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Experimental validation of the sound transmission of rectangular baffled plates with general elastic boundary conditions

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Abstract: Several prediction methods have recently been developed for systematically studying the effects of general boundary conditions on the sound transmission loss (STL) of plate-like structures. But corresponding experimental validation studies remain scarce owing to the difficulty of obtaining accurate boundary conditions for practical structures. This paper presents a convincing experiment conducted on a baffled plate system to validate the STL prediction model in a previous paper by Yu *et al.* [Noise Control Eng. J. **58**(2), 187–200, 2010]. A method is proposed to determine the boundary conditions of this system, and experimental STL compares well with the predictions based on the identified boundary condition.

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1. Introduction

The effects of elastic boundary supports (also called "elastic boundary conditions") on the vibroacoustic response of plate-like structures have been studied for decades.[1–4] These investigations have indicated that boundary supports significantly affect the sound insulation properties of plates, especially in the low frequency domain. More recently, several simulation methods[5–7] have been developed that allow for efficiently computing the vibroacoustic response of plates with arbitrary elastic boundary conditions. For instance, the component mode synthesis technique (CMS) was applied to calculate the sound transmission loss (STL) of baffled plates with general boundary conditions.[6] Also, Yu *et al.*[7] proposed a coupled finite element method and boundary element method (FEM/BEM) that could examine the effects of general boundary conditions by taking into account the effect of fluid loading.

Previous researchers[5–7] dealing with general boundary conditions, however, have only provided numerical examples in their studies. The lack of experimental implementation and validation studies reflects the difficulty of measuring accurately the boundary parameters of a specific plate system.[6] In one study, Jessop[8] measured the STL data of baffled plates with general elastic boundary supports; he achieved the elastic supports by placing lower-density elastic materials along the contour of the tested plate. The corresponding boundary parameters were obtained according to the material stiffness data provided by the manufacturer. Jessop pointed out, however, that the predicted results did not agree well with the measured data, one explanation being the lack of accurate information on the structural boundary conditions.

The aim of the present paper is twofold. The first objective is to present a simple but effective method for identifying structural boundary conditions (hereinafter the "BCI method"), which is based on a coupled FEM/BEM model. The BCI method

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allows taking into account the fluid loading effects and thus is able to identify structural boundary conditions with higher accuracy. Only a few low-order natural frequencies are needed when using this method.

The second objective is to design a convincing experiment to validate the STL prediction model in our previous paper.[7] For this purpose, a baffled plate system was designed and the following validation procedure was performed: (1) identifying the actual boundary condition of the plate system using the BCI method, (2) predicting the STL value using the prediction model[7] based on the identified boundary condition, (3) measuring the STL data of the plate system, and (4) comparing the measured STL with the predicted results obtained in (2).

The layout of this paper is as follows. Section 2 describes all measurements used in this study; these include modal testing and acoustic testing on a specific baffled plate system, which we used to determine the structural natural frequencies and the STL, respectively. Section 3 begins with a brief outline of the BCI method, followed by a detailed application of this method for identifying the boundary condition of the baffled plate system. In Sec. 4, the STL prediction model[7] is validated based on the measured STL data and the identified boundary condition. Finally, Sec. 5 presents some conclusions.

2. Measurements

2.1 Setup

Figure 1 schematically illustrates the experimental setup. The measurements were conducted in two connected chambers at The Hong Kong Polytechnic University. The net volumes of these two chambers were 200 m^3 and 70 m^3, respectively. The two chambers shared a common wall. To make the chambers semi-anechoic, acoustic absorptive materials were added to the surface of the walls except for the common wall. The common wall had a square port at its center sized 26 cm $\times$ 26 cm, which was designed to hold the tested panel. A 1 mm thick aluminum (Al) panel was mounted in this port using two identical steel frames that screwed directly into the port. Each frame was 34 cm by 34 cm square and 3 mm thick, with a 24 cm by 24 cm square opening cut out of the middle. The Al panel was cut to 25.6 cm by 25.6 cm square to allow 8 mm of each edge to be clamped between these two steel frames. Two sets of measurements were conducted on this plate system, as described in the following subsections.

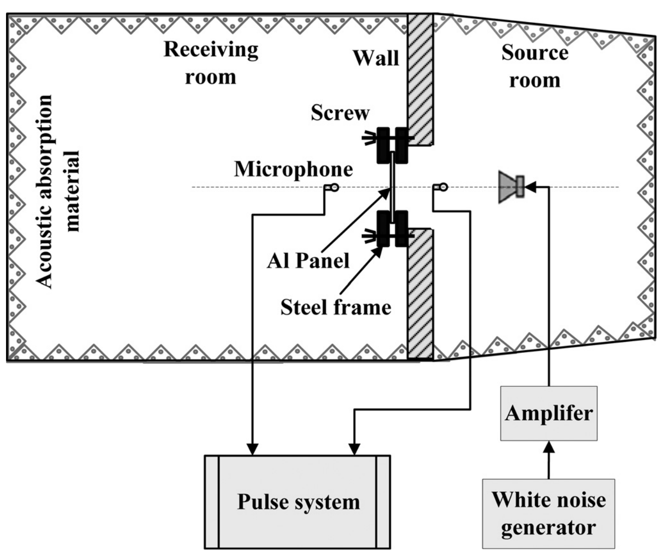

Fig. 1. Schematic diagram of the experimental setup.

Table 1. Measured and predicted natural frequencies.

Natural frequency	Measured (Hz)	Predicted (Hz)	Error (%)
f_1	116.25	116.25	0
f_2	239.30	239.00	−0.13
f_3	239.30	239.00	−0.13
f_4	341.50	341.02	−0.14

2.2 Modal testing

To determine the natural frequencies, we conducted a modal test on this plate system using impact excitation. This was done by exciting the Al panel with an impact hammer (Kistler: 9726A) and measuring the response with accelerometers (B&K: 4394). All measured data were collected by PULSE (B&K: 3160-B-042). A simple peak-picking method[9] was used to detect the natural frequencies and the damping. Table 1 lists the results of the natural frequencies. The damping ratio ζ_1 of the fundamental mode was estimated to be 0.0115.

2.3 STL measurement

STL measurements were also conducted on this plate system. A loudspeaker (diameter 25 cm) was located in the smaller chamber with a distance of 40 cm from the panel to provide an approximation of a normally incident plane wave. A broadband white noise signal (0–800Hz) was used to drive the speaker. Two microphones (B&K: 4935) were located respectively on the incident side and the radiated side at the same distance (20 cm) from the panel at the center line to measure the sound pressure on both sides. The microphone on the incident side was placed normal to the panel to give a representative sound pressure level of the whole radiated field.[10] All measured data were collected by PULSE (B&K: 3160-B-042). The STL of the plate system could then be determined using these data, as in Ref. 10. Figure 2 shows the measured STL value as a function of frequency.

3. Boundary condition identification

3.1 BCI method

Consider a thin, baffled, rectangular plate with uniform elastic boundary supports along the four edges, as shown in Fig. 3. The elastic supports, as in Refs. 2, 3, and 5–7, are modeled as a combination of translational and rotational springs. To identify the spring

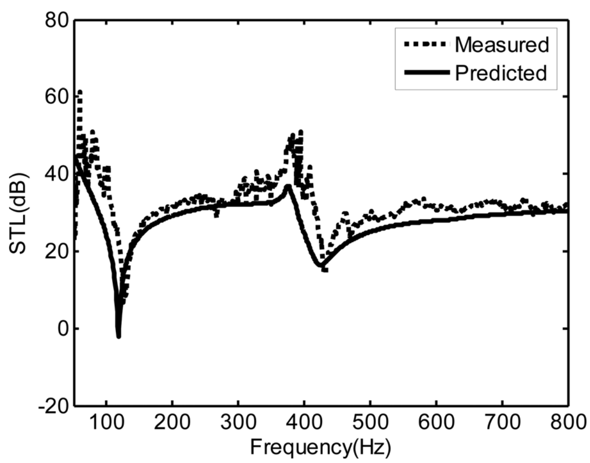

Fig. 2. Comparison of the predicted (heavy color) and measured results (light color).

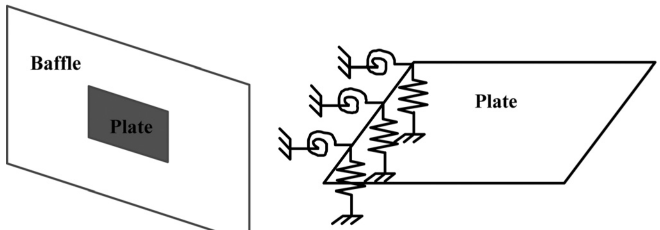

Fig. 3. Schematic illustration of a baffled rectangular plate system: (a) a plate mounted on an infinite rigid baffle; (b) elastic boundary supports along the edges (for simplicity and clarity, only the supports along the left edge are shown).

constants, one available method has been provided by Ahmadian *et al.*[11] The essence of their method is that a relationship between the natural frequencies and structural boundary conditions can be established by solving the characteristic equations. From this relationship, the boundary conditions can be identified using the measured natural frequencies.

The present BCI method is very similar to Ahmadian's method. The main difference between the two methods is the process of establishing the characteristic equations. In the BCI method, the coupled FEM/BEM method of Yu *et al.*[7] is used and the characteristic equation is given as

$$\left|(\{\mathbf{K}\}+\{\mathbf{S}\}-\omega^2\{\bar{\mathbf{M}}\})-2(ab)\{\mathbf{T}\}\{\mathbf{A}\}\{\mathcal{R}\}\right|=0, \quad (1)$$

where $\{\mathbf{K}\}$ and $\{\bar{\mathbf{M}}\}$ are the stiffness and mass matrices of the plate. Each small finite (boundary) element has a size of $a \times b$. $\{\mathbf{T}\}$ is a global transformation matrix converting centrally loaded pressure forces to the corresponding nodal forces. $\{\mathcal{R}\}$ is a global transformation matrix converting the nodal displacement vectors to the corresponding central displacement vectors. $\{\mathbf{A}\}$ is a matrix that describes the fluid loading effects, and $\{\mathbf{S}\}$ is the stiffness matrix for the boundary support.[7] Only three variables, S_t, S_θ, and S_ϕ ($S_\theta = S_\phi$), are contained in $\{\mathbf{S}\}$, since the boundary conditions along the four edges of the plate are supposed to be uniform.

Once the characteristic equations are formed, the next procedures to identify the boundary parameters are the same as in Ref. 11. They can be briefly described as the following two steps: (1) A set of solutions for the boundary parameters is obtained

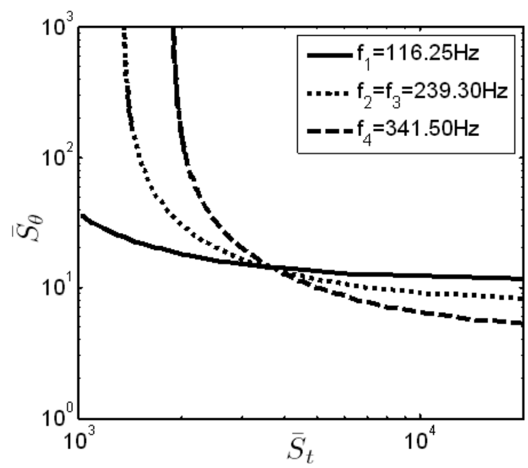

Fig. 4. Solutions for $\bar{S}_t$ and $\bar{S}_\theta$ that satisfy the characteristic equation.

by solving Eq. (1) for each measured mode, and (2) a unique solution is then obtained by selecting the one that satisfies Eq. (1) for all measured modes. Because of the inevitable measurement errors, there may be no unique solution that satisfies Eq. (1) for every mode. But the most likely solution can still be estimated based on the accuracy of each measured mode.[11]

The main advantage of the BCI method is that it allows taking into account the fluid loading effects on the structural natural frequencies and can thus be used when the structure is in contact with liquid. Even in the air, this method can give more accurate results since the effects of fluid loading have been proved to be more significant in near-resonant frequency regions.[7]

3.2 Application

In this subsection, the capability of the BCI method is verified by identifying the tested plate system used in Sec. 2. The measured natural frequencies obtained from the modal test (listed in Table 1) are used in the identification process. Figure 4 shows the acceptable solutions for each of the first four modes. The solution that best satisfies all modes can be found in the figure, which are $\bar{S}_t = 3201$ and $\bar{S}_\theta = \bar{S}_\phi = 13.28$. Here, $\bar{S}_t$, $\bar{S}_\theta$, and $\bar{S}_\phi$ are the dimensionless forms of S_t, S_θ, and S_ϕ, respectively. The dimensionless treatments are the same as those used in Refs. 3, 5, and 6. Table 1 also shows the predicted natural frequencies for the identified boundary solution.

4. Validation of the STL model

The measured STL values in Fig. 2 are used in this section to validate the STL prediction model in Ref. 7. To complete this validation, the identified boundary condition (in Sec. 3 B) and the damping ratio (in Sec. 2 B) of the tested plate system are treated as the inputs of the STL prediction model.[7] Figure 2 shows a comparison of the predicted and experimental STL values as a function of frequency (50–800Hz). STL values below 50 Hz do not exist, since this was the frequency range where the output of the loudspeaker was too poor to obtain a sufficient signal-to-noise ratio. As Fig. 2 shows, the predicted STL results agree well with the experimental data. The discernible discrepancies can be attributed to a number of factors, such as the unavoidable flanking transmission paths, uneven panel thickness, and non-uniform boundary conditions along the plate edges.

5. Conclusion

A method has been proposed to identify the boundary conditions of practical plate-like structures, which is based on a coupled finite element and boundary element method (FEM/BEM) that allows taking into account the fluid loading effects and thus is able to obtain more accurate results. Only a few low-order natural frequencies of the structure are needed when using this method. This method has been demonstrated by identifying the boundary condition of a practical plate system.

The STL measurements have also been conducted on this plate system. The measured STL value and the identified boundary condition are then used to validate the STL prediction model in Ref. 7. The results show that the prediction model has good accuracy and reliability.

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