducer positions far from the propeller. At high frequencies strong influence has been reported from local plate vibrations.

It is usually assumed that the influence of vibrations is small at model testing but can be important on the ship having a more flexible structure. If this occurs and no correction is made the comparison between the amplitudes at model and full scale can be of limited relevance.

Calibration procedures based on measurements of the vibrations at transducer positions have been developed and tested. The experience from these problems is however limited and specific procedures are not engineering standard.

To avoid the problems the following simple guidelines are recommended:

- Use a model/dummy being stiff enough to reduce vibrations at relevant frequencies. This is particularly important for at least one reference transducer in the center line and close to the propeller.
- If the model cannot be made stiff enough, avoid putting transducers far from the propeller or within or close to areas where vibration can be expected.
- Check vibration levels, at least for some typical models, by mounting accelerometers close to pressure transducers. Then apply an exciter to the model (without the propeller in operation) so it performs vibrations like those generated by the propeller. From such experiments a correction can be found. In principle the correction can alternatively be calculated by methods being able to determine the added mass of a body vibrating in water. However, particularly for a model clamped to a cavitation tunnel this latter method can be difficult. Take account of phase relations and bandwidth effect in the measuring system.

A different kind of influence occurs if the transducer is mounted at some distance from the vibrating surface or part of the surface. An example of this case is vibration of the walls of a cavitation tunnel which can disturb measurements significantly. The way around the problem is to reduce the wall vibrations and avoid transducers far from the propeller and close to the walls.

Above resonant vibration of the tunnel walls there is also a contribution from acoustic reflections in mainly stiff walls. At some distance from the propeller the free field will be disturbed by the reflections. The distance at which this occurs depends on the size and stiffness of the test section and the amount of free gas bubbles in the water. This effect also limits the distance from the propeller at which a transducer can record a relevant pressure signal.

To find out such limitations an acoustical calibration of the tunnel is recommended. The calibration should, due to the influence of standing waves, be made at realistic free gas content. In this way transfer functions can be determined by which for example the free field pressure can be estimated. Particular for the higher harmonics this procedure can be useful.

2.6.4 Free Surface Effects

It is concluded that the influence of the free surface on the pressure amplitudes must be accounted for in most tests. Exceptions being amplitudes measured at transducers close to the propeller on fully loaded super tankers and similar.

The highest accuracy in simulation of the boundary conditions, like the one at the free surface, can be reached in a very large cavitation facility with a free surface. Data from all other facilities, i.e. from most cavitation tunnels, must be transformed by some procedure to include the free surface effect.

If not free surface and solid boundary effects for the correct shape of the hull are automatically considered by use of a proper model/dummy tested in a free surface facility, corrections have to be applied afterwards to find the relevant pressure amplitude. The correction factor can be empirical or computed as explained in the 23rd ITTC Report on Cavitation Induced Pressure Fluctuations.

For a correct solid boundary factor the model/dummy must be reasonably similar to the ship and the transducer has to be in approximately the position in which the pressure amplitude is intended to be predicted. The reason is that the solid boundary factor changes slightly with position (due to hull shape) but also that the propeller has some directivity implying that a distance correction based on 1/r should be avoided (This is particularly true for minor cavitation, a condition at which the dipole contribution from the blade loading cannot be neglected).

The correction for the absence of a free surface and possible shortcomings in the solid boundary effect can be determined numerically.

It is noted that empirical corrections based on full scale correlation consider also different scale effects on the cavitation, a reason to work with such correlations also if a numerical free surface correction is applied.

3. PARAMETERS

3.1 Parameters to be considered

Parameters that need to be considered during pressure fluctuation measurements are basically the same as for cavitation tests (ITTC Procedure

7.5-02-03-03.1). For pressure fluctuation measurements they can be categorized into "data absolutely necessary" and in "data worthwhile to have" (Section 2.3). If the latter are considered, the reliability and the quality of the measurements will considerably be improved. See also the checklist in the Annex, Table 1.

3.2 Basic Measurement quantities

D	propeller diameter	(m)
n	propeller rotational speed	(Hz)
p_A	ambient pressure (representative static pressure at the point of interest) (Sec 2.2.2)	(Pa)
Q	propeller torque	(N·m)
r	blade section radius	(m)
T	propeller thrust	(N)
t	water temperature	(°C)
V_T	tunnel velocity	(m/s)
α	gas content	(ppm)
θ	phase angle	(°)

3.3 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 Reynolds number (-)

$$Re = \frac{V_A D}{\nu}$$

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

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

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 2.2.2)	(m/s)
σ_v	vapor cavitation number	(-),

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

3.4 Recommendations of ITTC for Parameters

ITTC recommendations for the various parameters above are contained within the body of this procedure, section 2. Some parameters are also listed in the checklist in Annex, Table 2.

4. VALIDATION

4.1 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 considered 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 (see also section 2.5.3). The uncertainty assessment methodology should inform about

A) measurement systems.
B) error sources considered.
C) all estimates for bias and precision limits and the methods used in their estimation (e.g., manufacturers specifications, comparisons against standards, experience, etc.).
D) 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.

ISO, 1993a, “Guide to the Expression of Uncertainty in Measurement,” ISO, First edition, ISBN 92-67-10188-9.

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6. KEYWORDS

ITTC; Guideline; Procedure; cavitation; model-scale; experiment; pressure fluctuation; pressure pulse

ANNEX

Table 1: Checklist of parameters to be considered.

	Absolutely required	**Worthwhile to have**
General information (Ship, propeller operating conditions)	• Type of ship • Engine power and RPM • Propeller main particulars • Shaft immersion • Tip clearance	• Ship main particulars • Propeller geometry data (Section, Pitch Chord distribution etc) • Propeller design conditions • Drawing of stern shape including arrangement of appendages
Model propeller operating conditions	• Propeller model material • Flow velocity including wake distribution • Static pressure • Propeller thrust and torque • Propeller RPM	• Detailed inspection of blade geometry • Intrinsic unsteadiness of facility • Pressure drop through test section • Level of turbulence upstream propeller
Water quality	• Water temperature • Gas contents as % saturation or % oxygen saturation	• Tensile strength of the water • Nuclei distribution number and size
Instrumentation	• Type and capacity of pressure transducer • Type of amplifiers • Type of shaft encoder	• Type and capacity of hydrophone • Type and capacity of accelerometer • Vibration characteristics of the measuring plate
Measurement and analysis	• Interval for signal acquisition • Measuring time • Level of the pressure fluctuation at blade frequencies	• Acceleration measurement next to pressure transducers • Noise level near the propeller • Narrow band spectra of pressure, noise and accelerations • Recording all data stream

Table 2: Recommendations of ITTC for parameters

Parameter	**Recommended values**	**COMMENTS / RECOMMENDED IN**
Pressure adjustment to	0.7 ~ 0.9 R	
Blockage	Less than 20 % of test section size	For wire screen, blockage is for propeller disk area. For dummy hull or full hull, blockage is the fullest section of the hull.
Number of revolutions of model propeller	As high as possible in accordance with tunnel speed	ITTC 1996 Cav. Com.
Minimum Reynolds-number	Minimum value of 0.5 million based on the blade chord length at 0.7 R. Target of 1 million.	
Number of pressure transducers	5 ~ 20	
Gas content / nuclei Distribution	As high as possible according to the facility experience. Values of total gas content or Oxygen content should be mentioned	ITTC 1984 ITTC 1996 Cav. Com.
Noise	Low values of the facilities	ITTC 1990 Cav. Com.
Reproducibility	At least two different rotation rates of the model propeller should be tested	ITTC 1993 Cav. Com.
Model propeller diameter	> 200 mm	