Building and Environment 94 (2015) 867–872

Contents lists available at ScienceDirect

Building and Environment

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

Investigation of performance improvements for active reflection control system through 2D time-domain simulation

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ARTICLE INFO

Article history:
Received 24 March 2015
Received in revised form
9 May 2015
Accepted 2 June 2015
Available online 11 June 2015

Keywords:
Active reflection control
Time-domain simulation
Chebyshev collocation method

ABSTRACT

Active reflection control system is a useful tool to improve the low-frequency performance of the sound absorption coating. However, the reflection reduction level of the previous system is unsatisfactory. It is of great value to evaluate the various factors that may affect the control performance, and to identify the main limitations, which in turn helps to develop an effective control system. For this purpose, the 2D (two-dimensional) time-domain simulation based on the Chebyshev collocation method is exploited to investigate the main influence factors in the control system. The simulation scheme is accurate enough to provide efficient and reliable solutions; in addition, it avoids the defects in experiments, where all the influence factors are mixed together so that they cannot be judged independently. Three factors are chosen to be analyzed one by one, and the design principles to improve the control performance are obtained: the accuracy of the time delay from the reflective surface to the virtual error sensor is the most important one, thus a FIR (Finite Impulse Response) filter should be introduced in the control algorithm, in order to predict an accurate reflected sound pressure; a compromise is required between the good performance and the compactness of the control system.

1. Introduction

Low-frequency sound absorption coating is crucial for extending the low-frequency range of wedges for building anechoic rooms or making an object invisible to the incident acoustic wave. It is known that active control technology is a useful tool to reduce the low-frequency reflections from the reflective bodies. Bao et al. [1] and Howarth et al. [2,3] proposed a piezocomposite actuator for absorbing both the reflection and transmission of normally incident waves. Orduña-Bustamante and Nelson [4] used a secondary source as an active sound absorber in duct. Zhu et al. [5] considered an active control of the acoustic reflection, absorption, and transmission using thin panel speakers. The anechoic termination [6] was also implemented for the vibration control, by applying a force close to one end of the structure. The force there was determined by a feed-forward adaptive algorithm that used the estimations of the incident and reflected waves as the reference and error signals.

For the compact structures, Han et al. [7] reported an active reflection control system in duct, where an attenuation of 12.2 dB was obtained experimentally for the impulsive sound in the low-frequency range. Based on the 1D (one-dimensional) case, they further designed a 3D (three-dimensional) control system for the impulsive scattered radiation [8], and 8.2 dB attenuation of the scattered pressure was obtained experimentally. However, compared with the common 20–30 dB reduction level in the applications of the active control technology [9], the performance of the active reflection control appears to be very poor, and it should have much room to be improved. It is of great value to evaluate the various factors that may affect the control performance, and to identify the main limitations, which in turn helps to develop an effective control system. However, analyzing each factor independently is inefficient and unrealistic in experimental studies, because the system installations must be adjusted whenever the value of the factor has a little modification, and all of the influence factors are mixed together so that one factor cannot be analyzed with the ideal zero-effect of the other factors.

On the other hand, numerical simulations provide a feasible approach. Wang and Huang [10] proposed a time-domain acoustic simulation based on the Chebyshev collocation method, with the numerical error of 10^{-10} or smaller. According to it, Han and Wang [11] further presented a simulation scheme for the in-duct active

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http://dx.doi.org/10.1016/j.buildenv.2015.06.003

noise control, which emulates the electrical control system and the corresponding acoustic field evolution simultaneously. Its reliability as well as the accuracy was validated by experiments, and the control mechanism was revealed through investigating the acoustic impedance in the simulated acoustic field.

In this paper, the similar simulation model will be adopted, and applied to the active reflection control. It will be optimal if the simulation model is constructed in a 3D sound field for the practical applications, but its calculation is very complicated for two reasons. 1. In the control algorithm, even for the reflection control in a very small 3D area shown in [8], it needs four microphones to measure the sound pressure on the reflective surface; for a larger area control, multi-channel control system is required. 2. The sound field simulation based on the Chebyshev collocation method is difficult for 3D case, because the control area and the acoustic boundary conditions are different in various 3D applications. On the other hand, except for the number of the transducers (microphone/loudspeaker), the control algorithm and the physical configuration are similar in the 2D and 3D control system, and the 2D model with simple calculations has the ability to express the main characteristics of the near field and far field of the sound sources, thus the 2D simulation model is applied in the investigation of the active reflection control. Three factors in the control system are chosen to be analyzed, and their effects on the control performance are identified quantitatively. According to the results, the main factors limiting the reflection reduction are discovered, and the improved calculation accuracy and design guides will be introduced in the previous control systems, to obtain higher reduction level.

2. Simulation model for the active reflection control

2.1. Active reflection control system

Fig. 1 shows the 2D simulation model for the active reflection control in duct, whose objective is to minimize the sound pressure induced by the primary source and reflected by the reflective surface. The coordinate origin $x = 0$ is on the reflective surface x_0, and x_e is the position for error signal. The secondary source is located between x_0 and x_e. When the sound frequency is below the cut-off frequency, there is only plane wave propagating in the duct.

Due to the work of Han et al. [7], the reflected pressure p_r at $x = x_e$ is predicted by the measured sound pressure p_0 and particle velocity v_0 at x_0

$$p_r = (p_0 - \rho_0 c_0 v_0) e^{j\omega x_e / c_0} \Big/ 2 \tag{1}$$

where $e^{j\omega x_e/c_0}$ is regarded as the time delay $\vartheta = -x_e/c_0$, which is the time for a reflected wave traveling from the reflecting surface to the point $x = x_e$. For a rigid reflective surface, $v_0 = 0$, thus p_r can be obtained directly by measuring the sound pressure on the reflective surface. The virtual error signal err at x_e comprises of the reflected sound pressure p_{pr} from the primary source, the reflected sound pressure p_{sr} and the incident sound pressure p_{si} from the secondary source, i.e., $err = p_{pr} + p_{sr} + p_{si}$. It is further expressed as

$$err = \mathbf{S}_i^e * q_s + T_r * p_0 \tag{2}$$

where $\mathbf{S}_i^e$ is the impulse response from the secondary source strength q_s to its incident sound pressure at x_e, $*$ is the convolution operator, and T_r is $\delta(t-\vartheta)/2$ with the Kronecker delta function δ. $\mathbf{P}^0$ and $\mathbf{S}^0$ are defined as the impulse responses from the primary and the secondary source strengths to their sound pressures at x_0, and then the FXLMS algorithm for the reflection control [7] is shown in Fig. 2.

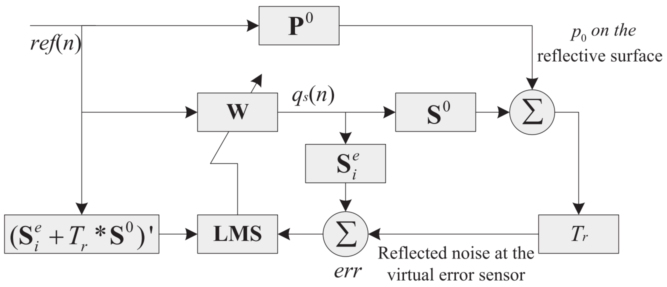

Fig. 2. Active reflection control algorithm for the rigid reflective surface.

2.2. Time-domain simulation of the active reflection control

The time-domain simulation scheme for the active reflection control involves the electrical control system and the duct acoustic field. The modeling procedures for these two aspects are similar to that in [11], but the impulse responses $\mathbf{S}_i^e$ and $\mathbf{S}^0$, as well as the boundary conditions are different. In the following, the modeling procedures for the electrical system and the acoustic field are described briefly, and the combination of the two parts is then introduced. For simplicity, the reference signal is obtained from the input of the primary source directly, and the transfer function of microphones is set to be a constant.

Fig. 3 shows the active reflection control system in 2D duct. Its objective is to minimize the reflected sound pressure predicted at x_e, i.e. err in Eq. (2). The χ-order digital filter $\mathbf{W}(n)=[W0(n)W1(n)\ldots W\chi-1(n)]T$ is tuned by FXLMS algorithm [12].

$$\mathbf{W}(n+1) = \mathbf{W}(n) - \alpha \cdot err(n) \cdot \mathbf{f}(n) \tag{3}$$

where $\mathbf{f}(n)$ is the vector of the reference signal filtered by $\mathbf{S}_i^e + T_r * \mathbf{S}^0$, the superscript T denotes the transpose, and α is the chosen convergence coefficient. The control signal $V_d(n)$ is found as

$$V_d(n) = \mathbf{ref}^T(n)\mathbf{W}(n) \tag{4}$$

where $\mathbf{ref}(n)$ is the vector of the reference signal. $\mathbf{S}^0$, used in

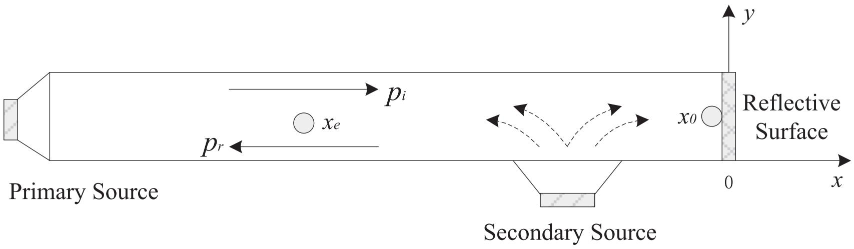

Fig. 1. Two-dimensional simulation model for the active reflection control in duct.