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Model scale noise measurements

1. PURPOSE OF THE GUIDELINE

The purpose of the guideline is to ensure consistent and reliable noise measurement results of cavitating propellers in model scale facilities. The noise measurements are usually performed in order to predict the full scale acoustic source strength of the cavitating propeller with respect to the underwater radiated noise for a wide range of frequencies.

The guideline focuses on propeller cavitation noise measurements but is also applicable for noise due to other forms of cavitation such as e.g. rudder cavitation. Noise measurements to determine the source strength of non-cavitating flow are not described by this guideline.

Due to the focus on propeller cavitation noise, other ITTC procedures and guidelines related to model tests involving cavitating propellers are relevant as well. In particular, the following procedures and guidelines are of importance:

- 7.5-02-03-03.1: Model-scale cavitation tests
- 7.5-02-03-03.3: Cavitation induced pressure fluctuations, model scale experiments
- 7.5-04-04-01: Underwater noise from ships. Full scale measurements.

The difference between pressure fluctuation measurements and noise measurements is that pressure fluctuations are typically measured on the ship hull in order to investigate the risk for inboard noise and vibration. The pressures are measured in the low frequency range (between 1st and 5th to 20th blade rate frequency. Noise measurements are typically performed up to high frequencies (e.g. 100 kHz model scale) with the goal of determining the source strength for the far field underwater radiated noise.

Additional information on noise measurements can be found in the 27th ITTC Proceedings and the final report by the Specialist Committee on Hydrodynamic Noise (2014). The report also reviews the responses of a survey on both full scale and model scale noise measurements.

2. MODEL SCALE EXPERIMENTS ON PROPELLER CAVITATION NOISE

Model-scale experiments involving noise measurements of cavitating propellers are usually performed using one or more hydrophones mounted in the test facility in which the propeller is tested. Test facilities vary between variable pressure water tunnels and circulating water channels with a free surface in the test-section to a depressurized towing tank.

Whereas the propeller is always tested at geosim conditions, the ship model, generating the wake field in which the propeller operates, may deviate from geometric similarity.

2.1 Test Set-Up

2.1.1 Propeller Model

The size of a model propeller should be determined, within the capacity constraint of the test facilities and within an acceptable range of test-section blockage, to achieve the highest possible Reynolds number. A typical diameter for a model scale propeller is 250 mm. The accuracy of the propeller geometry should be according to ITTC guideline 7.5-01-02-02 which specifies that the offsets of the blade sections should be in the range ± 0.05 mm. Model propeller blades are usually made of strong aluminium alloys or brass. A thrust to disc area loading of about 4 kPa/blade is a useful upper limit value for strength considerations.

2.1.2 Wake Generation

The propeller operates in the wake of the ship hull which leads to loading variations of the propeller blade. These loading variations lead to cavitation inception and dynamics which give rise to cavitation noise. It is the loading variation that needs to be correctly modelled in the cavitation test facility which is accomplished by setting the correct wake field. The reference wake field is in general the nominal wake field measured in a towing tank but full scale nominal wake fields obtained by extrapolating the model scale wake field or by using CFD are used as well. More information on wake scaling methods can be found in the 26th ITTC proceedings of the Specialist Committee on Scaling of Wake Field (2011).

Relevant scaling parameters for the ship wake are the Reynolds number and the Froude number. The dependency on the Froude number is related to the influence of the free surface wave height on the wake field which can be important for some types of ships and for ships in ballast condition but in general the influence is small. The most important scaling parameter is the Reynolds number which determines the thickness of the boundary layer and the generation of vortices on the ship hull. However, similarity of Reynolds number cannot be obtained in model test for practical reasons. In order to minimize Reynolds scale effects, the ship model and tunnel speed should be selected as high as possible. In smaller cavitation tunnels, one may use wire screens, possibly in combination with dummy models.

For the generation of the wake field, the following cases can be distinguished:

- A wire screen mesh is typically applied in tunnels with small test-sections and is a suitable and practical method when the axial velocity distribution is to be generated. They are not effective in simulating the tangential and radial velocity distribution. Disadvantage of wire screen meshes is that they may vibrate and cavitate which increase the background noise.
- A dummy model possibly in combination with wire screens is typically applied in medium size test-sections.
- For twin screw ships, the inclined shaft, brackets and bossing can be mounted in small to medium size test-sections.
- A full ship model, on which sometimes also wire screens are mounted or which may be shortened, is typically used in large size test-sections. For single screw ships it is especially the aft part of the hull lines that determine the propeller inflow. This part can also be modified in order to generate a wake field that closely resembles the full scale wake field.

For all cases it is recommended to include the (stern) appendages such as rudder at the correct location. The quality of the generated wake with respect to the target wake should be assessed using wake field measurements. Depending on the configuration one may measure the axial velocity component only, the axial and tangential velocity component or all three velocity components.

The accuracy of the full ship model should be according to ITTC procedure 7.5-01-01-01 which specifies a tolerance of ± 1 mm. In general the model is also used for resistance and propulsion tests but it is remarked that the model in the cavitation facility is typically tested at higher velocities and that the loading will therefore be higher. The model shall be equipped with all appendages and turbulence stimulators that may influence the propeller inflow. If observation windows or boroscopes are used for cavitation observation, these should not influence the propeller inflow. The maximum blockage of the ship model in the test-section is in the order of 10-20%.

2.1.3 Hydrophones

Usually commercially available hydrophones of piezoelectric type are used for measurement of underwater sound pressure levels in a test facility. The sensitivity should be as high as possible but has to be a compromise of the dimensions and the usable frequency range. A built-in integrated preamplifier is advantageous to reduce electronic noise of the measurement chain. Depending on the integration situation, either flush mounted or omni-directional type of hydrophone shall be used. The usable frequency range starts from about 1 Hz and the upper limit is between several 10 kHz and about 100 kHz. The maximum operating pressure for most of the hydrophones varies between 40 and 100 atm which is much more than required for model test facilities. Little information is available on the minimum operating pressure, which is mainly obtained by practical experience of specific hydrophones at the operating conditions of a test facility.

Hydrophones shall be periodically calibrated with respect to the manufacturer's calibration reference, e.g. by use of a hydrophone calibrator. Typically at least one hydrophone should be located at the propeller plane. Additional hydrophone positions up- and down-stream, as well as abeam, should be included if feasible to augment acoustic testing. Hydrophones should preferably be installed one of the following ways:

- In a large or medium sized acoustic chamber below the test section
- Outside of the walls or windows
- Flushed to walls or windows
- To a rake in the flow
- Inside the basin

The stand-off distance to a window or wall should be at least 0.2m and is typically in the range from 0.3m to 1m.

Hydrophone arrays enable noise measurements with high directivity to scan the model to identify local noise source regions and should be used if permitted by facility capabilities and testing budget.

2.2 Test Conditions

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

The two basic parameters of a propeller operating conditions are:

- Propeller loading K_T
- Cavitation number σ

2.2.1 Propeller Loading Condition

The propeller loading at the predicted full scale K_T or K_Q (thrust or torque identity) is obtained through the kinematic condition for $J = V_A/(nD)$. Here, V_A = propeller speed of advance, D = propeller diameter (m), n = rotational speed (1/s), $K_T = T/(\rho n^2 D^4)$, and $K_Q = Q/(\rho n^2 D^5)$. Usual practice in water tunnel testing is to satisfy the thrust identity by varying the facility speed V_{fac} , although there are circumstances where the torque identity approach is used.

2.2.2 Cavitation number

The facility pressure needs to be adjusted to obtain the correct full scale cavitation number $\sigma = (p_0 - p_V)/(1/2 \rho V^2_{ref})$; where p_0 = total static pressure consisting of atmospheric pressure plus submergence depth pressure taken to a reference location on the propeller blade, and with the reference velocity V_{ref} 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 0.7R, 0.8R or 0.9R above the propeller centreline although the propeller centerline is also used.

Inclusion of the effect of stern wave heights can be determined based on discussions with customers and/or 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.

It is recommended to perform additional tests at different drafts with off-design loading conditions.

Noise measurements shall be supported by additional investigations like cavitation observation, cavitation inception and/or hull pressure pulse measurement.

2.3 Overall Instrumentation

2.3.1 Introduction

The requirements for measurements and instrumentation for noise testing fall into two main groups. The following lists identify the parameters to be measured and give special notes about the instrumentation [in brackets].

<u>Basic Test Measurements</u>

Parameters that are ‘required’ to be measured include:

- facility flow velocity V_{fac} ;
- facility static pressure p;
- propeller thrust and torque T, Q;
- propeller rotational speed n;
- water temperature t;
- air saturation index α or % oxygen saturation index.,

In the category of ‘recommended’ falls

- the measurement of cavitation nuclei number and size distributions [using a cavitation susceptibility meter or Cavitation Nuclei Counter device].

Sound Pressure Measurements

Parameters that are required to be measured include:

- time series or narrow band spectra [spectrum analyzer] of the underwater sound pressure ;
- The category of ‘recommended’ includes
- control pulses per shaft rotation for data sampling [shaft encoder device with minimum number of pulses per rotation = 5*(highest blade rate harmonic)*(blade number)];
- vibration characteristics of ship hull, propeller shaft and facility walls;
- cavitation observations;

2.3.2 Calibration

For a successful underwater noise measurement, the cavitation pattern on the propeller blade must be simulated properly. As part of the preparation and set-up of the test, the following (calibration) tests should be performed:

- For the thrust and torque dynamometer, load response calibrations should be carried out with applied loads, and also long term stability of the calibrated data needs to be confirmed.
- The torsional or lateral vibrations of the model propeller shaft may have an influence on the background noise. Attention should be paid to the vibration level of the shaft at each test condition.
- Hydrophones should be calibrated within an established time period prior to the test.

2.4 Background Noise Measurements

To check the quality of the noise measurements, i.e. of the cavitating propeller, the contribution of facility dependent noise – i.e. the propeller drive system, the tunnel operation or towing carriage, the water flow, the measurement chain etc. - has to be determined. The so called background noise shall be measured in absence of the propeller cavitation – by replacing the propeller by a dummy boss or by increasing the tunnel pressure until cavitation is fully suppressed - but with all other operating conditions as similar as possible. These operating conditions are:

- Shaft rotational speed n
- Propeller load K_T
- Facility speed V_{fac}
- Tunnel pressure p
- Gas content α

Both procedures to measure background noise have specific pros and cons. The increase of tunnel pressure allows to keep the propeller load condition K_T and to detect propeller non-cavitating noise (e.g. propeller singing) but changes the gas content. The replacement of the propeller by a dummy boss keeps the same gas content but changes the load of the propeller drive system.

If flush mounted hydrophones or pressure transducers are used in the tunnel wall or ship hull, the contributions of the vibrations of the wall or hull to the noise measurements need to be assessed as part of the background noise measurements. The influence of hull vibrations on hull mounted pressure transducers is discussed in ITTC guideline 7.5-02-03-03.3.

Background noise shall be measured for every noise test condition.

2.5 Noise Data Acquisition and Processing

2.5.1 Measured Quantity and Presentation

The principal measured property of noise is the time varying pressure p at a location. The measurement of acoustic pressure that is conventionally reported is the root mean square (rms) of a pressure:

$$\bar{p}_{rms} = \sqrt{\frac{1}{T}\int_{-T/2}^{T/2} p(t)^2\,dt} \qquad (2.1)$$

In the context of noise assessment, the sound pressure level is the fundamental quantity of sound pressure, and it is defined in terms of a pressure ratio as follows:

$$L_p = 10\,\log_{10}\left(\bar{p}_{rms}^2 \big/ p_{ref}^2\right) \qquad (2.2)$$

where p_{ref} is the reference pressure set normally to 1μPa for water.

Analysis with filters is almost always used in connection with acoustic measurements. The most popular filters are those with 1/3 octave bandwidths. In 1/3 octave analysis, the bandwidth is equal to 23% of the centre frequency. Results of noise measurement can be converted from 1/3 octave bandwidth to equivalent 1 Hz bandwidth using the following expression:

$$L_{p,1Hz} = L_{p,1/3\,octave} - 10\log_{10}(0.23 f_0) \qquad (2.3)$$

where f_0 is the centre frequency. The 1/3 octave band needs to be due to broadband noise and should not be dominated by tonals for this to apply.

The results of model noise measurement should include:

1) 1/3 octave bandwidth spectrum
2) Narrowband spectrum normalized to 1Hz bandwidth

The 1 Hz spectrum levels obtained from 1/3 octave band levels is considered ”recommended".

2.5.2 Data Acquisition System and Frequency Analysis

The data acquisition system mostly includes the transducer, pre- or charge amplifier, filters and A/D board. Figure 2.1 shows a signal flow chart to illustrate the elements in a simple noise measurement.

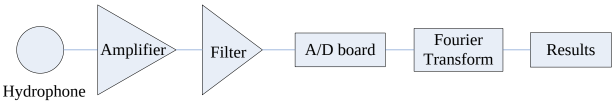

Figure 2.1: The signal flow chart of an acoustic measurement

The frequency range of the measurement is usually determined by the characteristics of the hydrophone and the A/D board. However, the reverberation in the cavitation tunnel should be considered as well as it may determine the lower frequency limit as discussed in section 2.5.5.

The upper limit of the frequency range is directly related to the sampling frequency:

$$f_H \le \frac{f_s}{2} \qquad (2.4)$$

where f_H is the upper limit of the frequency range and f_s is the sampling frequency. An anti-aliasing filter should used to avoid any influence of signals with frequency above f_H. More than 20 seconds of the measurement time are proposed in order to have sufficient data for the analysis.

2.5.3 Distance Normalisation

As the measured noise levels are heavily influenced by the distance between the noise source and the measurement transducer, a distance normalisation is usually applied. The noise levels are usually corrected according to the following expression:

$$L_S = L_p + 20\ \log_{10}\left[\frac{d}{d_{ref}}\right] \tag{2.5}$$

where d is the distance between the acoustic source and the hydrophone location in meters and d_{ref} the reference distance of 1m. The centre of the acoustic source for model propeller is usually considered to be at the shaft centre or at 0.7*R* above the shaft centre.

2.5.4 Correction for Background Noise

The measured cavitation noise levels can be influenced by the background noise of the test set-up and the facility. The background noise should therefore be measured as described in Section 2.4. A correction to the measured model noise levels for each 1/3 octave band can be made using the difference ΔL between the pressure levels which is defined as

$$\Delta L = L_{p_{s+n}} - L_{p_n} = 10\log_{10}\left(\frac{\bar{p}^2_{rms_{s+n}}}{\bar{p}^2_{rms_n}}\right) \tag{2.6}$$

where $L_{p_{s+n}}$ is the sound pressure level of the model noise measurement, and L_{p_n} is the sound pressure level of the associated background noise measurement. If ΔL is greater than 10 dB then no adjustments are necessary. On the contrary, if ΔL is less than 3 dB then measurements are dominated by background noise and cannot be used. Finally if $3\text{ dB} \le \Delta L < 10\text{ dB}$, adjustment on measurements are required and the following expression can be used:

$$L_p^{'} = 10\log_{10}\left[10^{\left(L_{p_{s+n}}/10\right)} - 10^{\left(L_{p_n}/10\right)}\right] \tag{2.7}$$

If the noise measurements contain contributions due to e.g. vibrations of a specific element in or outside the facility, the measurements can be corrected by subtracting the coherent part of the noise with the vibrations of the element, Bendat and Piersol (2011).

2.5.5 Influence of Wall Reflections

When the noise is measured in model scale test facilities, we should keep in mind that the test sections do not resemble a free-field environment. The reflections by the walls cause a different sound field which depends on frequency. The influence of reflections due to the walls must be investigated, and a correction procedure should be determined.

In order to assess the influence of these reflections, an acoustic calibration could be made using a known sound source put at specific locations in the test section. A transfer function between source and the received acoustic signal of the measurement system is then obtained provided that the coherence between the received signal and the source signal is close to one.

For facilities with a free surface, the influence of this free surface on the noise measurements should also be assessed and, if necessary, corrected for with an acoustic calibration test. In general, the free surface gives a reduction of the measured noise levels at low frequencies where the influence increases with decreasing frequency. The influence of the free surface on pressure transducers mounted flush with the ship hull is discussed in ITTC guideline 7.5-02-03-03.3.

In addition, the diffusivity in the (reverberant) cavitation tunnel should be considered. In the Cavitation Committee report of the 15th ITTC (1978), the number of acoustic modes N in a frequency band of 1/3 octave bandwidth is defined. This number depends on the frequency and the volume of test section, V , according to the formula

$$N = \frac{\pi f^3 V}{c_0^3} \tag{2.8}$$

where f is frequency and c_0 is the speed of sound in the water. For the application where the objective is to obtain an equivalent free-field level, the model noise measurement will be most precise if the number of modes N in the frequency bandwidth exceeds one.

A criterion given in Kuttruff (2009) is the so-called Schroeder frequency which is the lower frequency limit below which the noise field is influenced by separate modes instead of statistical properties. The frequency is given by

$$f = \sqrt{\frac{c_0^3 T_{60}}{4V \ln 10}}\ \text{Hz} \tag{2.9}$$

with T_{60} the reverberation time which is the time interval in which the noise decay level drops down by 60 dB.

2.6 Other Items

This section deals with some other items that need to be taken into account when performing noise measurements but for which no concrete guidelines are available due to lack of published dedicated systematic test data. Instead, the best practice experience of the specific test facility is to be used.

2.6.1 Air Contents, Cavitation Nuclei and Cavitation Stabilization

It is generally accepted that testing at relatively high air content, implying a larger amount 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 create tiny air bubble in great quantities, deteriorate the visibility inside the tunnel and introduce a damping effect on the measured underwater sound pressure levels.

Hence the optimum air 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.

2.6.2 Influence of Blockage

Blockage will affect the flow field in the tunnel and the interference among the propeller, the hull and the wall of the tunnel. For noise measurements, a propeller as large as possible should be used in order to increase the Reynolds Number. However, the effect of blockage on noise measurement has not accurately been investigated.

Systematic studies on this effect will be needed, and it is recommended that each facility gains experience by comparing the results for different size propellers.

For closed-jet type cavitation tunnel, a blockage of less than 20% of the test section size is recommended.

3. SCALING METHODS

3.1 Scaling Method

Scaling procedures are available to obtain full-scale noise levels of a cavitating propeller tested at model scale. Published comparisons between model scale and full scale (e.g. Levkovskii 1968; Bjorheden and Astrom 1977; Lovik 1981; Bark 1982 and 1992, etc.), show differences which may however not necessarily be due to the scaling procedure. For instance, the cavitation dynamics may not be similar due to differences in the ship wake field, nuclei content, gas content or differences in Reynolds number. Also, the correction for the reverberant environment of the model tests is a potential source of error. Finally, there is an uncertainty involved in the full scale noise measurements as well, especially in the distance normalization.

A prediction of the full-scale noise levels can be made using scaling laws recommended by the Cavitation Committee of the 18th ITTC (1987). These laws concern only differences in dimensions and operating conditions of the model and full scale propellers and therefore do not correct for reverberation or dissimilarity in cavitation pattern and dynamics.

The increase in noise levels from model to full scale is given by:

$$\begin{aligned}\Delta L = 20\,\log_{10}\left[\left(\frac{D_s}{D_m}\right)^{z}\left(\frac{r_m}{r_s}\right)^{x}\left(\frac{\sigma_s}{\sigma_m}\right)^{y/2}\right]\\ +20\,\log_{10}\left[\left(\frac{n_s D_s}{n_m D_m}\right)^{y}\left(\frac{\rho_s}{\rho_m}\right)^{y/2}\right]\end{aligned} \qquad (3.1)$$

and the frequency shift is given by

$$\frac{f_s}{f_m} = \frac{n_s}{n_m}\sqrt{\frac{\sigma_s}{\sigma_m}} \qquad (3.2)$$

In the above, the subscripts s and m refer to full-scale and model-scale respectively and the increase in noise level is for proportional band width.

These formulations are applied in different facilities according to the analysis of questionnaire initialized by the Specialist committee on Hydrodynamic Noise of the 27th ITTC (2014) which also provide a review of values used. The exponents x, y and z have different values depending on theoretical assumptions, test facility , range of Reynolds number applied, and the model test method.

3.2 Scaling Method of Tip Vortex Cavitation

In order to accurately predict the radiated noise of a propeller, it is important to know the cavitation extent for the operating conditions of the propeller. As a matter of fact, even near cavitation inception a noticeable increase of the radiated noise occurs. For tip vortex cavitation, the scale effect on cavitation inception must be considered.

For vortex cavitation inception, one traditionally scales the inception cavitation number using some form of the equation presented by McCormick (1962):

$$\frac{\sigma_{i,\text{full-scale}}}{\sigma_{i,\text{model-scale}}} = \left(\frac{\text{Re}_{\text{full-scale}}}{\text{Re}_{\text{model-scale}}} \right)^{m} \qquad (3.3)$$

The Reynolds number exponent m was found to vary mostly in the range of 0.3-0.5 and is attributed to test facility differences, range of tested Reynolds number, and variation of water quality, see the report of the Cavitation Committee of the 21st ITTC (1996). Shen et al (2009) present a formulation for m that depends on Reynolds number.

For tip vortex cavitation noise, the scaling method is under investigation. However, test conditions may occur where at full scale a cavitating tip vortex is present while at model scale the vortex does not cavitate due to the delay in inception. This makes the scaling procedure rather complicated.

4. REVIEW OF PARAMETERS

4.1 Parameters to be Taken into Account

Parameters that need to be considered during noise measurements are basically the same as for cavitation tests (ITTC Procedure 7.5-02-03-03.1) and pressure fluctuations tests (ITTC Procedure 7.5-02-03-03.3). The parameters can be categorized into "required data " and in "recommended data " (section 2.4). If the latter is taken into account, the reliability and the quality of the measurements will considerably be improved. The review of parameters is given in Table 4.1.

Table 4.1: Review of parameters to be taken into account

	Required	**Recommended**
General information (Ship, propeller operating conditions)	● Type of ship ● Engine power, RPM and ship speed ● 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	● Facility flow velocity including wake distributions ● Facility 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 ● Air content as % saturation or % oxygen saturation	● Tensile strength of the water ● Nuclei distribution number and size
Instrumentation	● Review of data acquisition system ● Type, sensitivity and locations of hydrophone(s) ● Type and settings of amplifier and filters	● Shaft encoder ● Type, sensitivity and locations of accelerometers
Measurement and analysis	● Measuring period ● Underwater sound pressures ■ 1/3 octave band ■ Narrowband ■ Source levels	● Vibration characteristics of ship hull, propeller shaft and facility ● Cavitation observations

4.2 Checklist of Parameters

The checklist presented in Table 4.2 shall help the test engineers.

Table 4.2: Checklist of parameters

Basic measured data		**Derived parameters**	
Representative static pressure at reference point (shaft, 0.8-0.9R) [Pa]	$p_{static,ref}$	Cavitation number	$\sigma_n = \dfrac{p_{static,ref} - p_V}{\frac{1}{2}\rho V_{ref}^2}$, $V_{ref} = V_A,\ nD, \pi nD$
Rotational velocity [rps]	n		
Propeller thrust [N]	T	Thrust coefficient	$K_T = \dfrac{T}{\rho\ n^2 D^4}$
Propeller torque [Nm]	Q	Torque coefficient	$K_Q = \dfrac{Q}{\rho\ n^2 D^5}$
Facility speed [m/s]	V_{fac}	Apparent advance coefficient	$J_A = \dfrac{V_{fac}}{nD}$
Water temperature [° C]	t	Vapor pressure	p_V
Sound pressure	p	Sound Pressure Level SPL	$L_p = 10\log_{10}\left(\dfrac{\overline{p}_{rms}^2}{p_{ref}^2}\right),\ p_{ref} = 1\mu\text{Pa}$
Distance hydrophone to acoustic centre	d	Underwater sound radiated noise level at 1 m	$L_S = L_p + 20\log_{10}\left(\dfrac{d}{d_{ref}}\right),\ d_{ref} = 1m$
Air Content []	$/\ \ _{s}$		
Oxygen Content []	0_2		

4.3 Recommendations for Parameters

The recommendations for parameters are presented in Table 4.3.

Table 4.3: Recommendations for Parameters

Parameter	**Recommended values**	**COMMENTS / CITATION WHERE RECOMMENDED**
Pressure adjustment to	0.7 ~ 0.9 *R, top dead centre*	ITTC 2002 Pressure Fluct. Com.
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*	ITTC 2002 Pressure Fluct. Com.
Air content / nuclei Distribution	According to the facility experience. Values of total air content or Oxygen content should be mentioned	ITTC 1984 ITTC 1996 Cav. Com. ITTC 2002 Pressure Fluct. Com.
Background noise of the facility and driving train	10 dB below cavitation noise level	
Model propeller diameter	> 200 mm	ITTC 2002 Pressure Fluct. Com.

5. UNCERTAINTY AND VALIDATION

5.1 Sources of Error

Usually the main error sources of noise measurement of cavitating propellers are due to hydrodynamic phenomena introduced by approximations made in a model test. The hydrodynamic phenomena result in lack of similarity between model and full scale cavitation and its noise, a fact implying that analysis and interpretation of model results become complex and can result in errors difficult to quantify.

Obviously all sources of error have to be estimated and weighted in some way. Among the standard errors those related to instrumentation can be reduced, simply by giving priority to a professional selection and operation of modern measuring systems. The errors from the measurement chain have to be added to the errors emanating from the hydrodynamic approximations. Examples are:

- Error in the velocity distribution of the ship wake field. The error arises due to differences in Reynolds number and the method of wake generation in the test.
- 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 noise measurement test. The source of this error includes deviations in controlling the tunnel setting (to properly fulfil K_T-identity etc.) and ignoring the Froude number effect (often considered to be small). Also possible effects of use of approximate similarity conditions are included in this group of errors.
- Deviations in propeller geometry

The Cavitation Committee of the 20th ITTC (1993) mentioned critical issues concerning scale effects in cavitation testing. They were related to fluid effects (the ship wake field) and bubble dynamics. These must be taken into account when estimating errors of an experiment. The importance of these error sources can vary, not only between different facilities but also between different projects. It is very important therefore to analyze 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, say +/- 5 or 10% variation, as a guess. Performing the tests and the sensitivity of the results for input errors can be estimated. With such assumptions the output error can also be estimated and the risk of a certain design can be evaluated.

It is recommended to estimate the reproducibility and uncertainty of the scaling procedure in for instance a research type project by performing the model tests for at least two different rotation rates of the propeller.

5.2 Uncertainty Analysis

Customers should be informed of the uncertainty assessment methodology used and which uncertainties can be expected for the tests. The uncertainty assessment methodology should inform about:

- measurement systems.
- error sources considered.
- all estimates for bias and precision limits and the methods used in their estimation.
- 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.

ISO, 1993b, “International Vocabulary of Basic and General Terms in Metrology,” ISO, Second edition, ISBN 92-67-01075-1.

ITTC 2008 , Recommended Procedures and Guidelines, 7.5–02–01–01: “Guide to the Expression of Uncertainty in Experimental Hydrodynamics“.

5.3 Benchmark Tests

The following benchmark tests related to noise measurements have been reported in ITTC proceedings:

3) Comparative Noise Measurements with the Sydney Express Propeller Model (16th ITTC, 1981, pp.447-453)
4) Comparative Noise Measurement with Sydney Express Propeller Model (17th ITTC, 1984, pp.255-256)
5) Comparative Noise Measurements with "SYDNEY EXPRESS" Propeller Models (18th ITTC, 1987, pp. 210-211)

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