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Performance of a multichannel active sound radiation control system near a reflecting surface

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ABSTRACT

Prior research shows that introducing a reflecting surface near an active control system can improve its noise reduction performance; however the mechanism of the performance improvement is not completely clear. This paper investigates the effects of a reflecting surface on multichannel active sound radiation control systems with a primary monopole source located on the surface. By using a genetic searching algorithm, the locations of secondary sources were optimized to maximize the noise reduction and the frequency range that can be beneficial from the reflecting surface is discussed. It is found that the performance improvement by introducing a reflecting surface is due to the increased sound pressure generated by the secondary sources at the primary source location. The beneficial frequency range extends with the number of the channels of the control system and has an upper limit frequency determined by the distance between the secondary sources and the primary source. Experiments are conducted to validate the results.

1. Introduction

An active sound radiation control system employs secondary sound sources around a primary source to control its sound radiation [1]. In practice, there are usually reflecting surfaces around the system, for example, the ground and/or fire barrier walls around outdoor power transformers. This paper investigates the effects of a reflecting surface on sound radiation control performance of multichannel active noise control (ANC) systems and explores the optimal configuration of the secondary sources of the systems.

The radiation properties of sound sources near a reflecting surface are already well understood [2,3]. An in-phase image source with an equal strength is usually introduced in the calculation when an infinitely large rigid plane presents, and the sound radiation power of a dipole source can be significantly reduced when a rigid plane is placed vertically to the dipole source axis line due to the radiation impedance reduction presented to the source by the reflecting surface [3].

The performance of a single channel ANC system in parallel and perpendicular to a rigid or soft plane has also been investigated [4]. Cunefare and Shepard found that the vertical configuration provided better noise reduction performance than the horizontal configuration for that particular application, and the influence of the plane can be neglected when the sources are placed far away from the plane (greater than one wavelength). For an ANC system with characteristic dimensions comparable to the acoustic wavelength, further study based on the boundary element models shows that the reflecting surface affects the performance significantly if the geometric center of a source is within 1/5 of a wavelength from the plane [5].

After calculating the overall power radiation from a single channel ANC system near a reflecting surface, Pan et al. found that the control system should be vertically placed with respect to the surface to form a longitudinal quadrupole to achieve more power reduction [6,7]. Xue et al. studied the performance of a single channel ANC system near two reflecting surfaces, and proposed that the power reduction can be further improved by introducing another reflecting surface with optimized locations of the sources and surfaces [8].

When a rigid sphere is put near a single channel ANC system, the rigid sphere has scattering effects on both the primary and secondary fields and can increase global sound radiation control performance after optimizing the locations of secondary sources; however, no detailed mechanism was investigated [9]. It was also discovered that the presence of a human head in a three

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dimensional virtual sound barrier system can improve or decrease the system performance depending on the size of the quiet zone surrounded by the error sensors and the noise frequency [10].

The above-mentioned papers use the total sound radiation power as the cost function, and the objective was to understand the effects of reflecting surfaces on the performance of ANC systems for global sound radiation control. There are also several papers investigating the effects of the reflecting surfaces on the performance of local ANC systems, where the main objective is to understand the variation of the quiet zone geometry rather than the total sound radiation power with control [11–15].

With all research mentioned above, no systematical research has been carried out on the location optimization of secondary sources for multichannel ANC systems with a reflecting surface [16]. This paper investigates the maximal noise reduction of a multichannel ANC system with a reflecting surface by using a genetic searching algorithm to optimize the strengths and locations of the secondary sources. The formulas of the sound radiation power of a multichannel ANC system without and with a reflecting surface are given first, and then the interaction between the multichannel ANC system and a reflecting surface is analyzed to illustrate the mechanism for ANC performance improvement. Finally the effective frequency range where the noise reduction can be increased by the reflecting surface is discussed.

2. Theory

The sound radiation power of a multichannel ANC system consisting of one primary source with a constant volume velocity and N secondary sources can be formulated using the following quadratic form [17]

$$W_{\mathrm{opt}} = \mathbf{Q}^{\mathrm{H}}\mathbf{A}\mathbf{Q} + \mathbf{Q}^{\mathrm{H}}\mathbf{b} + \mathbf{b}^{\mathrm{H}}\mathbf{Q} + c, \tag{1}$$

where $\mathbf{Q}$ is the strength vector of the secondary sources, $\mathbf{A}$ is a $N \times N$ matrix composed by the radiation resistances between two corresponding secondary sources, $\mathbf{b}$ is a $N \times 1$ vector consisting of the mutual radiation resistances from the primary source to secondary sources, and c is the sound radiation power of the primary source without control.

Assume the distance between each secondary source and the primary source is l, the elements of the matrixes in Eq. (1) in free field are $A_{ij} = 0.5Z_0\mathrm{sinc}(kd_{ij})$, $b_i = 0.5Z_0Q_{\mathrm{p}}\mathrm{sinc}(kl)$, and $c = 0.5Z_0Q_{\mathrm{p}}^2$, where $Z_0 = \omega^2\rho_0/4\pi c_0$ is the self-radiation resistance of a monopole in free field, ω is the angular frequency, ρ_0 is the air density, c_0 is the sound speed, $k = \omega/c_0$ is the wave number, d_{ij} is the distance between the ith and the jth secondary sources, Q_{p} is the strength of the primary source, and the function $\mathrm{sinc}(x) = \sin(x)/x$ [4]. Fig. 1 shows a primary sound source located at the origin of the coordinates and an infinitely large rigid plane at the plane $z = 0$.

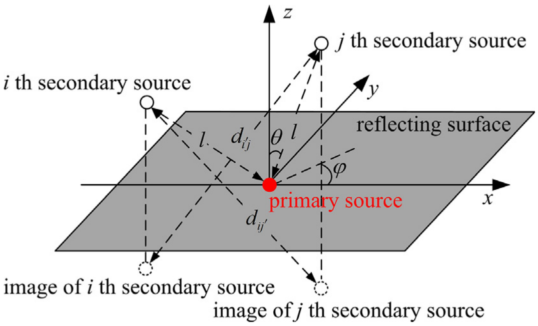

Fig. 1. A multichannel ANC system (only two secondary sources are shown in the figure) with the primary source on an infinitely large rigid surface, the distance between each secondary source and the primary source is l.

The primary sound pressure in the upper half space above the reflecting surface can be obtained by adding the contributions from the primary source and its in-phase image source. The sound radiation power of the primary source W_1 turns to [17]

$$W_1 = 2W_0, \tag{2}$$

where $W_0 = 0.5Z_0Q_{\mathrm{p}}^2$ is the sound radiation power in the free field.

When an infinitely large rigid plane is introduced, the matrix elements in Eq. (1) are $A_{ij} = 0.5Z_0[\mathrm{sinc}(kd_{ij}) + \mathrm{sinc}(kd_{i'j})]$, $b_i = Z_0Q_{\mathrm{p}}\mathrm{sinc}(kl)$, $c = Z_0Q_{\mathrm{p}}^2$, where $d_{i'j}$ is the distance between the image of the ith secondary source and the jth secondary source [4].

The optimal secondary source strength for both situations can be obtained by [17]

$$\mathbf{Q}_{\mathrm{opt}} = -\mathbf{A}^{-1}\mathbf{b}, \tag{3}$$

and the sound radiation power with active control is [17]

$$W_{\mathrm{opt}} = c - \mathbf{b}^{\mathrm{H}}\mathbf{A}^{-1}\mathbf{b}. \tag{4}$$

The noise (sound radiation power) reduction is defined as

$$NR = -10\log\left(\frac{W_{\mathrm{opt}}}{W_0}\right), \tag{5}$$

where the sound radiation power of the primary source in the free field is used as the reference so the obtained noise reduction is the net sound radiation power change to that in free field. As shown in Eq. (2), the noise reduction without active noise control is −3 dB when a reflecting surface is introduced against the primary source with a constant volume velocity.

Comparing Eq. (4) with Eq. (1) shows that the sum of the first two terms on the right hand side of Eq. (1) equals to zero with the active noise control. This indicates that the sound radiation power of the secondary sources is completely unloaded and the total sound radiation power with control is determined by the mutual unloading of the self-radiation power of the primary source [1]. It is the mutual radiation power of the primary source from the secondary sources, the $\mathbf{b}^{\mathrm{H}}\mathbf{Q}_{\mathrm{opt}}$ term, that dictates the total sound radiation power with control.

This mutual radiation power can also be formulated as $0.5\mathrm{Re}\{p_{\mathrm{S}}^{*}Q_{\mathrm{p}}\}$, where p_{S} is the sound pressure generated by the secondary sources at the primary source, Re{} indicates the real part of {}, and * denotes complex conjugation. Because the primary source strength Q_{p} is fixed, the increase of the mutual radiation power magnitude is proportional to the increase of the sound pressure generated by the secondary sources, and this sound pressure can be expressed as

$$p_{\mathrm{S}} = \frac{1}{2\pi l}e^{-jkl}\mathbf{I}^{\mathrm{T}}\mathbf{Q}_{\mathrm{opt}}, \tag{6}$$

where $\mathbf{I}$ is a $N \times 1$ unit vector and the superscript $^{\mathrm{T}}$ is the operator of matrix transposition. Eq. (6) shows that sound pressure produced by the secondary sources at the primary source increases with the secondary source strength and is inversely proportional to the matrix $\mathbf{A}$ according to Eq. (3). When a reflecting surface is introduced against the primary source, the total noise reduction becomes larger if the elements of $\mathbf{A}$ become smaller.

For sufficiently low frequency, A_{ij} depends only on the distance between the ith and the jth secondary sources and the distance between the image of the ith secondary source and the jth secondary source. The larger these two distances are, the smaller the value of A_{ij} will be. Therefore, the optimal secondary source locations for achieving the maximal noise reduction can be obtained by searching the minimum value of the matrix $\mathbf{A}$.

Considering a single channel ANC system in free field, the optimal strength and the noise reduction can be obtained as [8]