Applied Acoustics 129 (2018) 306–315

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Best practice for positioning sound absorbers at room surface

Wan-Ho Cho [a,*], Jeong-Guon Ih [b], Tomohisa Katsumata [c], Takeshi Toi [c]

[a] Center for Fluid Flow & Acoustics, Division of Physical Metrology, Korea Research Institute of Standards and Science, 267 Gajeong-ro, Yuseong-gu, Daejeon 34113, Republic of Korea
[b] Center for Noise and Vibration Control, Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Science Town, Daejeon 34141, Republic of Korea
[c] Department of Precision Mechanics, Chuo University, 1-13-27 Kasuga, Bunkyoku, Tokyo 112-8551, Japan

ARTICLE INFO

Article history:
Received 4 January 2017
Received in revised form 14 August 2017
Accepted 16 August 2017
Available online 20 August 2017

Keyword:
Absorbing patches positioning

ABSTRACT

A method to facilitate the efficient positioning of sound absorbing materials on the walls of an enclosure is proposed by quantifying the contribution of each wall segment to the sound field in a vibro-acoustic transfer matrix. Wall reflections can be considered as secondary sources of radiation, whose strengths depend on the primary source and the amount of absorption by the walls. Based on this idea, the proposed evaluation method to quantify the degree of effectiveness for each wall segment is to quantify the linear independence of the rows or columns in a transfer matrix. The multiplication of quantified linear independence of elements in two transfer matrices consisting of the transfer path of sound is suggested as an observation parameter for selection. The proposed method is verified through numerical simulations and experiments. As absorbing patterns are treated at the surfaces with the highest linear independence in the transfer matrix, the sound pressure at most frequencies decreases for a point receiver or a finite region of receivers. The proposed method has advantages in terms of required effort, because it does not require any iteration process. The proposed method can produce a practically applicable solution without any detailed assumptions about the sound source and boundary conditions which are not clearly known at the design stage.

1. Introduction

Obtaining an efficient configuration for absorbing materials in an enclosed space with sound sources is a common issue in noise control and room acoustics. The amount of sound pressure reduction by the absorbing materials on the walls depends on the size of the absorbing materials and their absorption coefficients. However, the absorption of such materials also depends on their configuration, even the case having same size. Parkinson reported that configuration affects absorption, concluding that a uniformly distributed pattern has better performance than several other patterns [1]. Other researchers have reported similar results, especially in research focused on the use of absorptive strips that induce diffusion [2–5].

Although these results provide useful information for designing absorbing patches, it is difficult to generalize an efficient position for installing absorbing patches or panels on large wall areas. Several studies have been conducted to determine the effect of the configuration of absorbing patches. Shen et al. investigated the position effect of different positions of absorbing patches by observing the modal characteristics in a rectangular cavity [6]. Chiang et al. observed the change of impressions in a recital hall based on changes in the sound source and absorbing patches [7]. However, these approaches were aimed at observing general trends, not at developing an optimized design solution. The objective of this paper is to develop a practical design methodology for placing sound absorbers.

In practical situations, the probability to exist a source at specific position is not uniform for a whole room. Also, the target zone of interest to be controlled is not always the entire space. In these cases, a uniform distribution of absorbing patches may be not the best solution, especially when the layout of sources and the control region are specified for a selected region. Trials to optimize the distribution of absorbing patches for specific sources and systems have been conducted using an optimization processes, such as a gradient method [8] or genetic algorithm [9]. Recently, a topology optimization was applied not only for absorbing material and but also for other structures such as resonators [10–12]. These studies were based on simulations or on measurements using full models of the sound source and space. Additionally, optimization processes based on the simulations require iterative calculations with various candidates of the full model and thus involve

* Corresponding author at: Center for Fluid Flow & Acoustics, Division of Physical Metrology, Korea Research Institute of Standards and Science, 267 Gajeong-ro, Yuseong-gu, Daejeon 305-340, Republic of Korea.

E-mail address: chowanho@kriss.re.kr (W.-H. Cho).

http://dx.doi.org/10.1016/j.apacoust.2017.08.015
0003-682X/

considerable effort. Moreover, in most practical situations, the many parts of a system are often not precisely determined during the early design stage. Therefore, the detailed characteristics and positions of the expected sound sources may not be fully known.

One more important problem is uncertainty concerning the absorption coefficient. Basically, the absorption characteristic of a surface also depends on the incidence angle of wave [13] and the measurement method [14,15]. Moreover, a real-valued absorption coefficient does not include the phase information described by a complex-valued impedance [16,17] which makes it difficult to apply a proper value for the boundary condition during an optimization process based on numerical calculations. Therefore, a practical method for best practice should be proposed to obtain a broadly applicable solution.

In this paper, the performance index is the sound pressure reduction provided by a fixed area of absorbing patches for a given layout of sources and target control zone. To this end, the method based on observing the contributions of the primary sources to secondary sources describing wall reflection and of secondary sources to the target control region is proposed based on the relations between the transfer matrices in an enclosed space. Because the contribution of direct sound is unchanged regardless of the absorber configuration, the present study focuses on controlling the wall reflection through the secondary source concept. The wall reflections are represented by the secondary sources at the boundary surfaces of an enclosure, and their strengths are related to the absorption coefficients

2. Theory

2.1. Basic concept

A steady sound field in an enclosed space consists of both direct radiation field from the actual sound sources and the reverberant field due to reflections from boundary walls which can be considered equivalent secondary sources [18]. Therefore, one can solve the problem of minimizing the sound pressure formed by the secondary sources within the target field.

The contribution from the secondary source depends on two factors: the room geometry and the strength of the reflected sound at the boundary surfaces. More specifically, the room geometry is related to the transfer function between the secondary sources and the specified receiver positions. In addition, the strength of the reflected sound, as the secondary source strength is related to its position relative to the primary source and the absorption coefficients of the boundary surfaces. Here, the problem is to find the configuration of absorbers that minimize the contribution of secondary sources. Therefore it is necessary to find the relations between the boundary surfaces and specified receiver positions and the relation between the primary source and boundary surfaces.

2.2. Formulation of the transfer matrix in terms of secondary sources by the boundary element method

To formulate the relations, a modelling process is required for each transfer path. In this study, the boundary element method (BEM) is used to calculate the transfer matrix of each path. The sound field in any selected area can be described by the Kirchhoff-Helmholtz integral equation [19,20]: the discretized form is typically expressed in the following matrix forms to estimate the sound field [20]:

$$\mathbf{p}_f = (\mathbf{D}_f\mathbf{D}_s^{-1}\mathbf{M}_s + \mathbf{M}_f)\mathbf{v}_s \equiv \mathbf{G}_v\mathbf{v}_s = \mathbf{G}_v\begin{bmatrix}\mathbf{v}_{s,1}\\ \mathbf{v}_{s,2}\end{bmatrix}, \tag{1a}$$

$$\mathbf{p}_f = (\mathbf{D}_f + \mathbf{M}_f\mathbf{M}_s^{-1}\mathbf{D}_s)\mathbf{p}_s \equiv \mathbf{G}_p\mathbf{p}_s = \mathbf{G}_p\begin{bmatrix}\mathbf{p}_{s,1}\\ \mathbf{p}_{s,2}\end{bmatrix}, \tag{1b}$$

where $\mathbf{G}_v$ and $\mathbf{G}_p$ are the vibro-acoustic transfer matrices between the source plane and the observation field, $\mathbf{v}_s$ is the surface velocity on the boundary, $\mathbf{p}_f$ is the field pressure, $\mathbf{p}_s$ is the surface pressure on the boundary, $\mathbf{D}_s$ and $\mathbf{M}_s$ are the monopole and dipole matrices on the surface, respectively, and $\mathbf{D}_f$ and $\mathbf{M}_f$ are the monopole and dipole matrices between the source and the field points, respectively. To separate the effect of secondary source, the boundary surface is classified into two regions: the primary source surface and other surfaces that act as secondary source surfaces. Fig. 1 shows the conceptual layout of an enclosed space, including an active primary source, in which the sound field of interest is denoted as $\mathbf{p}_f$. The sound pressure on the active surface of the actual sound source is denoted as $\mathbf{p}_{s,1}$ and that on the passive surface related to the sound reflection is defined by $\mathbf{p}_{s,2}$, respectively. Using this notations, the surface pressures at all boundaries can be expressed as in [21]

$$\begin{bmatrix}\mathbf{D}_{s,11} & \mathbf{D}_{s,12}\\ \mathbf{D}_{s,21} & \mathbf{D}_{s,22}\end{bmatrix}\begin{bmatrix}\mathbf{p}_{s,1}\\ \mathbf{p}_{s,2}\end{bmatrix} = \begin{bmatrix}\mathbf{M}_{s,11} & \mathbf{M}_{s,12}\\ \mathbf{M}_{s,21} & \mathbf{M}_{s,22}\end{bmatrix}\begin{bmatrix}\mathbf{v}_{s,1}\\ \frac{\mathbf{p}_{s,2}}{\mathbf{z}_{s,2}}\end{bmatrix}. \tag{2a}$$

Rearranging this, one can obtain

$$\begin{bmatrix}\mathbf{p}_{s,1}\\ \mathbf{p}_{s,2}\end{bmatrix} = \begin{bmatrix}\mathbf{D}_{s,11} & \mathbf{D}_{s,12} - \frac{\mathbf{M}_{s,12}}{\mathbf{z}_{s,2}}\\ \mathbf{D}_{s,21} & \mathbf{D}_{s,22} - \frac{\mathbf{M}_{s,22}}{\mathbf{z}_{s,2}}\end{bmatrix}^{-1}\begin{bmatrix}\mathbf{M}_{s,11}\\ \mathbf{M}_{s,21}\end{bmatrix}\mathbf{v}_{s,1} \equiv \begin{bmatrix}\mathbf{G}_{v,s,1}\\ \mathbf{G}_{v,s,2}\end{bmatrix}\mathbf{v}_{s,1}, \tag{2b}$$

where $\mathbf{z}_{s,2}$ denotes the specific acoustic impedance of the passive surface. Substituting Eqs. (2) into Eq. (1), one obtains

$$\begin{aligned}\mathbf{p}_f &= (\mathbf{D}_f + \mathbf{M}_f\mathbf{M}_s^{-1}\mathbf{D}_s)\begin{bmatrix}\mathbf{p}_{s,1}\\ \mathbf{p}_{s,2}\end{bmatrix} = \mathbf{G}_{p,s}\begin{bmatrix}\mathbf{G}_{v,s,1}\\ \mathbf{G}_{v,s,2}\end{bmatrix}\\ \mathbf{v}_{s,1} &\equiv \mathbf{p}_{f,1} + \mathbf{p}_{f,2} = [\mathbf{G}_{p,s,1} \quad \mathbf{G}_{p,s,2}]\begin{bmatrix}\mathbf{G}_{v,s,1}\\ \mathbf{G}_{v,s,2}\end{bmatrix}\mathbf{v}_{s,1}.\end{aligned} \tag{3}$$

where $\mathbf{p}_{f,1}$ is the direct sound field radiated from the active sources, and $\mathbf{p}_{f,2}$ is the sound field induced by secondary sources as given by

$$\mathbf{p}_{f,2} = \mathbf{G}_{p,s,2}\mathbf{p}_{s,2} = \mathbf{G}_{p,s,2}[\mathbf{G}_{v,s,2}\mathbf{v}_{s,1}]. \tag{4}$$

To estimate the transfer matrices $\mathbf{G}_{p,s,2}$ and $\mathbf{G}_{v,s,2}$, the geometry of primary sources for modelling and the information on the boundary conditions of walls are also required. However, in practice, wall conditions are often not precisely determined during the design phase. Therefore, various assumptions for boundary conditions are needed for the initial calculation, and repeated calculations should be conducted with various candidates for boundary conditions. To avoid the dilemma of being unable to consider the actual acoustic condition of space of interest, one can utilize the acoustical reciprocity principle [22] which permits a reversible relation between the source and receiver. Based on the acoustic reciprocity principle, the relation between an actual source and the secondary source plane on a wall can be replaced by the relation between the secondary source plane and the field pressure at the source position. Fig. 2 shows a conceptual description of two separated the transfer paths consisting the sound field related to the secondary source plane. By applying the reciprocity principle, the transfer path between the primary source and secondary source can be substituted by the path between the secondary source and primary source position as shown in Fig. 2(b).

Using this description, the transfer matrices in Eq. (4) can be estimated using the separated model shown in Fig. 2, and the system can be described in terms of the surface pressure:

$$\mathbf{p}_{f,2} = (\mathbf{D}_f\mathbf{D}_{s,2}^{-1}\mathbf{M}_{s,2} + \mathbf{M}_f)\mathbf{v}_{s,2} \equiv \mathbf{G}_{S-F}\mathbf{v}_{s,2}, \tag{5a}$$

$$\mathbf{p}_{f,s} = (\mathbf{D}_{f,s}\mathbf{D}_{s,2}^{-1}\mathbf{M}_{s,2} + \mathbf{M}_{f,s})\mathbf{v}_{s,2} \equiv \mathbf{G}_{S-P}\mathbf{v}_{s,2}, \tag{5b}$$