ITTC Quality System Manual

Recommended Procedures and Guidelines

Guideline

Model-Scale Propeller Cavitation Noise Measurements

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Model-Scale Propeller Cavitation 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 level 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 acoustic source strength of the propeller for non-cavitating flow are not described by this guideline.

Note that in 2020 the identification number of the ITTC guideline on Model-Scale Propeller Cavitation Noise Measurement has changed from 7.5-02-01-05 to 7.5-02-03-03.9.

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 levels for the far field underwater radiated noise.

Additional information on noise measurements can be found in the ITTC Proceedings and final reports by the 27th, 28th and 29th Specialist Committee on Hydrodynamic Noise (2014, 2017, 2020). The 2014 and 2017 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 high Reynolds number is beneficial in achieving turbulent flow on hull and propeller, and for the inception of cavitation. The accuracy of the propeller geometry should be according to ITTC procedure 7.5-01-02-02:2005 which specifies that the offsets of the blade sections should be in the range ± 0.05 mm with the typical propeller diameter used for cavitation tests in the range between 180 and 300 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 within 0.5% of the 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 applying 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 at full-scale which is further discussed in Section 2.2.2. The most important scaling parameter is the Reynolds number which determines the thickness of the boundary layer and the formation 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 should be noted 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 borescopes are used for cavitation observation, they should not influence the propeller inflow. The recommended value for 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 field 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. Attention should be paid to vortex formation at the bossing where the shaft protrudes the hull as this vortex may enter the propeller plane

For all cases it is recommended to include the (stern) appendages, i.e. rudder and struts, if present, 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 is 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 in excess of that 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 the 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 (T) or torque (Q) 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 $K_Q = Q/(\rho n^2 D^5)$ where ρ is the fluid density.

Usual practice in a 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, p_v is the vapour pressure 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. This point is usually 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 for cases with e.g. high shaft inclination where the maximum cavitation extent is occurring at 90 or 270 deg. 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 cavitation tests and especially for dummy hull type testing configurations.

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.

If the noise is dominated by tip-vortex cavitation, reduction of the cavitation number may be applied to correct for the Reynolds number scale effect on the inception of vortex cavitation. Such a reduction of the cavitation number is required if the vortex does not cavitate in the model test whereas, for example based on a cavitation inception test, a cavitating vortex is expected at full scale. This topic is further discussed in Section 3.3.

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. The recommended technique is based on defocused imaging due to its non-intrusive and adaptability advantages (see the report of the 29th ITTC Specialist Committee on Hydrodynamic Noise, 2020), but other techniques (as shadowgraphy, cavitation susceptibility meter, Phase Doppler Anemometry) can also be used if available.

Sound Pressure Measurements

Parameters that are ‘required’ to be measured include:

- time series or narrow band spectra of the underwater sound pressure;
- cavitation observations.

The category of ‘recommended’ includes

- video observations showing the dynamic behaviour of the cavitation;
- 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.

To get quantitative information on the uncertainty of the measurements it is recommended to investigate the change in noise levels for small variations in thrust coefficient (typically 5%) and cavitation number (typically 10%).

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.
- The acoustic transfer function of the facility should be determined if it is considered to significantly affect the noise measurements, see Section 2.6.

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. - should be determined. This 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 vibration of the wall or hull to the noise measurements needs 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 Data Acquisition and Processing

2.5.1 Measured quantity and presentation

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

$$\bar{p}_{rms} = \sqrt{\frac{1}{T}\int_0^T p(t)^2 dt} \tag{2.1}$$

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[1]:

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

where p_{ref} is the reference pressure, typically chosen as 1 µPa for water.

Noise is usually represented by a spectrum calculated from the sound pressure signal of a hydrophone *p(t)*. 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 $\phi_{pp}(f, \Delta f)$, for a given centre frequency f and for a frequency bandwidth Δf, i.e. defined for $\left[f - \frac{\Delta f}{2}; f + \frac{\Delta f}{2}\right]$. Among the various representations of the Sound Pressure Level *SPL(f,Δf)*, the most frequently used are:

- the Sound Pressure spectral density Level The unit of SPL is then dB re 1µPa²/Hz.

$$SPL(f, \Delta f) = 10 \cdot log_{10}\left(\frac{\phi_{pp}(f,\Delta f)}{p_{ref}^2}\right) \tag{2.3}$$

- the Sound Pressure power spectrum Level 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

$$SPL_{\Delta f}(f, \Delta f) = 10 \cdot log_{10}\left(\frac{\phi_{pp}(f,\Delta f)}{p_{ref}^2}\right) + 10 \cdot log_{10}(\Delta f) \tag{2.4}$$

It is then 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 1 shows a signal flow chart to illustrate the elements in a simple noise measurement.

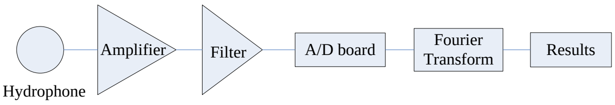

Figure 1: The signal flow chart of an acoustic measurement

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):

$$f_H \leq \frac{f_s}{2} \tag{2.5}$$

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[1] Note that ISO standard 18405 :2017 on Acoustic Terminology uses the symbol L_p to denote SPL in equations. In this document, acronyms were kept in equations for ease of reading. The ISO symbols are given in Table 4.2.

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. An acquisition period of greater than 20 seconds is recommended 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 (Welch, 1967). 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 if background noise sources need to 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 may include 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

$$\Delta SPL = SPL_{s+n} - SPL_n = 10\ log_{10}\left(\frac{\bar{p}^2_{rms_{s+n}}}{\bar{p}^2_{rms_n}}\right) \qquad (2.6)$$

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:

$$SPL_s = 10\ log_{10}\left[10^{\left(SPL_{s+n}/_{10}\right)} - 10^{\left(SPL_n/_{10}\right)}\right] \qquad (2.7)$$

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

If the noise measurements contain contributions due to, for example, 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 & Piersol, 2011).

2.5.4 Distance normalisation

As the measured noise levels heavily depend on 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):

$$RNL = SPL + 20 \cdot log_{10}\left(\frac{r}{r_{ref}}\right) \qquad (2.8)$$

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 correction term is the propagation loss by spherical spreading, N_{sph}.

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 location of the acoustic centre should be given. The RNL of cavitation noise 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$_{1/3}$.

2.6 Acoustic Transfer Function of Facility

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 interference between pressure waves which depend on wave length (and therefore frequency) and lead to acoustic modes in the test section at low frequencies (see e.g. Boucheron *et al.*, 2017). The frequency range of this effect depends on the size of the test-section and is larger for the smaller size cavitation tunnels, but the effect is clearly visible for larger size facilities at low frequencies also.

The effect of the reflections (or reverberation) can be determined through acoustic transfer function measurements using e.g. a sound source with known characteristics put at specific relevant locations in the test section, see Figure 2.

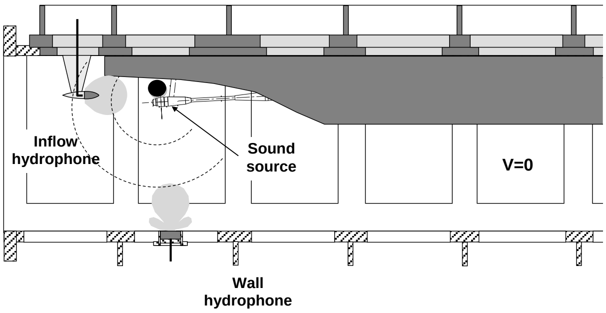

Figure 2: Transfer function measurement set-up in cavitation tunnel

The theoretical model on which such procedure is based is quite simple, as reported in Figure 3 (Tani *et al.*, 2016). The target system is schematized as a single input – single output system, for which the output (in our case the hydrophone measurement) is a deterministic function of the input (the propeller noise in cavitation tests, or the noise emitted by the transducer in calibration tests).

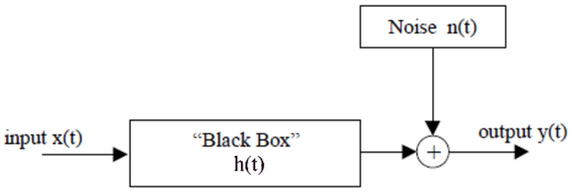

Figure 3: Scheme of input/output system (Tani *et al.*, 2016b).

Under the hypotheses of linearity and time-invariance, the output $y(t)$ of the system may be obtained by means of the convolution between the input signal $x(t)$ and the impulse response of the system $h(t)$ plus the noise $n(t)$:

$$y(t) = x(t) \otimes h(t) + n(t) \tag{2.9}$$

Considering only the steady response of the system and avoiding inclusion of information on the phase at different frequencies, the Transfer

Function may be evaluated as the ratio between the power spectral densities of the output and input signals, which leads, in logarithmic representation, to the following equation:

$$TF = SPL_y - SL_x \tag{2.10}$$

The input and output signals in the specific case are represented by the signal emitted by the source, defined as source level[2], and the sound pressure level perceived by the hydrophone, respectively. As an alternative, the power spectrum of the impulse response $h(t)$ may be used. The determination of the source level SL_x requires special attention. Often is determined from the applied voltage and the Transmitting Voltage Response (TVR[3]) of the acoustic source. The unit of TF is dB re 1m^2.

The transfer function is used to obtain the Source Strength Level (SL) from the net noise level SPL_s, previously evaluated considering the total noise level and the background noise level:

$$SL = SPL_s - TF \tag{2.11}$$

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

If a transfer function is available, the distance normalisation of the propeller noise measurements (Section 2.5.4) is not required for it is accounted for in the transfer function.

Note that in free-field conditions, the transfer function equals:

$$TF = -20 \cdot log_{10}\left(\frac{r}{r_{ref}}\right) \tag{2.12}$$

Examples of measuring the transfer function of Equation (11) can be found in Briancon *et al.* (2013), Lafeber *et al.* (2015), and Park *et al.* (2016), while Tani *et al.* (2016a,b) and Tani *et al.* (2019) make use of the impulse response. Some specific points of attention are discussed next.

2.6.1 Characterisation of transmitting chain, including TVR

The basis of the procedure is the availability of a suitable transducer. Normally, the emitting characteristics of the transducer are provided by manufacturers[4] for open field conditions. However, these TVR data may cover a frequency range smaller than required and dedicated tests might be necessary, for instance to extend the TVR to lower frequencies. As an alternative, the TVR may be extrapolated (e.g. if too low SNR is present). The TVR of the transducer should be checked on a regular basis.

2.6.2 Type of sound projector

The type of transducer may affect the transfer function; particularly important characteris-

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[2] The source level is defined as the sound pressure level at a distance of 1 m from the source placed in a infinite uniform lossless medium (ISO18405:2017).

[3] The TVR is defined as the output sound pressure level at 1 m from the sound source per 1V input voltage as function of frequency.

[4] It is worth mentioning that sources are calibrated for free field conditions. In a closed environment the source creates an acoustic field which affects in return the behaviour of the source itself. This effect is likely to be small, but this has not been investigated.

tics of the transducer are its dimensions, directivity and linearity[5]. Smaller transducers are preferred, with the aim of adopting not too large dimensions compared to the cavitation extent on the propeller; this requirement may be problematic at lower frequencies, for which larger transducers are needed in order to maintain a sufficient SNR.

The transducer adopted should be as omnidirectional as possible; as an example, piston type transducers could be problematic, especially when facility dimensions are limited. The directionality of the piston type transducer is related to the ratio of piston size and wave length.

Finally, the linearity of the transducer response to the input signal should be checked by means of repeat tests at different input voltages.

2.6.3 Type of signal

The signals used to drive the transducer can be pure tones, white or pink noise, chirps, sweeps, or maximum length sequences (MLS). Wideband signals are definitely preferred to pure tones, since a wider frequency range band is covered by a single measurement, reducing time demand. Tones allow to obtain a higher SNR.

In the twin screw ship case requiring two sound sources, a non-deterministic signal, such as white noise, is preferred in order to obtain more accurate results (Park *et al.*, 2018). In all cases, it is recommended to use signals allowing to obtain a SNR higher than 10 dB.

2.6.4 Position of projector

The transducer position is important since it affects the transfer function. It is normally near the position of the main noise source, i.e. where the collapse of cavitation occurs; for single screw ships this is usually in proximity of the propeller tip at top dead centre.

Generally, cavitation is not present at a unique position and characteristics of the transfer function may vary with position, the transfer function should be obtained from the average of measurements for multiple transducer positions (Briancon *et al.*, 2013; Tani *et al.*, 2019). This averaging also has the advantage of smoothening the transfer function which otherwise may present rather large humps and hollows. As an indication, 5-10 positions should be adopted if the whole propeller disc is considered. In case a smaller angular range is of interest, the number of measurements could be reduced. It is recommended to adopt at least 3 positions, in order to check the variability of the transfer function and the necessity of additional measurements.

2.6.5 Testing conditions, including air content

Transfer functions are normally measured with water at rest and without depressurizing the facility. These conditions differ from cavitation tests, in which also traveling (cavitation) bubbles may influence the noise transmission. The influence of such effects is not well known and should be further investigated in order to develop dedicated procedures. Blake & Sevik

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[5] Note that the transducer also has a certain response time with respect to the input signal. This is a second order effect, which could affect initial transients when performing measurements.

(1982) proposed acoustic monitoring approaches to cope with this problem, but the influence of such effects is still not well known and should be further investigated in order to develop dedicated procedures.

2.6.6 Free surface effects

A free surface, if present, also affects reverberation and the effect on the noise measurements should 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).

2.6.7 Further general considerations

The procedure for measuring the Transfer Function makes use of deterministic signals and fixed sound source locations. However, cavitation noise at high frequencies is better approximated by a distribution of uncorrelated sources, thus being a random process. Therefore, some of the wavy patterns in the transfer function are not observed in propeller noise spectra and smoothening of the transfer function should be applied as discussed above.

An order of magnitude of the frequency limit for diffusivity in the facility should be determined when performing noise measurements. The so-called Schroeder cut-off frequency represents this limit between the frequency domain influenced mainly by the acoustic modes of the facility and between the diffuse domain where statistical properties of the acoustic field holds.

For an acoustic measurement in a tank, this Schroeder frequency, given in Kuttruff (2009), should be computed with

$$f = \sqrt{\frac{c_0^3 T_{60}}{4\,V \ln 10}}\ \text{Hz} \qquad (2.13)$$

with T_{60} the reverberation decay time which is the time interval for noise levels to decay by 60 dB, V the volume of the tank and c_0 the water celerity.

In particular, for cavitation tunnel applications the noise field is dominated by the early reflections by the nearby test-section walls and the volume of the test-section or tunnel is less relevant. A formulation for this cut-off frequency of a test-section of infinite length, with source and hydrophone located in the test-section, has been derived by Boucheron (2019):

$$f = \alpha\ \frac{EDT\ c_0^2}{S}\ \text{Hz}, \qquad (2.14)$$

with *EDT* the Early Decay Time (the time required for the noise level to decay by 60 dB from the initial level, usually obtained from a 10 dB decay in the measurements) measured in the test section of area *S*. Parameter α is a constant depending on the test section shape and equals 0.272 for rectangular test section and 0.651 for a circular one. This frequency limit is generally of the order of a few kHz in cavitation tunnels.

Generally, it is found that the problem of reverberation in test facilities should be further investigated in order to enhance transfer function measurement procedures and define suitable post-processing techniques.

2.7 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.

2.7.1 Air contents, cavitation nuclei and cavitation stabilization

It is generally accepted that testing at relatively high air content, implying a larger population 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.

Whereas the dissolved gas content (or dissolved oxygen content) can easily be measured, the measurement of the nuclei concentration is much more complicated. A short review on this topic is provided in the Report of the 29th Specialist Committee on Hydrodynamic Noise (2020). 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, 2002).

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 typically between 30% and 70% of the saturation rate at atmospheric pressure. Alternatively, 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. 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.

Cavitation on the model propeller blade is sometimes stabilized by applying (sand grain) roughness on the leading edge. However, 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).

As already mentioned, excessive levels of air content may create tiny air bubbles in great quantities, deteriorating the visibility inside the tunnel and introducing a damping effect on the measured high-frequency sound pressure levels. Also, the assessment of the transfer function realized at zero speed and atmospheric pressure might not be representative of the sound propagation at high air content, especially in the high frequency range.

2.7.2 Influence of blockage

Blockage will affect the flow field in the tunnel and the interference among the propeller, hull and 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, as yet, been accurately 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 tunnels, 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 no longer an issue.

3. SCALING METHODS

3.1 General 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 & 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 noise sources other 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

$$\frac{f_s}{f_m} = \frac{n_s}{n_m} \cdot \sqrt{\frac{\sigma_s}{\sigma_m}} \tag{3.1}$$

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

$$\Delta SPL = 20\,log_{10}\left[\left(\frac{\sigma_s}{\sigma_m}\right)^w \left(\frac{r_m}{r_s}\right)^x \left(\frac{n_s D_s}{n_m D_m}\right)^y \left(\frac{D_s}{D_m}\right)^z\right] \tag{3.2}$$

In the above, the subscripts *s* and *m* refer to full-scale and model-scale, respectively. The cavitation number uses *nD* as the 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. Alternatively, 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 (3.2) are given in Table 1 for proportional bandwidth (power spectrum) and Table 2 for constant bandwidth (power spectrum or power density spectrum).

Table 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 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, see Figure 4.

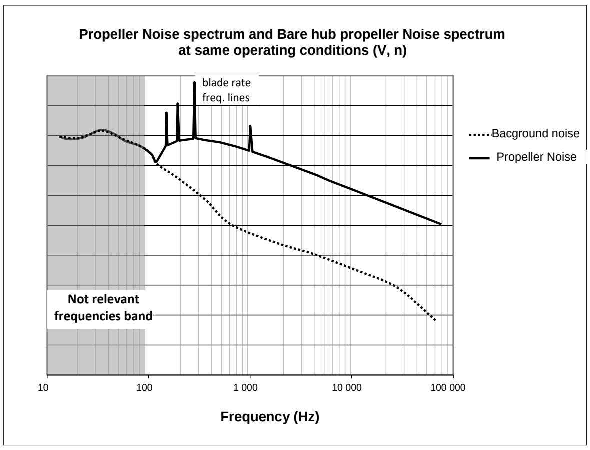

Figure 4: Relevant frequency range for scaling

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.

Moreover, the Doppler effect due to the rotating noise source disturbs the spectrum. It appears when a static hydrophone is measuring the noise from a moving source. This affects mainly the different tonals associated to the blade passage frequency. Artificial peaks appear on each side of the tonals frequency f_{tonals} at frequencies $f_{tonals} \pm n\ f_{rot}$. Their magnitudes are generally lower than the main peak at f_{tonals}, with the difference depending on the geometrical configuration, see for example, Boucheron (2016). This could produce some error in estimating the real level. Comparison between different hydrophones could be a suitable way to discriminate this effect.

3.3 Scaling Method of Tip Vortex Cavitation

In order to accurately predict the radiated noise of a propeller, it is important that the cavitation extents and dynamics in the model-scale test are similar to those at full-scale. This requires the correct wake field, propeller loading, and cavitation number as discussed in Section 2. For tip vortex cavitation an additional scale effect should be considered that is related to the Reynolds number.

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

$$\frac{\sigma_{i,s}}{\sigma_{i,m}} = \left(\frac{Re_s}{Re_m}\right)^n \qquad (3.3)$$

in which subscript s corresponds to full-scale, subscript m corresponds to model-scale, and Re corresponds to the Reynolds number of the propeller. The 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.

In a model test the inception of vortex cavitation is delayed due to the lower Reynolds number. If the model test does not show a vortex cavity, it is strongly recommended to perform a cavitation inception test (see also ITTC procedure 7.5-02-03-03.1), to check if vortex cavitation will occur on the propeller at full-scale.

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 Bosschers (2018) has shown that similar vortex cavity diameters are obtained near inception when the model scale cavitation number is set such that the ratio $\sqrt{\sigma_i - \sigma}/\sigma_i$ at model-scale is identical to full-scale. Whereas, for a fully developed cavitating vortex the effect of the Reynolds number on vortex cavity size becomes small and the cavitation number in the model test can be selected identical to full-scale. Formulations to prescribe the cavitation number for conditions in between these two limiting conditions are also given.

Scaling methods for the radiated noise of vortex cavitation accounting for differences in cavitation number between model test and full-scale have been proposed by Park & Seong (2017) and Bosschers (2018). Both methods show an improvement of the model test predictions of full-scale noise levels. Further research and validation studies are required to develop an established procedure for this scale effect.

Note that the cavitation number at model-scale can only be reduced for isolated vortex cavitation, see Figure 5, 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, see Figure 6, there is a speed regime in which the cavitation pattern cannot be reproduced at model-scale.

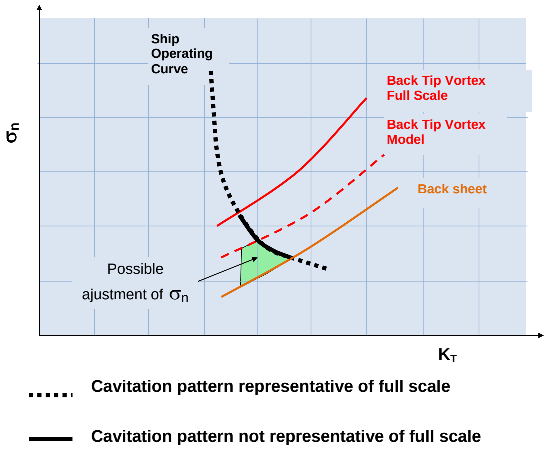

Figure 5: Cavitation inception diagram with isolated vortex cavitation at model-scale.

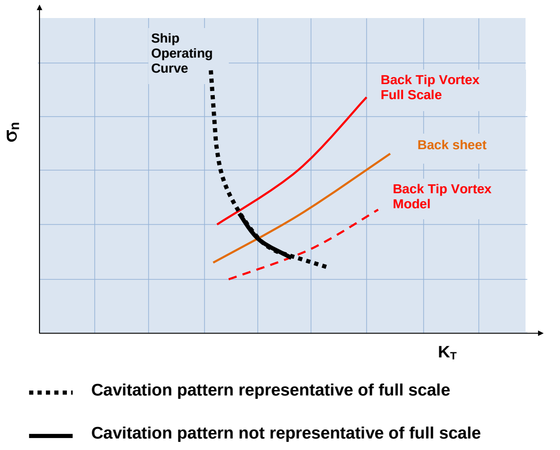

Figure 6: Cavitation inception diagram with no isolated vortex cavitation at model-scale

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 be considerably improved. The review of parameters is given in Table 3.

The checklist of parameters and their derived parameters is presented in Table 4. The table also includes the definition of SPL, RNL and SL.

The recommended values for some parameters are given in Table 5.

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 which are 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 are required 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 of uncertainties related to hydrodynamics and hydroacoustics 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 and published scaling formula for tip-vortex cavitation require further validation.
- 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 propeller rotation rates.

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/JCGM Guide to the expression of Uncertainty in Measurements (GUM) JCGM100:2008, JCGM 104:2009 (Introduction to GUM), JCGM200:2012 (International vocabulary of metrology – basic and general concepts and associated terms (VIM)), and ITTC procedure 7.5–02–01–01, Guide to the expression of uncertainty in experimental hydrodynamics.

It is remarked that for a given uncertainty in decibels a distinction should be made for the uncertainty in percentage for the upper bound and for the lower bound, but for small values of uncertainty this difference is negligible. The combined uncertainty L_{Uc} in decibels from uncorrelated sources L_{Ui} in decibels can be computed according to

$$L_{Uc} = \sqrt{\Sigma L_{Ui}^2} \qquad (5.1)$$

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 ship wake field, and the noise scaling. The uncertainty levels for the model-scale test results were estimated as 3 to 5 dB, and the uncertainty levels for the noise scaling procedure were also estimated as 3 to 5 dB[6]. This results into a combined uncertainty of the full-scale noise prediction of 4.2 to 7.1 db.

5.3 Benchmark Tests

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

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

More recently, a round robin test has been performed with a propeller in uniform inflow, of which the geometry is publicly available:

1. Tani, G., Viviani, M., *et al.* Round Robin test on radiated noise of a cavitating propeller. Sixth International Symposium on Marine Propellers, Rome, Italy, 2019

Candidates for benchmark tests of a propeller operating in a ship wake field are proposed in the Report of the Specialist Committee on Hydrodynamic Noise of 29th ITTC, 2020.

The comparison between data of full-scale noise measurements and data of extrapolated model-scale cavitation noise measurements should preferably be performed using source levels for both datasets. This in order to exclude the effect of propagation which is notably different for the two measurements.

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[6] These numbers are average values of the estimates as given by the respondents of the questionnaire and were not based on actual measurements. They may therefore be interpreted as expanded uncertainties for 95% confidence level.

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Table 3: 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	• Facility Transfer functions if source level is to be determined • Measuring period and data analysis procedure • Bare hub background noise or background noise without cavitation compared to noise levels with cavitation • Underwater source (or radiated noise) levels in 1/3 octave bands (corrected for background noise, facility transfer function, and scale effects) • Cavitation observations	• Vibration characteristics of ship hull, propeller shaft and facility • Narrowband received sound pressure levels • High speed video observations of cavitation dynamics • Inception test of vortex cavitation

Table 4: Checklist of parameters

Basic measured data		**Derived parameters**		
	Symbol, unit		Symbol[7] and unit	Relation
Representative static pressure at reference point (shaft, 0.7-0.9R)	$p_{static,ref}$ [Pa]	Cavitation number	σ [-]	$\sigma = \frac{p_{static,ref} - p_V}{\frac{1}{2}\rho V_{ref}^2}$ $V_{ref} = V_A, nD, \pi nD$
Propeller rotational speed	n [rps]			
Propeller thrust	T [N]	Thrust coefficient	K_T [-]	$K_T = \frac{T}{\rho n^2 D^4}$
Propeller torque	Q [Nm]	Torque coefficient	K_Q [-]	$K_Q = \frac{Q}{\rho n^2 D^5}$
Facility speed	V_{fac} [m/s]	Apparent advance coefficient	J_A [-]	$J_A = \frac{V_{fac}}{n\, D}$
Water temperature	T [° C]	Vapor pressure	pv [Pa]	
Sound pressure	p_{rms} [Pa]	Sound Pressure (spectral density) Level, SPL	$L_{p,f}$ [dB re 1μPa^2 /Hz]	$L_{p,f} =$ $10\log_{10} \frac{p_{rms}^2(f,\Delta f)}{p_{ref}^2\, \Delta f}$ p_r 1 μPa
		Sound Pressure (power spectrum) Level, SPL	L_p [dB re 1μPa^2]	L_p $= 10\log_{10} \frac{p_{rms}^2(f,\Delta f}{p_{ref}^2}$
		Radiated Noise Level, RNL	L_{RN} [dB re 1μPa^{2}m^2	$L_{RN} = L_p + N_{sph}$
		Source Level, SL	L_S [dB re 1μPa^{2}m^2	$L_S = L_p - TF$
Distance hydrophone to acoustic centre	r [m]	Propagation loss by spherical spreading	N_{sph} [dB re 1m^2]	$N_{sph} =$ $10\log_{10}\left(\frac{r^2}{r_{ref}^2}\right)$ $r_{ref} = 1$ m
Facility Transfer function	TF [dB re 1m^2]	Facility propagation loss	N_{TF} [dB re 1m^2]	$N_{TF} = -TF$
Air/Oxygen Content	α [%]			
Nuclei content	n [number /cm^3]			

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[7] Symbols for acoustic quantities are, if defined in these documents, taken from ISO standards 17208-2:2016 and 18405:2017. Note that L_p, L_{RN}, and L_S are usually defined in 1/3 octave band levels.

Table 5: Recommendations for Parameters

Parameter	**Recommended values**	**COMMENTS / CITATION WHERE RECOMMENDED**
Pressure adjustment (cavitation number)	Location of cavity collapse e.g. 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.