Estimation of the acoustic field of a vibrating cylindrical shell considering an unknown acoustic disturbance

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Many studies have been conducted on methods to predict the acoustic radiation characteristics produced by the structural vibration, but the effects of external acoustic disturbances on the structure have typically not been taken into consideration. To solve the problem of previous studies, methods are proposed in this article to improve acoustic field estimation performance by considering both the acoustic field affected by structural vibration and the one affected by unknown acoustic disturbances. First, a method is proposed for estimating the structure-borne acoustic field based on signals from vibration sensors attached to the structure. In addition, the positions and the frequency characteristics of unknown disturbance sources are investigated based on the difference between the acoustic signals measured at some receiving points and the acoustic field estimation results, using the genetic algorithm and the least square method. Finally, the acoustic field of the structure is estimated by considering both unknown disturbance sources and structural vibration. The proposed theory is validated through a numerical analysis performed using a commercial software program. © 2018 Institute of Noise Control Engineering.

Primary subject classification: 75.7; Secondary subject classification: 74.6

1 INTRODUCTION
Sources, such as a jet engine of airplane and a propeller of vessel or submerged structures, are generally dealt with as exciting forces in vibration and external acoustic disturbances in acoustics. The exciting forces lead to surface vibration of the structure and then it causes structure-borne noise. In contrast, the acoustic disturbances directly cause noise by propagating through acoustic media. It also affects acoustic field through scattering of the structure. Like these, the acoustic field is established by the effect of the structure-borne noise and the acoustic disturbance. For the evaluation or the noise reduction of the acoustic field, it is important to estimate the structure-borne noise and the acoustic disturbance.

Generally, the structure-borne noise can get numerically by process of estimating the structural vibration and the radiated noise analysis. The studies related to the method mentioned above have been researched well. Especially, the structure-borne noise of cylindrical shell which this article will deal with has been extensively studied.

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Harari and Sandman\textsuperscript{1} investigated radiating acoustic characteristics by analyzing the vibration characteristics of fluid-contacting, finite, reinforced cylindrical shells. Bae et al.\textsuperscript{2} studied the acoustic radiation of a liquid-contacting cylindrical shell using the method developed by Burroughs\textsuperscript{3} and the D-M equation. Guo et al.\textsuperscript{4} studied the acoustic radiation characteristics of a liquid-contacting finite cylindrical shell by using the boundary element method. Lee and Kwak\textsuperscript{5} used the Rayleigh–Ritz method to derive a dynamic model for a freely vibrating cylindrical shell. Liu and Maury\textsuperscript{6} analyzed the acoustic radiation mode of a cylindrical shell by using the pressure-velocity method.

Most of these studies, the structure-borne radiating acoustic characteristics of cylindrical shells were analyzed but these did not take into consideration the noise caused by the external acoustic disturbance. Thus, the estimated acoustic field only with the structure-borne noise could be inaccurate. In fact, the acoustic disturbance has an effect on not only acoustic field but also the vibration field. However, the acoustic disturbance generally does not have a significant effect on the vibrational field of the structure in air because it needs too much power to cause the structural vibration by energy propagation through air with low-density. In other words, the acoustic disturbance rarely contributes to the vibration of structure in air, compared with a mechanical excitation. However, it does have a very large effect on the acoustic field around the
structure because it transmitted directly through the media or scattered from the structure surface.

Accordingly, this article proposed methods for investigating the acoustic field around the vibrating cylindrical shell affected by an exciting force and an unknown acoustic disturbance. In Sec. 2.1, the structure-borne acoustic field of the cylindrical shell was estimated based on the optimal sensor placement method\textsuperscript{7,8}, the modal expansion method\textsuperscript{9,10}, and acoustic transfer matrix method\textsuperscript{11}. In Sec. 2.2, the acoustic field caused by the acoustic unknown disturbance was estimated. Especially, the estimation method of locations of the unknown source based on genetic algorithm\textsuperscript{12-14} and the identification method of the unknown source based on the least square method were utilized. Then, in Sec. 3, the suggested methods were verified from the numerical analysis and its results.

2 THEORY OF ACOUSTIC FIELD ESTIMATION

Theories to estimate structure-borne acoustic field and acoustic field caused by an acoustic disturbance are introduced in Secs. 2.1 and 2.2, respectively. Especially, in Sec. 2.2, the source location prediction and the frequency spectrum prediction of the acoustic disturbance are explained in detail.

2.1 Optimal Sensor Placement and Structure-Borne Acoustic Field Estimation

A structure-borne acoustic field is estimated by using the mode expansion method with optimal sensor placement and an acoustic transfer matrix. The mode expansion method with optimal sensor placement is a method of estimating the vibration field of a structure that is the noise source of a structure-borne acoustic field.

In contrast to the conventional method, in this study, the sensor location information used for the calculation was based on values obtained from the genetic algorithm. The fitness function of the genetic algorithm was used to obtain the optimal sensor location information, which is expressed in the following equation [Eqn. (1)]:

$$\text{minimize} \sum_{i,j=1}^{N} \text{MAC}_{ij}$$

where

$$\text{MAC}_{ij} = \frac{||\Phi_i^T \Phi_j||^2}{\langle \Phi_i \rangle^T \{ \Phi_j \} \{ \Phi_j \}^T \{ \Phi_i \}}$$

where \{\Phi_i\} and \{\Phi_j\} respectively denote the ith and jth eigenmode vectors. MAC_{ij} is a determinant used to decide the independence or mutual dependence between eigenmodes; the value of 0 means mutual independence, while value of 1 means that the vectors are the same. Therefore, the diagonal elements of MAC_{ij} are always 1. When an eigenmode reconstructed by extracting some values is used, the diagonal elements have a value between 0 and 1, and thus the independence between the eigenmodes is not secured. Thus, the sensor placement was optimized in the present study to maintain independence between the eigenmodes as much as possible.

The mode expansion method using the optimal sensor placement information enables the highly accurate estimation of a vibration field even if a limited number of sensors are used. The mode expansion method is used to estimate the contributions of eigenmodes through the mode superposition principle, and to estimate vibration of responses of positions where measurement is not performed from the contributions. However, the modal expansion method can provide the reliable vibration responses when the number of responses, m, is more than the number of the contribution of the eigenmodes, n. In other words, the relationship equation between responses and eigenmodes must be over-determined problem.

The contribution of the eigenmode, \{\varpi(\omega)\}, is calculated by the following equation [Eqn. (2)]:

$$\{\varpi(\omega)\}_{n \times 1} = \left[\Phi^T\right]_{m \times n} \{x(\omega)\}_{m \times 1}$$

where \{\varpi(\omega)\} denotes the displacement responses obtained from m sensors, \left[\Phi^T\right] is the matrix reconstructed with n eigenmode vectors, and \dagger is the pseudo-inverse matrix. The contribution of the n eigenmodes estimated from Eqn. (2) is used to estimate the displacement response at the positions where measurement is not performed, \{x(\omega)\}, as shown in the following equation [Eqn. (3)]:

$$\{x(\omega)\}_{N \times 1} = [\Phi]_{N \times n} \{\varpi(\omega)\}_{n \times 1}$$

where \{\Phi\} is the eigenmode matrix of the entire system and N is the total degrees of freedom. The vibration field estimated using Eqn. (3) is used to estimate the structure-borne acoustic field. The acoustic field is estimated by using an acoustic transfer matrix. The governing equation for the boundary element method may be expressed as in the following equation [Eqn. (4)]:

$$C^0(X)p(X) = \int_S \left[ p_r(Y) \frac{\partial \Psi}{\partial n}(X,Y) \right. + p_i \nu_n v_n(Y) \left. \Psi(X,Y) \right] dS(Y)$$

$$C^0(X) = \lim_{\tau \rightarrow 0} \int_{S_0} \frac{\partial \Psi_{l}}{\partial n} dS_0$$

where p(X) denotes the acoustic pressure, v_n is the velocity in the normal direction, X is the position of a receiving point, Y is the position of the infinitesimal element, dS(Y), in a boundary element, and \Psi_{l} is the fundamental solution of the Laplace equation for three-dimensional space.
The Green function for the three-dimensional Helmholtz equation is calculated as in the following equation [Eqn. (6)]:

$$\nabla \psi (X, Y) = \frac{e^{-ikr}}{4\pi r} \tag{6}$$

where \( r = |X - Y| \). By substituting Eqns. (5) and (6) to Eqn. (4) and simplifying the resulting mathematical formula for all the nodes of the boundary elements by using shape functions, the governing equation may be expressed with the matrix of the following equation [Eqn. (7)]:

$$[\bar{H}] \{p_s(Y)\} = [\bar{G}] \{v_s(Y)\} \tag{7}$$

where \([\bar{H}]\) and \([\bar{G}]\) are the matrices defined by the Green function, and the subscript \(s\), means the structural surface. Equation (7) may be used to calculate the acoustic pressure function, and the subscript \(o\), means the structural surface.

Equation (7) may be used to calculate the acoustic pressure vector, \(\{p_o(Y)\}\), at all the nodes of the boundary elements from the velocity vector on the structural surface, \(\{v_o(Y)\}\). With the normal velocity vector and the acoustic pressure vector on the structural surface, the acoustic pressure vector at receiving points, \(\{p_r(X)\}\), may be estimated as in the following equation [Eqn. (8)]:

$$\{p_r(X)\} = [h(X, Y)]^T \{p_o(Y)\} + [g(X, Y)]^T \{v_o(Y)\} \tag{8}$$

where \(h(X, Y)\) and \(g(X, Y)\) are the vectors derived from Eqn. (4) and the subscript \(F\), denotes the receiving points. Substitution of Eqn. (7) to Eqn. (8) gives the following equation [Eqn. (9)]:

$$\{p_r(X)\} = [A] \{v_o(Y)\} \tag{9}$$

where the acoustic transfer function, \([A]\), is given as follows:

$$[A] = [h(X, Y)]^T H(X, Y)^{-1} G(X, Y) + g(X, Y)^T \tag{10}$$

If the acoustic transfer matrix is known, the acoustic pressure at a receiving point may be calculated by using the normal velocity vector of the structural surface. The normal velocity vector of the structure, \(\{v_o(Y)\}\), may be expressed as a product of the structural displacement in Eqn. (3), \(\{x(\omega)\}\), and the transformation matrix, \([T]\), as shown in the following equation [Eqn. (11)]:

$$\{v_o(Y)\} = j\omega[T]\{x(\omega)\} \tag{11}$$

Hence, from Eqns. (8), (9), and (11), the acoustic pressure vector on the structural surface, \(\{p_o(Y)\}\), and that on a receiving point, \(\{p_r(X)\}\), are defined as follows:

$$\{p_o(Y)\} = j\omega[H]^{-1}[G][T]x(\omega) \tag{12}$$

Consequently, the structure-borne acoustic field may be estimated by using the displacement signals on the structural surface estimated by the mode expansion method with optimal sensor placement.

### 2.2 Estimation of Acoustic Field Considering an Unknown Acoustic Disturbance

#### 2.2.1 Theory for estimating the position of an unknown sound source

The actual acoustic pressure measured by a microphone includes not only the radiating structure-borne acoustic pressure but also the acoustic pressure transferred from external sound sources. However, the position and the magnitude of the external sound sources are often unknown. Therefore, the position of external sound sources was estimated as follows.

As shown in Fig. 1, when acoustic waves from sound source at unknown positions are transferred to two microphones, the cross-spectrum of the signals measured at the two microphones is defined as in the following equation [Eqn. (14)]:

$$S_y(\omega) = P_i(\omega)^*P_j(\omega) \tag{14}$$

where \(P_i(\omega)\) and \(P_j(\omega)\) denote the acoustic pressure spectrum which are induced by the unknown acoustic disturbance and obtained from the microphones \(i\) and \(j\), respectively, and the superscript * denotes the complex conjugate. If distances between sound source and each microphone are much longer than the distance between the two microphones, the
phase of the cross power spectrum, $\theta$, has the following relation with $\tau$, the time delay between the two signals and frequency, $f$:

$$\tau = \frac{\theta}{2\pi f}. \quad (15)$$

The time delay between the two signals, calculated by using Eqn. (15), is used to calculate the relative distance from the sound sources, $\Delta d_{ij}$, as shown in the following equation [Eqn. (16)]:

$$\Delta d_{ij} = c\tau \quad (16)$$

where $c$ is the propagation speed of the medium. If the position of the acoustic disturbance is assumed to be $(x, y, z)$ and the positions of the microphones to be $(x_i, y_i, z_i)$ and $(x_j, y_j, z_j)$, respectively, the relative distance from the sound sources to the receiving points shown in Eqn. (16) may be expressed as in the following equation [Eqn. (17)]:

$$\Delta d_{ij}^{est} = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - \sqrt{(x - x_j)^2 + (y - y_j)^2 + (z - z_j)^2} \quad (17)$$

If the positions of the sound sources are accurate, Eqns. (16) and (17) give the same value. However, if the positions of the sound sources are inaccurate, a relative error exists. In the present study, the genetic algorithm was used to determine the unknown sound sources that would minimize this error. The fitness function of the genetic algorithm for determining the unknown sound sources is expressed as in the following equation [Eqn. (18)]:

$$\text{Minimize } \sqrt{\frac{1}{N C_2} \sum_k (\Delta d_{ij} - \Delta d_{ij}^{est})^2} \quad (18)$$

where $C$ is combination and $N$ denotes the number of receiving points. The genetic algorithm based on Eqn. (18) may be used to determine the position of the unknown sound sources $(x, y, z)$.

### 2.2.2 Theory for estimating the frequency spectrum of an unknown sound source

The frequency spectrum of an unknown sound source was investigated using the following procedures. The acoustic pressure caused by an unknown sound source may be expressed as the difference between the acoustic pressure

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Table 1—Material properties of the cylindrical shell.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>210 GPa</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Mass density</td>
<td>7850 kg/m³</td>
</tr>
</tbody>
</table>

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Fig. 2—Geometry of the cylindrical shell.

Fig. 3—Spectrum of force exerted on the shell structure.

Fig. 4—Spectrum of acoustic disturbance which cannot be measured.
measured at a receiving point and that caused by structure-borne radiating noise, as in the following equation [Eqn. (19)]:

\[ \{p_d\} = \{p_m\} - \{p_F\} \quad (19) \]

where \(\{p_m\}\) denotes the acoustic pressure measured at a receiving point, \(\{p_F\}\) is the estimated acoustic pressure caused by structure-borne radiating noise, and \(\{p_d\}\) is the acoustic pressure caused by an unknown disturbance, which can include background noise. Here, the acoustic pressure caused by an unknown disturbance, \(\{p_d\}\), is expressed as a product of the acoustic source spectrum and the transfer function in the frequency region, as shown in the following equation [Eqn. (20)]:

\[ \{p_d(\omega)\} = [G(\omega)]\{Q(\omega)\} \quad (20) \]

where \(Q(\omega)\) is the frequency spectrum of the unknown sound source, \(G(\omega)\) is the transfer function from the position of an unknown sound source estimated in Sec. 2.2.1 to the receiving point, and \(\omega\) is the frequency. Since the transfer functions \(G(\omega)\) and \(p_d(\omega)\) in Eqn. (20) are known, the frequency spectrum of an unknown sound source may be estimated by the least square method, as shown in the following equation [Eqn. (21)]:

\[ \{Q(\omega)\} = [G(\omega)]^+\{p_d(\omega)\} \quad (21) \]

where \(^+\) denotes the pseudo-inverse matrix.

3 NUMERICAL ANALYSIS AND RESULT

3.1 Numerical Model

In Sec. 3, the structure-borne and unknown disturbance-borne acoustic fields of a cylindrical shell are estimated based on the theoretical equations introduced in Sec. 2.

The numerical model used in this article represents a steel cylindrical shell having a diameter of 1 m, a length of 2 m, and a thickness of 10 mm. Material properties of the cylindrical shell are represented in Table 1. The finite element model included 1640 nodes and 1600 elements.

The theories suggested in this article were validated by numerical analysis data. Figure 2 shows information of the analytical model used for the validation. The information includes the cylindrical shell structure, receiving point elements, excitation points, and the positions of the external disturbance (2000, 3200, 7500) mm. Figures 3 and 4 show the spectra of the input excitation force and the external disturbance, respectively. The numerical analysis was performed using MSC Nastran and LMS Sysnoise in a frequency range from 1 to 500 Hz.

3.2 Estimation of the Acoustic Field

3.2.1 Estimation of the Structure-Borne Acoustic Field

Before estimating the structure-borne acoustic field, the vibration field of the cylindrical shell was estimated
using the mode expansion method with optimal sensor placement, as described in Sec 2.1. Figure 5 shows the 40 optimal sensor positions obtained with the optimal sensor placement. The vibration field was estimated through the mode expansion method using signals measured at the optimal sensor positions shown in Fig. 5.

Figure 6 compares the acoustic field (called estimation) estimated using the 40 sensor signals and 40 eigenmodes, and the one in the validation model (called reference). Estimated vibration fields are almost matched to the vibration field of reference. For the quantitative analysis, this article uses the error index defined as follows:

$$E(\omega) = \sqrt{\sum_{i=1}^{N} \left( \frac{x_{\text{ext},i}(\omega) - x_{\text{ref},i}(\omega)}{x_{\text{ref},i}(\omega)} \right)^2} \times 100$$  \hspace{1cm} (22)$$

where $N$ is the number of nodes, $x_{\text{ext},i}(\omega)$ is the estimated vibration (or acoustic) response at $i$th node at specific frequency and $x_{\text{ref},i}(\omega)$ is the reference vibration (or acoustic) response at $i$th node at specific frequency. Table 2 represents the errors calculated by Eqn. (22) at harmonic frequency of exciting force. It shows the estimation of vibration fields is well and valid because the normalized errors are within about 0.008%, which is sufficiently small.

Next, the acoustic field estimated by using the mode expansion method and the acoustic transfer matrix of the cylindrical shell model were used to calculate the structure-borne acoustic field, as shown in Fig. 7. For comparison, the structure-borne acoustic field of the validation model is also shown. As can be seen from Fig. 7, the structure-borne acoustic fields also well estimated when those are compared to reference acoustic fields. Table 3 shows the errors calculated by Eqn. (22) at harmonic frequency of exciting force. It also shows good agreement since the errors are within 0.003%, which is sufficiently small.

### 3.2.2 Estimation of acoustic field formed by an unknown sound source

The positions of unknown sound sources were estimated using the theory described in Sec. 2. Figure 8 shows the

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Error (%)</th>
<th>Frequency (Hz)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>7.855e-3</td>
<td>300</td>
<td>4.899e-3</td>
</tr>
<tr>
<td>100</td>
<td>6.237e-3</td>
<td>350</td>
<td>5.981e-3</td>
</tr>
<tr>
<td>150</td>
<td>3.060e-3</td>
<td>400</td>
<td>4.803e-3</td>
</tr>
<tr>
<td>200</td>
<td>5.973e-3</td>
<td>450</td>
<td>6.139e-3</td>
</tr>
<tr>
<td>250</td>
<td>3.803e-3</td>
<td>500</td>
<td>6.273e-3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Error (%)</th>
<th>Frequency (Hz)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
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<td>50</td>
<td>1.135e-6</td>
<td>300</td>
<td>3.263e-4</td>
</tr>
<tr>
<td>100</td>
<td>2.434e-6</td>
<td>350</td>
<td>6.737e-4</td>
</tr>
<tr>
<td>150</td>
<td>2.796e-3</td>
<td>400</td>
<td>7.200e-4</td>
</tr>
<tr>
<td>200</td>
<td>1.531e-6</td>
<td>450</td>
<td>4.732e-4</td>
</tr>
<tr>
<td>250</td>
<td>6.181e-4</td>
<td>500</td>
<td>3.583e-4</td>
</tr>
</tbody>
</table>

![Fig. 7—Estimation of structure-borne acoustic-field due to exciting force.](image)
receiving points for the estimation of the unknown sound source positions. Table 4 shows the coordinates of the individual receiving points. Table 5 shows the parameters of the genetic algorithm, and Table 6 shows the unknown sound source positions estimated by implementing the algorithm 10 times.

Since the actual positions of the sound sources are 2000, 3200, and 7500 mm, the positions of the unknown sound sources were estimated, within an error of 2.1%. The error of the estimated acoustic disturbance position, e, is defined as in the following equation [Eqn. (23)]:

\[
e = \frac{\sqrt{(x_{\text{true}} - x)^2 + (y_{\text{true}} - y)^2 + (z_{\text{true}} - z)^2}}{\sqrt{(x_{\text{true}})^2 + (y_{\text{true}})^2 + (z_{\text{true}})^2}} \times 100
\]

where \(x_{\text{true}}, y_{\text{true}},\) and \(z_{\text{true}}\) respectively represent the actual coordinates of the sound sources, and \(x, y,\) and \(z\) represent the coordinates of the sound sources estimated by the theory described in Sec. 2.2.1.

The estimated positions of the unknown sound sources, the transfer functions from the unknown sound source positions to the receiving points, and the acoustic pressure data calculated in Sec. 3.2.1 were used to obtain the

Table 4—Input data of coordinates of field points where microphone was located.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>Z (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>①</td>
<td>0</td>
<td>0</td>
<td>15,000</td>
</tr>
<tr>
<td>②</td>
<td>200</td>
<td>200</td>
<td>15,000</td>
</tr>
<tr>
<td>③</td>
<td>400</td>
<td>400</td>
<td>15,000</td>
</tr>
<tr>
<td>④</td>
<td>600</td>
<td>600</td>
<td>15,000</td>
</tr>
<tr>
<td>⑤</td>
<td>600</td>
<td>0</td>
<td>15,000</td>
</tr>
<tr>
<td>⑥</td>
<td>0</td>
<td>600</td>
<td>15,000</td>
</tr>
<tr>
<td>⑦</td>
<td>200</td>
<td>400</td>
<td>15,000</td>
</tr>
<tr>
<td>⑧</td>
<td>400</td>
<td>200</td>
<td>15,000</td>
</tr>
</tbody>
</table>

Table 5—Input data of genetic algorithm used to estimate the location of the sound source.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>150</td>
</tr>
<tr>
<td>Maximum generation</td>
<td>1500</td>
</tr>
<tr>
<td>Crossover probability</td>
<td>70%</td>
</tr>
<tr>
<td>Mutation probability</td>
<td>2%</td>
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</table>

Table 6—Converged results of the locations of sound source determined by genetic algorithm.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Converged value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>①</td>
<td>(2013, 3221, 7448)</td>
</tr>
<tr>
<td>②</td>
<td>(2013, 3221, 7448)</td>
</tr>
<tr>
<td>③</td>
<td>(2013, 3212, 7471)</td>
</tr>
<tr>
<td>④</td>
<td>(2012, 3221, 7448)</td>
</tr>
<tr>
<td>⑤</td>
<td>(2028, 3248, 7341)</td>
</tr>
<tr>
<td>⑥</td>
<td>(2012, 3221, 7448)</td>
</tr>
<tr>
<td>⑦</td>
<td>(2028, 3248, 7378)</td>
</tr>
<tr>
<td>⑧</td>
<td>(1,963, 3136, 7662)</td>
</tr>
<tr>
<td>⑨</td>
<td>(2012, 3221, 7448)</td>
</tr>
<tr>
<td>⑩</td>
<td>(2007, 3212, 7471)</td>
</tr>
</tbody>
</table>

Fig. 8—Field points where microphone was located to measure acoustic pressure.

Fig. 9—Estimation of acoustic disturbance.
acoustic pressure data of the unknown sound sources, as shown in Fig. 9.

Figure 9 shows the estimated spectrum of the unknown sound sources. Figure 10 shows the acoustic fields caused by the acoustic disturbance and the reference acoustic fields. It represents the estimated acoustic fields caused by the acoustic disturbance which is well matched to the reference acoustic fields. Table 7 represents the errors from Eqn. (22). It shows that the progresses in this article are proper to estimate the acoustic field caused by the acoustic disturbance since the errors are within about 0.2766%, which is sufficiently small.

3.2.3 Structure-borne acoustic field considering unknown disturbance

The acoustic field was calculated by considering both the structure-borne acoustic field and the acoustic field formed by the unknown disturbance. Figure 11 shows the acoustic field estimated by considering all noise effects, and the acoustic field that was actually measured is also shown for comparison.

The results in Fig. 11 show that the acoustic field estimated using the vibration signals obtained at the actual optimal sensor positions, and the acoustic signals obtained from some receiving points, correctly estimated the actual acoustic field. Table 8 represents the errors from Eqn. (22). It also shows good agreement since the errors are within about 0.4986%, which is sufficiently small.

4 CONCLUSIONS

This study suggested theories that can be used to estimate the acoustic field produced by the surface vibration and unknown source. Especially, this article dealt with a cylindrical shell affected by an exciting force in the field with an acoustic disturbance. For this structure, the suggested theories were validated from the comparison between the estimated acoustic fields and the reference obtained from the proper numerical analysis. Accordingly, this article comes to the conclusion as follows.

First, a theory that combined the modal expansion method utilizing spectra of optimal located sensors with the acoustic transfer matrix for the structure-borne acoustic field estimation was developed. The vibration field was estimated within an error of 0.008%, and the structure-borne acoustic field was estimated within an error of 0.003%, in spite of using a limited number of vibration sensors.

Second, a theory estimating the source position by using the genetic algorithm and a theory estimating the frequency spectrum of the source by using the least square method were developed for the estimation of the acoustic field by an acoustic disturbance. The position of the unknown source was estimated within an error of 2.1%. The frequency spectrum of the acoustic disturbance also correctly determined when it compared with the actual input spectrum. Then, the acoustic field by the acoustic disturbance

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.0866</td>
</tr>
<tr>
<td>300</td>
<td>0.0578</td>
</tr>
<tr>
<td>450</td>
<td>0.2766</td>
</tr>
</tbody>
</table>
was estimated within an error of 0.2766%. In addition, the acoustic field combined with the effect of the structure-borne radiation and the scattering of the acoustic disturbance was estimated within an error of 0.4986%.

Since the theories suggested in this article can accurately estimate the practical acoustic field around a structure even though the number of the sensors is lacking and the characteristics of an acoustic disturbance are unknown, the theories may help to evaluate the individual contributions of a structure-borne acoustic field and one formed by unknown sound sources, and to understand the characteristics of the individual acoustic fields.

5 REFERENCES


Table 8—Errors between the estimated acoustic fields combined with the effect of the structure-borne radiation and the scattering of the acoustic disturbance and the reference at specific frequencies.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.0366</td>
</tr>
<tr>
<td>300</td>
<td>0.0940</td>
</tr>
<tr>
<td>450</td>
<td>0.4986</td>
</tr>
</tbody>
</table>

Fig. 11—Estimation of acoustic-field due to vibrating-structure under acoustic disturbance.