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Sound leakage identification for an enclosed room using the probabilistic approach and model class selection index: An experiment

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Abstract

This study presents a full-scale experiment to identify the sound leakages on a wall of an enclosed room using the probabilistic approach. This study furthers the work in companion papers [Y.Y. Lee et al., Reconstruction of the interior sound pressure of a room using the probabilistic approach, *Journal of Sound and Vibration* 298(4–5) (2006) 887–891; H.Y. Sun et al., Distinguishing between the interior pressures induced from two independent sources within a room using the probabilistic approach, *Applied Acoustics* (2007), accepted and forthcoming; T.C. Hsia, *System Identification: Least-Squares Methods*, Lexington Books, D.C., Heath and Company, Lexington, MA, 1977]. A model class selection index is developed and used to identify the number of leakages, which is an unknown parameter in the identification process. The experiment was conducted to prove the validity of the probabilistic approach.

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1. Introduction

The probabilistic approach that is proposed in this study has recently been employed to solve interior acoustic problems in companion papers by Lee et al. [1] and Sun et al. [2]. In a previous study, a theoretical comparison of the probabilistic approach with the most common least error square method [3] verified that the probabilistic approach, which was originally used in the area of structural health monitoring, was an alterative effective method for (1) distinguishing between the interior pressures that are induced from independent sources within an enclosed room, and (2) identifying sound leakages on a wall surface. Note that the more advanced least error square method presented by Hsia [4] was not included in Ref. [2]. This study presents an experiment to verify the effectiveness of the probabilistic approach for identifying sound leakages on a wall surface.

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2. Theory

According to the theoretical work in the companion papers [1,2], the posterior marginal probability density function (PDF) of the unknown parameters **a** in the acoustic model $M_{\bar{K}}$ and a model class selection index to evaluate a model with $\bar{K}$ sound leakages are given by, respectively,

$$\pi(a*|D_N, M_{\bar{K}}) = \int_{S(\mathbf{a}')} \pi(\mathbf{a}|D_N, M_{\bar{K}})\,\mathrm{d}\mathbf{a}',$$
$$I_{\bar{K}} = \frac{\int_{S(a)} \pi(\mathbf{a}|D_N, M_{\bar{K}})\,\mathrm{d}\mathbf{a}}{S(\mathbf{a})}, \qquad (1a, b)$$

where D_N is the set of measured sound pressure data, $M_{\bar{K}}$ the acoustic model of an enclosed room with sound leakages, which is developed from the wave equation and modal analysis approach (see Refs. [1,2,5] for the derivations), $\mathbf{a}'$ the uncertain parameter vector that excludes $\boldsymbol{a}^*$, and $S(\mathbf{a})$ is the predefined domain of **a**.

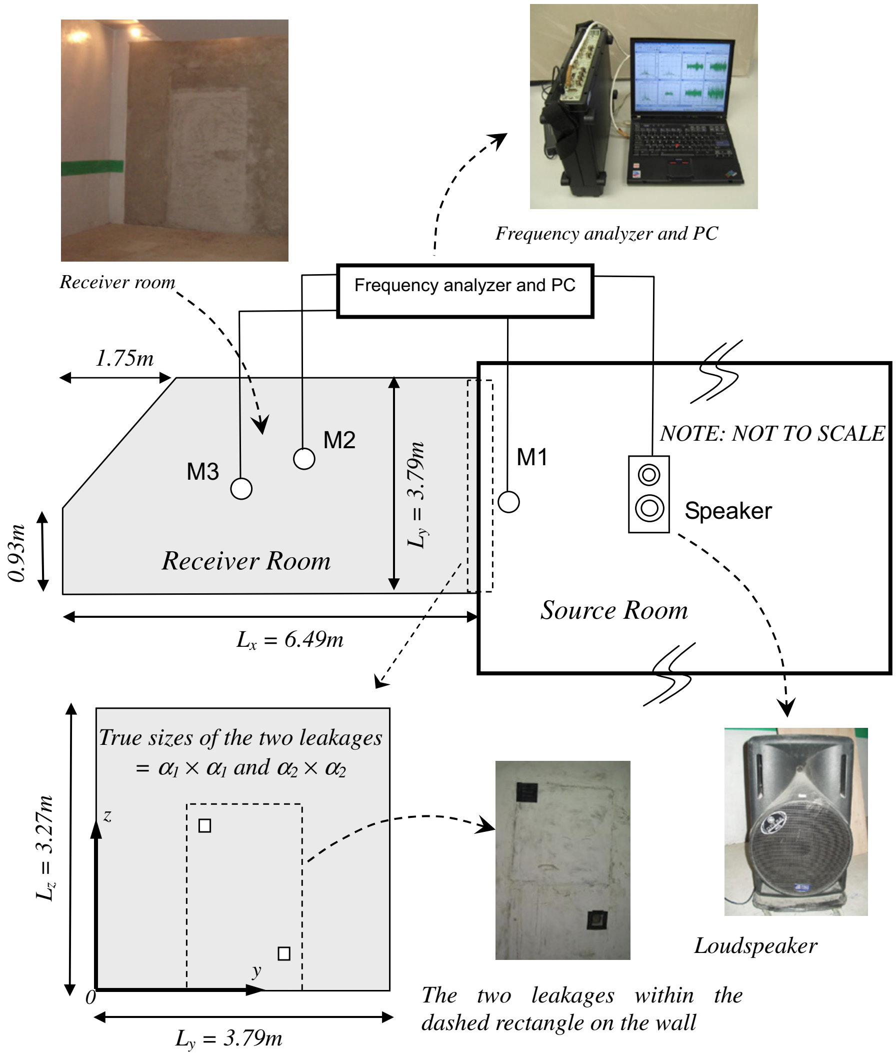

Fig. 1. Layout of the full-scale experiment.

The term $\pi(\mathbf{a}|D_N, M_{\bar{K}})$ in Eqs. (1a,b) is given by

$$\pi(\mathbf{a}|D_N, M_{\bar{K}}) = c\int_0^{\infty} \frac{1}{(\sqrt{2\pi}\sigma)^{NN_o}} \times \exp\left[-\frac{1}{2\sigma^2}\sum_{\tau=1}^{N} ||\hat{p}(\tau) - p(\tau;\mathbf{a})||^2\right] \mathrm{d}\sigma, \tag{2}$$

where N_O is the number of measurement stations, N is the number of measured time steps at each measurement location, σ represents the prediction error and is the uncertain parameter of the probabilistic model, c is a normalizing constant, $\hat{p}(\tau)$ is the vector of measured sound pressures at the τth time step, $p(\tau;\mathbf{a})$ is the vector of calculated sound pressures that is based on the model $M_{\bar{K}}$ for the given set of uncertain parameters **a**, and $||\ ||$ is the usual Euclidean norm of a vector. The PDF and index in Eqs. (1a,b) are normalized so that the maximum values are equal to one, where $\tilde{K}$ is the number of models that is considered. It can be seen that a higher index value implies a higher probability of the number of sources equal to $\bar{K}$.

3. Experiment

The acoustic experiment was carried out in Hong Kong in the laboratory of Acoustics and Air Testing Laboratory Co. Ltd. The layout of the laboratory is shown in Fig. 1. The walls, floors, and ceilings of the rooms are acoustically rigid. A loudspeaker was set in the source room. A microphone, M1, (B&K type 4188)

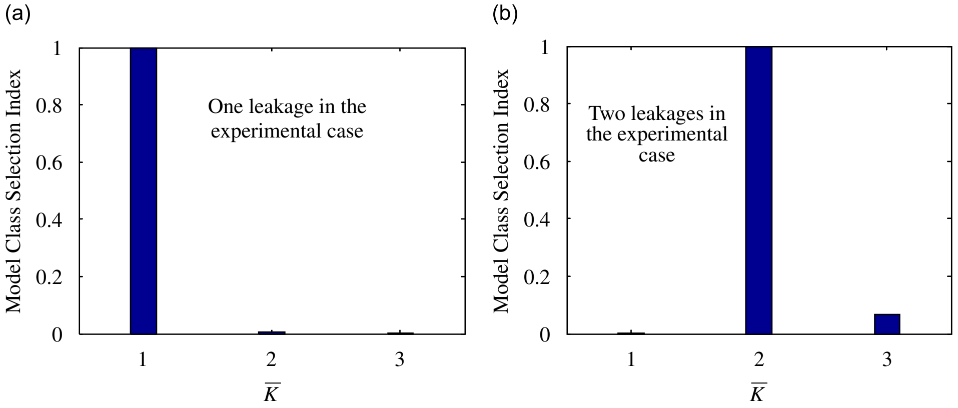

Fig. 2. Model class selection indexes.

Table 1
Identification results for the two-leakage case

(α_1, α_2) $(10^{-1}$ m)	True sizes of the two leakages	(1.2, 1.2)	(0.6, 0.6)	(0.3, 0.3)
	Predicted	(1.25, 1.09)	(0.56, 0.52)	(0.29, 0.25)[a]
	Error (%)	(4.12, −8.93)	(−5.9, −13.85)	(−2.63, −17.0)
(y_1, z_1) (m)	True first leakage location	(2.23, 0.77)	(2.26, 0.80)	(2.28, 0.82)
	Predicted	(2.43, 0.64)	(2.55, 0.73)	(2.49, 0.72)[a,b]
	Distance error (m)	0.23	0.30	0.233
(y_2, z_2) (m)	True second leakage location	(1.43, 1.98)	(1.46, 2.01)	(1.48, 2.03)
	Predicted	(1.37, 1.92)	(1.27, 1.92)	(1.26, 1.96)[a,b]
	Distance error (m)	0.08	0.21	0.233

[a] See Figs. 3a–c for the normalized PDFs.

[b] See Fig. 4 for the leakages locations on the wall.

was placed near the wall with the leakages, in the same room, and used for the external sound pressure measurement. All leakages in the experiment were square. Random white noise signals were generated by a multianalyzer system (PULSE^{TM} type 3560c), input into the loudspeaker, and monitored by a PC. The lower and upper cut-off frequencies of the loudspeaker were 65 and 115 Hz, respectively. Two other microphones,

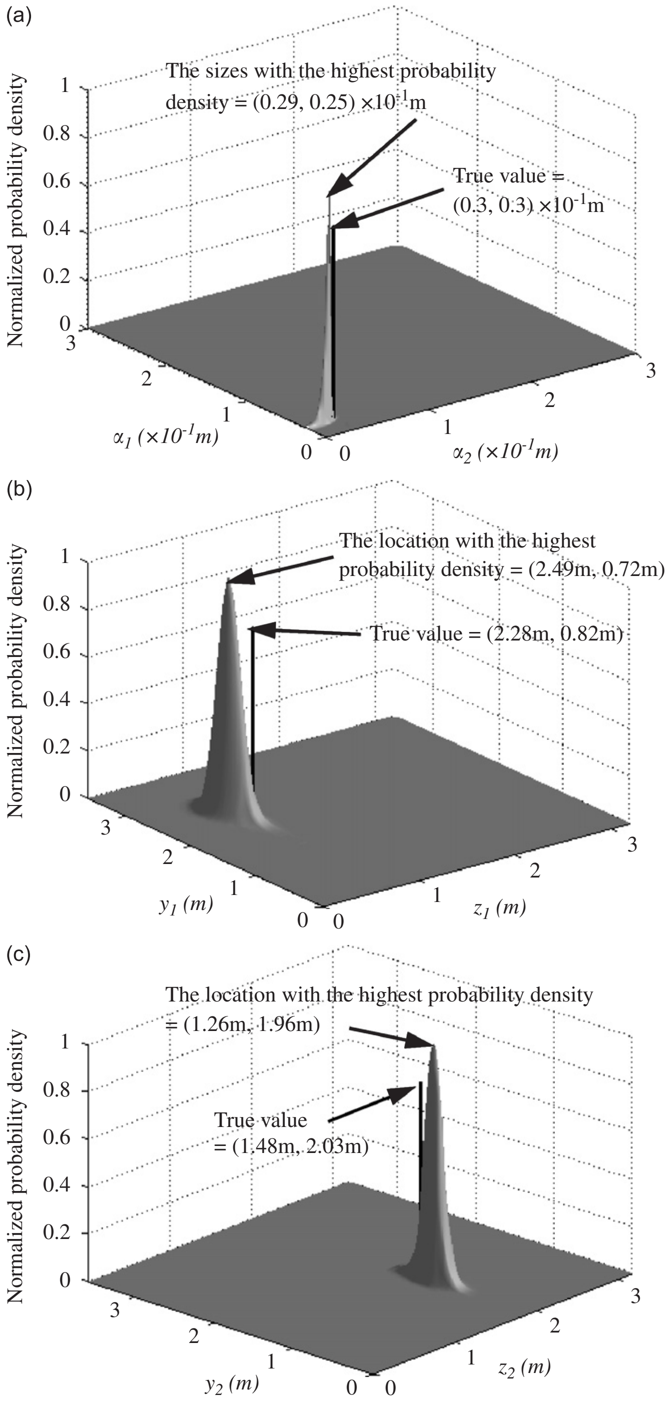

Fig. 3. (a) Normalized probability density plotted against different leakage sizes. (b) Normalized probability density vs. the coordinates of the first leakage. (c) Normalized probability density vs. the coordinates of the second leakage.

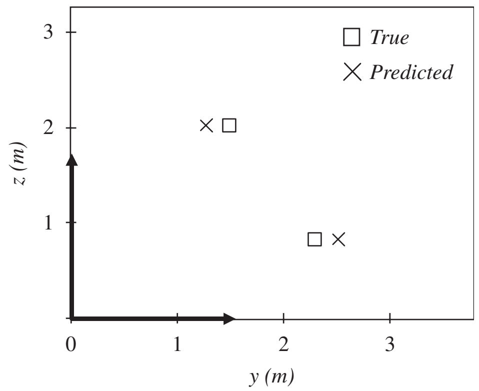

Fig. 4. True and predicted leakage locations on the y–z wall.

M2 and M3, were placed at (4.09, 2.19, and 0.9 m) and (3.39, 1.0, and 1.04 m), respectively, in the receiver room to measure the interior sound pressure levels. Sound signals of 2 s that were measured by the microphones at a time step of 0.9766 ms were recorded via the software PULSE, and stored on the PC.

4. Results

The model class selection index that is defined in Eq. (1b) is studied first and used for the acoustic problem in which the number of leakages is uncertain. Experimental cases of one leakage and two leakages were carried out. In the Bayesian system identification process, the locations and sizes of the leakages were unknown, and models of one to three leakages were considered. Models with different numbers of leakages were assessed by the index. The first and second leakages measured 12 cm × 12 cm, and were made at the locations $(y_1, z_1) = (2.23, 0.77\,\text{m})$ and $(y_2, z_2) = (1.43 \text{ and } 1.98\,\text{m})$, respectively. Note that when the case of single leakage was carried out, the second leakage was blocked.

Figs. 2a and b clearly show that the index values of the one- and two-leakage models are the highest in the experimental cases of one and two leakages, respectively. The model with the highest index is the model that best fits the experimental data, and its corresponding number of leakages is most possibly the true number. It is proven that the index that is defined in Eq. (1b) is a valid indicator to identify the number of leakages, which is one of the contributions in this study.

The two-leakage model is selected and used to identify the unknown parameters in the experimental case of two leakages, as the corresponding model class selection index in Fig. 2b is the highest. Table 1 shows the identification results of the unknown parameters. The maximum error among the identification results is reasonable and less than 17%. The case of a leakage size equal to 0.03 m × 0.03 m is marked with an asterisk. The projections of the normalized PDFs are obtained from Eq. (1a) and shown in Figs. 3a–c. The true and predicted leakage locations are shown in Fig. 4. It is clearly shown that model updating is identifiable according to the definition in Ref. [6].

5. Conclusions

This study presented experimental verification of the effectiveness of the application of the proposed probabilistic method to sound leakage identification. A probabilistic system identification framework was used to obtain the posterior PDF of the set of uncertain model parameters that are based on a given set of measured sound responses. The experimental results show that (1) the model class selection index can be used to identify the model that best fits the measured data to find the unknown number of leakages, (2) the optimal values for the uncertain parameters can be identified crisply according to the highest value of the corresponding PDFs, and (3) the system identification problem in this study is identifiable.

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