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SHORT NOTE

Evaluation of the acoustic radiation efficiency for ship structures using the reciprocity method

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1. Introduction

To reduce radiated noise from large structures like ships, it is important to know the acoustic radiation efficiency on the hull plate. However it is difficult to measure this factor by direct excitation on the ship structures from inside because of inaccessibility to the measuring point from inside of the ship. Hence the method to measure the radiation efficiency using the vibro-acoustic reciprocity was developed by Steenhoek, ten Wolde and co-workers [1–4]. In this article, the application of the reciprocity to determine the acoustic radiation efficiency for the ship hull is presented.

2. Radiation efficiency by the vibro-acoustic reciprocity principle

The acoustic radiation efficiency of the hull plate is given by [5]

$$\eta_{\mathrm{rad}} = W_{\mathrm{ac}}/W_{\mathrm{vibr}}, \tag{1}$$

where W_{ac} is the radiated sound power and W_{vibr} is the vibratory power applied to the hull plate. By using the reciprocity principle, the mechano-acoustical transfer function defined as $T = p/F$ (F: force exerted to the hull plate, p: radiated sound from the hull plate) for the single-degree-of-freedom system can be replaced by the reciprocal system as shown in Fig. 1, which satisfies [6]

$$T = (p/F)_{U=0} = (v/U)_{F=0}, \tag{2}$$

where v is a normal velocity of the plate excited by an incident sound pressure from the source and U is a volume strength of the sound source defined as the diaphragm acceleration of the hydrophone times its effective diaphragm area.

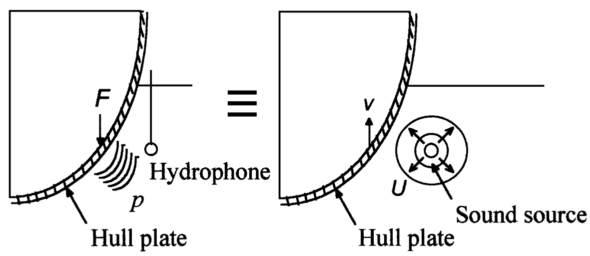

Fig. 1 Two identical vibro-acoustic systems for the ship structure.

Supposing that the radiation pattern of sound source on the hull plate is omni-directional, the power radiated from the hull plate into water can be approximated as

$$W_{\mathrm{ac}} = \frac{2\pi r^2 \bar{p}^2}{\rho c}, \tag{3}$$

where $\bar{p}$ is the rms radiated sound pressure, r is the distance from the excited point on the hull plate to the measuring point of the sound pressure, ρ is the density of water and c is the underwater sound speed.

By the definition of the input impedance shown as [7]

$$Z_i = F/v, \tag{4}$$

where F is the exciting force and v is the vibratory response of the plate at the point of application of force, W_{vibr} can be shown as $W_{\mathrm{vibr}} = Z_i \cdot \bar{v}^2$.

Cremer derived the input impedance of the plate for a point force excitation, which is given by [7]

$$Z_i = \frac{4}{\sqrt{3}}\mu' c_{\mathrm{p}} h, \tag{5}$$

where μ' is a total mass per unit area of the hull plate, h is its thickness and c_{p} is a wave speed in the plate. Combining these equations, we have [8]

$$\eta_{\mathrm{rad}} = \frac{8\pi\mu' c_{\mathrm{p}} h r^2}{\sqrt{3}\rho c}\left(\frac{\bar{p}^2}{F^2}\right). \tag{6}$$

For the monopole source, U can be approximated by [9]

$$U = \frac{4\pi r' p'}{j\omega\rho}, \tag{7}$$

where ω is its angular frequency and p' is the sound pressure at a distance r' from the source. By the reciprocal relation given by Eq. (2) and the vibratory acceleration on the plate which can be shown as $\alpha' = j\omega v$, Eq. (6) can be rewritten as

$$\eta_{\mathrm{rad}} = \frac{\rho\mu' c_{\mathrm{p}} h}{2\sqrt{3}\pi c}\left(\frac{r}{r'}\right)^2\left(\frac{\bar{\alpha}'^2}{\bar{p}'^2}\right). \tag{8}$$

By this equation, the radiation efficiency on the hull plate can be measured by the reciprocity method.

3. Measured result of the radiation efficiency on the ship hull plate

By this reciprocity method, the radiation efficiency on the hull plate of the ship, which has the dimension: 151 m in length, 17.3 m in width and 10 m in depth, where damping materials are applied for noise reduction was measured.

Configuration of the test devise for the reciprocal measurement is shown in Fig. 2. It consists of two projectors for a sound source mounted on both sides of the frame with the separation of 2 m and the monitoring hydrophone which is suspended by the rubber cable at the center of the frame. The test devise was attached on the hull plate by the diver with the magnets as shown in Fig. 3.

The acceleration of the hull plate induced by an incident sound from the projector was measured by the accelerometers formerly set on the measuring point of the hull plate from inside. The projector was driven by random noise provided from the signal generator through the controller. Signals from the accelerometer and the monitoring hydrophone were processed by the FFT analyzer to obtain the vibro-acoustic transfer function. Figure 4 shows the sound pressure level of the projector measured by the monitoring hydrophone and the resultant acceleration level on the hull plate.

Figure 5 shows the transfer function T' for calculating η_{rad}, which is given by

$$T' = \frac{\alpha'(f)}{p'(f)}, \tag{9}$$

where $\alpha'(f)$ and $p'(f)$ are frequency spectrums of α' and p' respectively. The coherence function γ, which is used for evaluating the statistical accuracy of the measurement, is also given by [10]

$$\gamma^2 = \frac{|\alpha'(f) \cdot p'(f)^*|^2}{p'(f)^2 \cdot \alpha'(f)^2}, \tag{10}$$

where $p'(f)^*$ is a conjugate of $p'(f)$.

From the value of γ shown in Fig. 5, it is seen that the incident sound and the resultant acceleration on the hull plate have a strong coherence over the frequency from 1 to 5 kHz. By setting $\mu' = 46.8\,\mathrm{kg/m^2}$, $c_{\mathrm{p}} = 5{,}000\,\mathrm{m/s}$, $h = 5\,\mathrm{mm}$ and $r/r' = 1$ for Eq. (8), the radiation efficiency for the frequency of interest (denoted as ◯ in Fig. 4 and 5) was calculated. The contour map of the radiation efficiency on the hull plate is shown in Fig. 6 as a projection to the vertical plane.

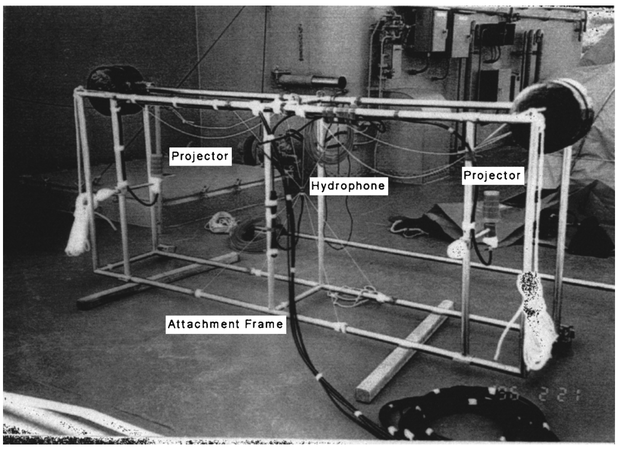

Fig. 2 Test devise for the reciprocal measurement.

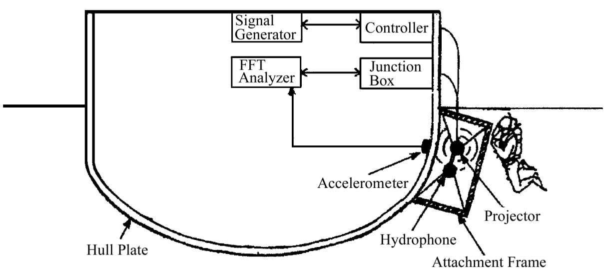

Fig. 3 Schematic diagram of the reciprocal measurement.

From this figure, ineffective damping area on the hull plate of the ship where the acoustic radiation efficiency is rather high compared with other parts of the ship can be located.

4. Conclusion

In this article, the reciprocity method for measuring the radiation efficiency on the hull plate of the ship is proposed. By the experiment conducted for the ship structure at sea, ineffective area of damping treatments on the hull plate of the ship can be located.

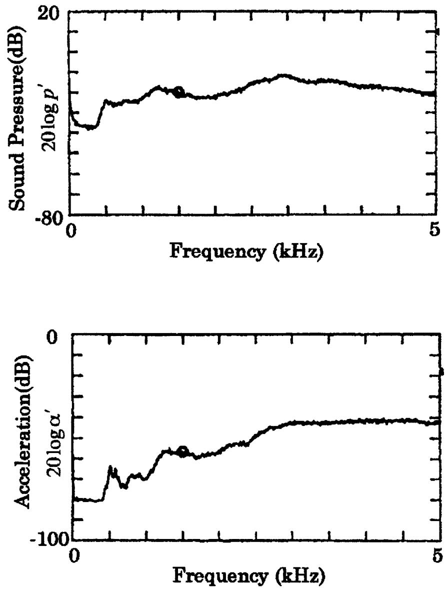

Fig. 4 Power spectra of the vibration and the sound pressure measured at the experiment.

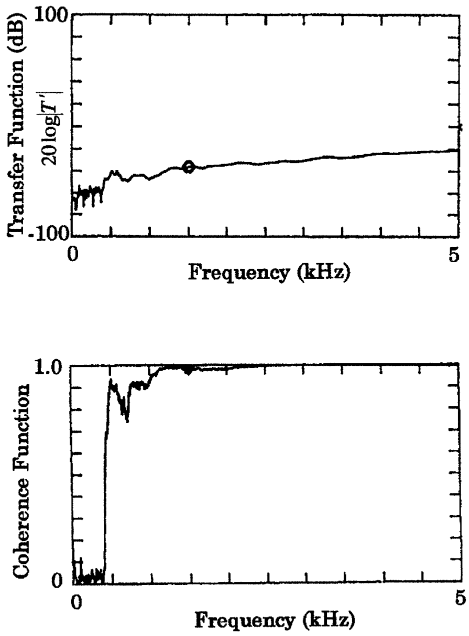

Fig. 5 Transfer function measured at the experiment and its coherence function.

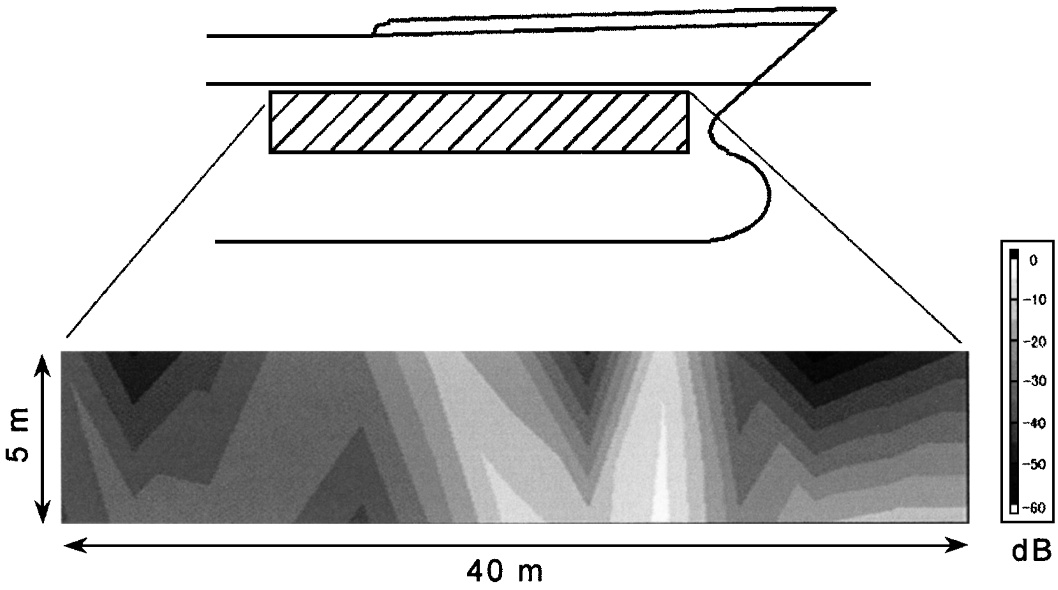

Fig. 6 Contour map of the radiation efficiency obtained by the reciprocity method.

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