ITTC Quality System Manual

Recommended Procedures and Guidelines

Guideline

Model-Scale Propeller Cavitation Noise Measurements

7.5	Process Control
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7.5-02-01	General
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Model-Scale Propeller Cavitation Noise Measurement

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
- 7.5-02-03-02.5: Experimental Wake Scaling Methods
- 7.5-02-03-03.2: Description of Cavitation Appearances
- 7.5-04-04-01: Underwater Noise from Ships. Full-Scale Measurements.

The difference between hull-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 ITTC Proceedings and the final report by the 27th and 28th Specialist Committee on Hydrodynamic Noise (2014, 2017). The reports also review the responses of surveys 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. The water tunnel and channel will both be referred to in this document as a cavitation tunnel.

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 procedure 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. Special care on manufacturing accuracy is needed in order to avoid cavitation occurrence sooner than expected. A thrust to disc area loading of about 4 kPa/blade is a useful upper limit value for strength considerations. For a controllable pitch propeller, it is also very important to set the pitch setting within 0.5% of design pitch.

2.1.2 Wake Generation

The propeller operates in the wake of the ship hull which leads to load variations of the propeller blade. These load variations lead to cavitation inception and cavitation dynamics which give rise to cavitation noise. It is the load variation that needs to be correctly modelled in the cavitation test facility which is accomplished by setting the correct wake field.

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 Froude similarity also gives a similar vertical gradient of the cavitation number as full scale. 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 product of ship model length and tunnel speed should be as high as possible.

In large cavitation test facilities, the current practice is to test the propellers with the complete hull geometrically scaled. However, there is also the possibility to use a modified hull geometry to make the wake field at the propeller plane closely resemble the full scale wake. It can be useful on twin screw ship for which the blades in the upper position are working in the ship hull boundary layer because the boundary layer thickness relative to the propeller diameter at model scale is different than at full scale. For single screw ships it is especially the aft part of the hull lines that determines the propeller inflow. This part can also be modified in order to generate a wake field that closely resembles the full scale wake field.

The accuracy of the ship model should be according to ITTC procedure 7.5-01-01-01. 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, they should not influence the propeller inflow. The maximum blockage of the ship model in the test-section is about 20%.

In smaller cavitation tunnels, one may use wire screens, possibly in combination with dummy models. The reference wake field is in general the nominal wake field measured in a towing tank but it is recommended to use the full scale nominal wake fields obtained by extrapolating the model scale wake field or by using CFD. More information on wake scaling methods can be found in the 26th ITTC proceedings of the Specialist Committee on Scaling of Wake Field (2011). 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 increases 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.

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.

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 at tens of kHz or even above 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.

The sensitivity of the hydrophones shall be periodically calibrated with respect to the manufacturer’s reference, e.g. by use of a hydrophone calibrator.

In the facility, at least one hydrophone should be located at the propeller plane. Additional hydrophone positions up- and downstream, as well as abeam, should be included if feasible to augment acoustic testing. Hydrophones should preferably be installed in one of the following ways:

- In a large or medium sized chamber with acoustic treatment below the test section
- Outside of the walls or windows
- Flush 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 0.2 m and is typically in the range from 0.3 m to 1 m.

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 cavitation 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 cavitation tunnel is to satisfy the thrust or torque identity by varying the revolution speed of the propeller at a given flow speed at which the hull wake has been measured.

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 centreline is also used. If the reference velocity is based on the revolution speed n, there is, then, no need for the free-stream flow speed to be representative of the ship speed. This is very convenient for all cavitation tests and especially for dummy hull type of testing arrangement.

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 results of a Froude scaled powering test in a towing basin may be used directly to set the propeller RPM and ship 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 with off-design load conditions to check the sensitivity of the noise measurements to changes in operational setting.

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].

Basic Test Measurements

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 or oxygen saturation index α;

In the category of 'recommended' falls

- 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 Test Preparation

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 – 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 bare hub 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
- facility speed V_{fac}

- gas content α
- either
  - Propeller thrust T or torque Q
  - Tunnel pressure p (bare hub)

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 which may influence the sound transmission. The replacement of the propeller by a bare hub keeps the same gas content but changes the load of the propeller drive system which may change the noise due to the drive train. The test report should state clearly which procedure has been adopted.

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:

$$\bar{p}_{rms} = \sqrt{\frac{1}{T}\int_0^T p(t)^2 dt} \quad (1)$$

In the context of noise assessment, the Sound Pressure Level (SPL) is the fundamental quantity of sound pressure, and it is defined in terms of a pressure ratio as follows:

$$SPL = 10\, log_{10}\left(\bar{p}_{rms}^2 / p_{ref}^2\right) \quad (2)$$

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

Noise is usually represented by a spectrum calculated from the sound pressure signal of a hydrophone *p(t)*. The sound pressure level is defined for a given centre frequency f and for a frequency bandwidth Δf, i.e. defined for $\left[f - \frac{\Delta f}{2}; f + \frac{\Delta f}{2}\right]$:

$$SPL(f, \Delta f) = 10 \cdot log_{10}\left(\frac{p_{rms}(f,\Delta f)}{p_{ref}}\right)^2 \quad (3)$$

where p_{rms} is the Root Mean Square of the sound pressure *p(t)* filtered within the frequency bandwidth $\left[f - \frac{\Delta f}{2}; f + \frac{\Delta f}{2}\right]$.

Nowadays, the spectral representation of a sound pressure signal *p(t)* is computed through an FFT, resulting in for instance the Power Spectral Density function $\phi_{pp}(f, \Delta f)$. Among the various representation of the Sound Pressure Level $SPL(f,\Delta f)$, the most frequently used are:

- the Power Spectral Density function for a constant bandwidth (very often $\Delta f=1Hz$ at model scale). The unit of SPL is then dB re 1μPa²/Hz.

$$SPL(f, \Delta f) = 10 log_{10}\left(\frac{\phi_{pp}(f, \Delta f)}{p_{ref}^2}\right) \quad (4)$$

- the Power Spectrum for a constant or proportional bandwidth (1/3 octave band level).

The unit of SPL is then dB re 1μPa². The relation between power spectrum and power spectral density is given by

$$SPL_{\Delta f}\left(f,\Delta f\right)=10log_{10}\left(\frac{\phi_{pp}\left(f,\Delta f\right)}{p_{ref}^{2}}\right)+ \\ +10log_{10}\left(\Delta f\right) \tag{5}$$

So it is required to state clearly what type of SPL representation is used when reporting on propeller noise measurements, for instance by giving the band width Δf in the subscript. The power spectrum in 1/3 octave band level can be given as $SPL_{1/3}$ [dB re 1μPa²].

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.

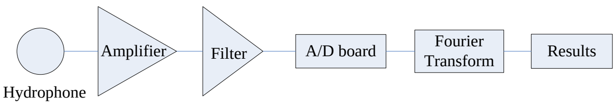

Figure 1: The signal flow chart of an acoustic measurement

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 (Nyquist criteria):

$$f_H \leq \frac{f_s}{2} \tag{6}$$

where f_H is the upper limit of the frequency range and f_S is the sampling frequency. An anti-aliasing filter should be 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.

One of the most common techniques to process the p(t) signal is to use the periodogram technique along with a window function using Welch's method of averaging modified spectrograms. The resulting spectrum is a time-averaged power spectrum or power spectral density. For noise signatures with tonal content, power spectra analysed in very narrow bandwidths (i.e. 0.1 Hz) are common for lower frequencies, whereas for higher frequencies band widths of 1 Hz to 10 Hz are used. These narrowband spectra are strongly recommended as background noise sources can be identified. The presentation of the power spectrum should include the applied averaging time, frequency band width and window function.

2.5.3 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 can be made using the difference ΔSPL between the pressure levels which is defined as

$$\Delta SPL = SPL_{s+n} - SPL_n = 10\ log_{10}\left(\frac{\overline{p}^2_{rms_{s+n}}}{\overline{p}^2_{rms_n}}\right) \tag{7}$$

where SPL_{s+n} is the sound pressure level of the model noise measurement, and SPL_n is the sound pressure level of the associated background noise measurement. If ΔSPL is greater than 10 dB then no adjustments are necessary. On the contrary, if ΔSPL is less than 3 dB then measurements are dominated by background noise and cannot be used. These background dominated noise levels can however be interpreted as an upper limit of the model-scale cavitation noise levels and – if properly indicated - can be presented as such. Finally if 3 dB ≤ ΔSPL <10 dB, adjustment on measurements are required and the following expression can be used:

$$SPL_s = 10\ log_{10}\left[10^{\left(SPL_{s+n}/10\right)} - 10^{\left(SPL_n/10\right)}\right] \tag{8}$$

The background noise corrected spectral levels are required for the presentation of the data.

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).

2.5.4 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 sound pressure level corrected according to spherical spreading loss defines the Radiated Noise Level (RNL):

$$RNL = SPL + 20 \cdot log_{10}\left(\frac{r}{r_{ref}}\right) \tag{9}$$

where r is the distance between the acoustic source and the hydrophone location in meters and r_{ref} the reference distance of 1 m. The centre of the acoustic source for model propellers is usually considered to be at the shaft centre, at 0.7R above the shaft centre or the centre location of the cavity collapse. The RNL is preferably expressed in one-third-octave band levels as dB re $1\mu Pa^2\ m^2$ which can be referred to as $RNL_{1/3}$.

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.

In a cavitation tunnel where the test section is mainly reverberant, it is recommended to take this transfer function into account as pointed out by Briançon et al. (2013) and Tani et al. (2015). This is done at zero flow speed and using a noise source at different locations in the propeller disk to average out the presence of standing waves. The transfer function is an average of the transfer function measured for the different locations, preferably at positions where the largest cavitation extension is expected to occur. In the transfer function measurements, the linearity of the response needs to be checked.

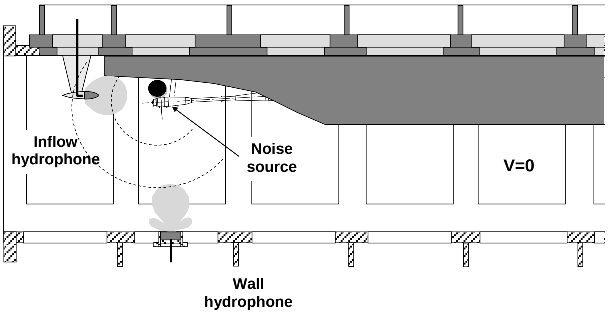

Figure 2: Transfer function measurement set-up in cavitation tunnel

If a transfer function is available, the distance normalisation of the propeller noise measurements (§2.5.4) is not required for it is taken into account in the transfer function. The transfer function G is then computed for each hydrophone using the Sound Pressure Levels of the signal of the noise source and of the signal of the hydrophone receiver:

$$G = SPL_{Source} - SPL_{Hydrophone} \quad (10)$$

SPL_{Source} is specified by knowing the voltage (or current) applied to the known source and the source's transmitting response function (TVR).

In free-field conditions, the transfer function would be:

$$G = 20 \cdot log_{10}\left(\frac{r}{r_{ref}}\right) \quad (11)$$

The transfer function is used to compute the propeller source strength levels SL from the measured (and background noise corrected) SPL in the cavitation noise measurements:

$$SL = SPL + G \quad (12)$$

The SL is preferably expressed in one-third-octave band levels as $SL_{1/3}$ [dB re $1\mu Pa^2\, m^2$].

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

$$N = \frac{\pi f^3 V}{c_0^3} \quad (13)$$

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 frequency limit below which the noise field is influenced by separate modes instead of statistical properties. The frequency is given by

$$f = \sqrt{\frac{c_0^3 T_{60}}{4V \ln 10}}\ \text{Hz} \quad (14)$$

with T_{60} the reverberation decay time which is the time interval for noise levels to decay by 60 dB. This frequency limit is generally of the order of a few kHz in cavitation tunnels.

For facilities with a free surface, the influence of this free surface on the reverberation and the noise measurements should also be assessed and, if necessary, corrected for with an acoustic calibration test, see for instance Lafeber *et al.* (2015). In general, the free surface gives a reduction of the measured noise levels at low frequencies where the influence increases with decreasing frequency (Lloyd mirror effect).

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. The relation between air content (usually expressed as percentage saturation rate) and nuclei is dependent on the facility (23rd ITTC specialist committee on Water Quality and Cavitation).

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.

In the case of water tunnels where the nuclei content is monitored by measuring the air content, the air content is between 30% and 70% of the saturation rate at atmospheric pressure.

In water tunnels where the nuclei content is monitored independently of the air content, the air content is of the order of 30% of the saturation rate at atmospheric pressure. Cavitation on the model propeller blade is sometimes stabilized by applying (sand grain) roughness on the leading edge but care has to be taken that the grain size depends on Reynolds number to minimize the change in cavitation inception speed (21st Report of the ITTC Propulsor Committee, 1996). In a towing tank electrolysis can be applied to supply nuclei. In that case, the air content is of the order of 30% of the gas content at atmospheric pressure saturation.

We should notice that too high levels of air content may create tiny air bubbles in great quantities, deteriorate the visibility inside the tunnel and introduce a damping effect on the measured high-frequency underwater sound pressure levels. Also, the assessment of the transfer function realized at zero speed might not be representative of the sound propagation at high air content, especially in the high frequency range.

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 measurements 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. If the propeller operating conditions are based on the K_T and σ with the reference flow speed as the rotational speed and if the ship wake is well simulated, then the blockage effect is not anymore an issue.

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 1985, Tani et al. 2016, 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 measured full-scale noise levels as well, especially due to the propagation loss. Also the full-scale noise levels can be influenced by other noise sources than cavitation such as machinery equipment.

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 frequency scaling between model scale and full scale is given by :

$$\frac{f_s}{f_m} = \frac{n_s}{n_m} \cdot \sqrt{\frac{\sigma_s}{\sigma_m}} \tag{15}$$

and the increase in Sound Pressure Levels from model to full scale is given by:

$$\Delta SPL = 20\log_{10}\left[\left(\frac{\sigma_s}{\sigma_m}\right)^w \left(\frac{r_m}{r_s}\right)^x \left(\frac{n_s D_s}{n_m D_m}\right)^y \left(\frac{D_s}{D_m}\right)^z\right] \tag{16}$$

In the above, the subscripts *s* and *m* refer to full scale and model scale, respectively. The cavitation number uses *nD* as reference speed.

In general, two sets of parameters (w, x, y, z) can be distinguished that depend on the variation of the acoustic efficiency. Levkovskii (1968) has derived a noise scaling formula in which the acoustic efficiency is a constant that is assumed to be valid for high frequencies. If the acoustic efficiency varies linearly with Mach number the scaling relation as presented by Strasberg (1977) and e.g. Bark (1985) is obtained. This formulation can also be derived from the (incompressible) Rayleigh-Plesset equation and is therefore assumed to be valid for low frequencies. Unfortunately, no information is available for the specific frequency range of both models.

The exponents for equation (16) are given in Table 3.1 for proportional bandwidth (power spectrum) and Table 3.2 for constant bandwidth (power spectrum or power density spectrum).

Table 3.1: Exponents for noise scaling valid for proportional bandwidth

formulation	w	x	y	z
’high frequency’	0.5	1.0	1.5	1.0
‘low frequency’	1.0	1.0	2.0	1.0

Table 3.2: Exponents for noise scaling valid for constant bandwidth

formulation	w	x	y	z
'high frequency'	0.25	1.0	1.0	1.5
'low frequency'	0.75	1.0	1.5	1.5

Both formulations are in use in the ITTC community with the majority using the 'low frequency' formulation as shown in the results of the questionnaire presented by the Specialist committee on Hydrodynamic Noise of the 27th ITTC (2014). Some members use slightly different values than given above.

The scaling formula should only be applied to the background noise corrected cavitation noise spectrum. The scaling should not be applied for frequency ranges where the background noise is higher than the radiated noise, Figure 3.

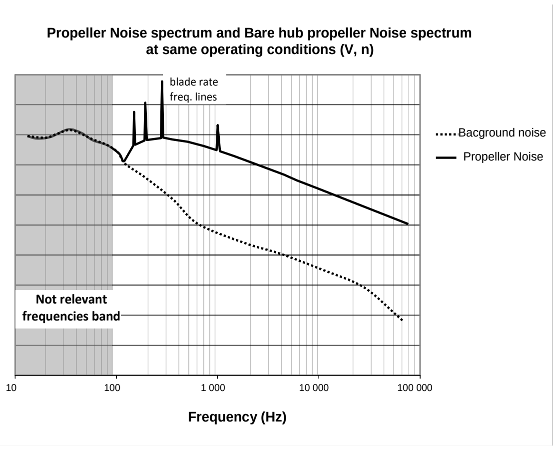

Figure 3: Relevant frequency range for scaling

3.2 Scaling Method of the spectrum tonal frequencies

Although, the scaling method is generally applied to the whole spectrum, it is recommended to analyse the peak levels at the harmonic frequencies of the blade rate frequency with care. It is noted that the low-frequency noise scaling formulation in proportional band width is consistent with the scaling of hull pressure tonals at the blade passage frequency and its harmonics (Bark, 1985). This indicates that the formulation for proportional band width has a correct scaling of tonal noise components. However, the noise at the blade passage frequency also contains a contribution from the non-cavitating blade that is of dipole nature. The model scale measurements should therefore be made in the acoustic far field. In addition, the facility noise transfer function should be taken into account due to the low frequencies of these tonals.

In conclusion, it is recommended to also consider the blade passage frequencies when presenting cavitation noise in proportional (1/3 octave) band levels and to be careful with presenting scaled tonals in narrowband data. More research and validation studies are required on this topic.

3.3 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 cavitation inception number using some form of the equation presented by McCormick (1962):

$$\frac{\sigma_{i,s}}{\sigma_{i,m}} = \left(\frac{Re_s}{Re_m}\right)^n \quad (17)$$

The Reynolds number exponent n 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 n that depends on Reynolds number.

For the noise measurements of an (isolated) cavitating tip vortex the cavitation number may need to be reduced in the model tests to take the delay in cavitation inception (σ_i) into account. A theoretical analysis by Baiter (1989) suggests that the model scale cavitation number should be set at identical value of $\sqrt{\sigma_i - \sigma}/\sigma_i$ when the cavitation number is just below inception with alternative formulations given in Blake (1986). For a fully developed cavity (where the cavity size is somewhat larger than the viscous core size) the cavity size appears to be not so much influenced anymore by the Reynolds number, Bosschers (2009), suggesting that cavitation number identity can again be used. More research and validation studies are required on this topic.

It is recommended to determine if at full scale vortex cavitation is present for the operating conditions of the propeller. For that purpose, the propeller operating conditions have to be located in the cavitation inception map (σ, K_T) of the model-scale and full-scale propeller as described in ITTC procedure 7.5-02-03-03.1. It is remarked that the cavitation number at model scale can only be reduced for isolated vortex cavitation, figure 4, and it should not lead to the appearance of other cavitation patterns such as sheet or bubble cavitation that typically generate more noise than vortex cavitation. For situations where for instance sheet cavitation occurs before vortex cavitation at model scale, figure 5, there is a speed regime of which the cavitation pattern cannot be reproduced at model scale.

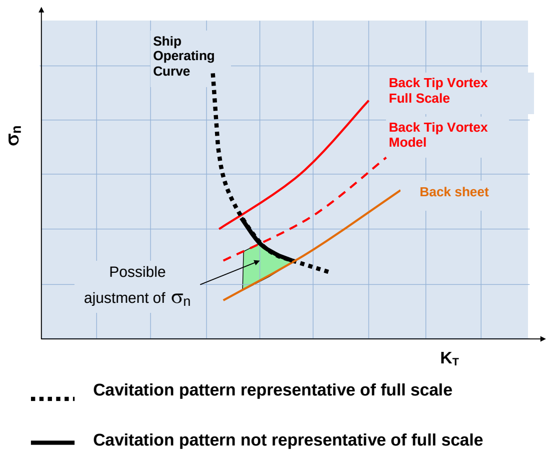

Figure 4: Cavitation inception diagram with isolated vortex cavitation at model scale.

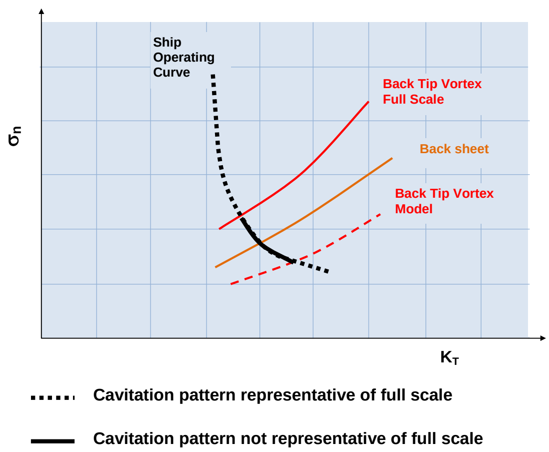

Figure 5: Cavitation inception diagram with no isolated vortex cavitation at model scale

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 "recommended data" (section 2.3). 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.

The checklist of parameters and their derived parameters is presented in Table 4.2. The table also includes the definition of SPL, RNL and SL.

The recommended values for some parameters are given in Table 4.3.

5. UNCERTAINTY AND VALIDATION

5.1 Sources of uncertainty and variability

Usually the main sources of uncertainty in 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 uncertainties difficult to quantify. It is noted that while the terms variability, repeatability, and error are used somewhat synonymously, they can mean different aspects of results in a final level of uncertainty. It is further noted, but not expanded upon, that in uncertainty analysis a distinction is made between Type A uncertainty, which is uncertainty evaluated by statistical analysis of a series of observations and Type B uncertainty which is evaluated by non-statistical methods (ITTC procedure 7.5-02-01-01).

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

- Uncertainty in the velocity distribution of the ship wake field. The uncertainty arises due to differences in Reynolds number and the method of wake generation in the test.
- Uncertainty in the specification of the loading condition (cavitation number and advance coefficient or mean thrust coefficient). The source of this uncertainty is the propulsion test or an equivalent for the determination of the loading condition.
- Uncertainty in simulating the correct cavitation extents and dynamics due to influence of differences in wake field, cavitation inception and gas content. Differences in cavitation inception may be caused by the nuclei content or, in case of vortex cavitation, difference in Reynolds number. The application or non-application of surface roughness to stimulate cavitation inception also should be taken into account in the uncertainty of cavitation extents. The cavitation extents and dynamics should be reported using sketches, photographs or video recordings.
- Uncertainty in obtaining the correct background noise level of the propeller test due to change of facility pressure or change of

bearing loading by replacing the propeller by a bare hub.

- Uncertainties in the scaling formula for cavitation noise. Two formulations are available giving slightly different results.
- Uncertainties in the transfer function to convert the measured noise level in the cavitation test facility to source levels.

The most critical aspects of the cavitation noise measurements are the ship wake generation and the cavitation dynamics. Both depend on the type of ship and cavitation on the propeller and the error may therefore vary between projects. It is therefore important to critically review the potential uncertainties for each project separately. At low frequencies, the noise transfer function of the facility can significantly influence the source levels and can therefore also become a critical aspect.

An engineering way to handle the hydrodynamically based uncertainties 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 uncertainties 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.
- sources of uncertainty considered.
- actual data uncertainty estimates.

The uncertainty analysis should be done in accordance with the ISO documents on uncertainty analysis, ISO (1992), ISO (1993a) and ISO (1993b) and ITTC procedure 7.5–02–01–01

From the questionnaire launched during the 28th ITTC, the primary sources of uncertainties are the instability of cavitation (especially if operating conditions are close to inception point), the noise scaling and the wake field. It is reported that the current uncertainty levels are estimated to be 3 to 5 dB, which includes the contribution of the uncertainty for the model scale noise levels and of the uncertainty for noise scaling.

5.3 Benchmark Tests

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

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

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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/oxygen content as % saturation rate	• Tensile strength of the water • Nuclei size distribution
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 and data analysis procedure • Bare hub background noise or background noise without cavitation compared to sound pressure levels with cavitation • Underwater sound source levels (corrected for background noise and scale effects) ▪ 1/3 octave band ▪ Source levels / Radiated Noise Levels	• Vibration characteristics of ship hull, propeller shaft and facility • Cavitation observations • Narrowband received sound pressure levels • Facility transfer function

Table 4.2: Checklist of parameters

Basic measured data		**Derived parameters**	
Representative static pressure at reference point (shaft, 0.7-0.9R) [Pa]	$p_{static,ref}$	Cavitation number	$\sigma = \frac{p_{static,ref} - p_V}{\frac{1}{2}\rho V_{ref}^2}$, $V_{ref} = V_A,\ nD, \pi nD$
Propeller rotational speed [rps]	n		
Propeller thrust [N]	T	Thrust coefficient	$K_T = \frac{T}{\rho\ n^2 D^4}$
Propeller torque [Nm]	Q	Torque coefficient	$K_Q = \frac{Q}{\rho\ n^2 D^5}$
Facility speed [m/s]	V_{fac}	Apparent advance coefficient	$J_A = \frac{V_{fac}}{n D}$
Water temperature [° C]	t	Vapor pressure	p_V
Sound pressure	p	Sound Pressure Level SPL	SPL $[dB\ re\ 1\mu Pa^2]$ / $[dB\ re\ 1\mu Pa^2/Hz]$
Distance hydrophone to acoustic centre	r	Underwater Radiated Noise level RNL	$RNL = SPL + 20 \cdot log_{10}\left(\frac{r}{r_{ref}}\right)$ $[dB\ re\ 1\mu Pa^2 m^2]$ $r_{ref} = 1m$
Facility Transfer function	G	Underwater radiated Source Level SL	$SL = SPL + G$ $[dB\ re\ 1\mu Pa^2 m^2]$
Air Content [mg/L]			
Oxygen Content [%]	O_2		

Table 4.3: Recommendations for Parameters

Parameter	**Recommended values**	**COMMENTS / CITATION WHERE RECOMMENDED**
Pressure adjustment (cavitation number)	0.7 ~ 0.9 *R, top dead centre* Use of rotational speed and propeller diameter as the reference velocity for cavitation number	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. ITTC 2002 Water Quality and Cavitation
Background noise of the facility and driving train	>10 dB below cavitation noise level	
Model propeller diameter	> 200 mm	ITTC 2002 Pressure Fluct. Com.