Dynamic characterizations of underwater structures using noncontact vibration tests based on nanosecond laser ablation in water: evaluation of passive vibration suppression with damping materials

Naoki Hosoya¹, Itsuro Kajiwara², Koh Umenai³ and Shingo Maeda¹

Abstract
Recently, the demand for higher performing underwater structures under diverse conditions has increased. Examples include improved precision and speed of the position control of robot manipulators. To prevent the control spillover problems when active controls are used, a control system is typically constituted with a low-pass filter to eliminate all modes except for the target modes. However, experimentally measuring the dynamic properties of an underwater structure in an environment where the structure and a fluid continuously influence each other is difficult. We have recently proposed a noncontact vibration testing method for dynamic characterizations of underwater structures in which the response to a laser ablation excitation force is measured by laser Doppler vibrometer. Integrating passive control using a vibration-damping material affixed onto the underwater structure and active control constituted with the low-pass filter may realize a more cost-effective system. To develop this combined control into a practical method, the reliability of the measured frequency response function must be validated. Additionally, the applicable frequency range must be expanded to encompass the high-frequency region (several tens of kHz) so that the vibration suppression quality of underwater structures can be evaluated. Herein we quantify the effect of random measurement errors on the measured frequency response function with a reliability factor based on the concept of coherence functions. Using the measured frequency response function with a reliability factor, we demonstrated that our method can evaluate passive vibration suppression effect of an underwater structure with a damping material in high-frequency ranges up to 20 kHz.

Keywords
Frequency response function, laser ablation, modal analysis, noncontact vibration tests, passive vibration suppression, underwater structure, reliability factor

1. Introduction
In an underwater environment, structures and fluids affect each other in a complicated manner through factors such as buoyancy, drag, and fluid-related vibrations, making it difficult to experimentally measure the dynamic properties of underwater structures (e.g. a submersible vessel with a mounted manipulator) (Marani et al., 2009; Xu et al., 2009; Chen et al., 2010; Han et al., 2011; Ismail and Dunnigan, 2011; Yao and Wang, 2011; Zhang and Chu, 2012; Farivarnejad and Moosavian, 2014; Song et al., 2014;
Jin et al., 2015; Sousselier et al., 2015). To tackle this issue, we proposed a noncontact vibration testing method in which the response to an underwater laser ablation (LA) excitation force is measured by laser Doppler vibrometer (LDV) (Hosoya et al., 2016a). Previously, we applied our method to aluminum plates (5052) fully submerged under water to measure the frequency response functions (FRFs) and vibrational mode shapes. To evaluate our method, the results were compared to those obtained by the finite element analysis (FEA) in which the fluid effects were considered as added mass. If the pulsed laser wavelength and fluence, the material and medium being irradiated, and the surrounding environment (e.g., temperature) remain constant, then the underwater LA excitation force can also be considered constant (Hosoya et al., 2016a). That is, if the underwater LA excitation force is pre-determined, our method does not require the input during the vibration test to be measured. In other words, the FRF of an underwater structure can be determined just from the output measurements.

Both numerical analysis methods (Ergin and Uğurlu, 2004; Zhou and Joseph, 2005; Young, 2008; Askari and Jeong, 2010; Askari et al., 2011; Rodriguez et al., 2012; Motley and Barber, 2014) and experimental methods (Kwak and Han 2000; Amabili, 2001; Liang et al., 2001; Ergin and Uğurlu, 2003; Li et al., 2011; Aureli et al., 2012; Askari et al., 2013) have been used to characterize the dynamic properties. For the former, the results must be verified by evaluating and comparing with those obtained from experiments. For the latter, researchers must work within certain experimental constraints; for example, the devices used for input and output measurements must be waterproof. Regardless, all of these methods are still in the research phase. Although investigations related to hydroelastic or fluid-coupled vibrations exist such as a free-edge circular plate (Kwak and Han, 2000; Amabili, 2001; Askari et al., 2013), a cantilever plate (Liang et al., 2001; Ergin and Uğurlu, 2003), a cantilever beam (Aureli et al., 2012), and a stiffened bottom plate of a tank (Li et al., 2011), these experimental conditions are non-consistent. Furthermore, measured FRFs were rarely met in previous studies (Kwak and Han, 2000; Amabili, 2001; Liang et al., 2001; Ergin and Uğurlu, 2003; Li et al., 2011; Aureli et al., 2012; Askari et al., 2013), specifically, a phase characteristic and a coherence function of measured FRFs have not been demonstrated yet in literature.

In recent years, the demand for higher performances of underwater structures applicable to diverse conditions has increased. Examples include improved precision and speed of the position control of robot manipulators, and reduced vibration and noise radiation (Song et al., 2014). Higher performances may be achieved by turning the structures into smart structures with built-in actuators and sensors to provide autonomous control capabilities. When active control is used, a low-pass filter is generally employed in order to prevent the control spillover problem at high-frequency band (Zhang et al., 2015). However, this type of control system is expensive when the target modes to be controlled are in the high-frequency range (several tens of kHz) due to limitations in the calculation speed. In order to control vibration in both low- and high-frequency regions, introducing a vibration damping material affixed onto the underwater structure, which would combine the passive and active controls, may make the system more cost-effective.

For such a method to have practical applications, the reliability of the measured FRF (Ewins, 2000; McConnel and Varoto, 2008; Hosoya et al., 2015) must be verified. Additionally, the method’s applicable frequency range must be expanded so that the vibration suppression of underwater structures can be evaluated in the high-frequency region (several tens of kHz).

In this paper, we show that by incorporating the concept of coherence functions in the measurement of underwater structure FRFs, the effect of random measurement errors on the FRFs measured by our method can be quantified by a reliability factor (Hosoya et al., 2015, 2016b). Furthermore, we use this reliability factor to guarantee that our method yields precise FRFs and vibrational modes even when the applied frequency range is up to 20 kHz, which is double that in our previous report (Hosoya et al., 2016a). We also show that our method can be used to evaluate passive vibration suppression in underwater structures with an externally applied vibration damping material.

2. Input-detection-free FRF measurements with reliability factors for underwater structures

2.1. Underwater LA excitation force

LA has various applications, such as in microfabrication (McCann et al., 2016), propulsion of flying objects (Yabe et al., 2002), peening (Hatamleh, 2008), laser-induced bubbles in inside liquids (Lazic et al., 2012), vibration testing (Kajiwara and Hosoya, 2011; Hosoya et al., 2012, 2016a), acoustic analysis (Hosoya et al., 2014), and damage detection (Huda et al., 2013; Hosoya et al., 2016b, 2016d, 2017a). Figure 1 shows the principle of underwater LA excitation force generation (Hosoya et al., 2016a). When a solid surface is irradiated with a pulsed laser, LA occurs when the laser fluence in the irradiated area exceeds the LA threshold value ($10^{12}$–$10^{14}$ W/m$^2$) (Torrisi et al., 2007; Kajiwara...
A high-temperature, high-density plasma plume of mass $\Delta m$ is ejected with velocity $v$. (The vaporized material contains atoms, electrons, and ions.) The resulting change in momentum, $\Delta mv$, becomes the excitation force against the irradiated structure. For underwater LA, the impulse from water vapor and the plasma confinement effect increase the excitation force (Hatamleh, 2008; Choi et al., 2010; Hosoya et al., 2016a). Moreover, irradiating a pulsed laser in air, when the laser fluence reaches the threshold for a laser-induced plasma (LIP), a shock wave is generated around the LIP as that expands. A LIP shock wave could be used to apply the target objects in acoustic or vibration tests (Hosoya et al., 2013, 2016b, 2017b; Huda et al., 2014). Because we should compare the results of our previous study (Hosoya et al., 2016a) with those of this study, we used the underwater LA excitation in this paper.

The underwater LA excitation force depends on the experimental conditions, including temperature, irradiated medium, and laser fluence. If the experimental conditions for the estimation of the LA excitation force match the conditions at the vibration test site, then the LA excitation force determined from an experiment will be the same as that at the test site. Consequently, only the output measurements are required during the vibration test to determine the FRF. If these conditions are dramatically different from each other, we can obtain the LA excitation force as long as we re-calibrate the estimation of that in test site.

### 2.2. Input-detection-free FRF measurements with reliability factors

Input-detection-free FRF measurements on an underwater structure (Hosoya et al., 2016a) are a three-step process. (i) Determine the underwater LA excitation force. (ii) Measure the response of the underwater structure to the excitation force. (iii) Correct the absolute value of the amplitude and phase characteristics of the FRF.

(i) Prepare a block of the appropriate material, size, and shape, which will remain rigid within the measurement frequency range. Immerse the block under water and irradiate with a pulsed laser to generate LA (Figure 2). Measure the resulting velocity response, $v(t)$, with a LDV. The LA excitation force $F$ can be obtained from Newton’s second law as follows. The Fourier spectrum $a(\omega)$ of the acceleration response obtained by differentiating the velocity response is averaged within the measurement frequency range to determine the fixed acceleration $a$. $F$ is a scalar that can be obtained as the product of $a$ and mass $m$ of the rigid block.

(ii) Measure the response $a_{\text{struct}}(\omega)$ of the underwater structure of interest relative to the LA excitation force with a LDV.

(iii) Correct the absolute value of the FRF by dividing $a_{\text{struct}}(\omega)$ by $F$ obtained by step (i). The phase
characteristics of the FRF are corrected by considering the dead time, $\Delta t$, contained in the response measurements, which is the difference between the measurement start time and the time at which the structure begins to respond. In conventional vibration experiments where the same $\Delta t$ is included in both the input and output measurements, there is no need to consider $\Delta t$. However, $\Delta t$ must be taken into account when only the output measurements are used to determine the FRF, such as in our method, unless the measured response does not contain $\Delta t$.

Next, we describe the reliability factor (Hosoya et al., 2015, 2016b). The reliability of the FRFs obtained from vibration tests based on the $H1$-estimator is evaluated by the coherence function $\gamma^2(\omega)$. If $G_{\text{input}}(\omega)$ is the input power spectrum, $G_{\text{output}}(\omega)$ is the output power spectrum, $G_{\text{input-output}}(\omega)$ is the cross spectrum between the input and output, and $N$ is the number of trials in the vibration experiment, then

$$\gamma^2(\omega) = \frac{|G_{\text{input-output}}(\omega)|^2}{G_{\text{input}}(\omega)G_{\text{output}}(\omega)} \tag{1}$$

$$G_{\text{input}}(\omega) = \frac{1}{N} \sum_{i=1}^{N} |g_{\text{input}}(\omega)|^2 \tag{2}$$

$$G_{\text{output}}(\omega) = \frac{1}{N} \sum_{i=1}^{N} |g_{\text{output}}(\omega)|^2 \tag{3}$$

$$G_{\text{input-output}}(\omega) = \frac{1}{N} \sum_{i=1}^{N} |g_{\text{input-output}}(\omega)|^2 \tag{4}$$

Because the laser excitation force is a constant independent of frequency, it can be obtained as a scalar by averaging it over the measurement frequency range. If $G_{\text{laser}}$ is the power spectrum of the laser excitation force and $G_{\text{laser-output}}(\omega)$ is the cross spectrum between the laser excitation force and output, then

$$\gamma^2(\omega) = \frac{|G_{\text{laser-output}}(\omega)|^2}{G_{\text{laser}}G_{\text{output}}(\omega)} \equiv R^2(\omega) \tag{5}$$

Because the expression in equation (5) is not strictly equivalent to the coherence function, we define it to be the reliability factor $R^2(\omega)$. Similar to the coherence function, $R^2(\omega)$ has a value between 0 and 1. A value closer to 1 indicates that the effects of the random measurement errors are small, indicating a reliable FRF.

### 3. Evaluation of passive vibration suppression using FRF measurements of an underwater structure

#### 3.1. Laser excitation system

Figure 3 shows the laser excitation system used to evaluate vibration suppression in underwater structures. We used a high-output Nd:YAG pulsed laser (Surelite III-10, Continuum Inc., wavelength: 1064 nm, laser beam radius: 4.75 mm, pulse width: 5 ns, maximum output: 850 mJ, radial divergence angle: 0.25 mrad) mounted on an optical surface plate as the light source. The beam was focused with a spherical plano-convex lens (focal length: 200 mm) onto the surface of an underwater structure placed in an acrylic container to induce underwater LA. The laser pulse energy used in our experiment was 75.9 mJ. The acrylic container was a 150 mm cube with a wall thickness of 2 mm, and the water level inside the container during the experiment was set to about 130 mm. The response measured by a LDV (Polytec GmbH, NLV-2500-5) was analyzed by a spectrum analyzer (A/D: National Instruments Co., NI PXI-4472B; software: CATEC Inc., CAT-System). The sampling score, sampling frequency, measurement frequency, and number of trials were 32768 points, 102.4 kHz, 20 kHz, and 5, respectively. For the LDV measurements, a 2 mm x 2 mm reflector was attached to each measurement point. The pre-trigger mode of the spectrum analyzer was used so that the measurement start time $t = 0$ was set to 10 ms prior to when the analyzer received the transistor-transistor logic (TTL) signal output from the pulsed laser.

#### 3.2. Test piece

The stainless-steel plate (18%Cr-8%Ni, 100 mm x 50 mm x 5 mm) used as the test piece is shown in Figure 4. Figure 4(a) shows the excitation and measurement points, while Figure 4(b) shows the test piece’s
finite element (FE) model. The test piece was freely suspended on strings and submerged under water in an acrylic container where the water level was 130 mm (Figure 3). For comparison, we prepared test pieces with and without an externally applied damping material. The damping material was attached with an adhesive in the shaded region of the test piece (Figure 4(a)).

The FEA (NASTRAN) was used for the eigenvalue analysis of the test piece. Shell elements (1.25 mm mesh, 3315 nodes, 3192 elements) were used in the FE model. Triangular elements were used for the corner areas, and the eight nodes established for the circular holes for the support strings were connected by rectangular elements so that the other elements remained square. The measurement points matched with the nodes in the FE model. The water density and water level were taken into account by the fluid regions in NASTRAN. However, the strings which suspended the test piece and a viscosity of water were not considered in our FEA simulation. The modal damping ratio to determine the FRF from the FEA was adjusted by 0.2% for the first and second modes and by 1–4% for the third and higher modes so that the FRF amplitude obtained by our method matched that obtained by FEA.

3.3. Estimation of underwater LA excitation force

The underwater LA excitation force was estimated in an identical environment and under the same conditions as the underwater structure vibration test (see Figure 3). A 20 mm cube composed of the same stainless steel (18%Cr-8%Ni) as the test piece was submerged under water inside an acrylic container where the water level was 130 mm (Figure 2). The free–free boundary conditions were established by placing the cube on a cushion. Natural frequency analysis of the cube by FEA showed that its first-order natural frequency is 71 kHz, which is greater than the measurement frequency (20 kHz). Hence, the cube is considered to be a rigid body in our experiment.

The response waveform (velocity response) of the cube as measured by LDV is shown in full scale and in an expanded scale close to the time of LA in Figures 5(a) and (b), respectively. Figure 6 shows the Fourier spectrum corresponding to the waveform in Figure 5. The measured velocity response is not an impulse waveform but rather a damped vibration waveform (Figure 5(a)). The characteristic waveform observed in Figure 5(b) (marked by arrows) shows the same trends as the waveform obtained in our previous report on multi-pulses in underwater LA excitation (Hosoya et al., 2016a). From this, we conclude that the feature marked by the first arrow is caused by underwater LA, and the feature marked by the second arrow is caused by the bursting of the cavitation bubble. Several peaks can be observed in the measurement frequency spectrum in Figure 6. Given that the first-order natural frequency of the cube is 71 kHz, these peaks most likely arise from how the cube is...
supported as well as from reflections of the laser used in LDV at the interfaces of the acrylic container with water and air. Since the spectrum in Figure 6 should show a fixed value that is independent of frequency, we multiplied the amplitude of the spectrum in Figure 6, which was obtained by averaging the spectrum at the measurement frequency (20 kHz), by the mass of the cube to arrive at an estimate of 2.7 mN for the underwater LA excitation force.

According to our previous report (Hosoya et al., 2016a), the Fourier spectrum of the underwater LA excitation force when fluid drag is taken into account can be written as

\[ F(\omega) = m \frac{d}{dt} \{ U(\omega) \} + D(\omega) \]  \hspace{1cm} (6)

\[ D(\omega) = \frac{1}{2} C_p \rho U^2(\omega) S \]  \hspace{1cm} (7)

In the above equations, \( U(\omega) \) can be thought of as the absolute velocity because the water is still in our experiment. \( D(\omega) \) is the Fourier spectrum of the fluid drag, while \( C_p, \rho \) (kg/m\(^3\)), and \( S \) (m\(^2\)) are the drag coefficient, fluid density, and reference area, respectively. We substituted the measured \( U(\omega) \) (see Figure 6), \( C_p = 1.05, \rho = 1000 \text{ kg/m}^3 \), and \( S = 0.0004 \text{ m}^2 \) into equation (7) to determine \( D(\omega) \) (The Japan Society of Mechanical Engineers, 2005). We then averaged \( D(\omega) \) at the measurement frequency (20 kHz), and found \( D = 0.17 \text{ pN} \). Because this value is much smaller than the underwater LA excitation force, we assumed that \( D \) can be ignored in our estimation of underwater LA excitation force.

3.4. Measured FRFs without passive vibration suppression

We demonstrate that our method can measure the auto- and cross-FRFs of underwater structures without any damping material up to 20 kHz, and their reliabilities can be evaluated with a reliability factor. In this experiment, we measured the auto- and cross-FRFs of the test piece shown in Figure 4 with points B and C as the excitation points and points A–D as the measurement points. The measurement conditions are the same as those described in the “3.1. Laser excitation system” subsection above. It is noted that our method can measure the dynamic properties of an underwater structure including the fluid drag. In our previous report (Hosoya et al., 2016a), we identified the characteristics of the modes up to 5 kHz (including three modes). In this study, we show that the applicable frequency range can be expanded by conducting modal analysis of the FRFs obtained by our method in the frequency range up to 20 kHz (including 12 modes). The modal analysis was conducted using the multi-point partial iteration method on the 50 FRFs obtained with point C as the excitation point and the points marked by “●” as the measurement points in Figure 4.

Figures 7 and 8 respectively show the auto-FRF (\( H_{CC} \)) at point C and the cross-FRF between points B and C (\( H_{BC}, H_{CB} \)), both determined with our method. For comparison, the FRFs obtained by FEA are overlaid. Additionally, the reliability factors are shown. Table 1 lists the natural frequencies obtained by our method and by FEA as well as the percentage error between them. Because the maximum percentage error is 2.9%, the data show that the natural frequencies obtained by our method agree well with those obtained by FEA considering water effects.

The reliability factors of the FRFs in Figures 7 and 8 are close to 1 near the resonance points but decrease significantly near the anti-resonance points. This is because the signal-to-noise ratio decreases near the
anti-resonance points, increasing the effect of random errors in the measured FRF. A similar trend is observed in the coherence function of the FRFs measured in conventional vibration experiments. Therefore, the reliability of the underwater structure FRFs obtained by our method can indeed be evaluated by the reliability factor.

The absolute value amplitudes of the FRFs obtained by our method and by FEA agree well with each other up into a high-frequency range up to about 20 kHz. Comparing the cross-FRFs \((H_{BC}, H_{CB})\) in Figure 8 shows that their absolute value amplitudes generally match each other. Although they are not perfectly linear systems, a certain degree of reciprocity can be discerned. Additionally, the input points for the two cross-FRFs are 90 mm apart in the water level, but the absolute value of the amplitude and phase characteristics of both the cross-FRFs are in good qualitative agreement. These results suggest that the underwater LA excitation force can be assumed to be constant within the water levels used in our experiments.

As for the phase characteristics obtained by the two methods, the trends in other regions only agree qualitatively, except in the frequency ranges below 5 kHz and around 15 kHz where they diverge. However, they match at the resonance points, where they are essentially 90 degrees. Additionally, Figure 9 shows that the vibrational mode shapes obtained by our method and by FEA agree qualitatively, while a slight difference in the figure was observed (1st, 2nd, 5th, and 6th). Possible causes for this discrepancy include non-linearity due to the fluid, fluid-related vibrations caused by interactions between the acrylic container, water, and the underwater structure, the cavitation bubbles formed during underwater LA, and the precision of the FE model.

These results demonstrate that our method can measure the FRFs of underwater structures up to 20 kHz and can identify the modal parameters of the measured FRFs, allowing the vibrational mode shapes to be obtained. Furthermore, the reliability of the measured FRFs can be quantified by the reliability factor.

### 3.5. Evaluation of passive vibration suppression in underwater condition

Next we evaluated passive vibration suppression in underwater structures, which is generally considered...
We used the test piece shown in Figure 4 with point C as the excitation and measurement points, and observed the waveform of the response and the auto-FRF at point C. The measurement conditions are as described in the subsection “3.1. Laser excitation system” above. A piece of butyl rubber (either 1 mm, 3 mm, or 5 mm thick) was attached with an adhesive to the underwater structure as a vibration damping material in the shaded area shown in Figure 4. This allowed for nonrestrictive passive vibration suppression.

Figures 10(a) and (b) show the response waveforms with the 1-mm and 5-mm-thick butyl rubber pieces, respectively. Figure 10(c) shows the waveform without passive vibration suppression. The auto-FRFs corresponding to Figures 10(a) and (b) are shown in Figures 11(a) and (b), respectively, and the auto-FRF without passive vibration suppression is overlaid for comparison. Table 2 shows the damping ratios obtained by the half-power bandwidth method. The waveform changes significantly when the damping ratio increases.

**Figure 9.** Mode shapes up to 20 kHz of the test piece obtained by an underwater laser excitation and calculated by finite element analysis (FEA).
Without passive vibration suppression, it takes about 75 ms for the maximum amplitude to be reduced to a tenth of its value, but the damped vibration waveforms take about 32 ms for the 1-mm-thick butyl rubber and 4 ms for the 5-mm-thick butyl rubber (Figures 10(a) and 10(b), respectively). Attaching a damping material decreases the reliability factor in the high-frequency region above 10 kHz and changes in the phase characteristics (Figures 11(a) and (b)). These behaviors most likely originate from an increase in the nonlinearity of the system owing to the added damping material. Furthermore, the reliability factor decreases as the signal-to-noise ratio decreases owing to damped vibration amplitude in the measurement, indicating the effect of random errors in the measured FRF.

The first and second natural modes are hardly affected by the vibration suppression from the damping material. However, the third and higher natural modes are greatly affected by vibration suppression; in the high-frequency region above 10 kHz, the vibration is suppressed so much that the peaks are difficult to discern. These results show that our method can experimentally evaluate passive vibration suppression of underwater structures in the high-frequency region above 10 kHz.

Table 2. Evaluation of passive vibration suppression.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Damping ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of damping material</td>
<td>1 mm</td>
</tr>
<tr>
<td>1st</td>
<td>0.15</td>
</tr>
<tr>
<td>2nd</td>
<td>0.16</td>
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<tr>
<td>3rd</td>
<td>0.19</td>
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<tr>
<td>4th</td>
<td>0.14</td>
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<tr>
<td>5th</td>
<td>0.26</td>
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<tr>
<td>6th</td>
<td>0.21</td>
</tr>
<tr>
<td>7th</td>
<td>0.40</td>
</tr>
</tbody>
</table>
4. Conclusions

In this study, we evaluated passive vibration suppression of underwater structures with an attached damping material in the high-frequency region up to about 20 kHz. We excited an underwater structure with underwater LA and measured the response with LDV. We also determined the FRF of the underwater structure with a noncontact vibration testing method. If both experiments of an underwater LA excitation force estimation and a vibration test have the same environment and conditions, then the underwater LA excitation force can be assumed to be the same. Consequently, by pre-determining the underwater LA excitation force under conditions identical to the actual experiment, only the output measurements are required to obtain the FRF. If these conditions are dramatically different from each other, we can obtain the LA excitation force as long as we re-calibrate the estimation of that in test site. Our method can estimate the underwater LA excitation force using Newton’s second law of motion.

In our experiments, we also investigated the reliability and the applicable frequency range of the FRFs obtained using our method. The reliability was evaluated by calculating the reliability factor, which corresponds to the coherence function in conventional vibration tests. We compared the phase characteristics and the absolute value amplitude of the FRFs and the vibrational mode shapes obtained with our method and with FEA taking the water mass and water level into account. The strings which suspended the test piece and a viscosity of water were not considered in our FEA simulation. Along with the evaluation of the reliability factors, we showed that our method to determine the FRFs can be applied to high-frequency ranges up to 20 kHz.

Additionally, we evaluated passive vibration suppression in underwater structures with an attached damping material. We used butyl rubber as the damping material, and the nonrestrictive passive vibration suppression was conducted. By studying the attainment of the response waveform and the absolute value amplitude of the auto-FRF, we accomplished the conventionally difficult task of evaluating passive vibration suppression of underwater structures in the high-frequency region up to 20 kHz through vibration tests, resulting in a sufficient capability to combine active vibration suppression.

Declaration of Conflicting Interests

The author(s) certify that there are no conflicts of interest with the Japan Society for the Promotion of Science.

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