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Technical Note

Performance of an independent planar virtual sound barrier at the opening of a rectangular enclosure

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ABSTRACT

Planar virtual sound barrier systems have been used successfully to reduce noise radiation through an opening without affecting natural ventilation and lighting. However, the complexity of a fully coupled control system grows at the rate proportional to the square of the number of channels and this make the system implementation become impractical for enclosures with large openings. To reduce the system complexity, this paper proposes an independent planar virtual sound barrier, which is a multi-channel system consisting of many independent single channel active noise control systems. Each single channel system is "independent" in the sense that the control source output of the system is updated only with the signal from its own error sensor. Based on the analytical model of sound radiation through the opening of a rectangular enclosure, the transfer functions from both primary and control sources are calculated first. Then the noise reduction performance, the stability, and the convergence behavior of both fully coupled and independent planar virtual sound barrier systems are investigated. It is found that the independent system with no control output constraint becomes inherently unstable at some frequencies; however its stability can be improved by applying some control output constraint. Reducing the number of channels and the distance between secondary loudspeakers and error microphones can also increase system stability but at the cost of smaller noise reduction. When the system is inherently stable and there is no constraint on control output, the independent system can provide the same noise reduction as the fully coupled one but with faster convergence speed.

1. Introduction

A virtual sound barrier is an array of sound sources and microphones forming an acoustic barrier, which blocks direct propagation of sound while allowing air and light to pass through [1]. It is a multi-channel active noise control system and previous studies have shown that such a system can create a quiet zone inside a given space when the boundary is surrounded by error microphones [2–4]. Current virtual sound barrier systems are typically fully coupled adaptive systems, where the transfer functions from all secondary control sources to all error sensors are employed in the adaptive algorithm of the controller. The computation load of such a fully coupled controller grows at the rate proportional to the square of the number of channels and therefore decentralized systems have been proposed to reduce the system complexity [4]. Decentralized systems can reduce the computation complexity of the system by updating the outputs of some control sources based on the inputs of some error sensors but have weakness of stability and deteriorate performance. The "independent" system discussed in this paper is a special type of the decentralized systems, which only uses one collocated error sensor to update its corresponding control source.

A planar virtual sound barrier (PVSB) is a virtual sound barrier with planar senor and actuator arrays in parallel [5,6]. Because of its planar geometry, a PVSB system can be designed and applied conveniently at an opening of an enclosure to prevent sound radiation from or sound transmission into the enclosure through the opening with little influence on natural ventilation and lighting [7–9]. Four single channel active noise control systems (being called Active Acoustic Shielding (AAS) cells) were used to constitute an independent PVSB system at a 0.25 m × 0.25 m window and the noise reduction in the receiving room was around 10–15 dB at frequencies between 500 Hz and 2 kHz [7]. Sixteen single channel active noise control systems were installed at an open window to attenuate the noise radiated from outside to inside, and a noise reduction of more than 10 dB was achieved in

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a frequency range of 200–700 Hz [8]. A fifteen-channel fully coupled PVSB system was installed at a 5 m^2 opening to investigate its noise reduction effect on transformer noise, and 16 dB and 7.7 dB noise reductions were achieved at 100 Hz and 200 Hz respectively in the far field [9]. These investigations showed that PVSB systems are effective for reducing noise radiation through an opening. However, the stability and the convergence behavior of PVSB systems have not been discussed.

Elliot et al. studied the convergence behavior of a multiple channel feedforward active control system in the frequency domain and proposed to describe this convergence in terms of the eigenvalues of the relevant Hessian matrix. In their study, both the sum of the mean-squared outputs of the error sensors and the sum of the mean-square inputs to the secondary sources were included in the cost function, and the coefficient of the latter term was defined as the weighting factor. It was pointed out that the weighting factor can change the convergence speed and provides a tradeoff between noise reduction performance and the output strength [10,11].

Elliot and Boucher also analyzed the interaction between multiple feedforward active noise control systems in the frequency domain using the gradient descent algorithm and proposed a condition that is sufficient but not necessary for stability assessment based on the Gerschgorin circle theorem for the independently operating systems [12]. This condition is useful for a decoupled two-channel active noise control system in a free field, but the minimum interval between the error microphone and its corresponding secondary loudspeaker required for stability is much larger than the actual value when the number of channels of the control system increases. Although the derived condition is conservative, the eigenvalues analysis method can be adopted to assess the stability of independent PVSB systems.

Cordioli et al. showed that decentralizing an active control system for an electrical transformer in a free field can considerably reduce the steady state performance of the system via numerical simulations [13]. It was also found that decentralized systems can be stabilized by increasing the weighting factor, and there is an optimal weighting factor that results in the best noise reduction performance. However, there was no further analysis on the stability and convergence properties of the decentralized systems in their paper.

Yu et al. proposed a cluster configuration (actually a decentralized system), where the multichannel system is divided into several independent subsystems and each subsystem is fully coupled, to balance the complexity and instability for tonal noise control [14]. They found that the interval between subsystems should be larger than half the distance between the secondary loudspeaker and its corresponding error microphone in the subsystems for maintaining the stability where the two subsystems of two channels are placed “face to face” symmetrically in a free space. Unfortunately, this result cannot be applied to the independent PVSB system where the error microphone and the control loudspeaker in each independent channel are arranged facing toward the same direction.

The stability of decentralized feedback active control systems has also been investigated by some researchers [15–17]. Leboucher et al. analyzed the convergence of the adaptive process and the stability of the feedback loop of a decentralized adaptive feedback active control system, and deduced two stability conditions from the small gain theorem and the Nyquist criterion [15]. Grosdidier and Morari proposed a new interaction measure based on the structured singular value to predict the stability and the performance loss for decentralized feedback systems [16]. Zhang et al. studied the performance of decentralized multi-channel feedback analog control systems and obtained a sufficient stability condition in terms of the predefined maximum noise amplification and the geometrical configuration of the independent controllers [17].

Despite all the research mentioned in the preceding text, no research has been found on the performance especially the convergence rate of the feedforward independent PVSB system for controlling noise radiation through the opening of an enclosure. This will be investigated in this paper. First, the transfer functions are calculated based on an analytical radiation model of a monopole source inside a rectangular enclosure with one opening. Then the noise reduction performance, the stability resulting from the geometric arrangement of the error microphones and control loudspeakers, and the convergence of the adaptation process of the independent PVSB system is studied and compared to those of the fully coupled system. Finally, experiments are conducted to verify the conclusions.

2. Theory

2.1. Sound radiation through the opening of a rectangular enclosure

Fig. 1 shows a simplified model for predicting the sound radiation through the opening of an enclosure, where a monopole located inside at $\mathbf{r}_s = (x_s, y_s, z_s)$ with a strength of q_0 is used to approximate the primary noise source. The enclosure dimensions are L_x, L_y, and L_z, and the opening surface is at $z = L_z$. A secondary loudspeaker array on the plane $z = L_c$ and an error microphone array on the plane $z = L_z$ are used to constitute the PVSB system.

Assuming that the opening of the enclosure is embedded in an infinite baffle, the sound pressure amplitudes generated by the monopole source in frequency domain can be calculated with [18]

$$p_{\text{in}}(x,y,z) = \sum_n \left(A_n^l e^{-jk_{nz}z} + A_n^r e^{-jk_{nz}z} \right) \phi_n(x,y) + \rho_0 \omega q_0 \sum_n \frac{\phi_n(x,y)\phi_n(x_s,y_s)}{2S\Lambda_n k_{nz}} e^{-jk_{nz}|z-z_s|} \quad \text{and} \tag{1}$$

$$p_{\text{out}}(x,y,z) = \iint_{S_0} \left[-jk_{nz} \left(-A_n^l e^{-jk_{nz}L_z} + A_n^r e^{-jk_{nz}L_z} \right) \phi_n(x_0,y_0) - j\rho_0 \omega q_0 \frac{\phi_n(x_0,y_0)\phi_n(x_s,y_s)}{2S\Lambda_n k_{nz}} e^{-jk_{nz}|L_z - z_s|} \right] \frac{e^{-jkr}}{2\pi r} dS_0 \tag{2}$$

where p_{in} and p_{out} are the sound pressure inside and outside the enclosure, respectively; A_n^l and A_n^r are coefficients of the nth mode which can be obtained by considering the boundary conditions. $\phi_n(x,y) = \cos(n_x\pi/l_x)\cos(n_y\pi/l_y)$ is the mode shape.

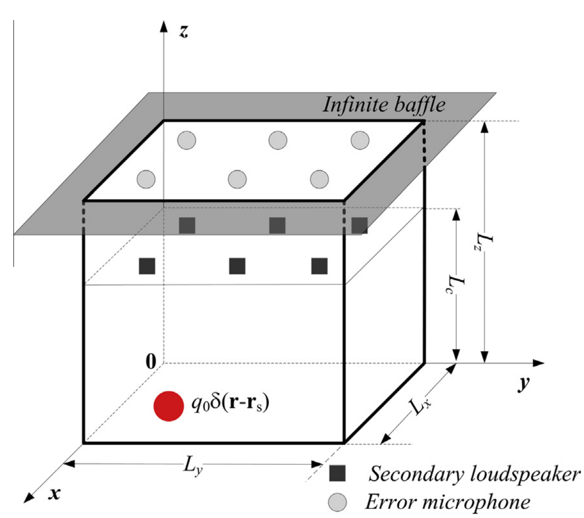

Fig. 1. A monopole sound source inside a rectangular enclosure with a baffled opening.