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Ships and marine technology — Model test method for propeller cavitation noise evaluation in ship design —

Part 1: **Source level estimation**

Navires et technologie maritime — Méthode d'essai sur modèle pour évaluer le bruit de cavitation des hélices dans la conception des navires —

Partie 1: Estimation du niveau d'émission de la source

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This document was prepared by Technical Committee ISO/TC 8, *Ships and marine technology*, SC 8, *Ship design*.

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Introduction

In order to reduce shipping noise, the characteristics of ship noise should be understood. Propeller noise, which is the major noise source in commercial ships, is mainly due to its turns as spectral harmonics and to cavitation as broadband noise. Special ships such as fishery research vessels and military vessels require quiet propellers with less or no cavitation in their operating conditions.

The propeller cavitation noise can be assessed by experimental and/or numerical methods in the propeller design stage. The numerical method such as CFD or empirical formulae might be a good alternative to propeller cavitation noise evaluations. However, the model tests are still used widely to predict the full-scale acoustic source strength of the propeller cavitation for a wide range of frequencies.

This document was developed to provide a standardized model test method for propeller cavitation noise evaluation. This document is aimed for appropriate evaluation of the propeller cavitation noise characteristics at the early design phase via model tests.

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Ships and marine technology — Model test method for propeller cavitation noise evaluation in ship design —

Part 1:
Source level estimation

1 Scope

This document specifies a model test method for propeller cavitation noise evaluation in ship design.

The procedure comprises reproduction of noise source, noise measurements, post processing and scaling. The target noise source is propeller cavitation. Thus, this document describes the test set-up and conditions to reproduce the cavitation patterns of the ship based on the similarity laws between the model and the ship. The propeller noise is measured at three stages. The measurement targets for each stage are propeller cavitation noise, background noise, and transmission loss. For the source level evaluations, corrections for the background noise and the transmission loss are applied to the measured propeller cavitation noise. Finally, the full-scale source levels are estimated from the model scale results using a scaling law.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 17208-1:2016, *Underwater acoustics — Quantities and procedures for description and measurement of underwater sound from ships — Part 1: Requirements for precision measurements in deep water used for comparison purposes*

IEC 61260, *Electroacoustics — Octave-band and fractional-octave-band filters*

ITTC — Recommended Procedures and Guidelines 7.5-02-01-05: *Model scale propeller cavitation noise measurements*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
acoustic centre
position where all the noise sources are co-located as a single point source

Note 1 to entry: The acoustic centre is the centre of the expected cavitation extent.

3.2
background noise
noise from all sources other than the source under test

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3.3
cavitation number
σ_n
non-dimensional quantity defined as $(p_0 - p_v)/\left(\frac{1}{2}\rho n^2 D^2\right)$ where

p_0 is the total static pressure;

p_v is the vapour pressure;

ρ is the density of the fluid;

n is the propeller rotational speed (rps);

D is the diameter of the propeller.

Note 1 to entry: The total static pressure (p_0) consists of atmospheric pressure and submergence depth pressure which is usually taken at a specific point approximating the centre of the expected cavitation extent in the upper part of the disk, such as 0,7 R(R : radius of the propeller), 0,8 R or 0,9 R above the propeller centreline, although the propeller centreline is also used.

3.4
noise source
noise generating mechanism or object

Note 1 to entry: For the purposes of this document, the main noise source is the propeller cavitation.

3.5
propeller plane
imaginary plane orthogonal to the shaft centre line and including the intersection (point) of the shaft centre line and generator line

3.6
propeller thrust coefficient
K_T
non-dimensional quantity defined as $T/(\rho n^2 D^4)$, where T is the thrust of the propeller

3.7
propeller torque coefficient
K_Q
non-dimensional quantity defined as $Q/(\rho n^2 D^5)$, where Q is the torque of the propeller

3.8
reference distance
distance used for source level conversion and defined as 1 m apart from the acoustic centre

3.9
reference field
sound pressure field that is measured using a virtual source located at a given position, i.e. acoustic centre

Note 1 to entry: The reference field shall be used to calculate the source level.

3.10
sound pressure level
SPL
L_p
ten times the logarithm to the base 10 of the ratio of the time-mean-square pressure of the measured sound pressure, in a stated frequency band, to the square of a reference value expressed in decibels by

$$L_p = 10 \log_{10}\left(\frac{p^2}{p_{ref}^2}\right)$$ where $p_{ref} = 1 \mu Pa$

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3.11
source level
SL
converted quantity of the measured sound pressure at a reference distance 1 m apart from the acoustic centre

3.12
virtual source
artificial sound source of which transmitting power is known *a priori*

3.13
wake
simulated ship wake at the propeller plane

Note 1 to entry: For the model test, ship wake is simulated using a wake screen or a ship model.

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4 Model test setup and conditions

4.1 Test setup

In order to evaluate the propeller cavitation noise performance via model tests, it is important to reproduce noise sources accurately, i.e. the cavitation patterns, based on the similarity laws between the model and the ship. Test setup for the purpose comprises test facilities, model propellers, and wake fields generation.

4.1.1 Test facility

Test facilities might vary between variable pressure water tunnels, circulating water channels with a free surface in the test section to a depressurized towing tank. The variable pressure water tunnels, which are called cavitation tunnels, are widely used for the model tests. Depending on their test section sizes, suitable devices to generate wake fields should be utilized.

4.1.2 Model propeller

The size of a model propeller depends on the capacity constraint of the test facilities and on the acceptable range of test section blockage. The size of the model propeller should be determined to achieve the highest Reynolds number within the capacity constraints of the test facility. A typical propeller diameter for a model scale propeller is in the range between 180 mm to 300 mm. The accuracy of the model propeller geometry should be according to ITTC — Recommended Procedures and Guidelines 7.5-01-02-02[1] which specifies that the offsets of the blade sections should be in the range ±0,05 mm.

4.1.3 Wake generation

For the propeller cavitation model tests, the wake fields are to be generated by the wake screen or the model ship. In general, the former is used in small-sized and medium-sized cavitation tunnels, while the latter is used in the large cavitation tunnel. The important scaling parameter for the cavitation test is the Reynolds number but its similarity cannot be achieved for practical reasons. In order to reduce scale effect, the Reynolds number should be determined as high as possible within the capacity of the test facilities.

For the medium-sized cavitation tunnels, the wake distributions are to be generated inside the cavitation tunnel by using a wake screen composed of wire meshes. When a full-scale ship wake is required, it is to be obtained by extrapolating the model scale wake field or by using computational fluid dynamics (CFD). A dummy model in combination with wake screens can be applied in the medium-sized tunnel as well. For twin screw ships, the inclined shaft, brackets and bossing can be mounted in small- to medium-sized test sections.

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For the large-sized cavitation tunnels, the wake can be generated typically from a ship model installed in the test section. In some cases, the ship model with grids or the shortened model can be used as well. The model ship is manufactured of various materials with the scale ratio that is dependent on the dimensions of the ship and the tunnel. The model ship is installed inside the tunnel corresponding to the full-scale draft. The free surface is covered by plates to suppress the wave interference to the model. The model ship draft in the tunnel is increased within the capacity constraint of the test facilities to compensate for the deceleration of the flow due to the boundary layer below these wave suppressing plates. The detailed configurations of the model are strictly based on the drawings of the full-scale ship. The accuracy of the model hull should be in accordance with ITTC — Recommended Procedures and Guidelines 7.5-01-01-01[2] which specifies a tolerance of ±1 mm. The maximum blockage of the ship model in the test section is in the order of 10 % to 20 %. A watertight dynamometer is to be installed together with an underwater motor aligned precisely to the propeller shaft inside the model ship. Thrust, torque and rotational speed of the model propeller are measured through the dynamometer.

The quality of the generated wake with respect to the target wake (measured wake in the towing tank or estimated full scale ship wake) should be assessed by wake field measurements using velocimetries, e.g. particle image velocimetry (PIV), laser Doppler velocimetry (LDV) or pitot tubes. Depending on the configuration one may measure the axial velocity component only, the axial and tangential velocity component or all three velocity components.

4.2 Test conditions

The cavitation test conditions are determined by the thrust identity method (or torque identity method) at discussed (or specified) self-propulsion point. In cavitation tests, the propeller operating condition is defined by the non-dimensional coefficients, propeller thrust coefficient K_T (or propeller torque coefficient K_Q) and cavitation number σ_n.

During the propeller cavitation observations and noise measurements the pressure in the cavitation tunnel is adjusted according to the local cavitation number at a specific point approximating the centre of the expected cavitation extent in the upper part of the disk, such as 0,7 R, 0,8 R or 0,9 R above the propeller centreline, although the propeller centreline is also used.

In the cavitation tunnel tests, inclusion of the effect of stern wave heights and sea margins for service conditions can be determined based on discussions with customers and/or experience of the model basin.

The air content of the water and the number and distribution of the cavitation nuclei play important roles in the cavitation inception and its development. Therefore, one or both of them should be considered based on experience of the test facilities.

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

For the measurement of cavitation noise in the cavitation tunnel and depressurized towing tank, it is necessary to stabilize the extent of cavitation since the cavitation noise slightly varies depending on the stability of cavitation extent[3]. There are several methodologies for stabilizing the extent of cavitation. One methodology is to add nuclei such as hydrogen microbubble in the water. Another methodology is to add roughness at the leading edge of the propeller blades at least on the back side.

Such treatments should be discussed in each facility by taking their standard experimental procedures into consideration, i.e. operation conditions including shaft speed and target velocity to be achieved, the scale of the model, water quality etc.

Although the extent of cavitation is stabilized by enough air content, depressurization in the cavitation tunnel and towing tank increases the number and the volume of bubbles in the water. Since the bubble attenuates the sound pressure, attention should be paid to the air content of the water in the cavitation tunnel and the depressurized towing tank.

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There are two definitions of air content:

— α/α_S: the air content under atmospheric pressure (1 atm);

— $(\alpha/\alpha_S)_{TS}$: the air content under hydrostatic pressure at the test section after depressurization.

These two values are different from each other, and thus it is necessary to state the definition of the air content used in the noise measurement in the cavitation tunnel and the depressurized towing tank.

4.3 Calibration

The devices to measure test conditions such as a dynamometer should be calibrated in accordance with the manufacturer's calibration reference.

5 Noise measurement instrumentation

5.1 Hydrophone and signal conditioning

In order to measure acoustic pressure, the terms hydrophone, underwater electro-acoustic transducer and underwater microphone may be used synonymously. For the purpose of this document, the term hydrophone is used. The hydrophone includes any signal conditioning electronics such as pre- or charge amplifiers either within or exterior to the hydrophone. The piezoelectric type hydrophones are usually used for measurement of underwater sound pressure levels in a test facility. Recommended specifications of the hydrophones and their mount method in the facility are listed in Table 1.

For the measurement, single hydrophone or multiple hydrophones may be used. For a reliable result, multiple hydrophone measurements are recommended. The test setups including hydrophone positioning might depend on the test facility. However, typically at least one hydrophone is recommended to be located at the propeller plane. Additional hydrophone positions could be up- and down-stream as well as abeam.

The mount method should be chosen in order to reduce the effects of flow and vibration on the hydrophone. In addition, unwanted acoustic phenomena such as a resonance might occur depending on the mount method and the hydrophone setup. Therefore, the acoustic characteristic of the hydrophone setup needs to be assessed after hydrophone installation by using a suitable test method such as using a virtual source.

Table 1 — Recommended specification of the hydrophones and their mount method

Receiving sensitivity	— −220 dB re 1 V/µPa or higher
Frequency range	— 1 Hz to 100 kHz or wider
Directivity	— Omni-directional
Operating static pressure	— 40 atm to 100 atm
Mount method	— Acoustic chamber below the test section — Outside of the walls or windows — Flushed to walls or windows — To a rake in the flow — Inside the basin

The use of a hydrophone array, which is not included in this document, enables noise measurement with high directivity to scan the model and to detect local noise sources.

The hydrophone should be individually calibrated before the test and periodically (typically every 12 months) with respect to the manufacturer's calibration reference, e.g. by use of a hydrophone calibrator, or in accordance with IEC 60565[4].

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5.2 Data acquisition

5.2.1 General

Data acquisition is performed using analogue-digital converters (A/D). The following should be considered for the A/D converter.

5.2.2 Sampling frequency

Sampling frequency should satisfy the Nyquist-Shannon sampling theorem, i.e. it should be at least twice the highest frequency under test. If possible, it is recommended to be over four times the highest frequency.

5.2.3 Resolution

The A/D converter should have more than 12-bit resolution. 16-bit resolution is recommended.

5.2.4 Synchronization for multiple channel sampling

The number of channels corresponds to the number of hydrophones and the data should be sampled simultaneously for entire channels especially when using a hydrophone array.

5.2.5 Filtering

In order to prevent the data aliasing, the low-pass filter should be applied before A/D converting. The cut-off frequency should be set to the highest frequency at least.

5.2.6 Acquisition time

The measurement time corresponding to 1 000 rotations of the propeller is recommended in order to have sufficient data for the analysis. The acquisition time, of which the specific value depends on the shaft rotational speed, would be a few tens of seconds in a cavitation tunnel and around 200 s in a depressurized towing tank.

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6 Noise measurement procedure

6.1 Propeller cavitation noise measurement

Propeller cavitation noise should be measured in accordance with 4.1 and 4.2 by using the noise measurement instrumentation in Clause 5.

6.2 Background noise measurement

The background noise comes mainly from the propeller drive system, the tunnel operation or towing carriage, the water flow, the measurement chain, etc. To check the quality of the noise measurements, i.e. of the propeller cavitation, the background noise level should be determined.

The background noise shall be measured in the absence of the propeller cavitation (propeller replaced by a dummy boss or increase of tunnel pressure to suppress cavitation) but with all other operating conditions as similarly as possible. Both procedures to measure background noise have specific pros and cons. The increase of tunnel pressure allows the propeller load condition, K_T/K_Q to remain and to detect propeller non-cavitation noise (e.g. propeller singing) but changes the air content. It also removes or at least reduces the cavitation from the wake screen and/or appendages of the ship model, which should be included in the background noise if it exists. The replacement of the propeller by a dummy boss keeps the same air content but changes the load of the propeller drive system. Thus it would alter mechanical noise characteristics from the propeller drive system.

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If flush mounted hydrophones or pressure transducers are used on 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 — Recommended Procedures and Guideline 7.5-02-03-03.3[5].

The disadvantage of using wake screens for noise measurement is that they may increase background noise due to the vibrations and cavitation from themselves. The increase of tunnel velocity yields singing of the wire mesh screen when it is utilized as a wake generator[6]. Under such an experimental configuration, the noise originating from the wire mesh screen must be measured as a background noise.

The background noise can be measured before or after measuring the cavitation noise of the propeller.

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6.3 Reference field measurement

6.3.1 Objective

When the noise is measured in model test facilities, it should be noted that the situation differs from the free field environment. For the cavitation tunnels, the test section including acoustic chamber is enclosed by the tunnel walls. The influence of multiple reflections due to the walls should be considered. For facilities with a free surface, the influence of this free surface on the noise measurements should be also assessed and, if necessary, corrected with an acoustic calibration test. In general, the free surface gives a reduction of the measured noise levels at low frequencies where the influence increases with decreasing frequency. The hydrophone setups would also cause reflections depending on the mount methods which cannot be easily known *a priori*.

In order to assess the influence of these reflections, an acoustic calibration could be made using a known virtual source which is located at a given acoustic centre.

6.3.2 Virtual source and input signal

For the reference field measurement, the propeller is replaced by a virtual source. The underwater transducer, which converts the electrical input to the pressure signal with its own transmitting voltage response (TVR), can be used as the virtual source. The source strength of the virtual source can be calculated directly from the known input signal in voltage and TVR. The input signal is usually generated using a function generator and is amplified, if necessary. Broadband signals such as white noise and linearly frequency modulated signal can be used as the input signal. The input signal should fully cover the frequency range of interest. However, it is noted that generating a low frequency signal is difficult due to the low TVRs of the most commercial underwater transducers. Below the lower limit of the effective frequency range, the reference field should be estimated by the other methods such as a simple geometrical spreading as defined in Formula (6).

6.3.3 Measurement condition

During the reference field measurements, the pressure should be kept the same as the propeller cavitation noise measurement in order to prevent a change of air content. However, the reference field can be measured without flows due to a low Mach number of the cavitation test.

7 Post processing and scaling

When noise measurement as given in Clause 6 has been completed, post processing is required to adjust sound pressure levels for background noise conditions and to convert the background noise-corrected sound pressure levels to the source levels by using measured reference fields. Finally, scaling procedures are required to obtain full-scale noise levels of a propeller cavitation from the measurements at model scale.

In general, all the quantities in decibels are evaluated in the one-third-octave band in accordance with ISO 17208-1:2016 and IEC 61260. The narrow band (1 Hz bandwidth) analysis can be performed especially when the discrete frequency components are important.

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7.1 Sound pressure level

In the context of noise assessment, the sound pressure level is the fundamental quantity of sound pressure, and it is defined by Formula (1):

$$L_p = 10\log_{10}\left(\frac{p^2}{p_{ref}^2}\right)\left[\text{dB re } 1\,\mu\text{Pa}\right] \tag{1}$$

where

p^2 is time-mean-square pressure of the measured sound pressure in one-third-octave band;

p_{ref} is the reference pressure of 1 μPa.

7.2 Background noise adjustment

The background noise shall be corrected in accordance with ISO 17208-1:2016 and ITTC — Recommended Procedures and Guidelines 7.5-02-01-05.

The signal-plus-noise-to-noise ratio (ΔL) for each one-third-octave band is defined by Formula (2):

$$\Delta L = L_{p_{s+n}} - L_{p_n} = \log_{10}\left(\frac{p_{s+n}^2}{p_n^2}\right)\left[\text{dB}\right] \tag{2}$$

where

$L_{p_{s+n}}$ is the sound pressure level of the propeller cavitation noise;

L_{p_n} is the sound pressure level of the background noise.

If ΔL is greater than 10 dB then no adjustments are necessary. On the contrary, if ΔL is less than 3 dB then measurements are dominated by background noise and cannot be used. Finally if 3 dB ≤ ΔL < 10 dB, adjustment on measurements are required. The following expression can be used:

$$L_p' = 10\log_{10}\left[10^{\left(L_{p_{s+n}}/10\right)} - 10^{\left(L_{p_n}/10\right)}\right]\left[\text{dB re } 1\mu\text{Pa}\right] \tag{3}$$

where L_p' is the background noise-adjusted sound pressure level of the propeller cavitation, computed in one-third-octave band.

7.3 Transmission loss

The effects of reflections from tunnel walls, free surface and hydrophone mount setups can be adjusted using the reference field described in 6.3.

At first, the time-mean-square pressure, p_i^2 of the virtual source at the distance of 1 m can be calculated from the input voltage signal and TVR by Formula (4):

$$p_i^2 = V_i^2 \frac{p_{ref}^2}{V_{ref}^2} 10^{\text{TVR}/10} \tag{4}$$

where

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V_i^2 is the time-mean-square voltage input to the virtual source for each one-third-octave band;

V_{ref} is the reference voltage of 1 V;

p_{ref} is the reference pressure of 1 µPa;

TVR is the transmitting voltage response of the virtual source for each one-third-octave band [dBre1µPa/V@1m].

Using the reference field data, the transmission loss for each one-third-octave band is defined by Formula (5):

$$TL = -10\log_{10}\left(\frac{p_r^2}{p_i^2}\right)[\mathrm{dB}] \tag{5}$$

where p_r^2 is the time-mean-square pressure of the measured reference field in one-third-octave band;

If the measurement of reference field is not available, the transmission loss can be simply estimated by:

$$TL_{est} = 10\log_{10}\left(\frac{r^2}{r_{ref}^2}\right)[\mathrm{dB}] \tag{6}$$

where r is the distance from the acoustic centre to the measurement point in metres. However, the measurement of reference field is recommended in order to adjust the propagation effects accurately in the test facilities.

7.4 Model scale source level

The model scale source level, L_s, is calculated by Formula (7):

$$L_s = L_p^{'} + TL\,[d\mathrm{B\,re\,1\,\mu Pa@1\,m}] \tag{7}$$

When the multiple hydrophones are used, the averaged source level can be obtained by Formula (8):

$$L_s = 10\log_{10}\left[\frac{1}{\mathrm{N}}\sum_{i=1}^{\mathrm{N}} 10^{\left(L_{s_i}/10\right)}\right][\mathrm{dB\,re\,1\,\mu Pa@1m}] \tag{8}$$

where N is the number of hydrophones.

7.5 Scaling to the full-scale noise levels

A prediction of the full-scale noise levels can be made using scaling laws recommended by ITTC[6]. These laws concern only differences in dimensions and operating conditions of the model- and full-scale propellers and therefore do not reflect the Reynolds scaling effect.

The increase in noise levels from model- to full-scale is given by Formula (9):

$$\Delta L_s = 20\log_{10}\left[\left(\frac{D_s}{D_m}\right)^z\left(\frac{r_m}{r_s}\right)^x\left(\frac{\sigma_s}{\sigma_m}\right)^{y/2}\left(\frac{n_s D_s}{n_m D_m}\right)^y\left(\frac{\rho_s}{\rho_m}\right)^{y/2}\right][\mathrm{dB}] \tag{9}$$

and the frequency shift relation is given by Formula (10):

$$\frac{f_s}{f_m} = \frac{n_s}{n_m}\sqrt{\frac{\sigma_s}{\sigma_m}} \tag{10}$$

where the subscripts $_s$ and $_m$ refer to full-scale and model-scale, respectively.

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The exponent factors x, y and z in Formula (9) are determined differently, which are attributed to test facility differences, range of tested Reynolds number, and the model test method.

7.6 Other option for full-scale noise prediction

To evaluate full-scale noise, utilizing empirical formula accompanied with experimental / computational methods can be one option and some of these methods can be found in References [7] to [9]. Since the input parameters for these formulae are major design parameters of the hull and propeller, they are useful at the early design stage.

As a computational tool, both the potential-based method and viscous flow simulation can be applied. Utilizing CFD could be beneficial in that it can take the full-scale ship wake into consideration as the inflow condition to the propeller, and it may contribute to resolve tip and hub vortex cavitation, although the rigorous validations for CFD are inevitable.

8 Uncertainty

The overall uncertainty is mainly due to the hydrodynamic phenomena introduced by approximations made in a model test, measurement uncertainty, and scaling to the full-scale.

The hydrodynamic phenomena in the model test are complicated to analyse and thus it is difficult to quantify their errors.

Some discussions on uncertainty can be found in Annex B for information only.

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