Underwater Noise Prediction and Development of Special Purpose Ships

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The Mitsubishi Heavy Industries Group has built many state of the art special purpose ships for many years. To fully demonstrate the performance of underwater investigation systems and to localize the escape behavior of marine life, it is important for these special purpose ships to reduce the underwater radiation noise from the ship itself. Our group developed a method for predicting underwater radiation noise in a wide frequency range using experimental data and large-scale analysis technology, and enabled a more silent design corresponding to the cruising speed of the special purpose ship. In the underwater noise measurement after ship construction, it was confirmed that the prediction method has good accuracy and the special purpose ship has an excellent quietness with low underwater radiation noise.

1. Introduction

In Japan, which is surrounded by the sea on all sides, the continuous execution of comprehensive oceanographic investigation and research of coastal and inshore water areas, as well as the utilization of marine resources in the ocean such as minerals and energy sources, are considered important issues. It is also important to maintain international contributions through research for unravelling the mechanisms of the global ocean environment and climatic change and for exploring the origins of the earth and organisms. With such a background, our group has built many special purpose ships, such as research vessels, investigation ships, exploring ships, training ships and cable laying ships for government agencies, universities, marine research institutes, marine resource development agencies, and ocean development companies[1].

To fully demonstrate the performance of underwater investigation systems and to localize the escape behavior of marine life, it is important for these ships to silence the underwater radiation noise from the ship itself. Regarding the impact on marine life, the International Council for the Exploration of the Sea (ICES) proposed the required level of underwater radiation noise from all ships used in fisheries research in 1995. It is necessary to reach the low level of underwater radiation noise in a broadband frequency range (1 Hz - 100 kHz) as shown in **Figure 1**[2].

Our group developed technology to predict underwater radiation noise from ships in a broadband frequency range using experimental data and large-scale analysis techniques and enabled silent design for special purpose ships. This paper describes an outline of these efforts.

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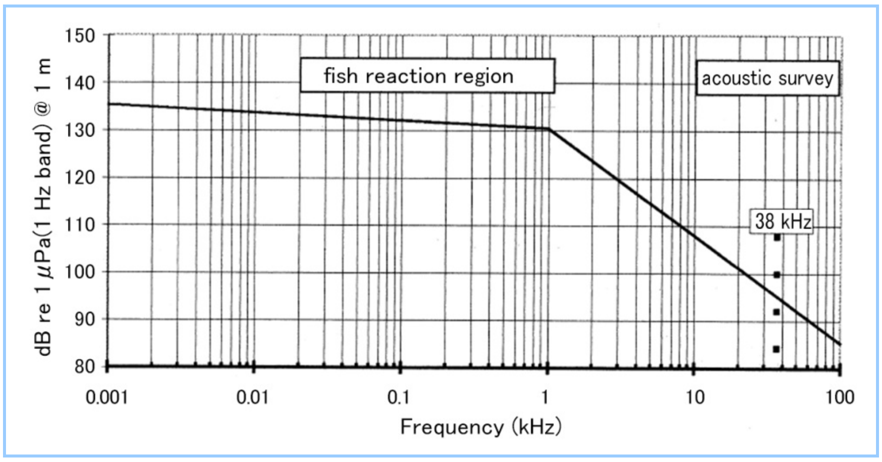

Figure 1 Required level of underwater radiation noise from ships used in fisheries research proposed by ICES

2. Underwater radiation noise prediction method

Designing ships with reduced underwater radiation noise requires the reduction of fluid noise and machinery noise. This section gives an overview of methods for predicting propeller noise and machinery noise that greatly contribute to underwater radiation noise from ships, as well as the types of countermeasures.

2.1 Propeller noise[3]

The most important phenomenon in predicting the propeller noise of special purpose ships is the propeller tip vortex cavitation as shown in **Figure 2**. To predict noise caused by propeller tip vortex cavitation, the following three prediction steps are considered necessary:

(1) Prediction of low pressure propeller vortex
(2) Prediction of cavitation which appears at propeller tip
(3) Prediction of noise caused by cavitation

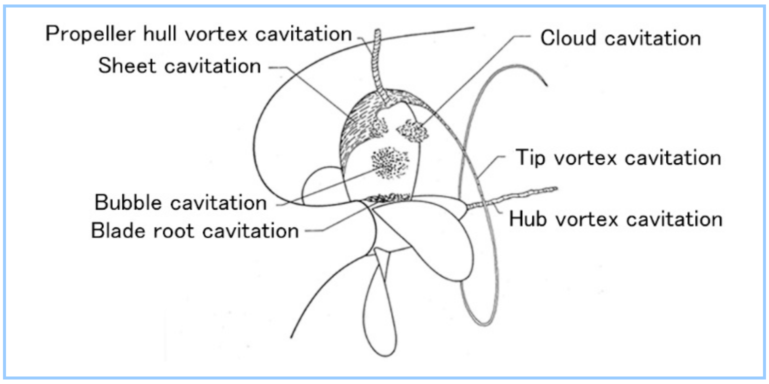

Figure 2 Cavitation generated around propeller

We established a technique of predicting underwater radiation noise caused by propeller tip vortex cavitation by combining a theoretical model on tip vortex and cavitation and knowledge based on experimental results.

As shown in **Figure 3**, the difference between the predicted value and the measured value on an actual ship is in the range of about ±3dB or less in general, and it was confirmed that this prediction technique is effective for designing the propeller noise of special purpose ships.

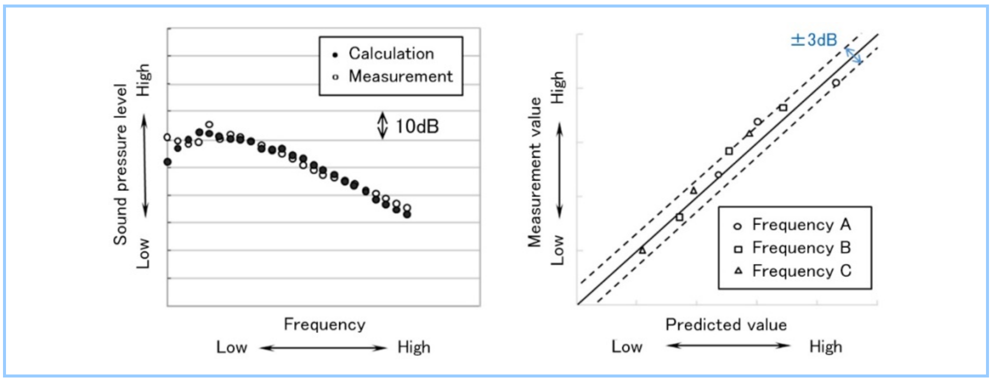

Figure 3 Comparison of predicted calculation value and actual ship measurement value of propeller noise

2.2 Machinery noise

Acoustics and vibration energy generated by the main engine, auxiliary machinery and other noise creating devices mounted onboard propagate through the air and the water inside and outside the hull and ship hull structures, and diffuse inside and outside the hull.

Whereas airborne sound diffuses in three-dimension, structure-borne sound propagates through beams, plates and other structural elements, and therefore the diffusion area is smaller than the propagation distance, and all structural elements contribute to the acoustic radiation, so that the area of radiation becomes wider. Furthermore, in steel plate structures such as ships, since the internal damping of structural elements is low, the structure-borne sound is more dominant than the airborne sound.

Figure 4 illustrates the mechanism of the generation of underwater radiation noise derived from the structure-borne sound of a ship. In prediction, the important parameters are the sound source level, characteristics of propagation paths and acoustic radiation characteristics. Since it is difficult to theoretically determine the sound source level and the characteristics of the ship structural material, actual measurement data is usually used. Therefore, for the noise prediction of a ship, it is important to estimate the structure-borne sound of the hull structure.

A ship is a structure with complicated propagation paths of vibrations and acoustic energy and has diverse sources of vibration and noise. In addition, the range of calculation frequencies is very wide. Therefore each structural element exhibits complex vibration characteristics. Regarding machinery noise, in consideration of the characteristics of the hull structure through which structure-borne sound propagates and the characteristics of the underwater frequency range, we apply Statistical Energy Analysis (SEA) for the high-frequency range as a method of analyzing structure-borne sound in a thin plate structure with complicated high-order vibration characteristics, and large-scale Finite Element Method (FEM) and Fast-Multipole Boundary Element Method (FMBEM) for the low-frequency range as a method of analyzing response of structure-borne sound and underwater radiation noise in a narrow band.

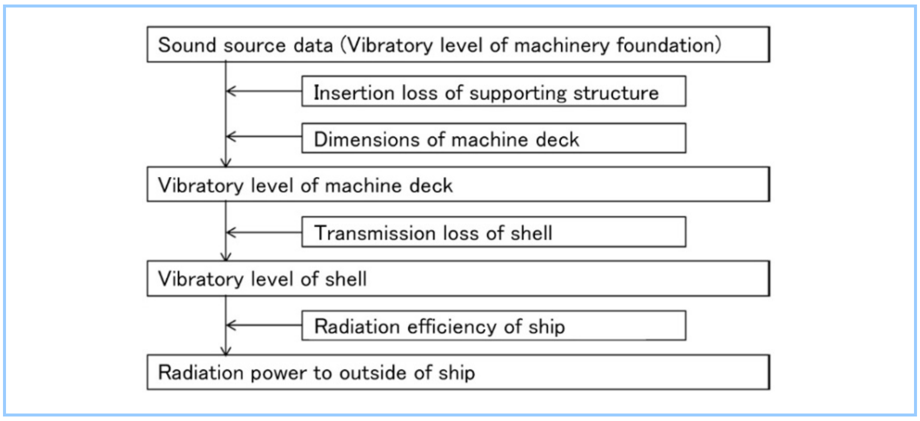

Figure 4 Generation mechanism of underwater radiation noise caused by structure-borne sound of ship

(1) High-frequency range (about 100 Hz or more)

To systematically analyze underwater radiation noise from ships, we developed the SEA House Code and applied it to the design of reducing shipboard noise and underwater radiation noise for actual ships. This section describes the application of this prediction system to underwater radiated noise prediction in the high-frequency range for machinery noise.

The power flow equation for multiple subsystems of SEA is expressed by:

$$\Omega Y E = W_0, \tag{1}$$

$$Y = D Y_c D^{\mathrm{t}} N^{-1} + Y_d,\ D = [d_{ij}], \tag{2, 3}$$

$$Y_c = [\mathrm{diag} \cdot \eta_{cij}], \eta_{cij} = \eta_{ij} N_{i,} \tag{4, 5}$$

$$Y_d = [\mathrm{diag} \cdot \eta_i], N = [\mathrm{diag} \cdot N_i], \tag{6, 7}$$

$$W_o{}^{\mathrm{t}} = [W_{o1}, W_{o2}, \ \cdots, W_{on}],\ E^{\mathrm{t}} = [E_1, E_2, \ \cdots, E_n], \tag{8, 9}$$

where, N_i, η_i, η_{ij}, W_{oi}, and E_i are the number of vibration modes, internal loss factor, coupling loss factor, input power, and subsystem energy, respectively, and the subscripts i and j represent subsystems. d_{ij} is 1 when the power flow is from subsystem i to j, -1 when the power flow is from subsystem j to i, and 0 when there is no power transfer between subsystems i and j. By solving equation (1) for all subsystems, the energy of each subsystem can be obtained. To solve equation (1), the SEA parameters of the structural system need to be given. **Figure 5** presents the flowchart of structure-borne noise analysis using the SEA method. Each parameter is derived from theoretical and actual measurement data[4].

The underwater noise radiated from the hull bottom plating is obtained by dividing the plating into subsystems and adding sound pressure p_i from individual subsystem i. Therefore, sound pressure p at the receiving point distant by $\sqrt{x^2 + y^2 + z^2}$ from the sound source is expressed by:

$$\begin{aligned} p^2 &= \sum_i p_i{}^2 \\ &= (\rho c)^2 \frac{1}{2\pi} \sum_i \sigma_i \int \frac{\mathrm{d}s_i}{x^2 + y^2 + z^2} \langle v_i{}^2 \rangle, \end{aligned} \tag{10}$$

where, ρc, σ_i, s_i, and $<v_i^2>$ are the acoustic impedance in water, and the acoustic radiation efficiency, area and spatial mean square velocity of individual subsystem i. In our system, the vibration level $<v_i^2>$ of each subsystem of the hull bottom plating is obtained by the SEA method, and the sound pressure level at a certain point is estimated by equation (10).

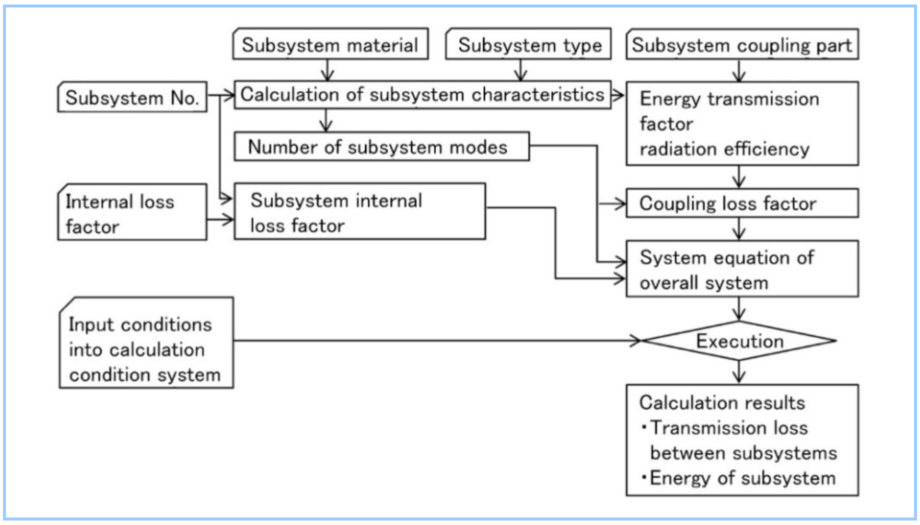

Figure 5 SEA analysis flowchart

(2) Low-frequency range (about 100 Hz or less)

For the low-frequency range, it is important to predict and evaluate the response amplitude and phase of each vibration mode at the excitation frequency of the mounted equipment in a narrow frequency band, therefore large-scale FEM (**Figure 6**: hundreds of thousands elements of model scales including virtual fluid mass elements) is used to predict structure-borne noise through the hull structure. The large-scale calculation of the entire ship is realized by our large-scale computers and the following techniques are used to shorten the calculation time:

- Mesh size tuning of fluid and structure in consideration of wavelength and interaction
- Vibration mode synthesis method in consideration of the influence of fluid
- Partial structure synthesis method

Regarding underwater radiation noise, large-scale calculation of ship size was difficult using conventional BEM (Boundary Element Method), therefore a large-scale analysis of several million elements was realized by applying FMBEM combined with the fast multipole method. The FMBEM model shown in **Figure 7** is a mirror image model that takes into account the effects of water surface reflection.

These methods enable detailed prediction of structure-borne sound and underwater radiation noise in the low-frequency range.

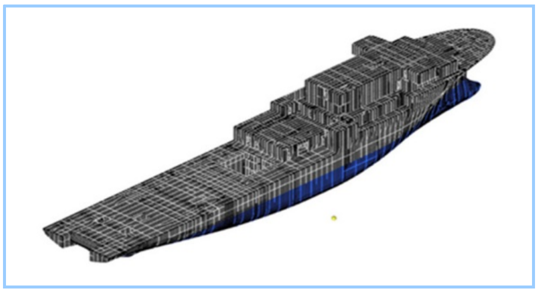

Figure 6 Example of large-scale FEM model of special purpose ship

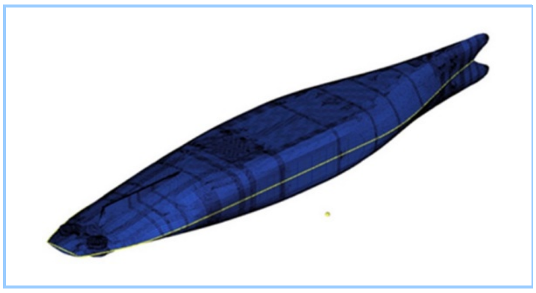

Figure 7 Example of FMBEM model of special purpose ship

2.3 Countermeasure design against underwater radiation noise

In the design stage, propeller shapes that control the propeller cavitation, support frames and vibration isolation supports that take into account the excitation frequencies of the apparatus mounted, the damping materials application area in hull structures that considers structure-borne sound, etc., were designed properly to reduce underwater radiation noise using these prediction methods.

3. Measurement of underwater radiation noise

To check the underwater radiation noise from the ship, underwater sound at the far field was measured using a measurement boat. **Figure 8** depicts a schematic diagram of the measurement carried out in the deep sea where acoustic reflection from the seabed can be ignored according to ISO17208-1:2016. During this measurement, the special purpose ship to be measured sailed away and returned near the measurement boat and also the distance between the two, both equipped with a Differential Global Positioning System (DGPS), was being measured every moment. Since hydrophones may generate noise depending on the sea conditions, measures against noise were also taken for hydrophone cables, etc.

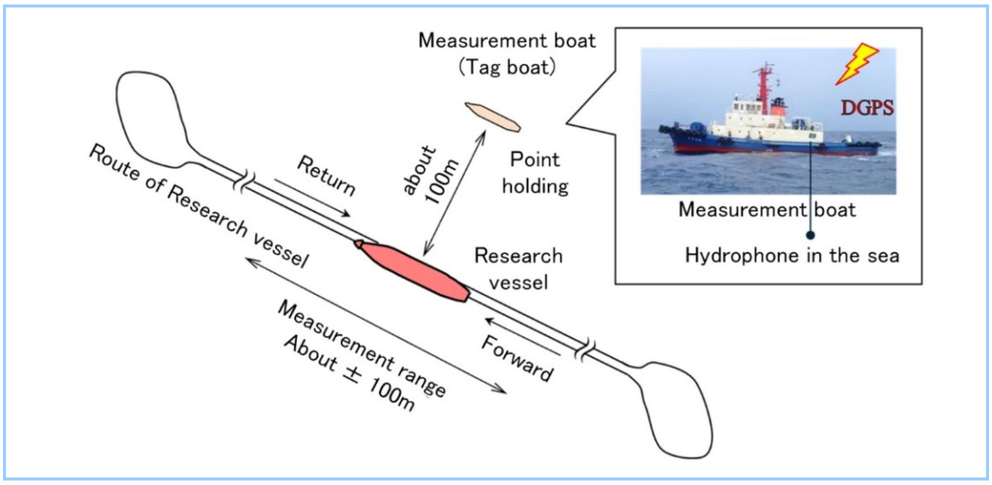

Figure 8 Outline of underwater radiation noise measurement of special purpose ship

4. Results

Figure 9 compares the predicted calculation value and the actual measured value of underwater radiation noise spectrum of a special purpose ship. The two spectral patterns are in good agreement, indicating that this prediction method is valid. Our group develops and builds ships with excellent quietness through various measures at the design stage using this prediction technology, responding to the required underwater radiation noise level of each special purpose ship, for example, underwater radiation noise satisfying the ICES proposal level.

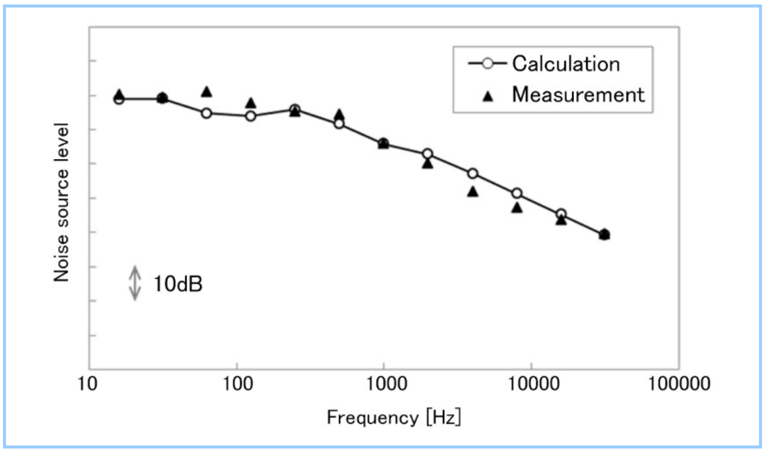

Figure 9 Comparison of predicted calculation value and actual ship measured value of underwater radiation noise

5. Conclusion

This paper introduced a method for predicting underwater radiation noise from ship propellers and machinery, and confirmed that the predicted underwater radiation noise spectral pattern is in good agreement with the actual ship measurement results to verify the validity of these prediction technologies.

Using these prediction technologies, our group has been designing propeller shapes that control the propeller cavitation, support frames and vibration isolation supports that take into account the excitation frequencies of the apparatus mounted the damping materials application area in hull structures that considers structure-borne sound, etc. to reduce underwater radiation noise of special purpose ships. We will continue to improve the quietness of ships.

References

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