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

Part 2: Noise source localization

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

Partie 2: Localisation de la source de bruits

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Introduction

Propeller cavitation is the major noise source in commercial ships. The propeller cavitation noise can be assessed by experimental and/or numerical methods in propeller design stage. The numerical methods, such as computational fluid dynamics (CFD) or empirical formulae, might be a good alternative to propeller cavitation noise evaluations. However, the model tests are still used widely for research on propeller cavitation noise.

The objective of the model test is to reduce the propeller noise in ship design by evaluating propeller cavitation noise characteristics at the design phase. Localizing the noise sources in the design stage, as well as predicting its noise levels, might be very helpful. ISO 20233-1 addresses the prediction of propeller noise levels. In order to specify the location of noise source, visual observation of cavitation is the most practical way in view of spatial resolution and efficiency, as the main source of hydrodynamic noise in merchant ship is cavitation. In addition to this observation, noise source localization technique using hydrophone array is under development for verifying the observed noise source location[1]. Thus this document devotes to the source localization method as a new part of a model test method for propeller cavitation noise evaluation in ship design.

The estimation methods of the propeller noise via model tests were widely studied for a long time and can be used in the shipbuilding industry nowadays. However, the noise source localization is easily accomplished by cavitation observation. This document also serves to provide an example of protocols for acoustic localization which is a relatively new research area.

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

Part 2: Noise source localization

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1 Scope

This document specifies a model test method for propeller cavitation noise evaluation in ship design, focusing mainly on the noise source localization.

The procedure comprises the model test set-up, noise measurements, data processing and source localization. The target noise source being propeller cavitation, this document describes the test set-up and conditions to reproduce the cavitation patterns of the ship, which is the same as in ISO 20233-1. The noise measurements are performed using a hydrophone array for the source localizations. Therefore, the instrumentation of the hydrophone array is also addressed, as well as a suitable array signal processing of the measured data. Finally, a method to visualize and to interpret the results is presented.

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 20233-1:2018, *Ships and marine technology — Model test method for propeller cavitation noise evaluation in ship design — Part 1: Source level estimation*

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:

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

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

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
hydrophone
underwater electro-acoustic transducer
underwater microphone
device to measure acoustic pressure, including any signal conditioning electronics such as pre- or charge amplifiers either within or exterior to it

Note 1 to entry: Piezoelectric hydrophones are usually used for the measurement of underwater sound pressure in a test facility.

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

Note 1 to entry: The reference field is used to calibrate the hydrophone array.

3.7
virtual source
artificial sound source of which the transmitting power is known *a priori*

4 Model test setup and conditions

In order to evaluate the propeller cavitation noise performance via model tests, it is important to reproduce accurately the noise sources, i.e. the cavitation patterns, based on the similarity laws between the model and the ship. Accuracy in reproducing the noise sources is required for the noise source localization as well as for the source level estimation. The test setup and conditions described in ISO 20233-1:2018, Clause 4, shall be applied to the model test for the noise source localization.

5 Noise measurement instrumentation

5.1 Hydrophone array

5.1.1 General

In order to localize the noise source, i.e. to find the position where the most probable noise occurs, the use of a special device to enable noise measurement with high directivity is required. The hydrophone array is the typical device for that purpose.

5.1.2 Hydrophone

Recommended specifications of the hydrophones are listed in Table 1.

The hydrophones should be individually calibrated before the test and periodically (typically every 12 months), either with respect to the manufacturer's calibration reference, e.g. by using a hydrophone calibrator, or in accordance with IEC 60565[2].

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Table 1 — Recommended specifications of the hydrophones

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

5.1.3 Array types

For the noise source localization, various types of hydrophone arrays can be used. The typical array types are listed in Table 2[3]. Especially in the propeller cavitation model tests, from the practical perspective it is recommended to use a 2-dimensional array, considering the performance and the cost-effectiveness.

A design method of hydrophone array patterns can be found in Annex A for information.

Table 2 — Hydrophone array types

1-Dimenonal array	— uniform line array — nested line array
2-Dimenonal array	— uniform linear plane array — nested linear plane array — circular-typed array — spiral-typed array — random array
3-Dimenonal array	— volume array

5.1.4 Array setup

For the noise source localization, a single array or multiple arrays can be used.

The arrays can be variously mounted, depending on the test facility. For the cavitation tunnel, the hydrophone arrays can be located in the acoustic chamber below the test section. They can be mounted outside of the walls (or windows) or be flushed to walls (or windows). For the towing tank, the arrays can be located inside the basin.

Regardless of the mounting method, however, the hydrophone should be installed in order to reduce the effects of flow and vibration on the hydrophones and to avoid unwanted acoustic phenomena such as resonance due to the mounting and the hydrophone setups.

5.1.5 Array calibration

When calibrating the hydrophone as recommended in 5.1.1, it should be confirmed that the hydrophone is correctly positioned in the array. In addition, it should be checked that the array localizes the correct virtual source position during the reference field measurement as described in 6.3.

5.2 Data acquisition

5.2.1 General

Data acquisition is performed using analogue-digital converters (A/D). 5.2.2 to 5.2.6 should be considered for the A/D converter.

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5.2.2 Sampling frequency

The 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 Syncronization for multiple channel sampling

The number of channels corresponds to the number of hydrophones and the data should be sampled simultaneously for entire channels.

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 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.

6 Noise measurement procedure

6.1 Propeller cavitation noise measurement

Propeller cavitation noise should be measured in accordance with ISO 20233-1:2018, 4.1 and 4.2, by using the noise measurement instrumentation of 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 if there exists any other noise source than the target noise, i.e. the cavitating propeller, the background noise should be measured.

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 to keep the propeller load condition, K_T/K_Q and to detect propeller non-cavitating 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. Although the cavitation of the propeller is removed by doing so, the propeller-induced noise can be localized due to the flow around propeller blades. 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.

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

6.3 Reference field measurement

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

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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 assessed as well. The hydrophone setups would also cause reflections depending on the mounting methods which cannot be easily known *a priori*.

In order to validate the localization results under the influence of these reflections, an acoustic calibration can be made using a known virtual source which is located at a given acoustic centre.

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 the 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.

During the reference field measurements, the air contents should be approximately the same as the propeller cavitation noise measurement.

7 Post processing

7.1 Array signal processing

7.1.1 Bartlett processor

The signal model, which is the main assumption for the array signal processing, is given in Annex B.

Cross-correlating the measured field with the replica leads to the Bartlett processor that evaluates the similarity between structures of two acoustic fields. If the positions of the virtual source and actual source coincide, the processor shows the highest correlation value, since the measured field vector and the replica field vector should be similar. To incorporate the broadband nature of the propeller cavitation noise, an incoherent broadband processor is given as follows:

$$\Phi_B\left(\hat{\boldsymbol{r}}_s\right) = \frac{1}{N_f}\sum_{j=1}^{N_f}\mathbf{w}_B^+\left(\boldsymbol{r},\hat{\boldsymbol{r}}_s,\omega_j\right)\mathbf{C}\left(\boldsymbol{r},\omega_j\right)\mathbf{w}_B\left(\boldsymbol{r},\hat{\boldsymbol{r}}_s,\omega_j\right) \tag{1}$$

and

$$\mathbf{w}_B\left(\boldsymbol{r},\hat{\boldsymbol{r}}_s,\omega\right) = \frac{\widehat{H}\left(\boldsymbol{r},\hat{\boldsymbol{r}}_s,\omega\right)}{\left\|\widehat{H}\left(\boldsymbol{r},\hat{\boldsymbol{r}}_s,\omega\right)\right\|},\ \mathbf{C}\left(\boldsymbol{r},\omega_j\right) = \left\langle\frac{D\left(\boldsymbol{r},\omega\right)D\left(\boldsymbol{r},\omega\right)^+}{\left\|D\left(\boldsymbol{r},\omega\right)^2\right\|}\right\rangle \tag{2}$$

where

- $\mathbf{C}$ is the cross-spectral data matrix;
- $\mathbf{w}_B$ is the weight vector of the Bartlett processor;
- $\mathbf{w}^+$ refers to the transpose of the complex vector $\mathbf{w}$;
- $\boldsymbol{r}$ is the receiver position;
- $\hat{\boldsymbol{r}}_s$ is a candidate source position;
- ω is the angular frequency to be included in the processing;

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N_f is the number of frequencies;

$\hat{H}$ is the replica field vector defined in Annex B;

D is the measured noise field vector;

$||\mathbf{a}||$ is the L_2 norm of a vector **a**;

$\langle b \rangle$ is the expected value of b.

7.1.2 MV processor

The incoherent broadband processor using the minimum variance (MV) processor is given as follows:

$$\Phi_{MV}\left(\hat{\boldsymbol{r}}_s\right) = \frac{1}{N_f}\sum_{j=1}^{N_f}\left(\mathbf{w}_B^+\left(\boldsymbol{r},\hat{\boldsymbol{r}}_s,\omega_j\right)\mathbf{C}^{-1}\left(\boldsymbol{r},\omega_j\right)\mathbf{w}_B\left(\boldsymbol{r},\hat{\boldsymbol{r}}_s,\omega_j\right)\right)^{-1}, \quad (3)$$

where $\mathbf{C}^{-1}$ is the inverse matrix of **C**. See Formulae (1) and (2) for the explanation of the symbols.

The MV processor has both pros and cons at the same time. It is optimum in the sense that the output noise power is minimized subject to the constraint that the signal be undistorted by the processor. It can achieve the best localization performance under the ideal conditions, such as a large signal-to-noise ratio (SNR) and without mismatch. However, the source of errors, such as an inaccurate array position, and the discrepancy between the measured signal and the replica can degrade its performance significantly.

7.1.3 Other option for the processors

Other processors such as the eigenvector processor and MUSIC (Multiple Signal Classification)[4] can be used for the array signal processing.

7.2 Graphical display of the output

Although the processor output can be visualized by 3-D display, it is practical to show them by 2-D slices. A slice, which is referred to as an ambiguity surface, represents the output values of Formula (1) or Formula (3). Each grid point in the ambiguity surface corresponds to the candidate source position. Therefore, areas of high correlation can suggest true source positions.

It is recommended that at least three orthogonal slices (X-, Y-, and Z-directions) which include the coordinate showing the highest correlation be presented in the report.

7.3 Spatial resolution

The spatial resolution is one of the main parameters to evaluate the array performance. However, predicting the spatial resolution analytically is not easy since it depends on the parameters such as source-array configuration, frequency bands, environmental complexity, and the signal-to-noise ratio. The spatial resolution can be evaluated by the half power beam width (HPBW), which is defined by the distance between the candidate points ($\hat{\boldsymbol{r}}_s$), where $\Phi\left(\hat{\boldsymbol{r}}_s\right)/\Phi\left(\boldsymbol{r}_s\right)=0,5$. For simplicity's sake, a monopole source is assumed when evaluating the spatial resolution by the numerical simulation or direct measurement using a virtual source.

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Annex A
(informative)

Hydrophone array design method

Hydrophone array patterns can be designed using an optimization technique. The design process comprises the classification of design parameters, the definition of an objective function and the optimization of the design parameters. The design parameters should be defined in accordance with the array types given in Table 2. The objective function should be defined in order to consider the mainlobe beamwidth and the maximum sidelobe level, simultaneously. A global optimization technique such as the simulated annealing[5] and the genetic algorithm[6] can be applied to find the optimum parameters. Finally, the peak sidelobe level and the mainlobe beamwidth of optimum arrays should be analysed for validation.

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Annex B
(informative)

Signal model for array signal processing

The acoustic data measured from a rotating propeller comprises signals of interest propagated from the propeller and additional noise due to other sources, such as unsteady flows along the body surface or/and facility walls and the inherent electrical noise of measuring devices. If a specific source is considered, the measured data $d(t)$ can be modelled by Formula (B.1), since the propagation of the source signal $s(t)$ through the medium can be expressed by convolution with an impulse response $h(t)$ in a linear time-invariant system[7]:

$$d(\boldsymbol{r},t)=s(\boldsymbol{r}_s,t)*h(\boldsymbol{r},\boldsymbol{r}_s,t)+n(\boldsymbol{r},t) \tag{B.1}$$

where

- $\boldsymbol{r}$ is the receiver position;
- $\boldsymbol{r}_s$ is the source position;
- $n(t)$ is the additional noise signal;
- $*$ refers to the convolution operator.

If more sources exist, the corresponding terms can be simply added to Formula (B.1). Applying Fourier transform to Formula (B.1), the frequency domain expression for the angular frequency ω becomes as Formula (B.2):

$$D(\boldsymbol{r},\omega)=S(\boldsymbol{r}_s,\omega)H(\boldsymbol{r},\boldsymbol{r}_s,\omega)+N(\boldsymbol{r},\omega) \tag{B.2}$$

where $H(\boldsymbol{r}, \boldsymbol{r}_s, \omega)$ is the transfer function from the source $\boldsymbol{r}_s$ to the receiver $\boldsymbol{r}$.

The transfer function can be obtained by the direct measurement[8] or the numerical simulation. The estimated transfer function is called the replica field.

For an array of M receivers, the measured noise field at all receiver points can be expressed by vector $\boldsymbol{D}=\left[D_1,D_2,\cdots,D_M\right]^T$. Similarly, we can construct a replica field vector $\boldsymbol{H}=\left[\widehat{H}_1,\widehat{H}_2,\cdots,\widehat{H}_M\right]^T$. Assuming a source is located at r_s, the transfer function of the tunnel can be modelled as:

$$\widehat{H}(\boldsymbol{r},\boldsymbol{r}_s,\omega)=\sum_{k=1}^{\infty}A_k(\boldsymbol{r},\boldsymbol{r}_s,\omega)e^{i\varnothing_k(\boldsymbol{r},\boldsymbol{r}_s,\omega)} \tag{B.3}$$

Formula (B.3) represents multiple arrivals with different amplitudes A and phases $\varnothing$.

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