A numerical study on active noise radiation control systems between two parallel reflecting surfaces

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Abstract. It is known that the noise reduction performance of active noise control systems can be improved by introducing reflecting surfaces. This paper investigates the feasibility of increasing the noise reduction of a single channel active noise control system on ground using two vertically placed and parallel reflecting surfaces. Simulations are made based on the normal mode theory inside a flat space. The effects of the surface interval, the included angle between the source line and the surfaces are simulated and analyzed. It is found that the noise reduction decreases significantly as the included angle increases, and the sound radiation of the primary source can be completely cancelled in principle if the surface interval is less than a half of wavelength and the source line is perpendicular to the surfaces. The mechanisms for the performance improvement are disclosed.

Keywords: Active noise control, Reflecting surfaces, Sound power, Layered media.

1 Introduction

In some noise control cases, there are reflecting surfaces around the noise sources such as sound barriers or walls around transformers [1]. For Active Noise Control (ANC) systems, the noise reduction performance is affected by nearby reflecting surfaces due to the source radiation resistances change caused by the surfaces [2, 3]. The effects of an infinitely large reflecting surface [4], a finite size reflecting surface [5], and two vertically placed reflecting surfaces perpendicular to each other [6] on ANC systems have been investigated. However, the performance of an ANC system with two vertically reflecting surfaces that are parallel to each other is still not known.

For single channel ANC systems, it is found that the noise reduction increases significantly when the primary and secondary sources are placed along a line perpendicular to a reflecting surface [4]. For multi-channel ANC systems with the primary source on the reflecting surface, the noise reduction can be maximally increased if the secondary sources are placed as far apart as possible to each other and the ground [3]. The mechanism is that the additional reflecting surface produces more image secondary sources which can enhance the performance of ANC systems.

For the case of ANC systems near two reflecting surfaces with the right included angle (90°), the noise reduction of the system has been investigated only with simulations [6]. Numerical results show that higher noise reduction can be achieved for the system compared with that case with only one reflecting surface after optimizing the locations of the sources and surfaces. However, there is no report on the effects of using two reflecting surfaces parallel to each other around ANC systems.

This paper investigates the feasibility of increasing the noise reduction performance of ANC systems on ground by introducing two vertically placed reflecting surfaces which are parallel to each other. The noise reduction of the ANC system inside two infinitely large reflecting surfaces is computed analytically first according to the normal mode theory inside a flat space, then the effects of the included angle between the source line and the normal line of the surfaces as well as the surface interval are investigated. The numerical results are presented and the mechanisms for the performance improvement are discussed.

2 Theory

Figure 1 shows a single channel ANC system on ground, where the distance between the primary source and the secondary source is d, and the separation distance between two vertically placed and parallel reflecting surfaces is D. The size of the reflecting surfaces is assumed to be sufficiently large compared with the wavelength of sound waves for simplicity. The included angle between the source line and the normal line of the surfaces, i.e. the line perpendicular to the parallel surfaces, is denoted by θ. The ground plane and the additional reflecting surfaces are assumed to be perfectly reflective throughout the paper.

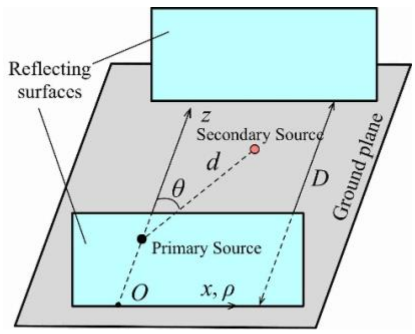


Fig. 1. An ANC system on ground with two vertically placed and parallel reflecting surfaces.

A cylindrical coordinate system (ρ, φ, z) is established with the origin, O, being located at the projection of the primary source on the nearest reflecting surface shown in Fig. 1. The z axis direction is perpendicular to the surfaces and pointing to the other reflecting surface. When the source is on the ground plane (y = 0), the point monopole and its image coincide. In this paper, all of the sources are assumed to be on ground to focus on the effects of the two parallel reflecting surfaces on ANC systems. The locations of the primary and the secondary sources are then $\mathbf{r}_p = (\rho_p, 0, z_p)$ and $\mathbf{r}_s = (\rho_s, 0, z_s)$, respectively.

The sound pressure at the point $\mathbf{r} = (\rho, \varphi, z)$ generated by a point monopole at $\mathbf{r}_0 = (\rho_0, 0, z_0)$ between two infinitely large and parallel reflecting surfaces can be obtained by [7]

$$p(\mathbf{r};\mathbf{r}_0) = \frac{\rho_{\text{air}}\omega k q_0}{2\pi}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{\pi}{kD}\varepsilon_n \cos\left(\frac{n\pi}{D}z\right)\cos\left(\frac{n\pi}{D}z_0\right)\mathrm{e}^{\mathrm{j}m\varphi} \times J_m\left(\sqrt{k^2-(n\pi/D)^2}\rho_<\right)H_m^{(1)}\left(\sqrt{k^2-(n\pi/D)^2}\rho_>\right), \tag{1}$$

where the effects of the ground has been taken into account, j is the imaginary unit, ρ_{air} is the air density, k is the wavenumber, ω is the angular frequency, q_0 is the source strength, $\rho_< = \min(\rho, \rho_0)$, $\rho_> = \max(\rho, \rho_0)$, ε_n is the Neumann factor, i.e. $\varepsilon_n = 1$ ($n = 0$) and $\varepsilon_n = 2$ ($n = 1, 2, 3, \ldots$), $J_m(\cdot)$ is the Bessel function of the first kind of order m, and $H_m^{(1)}(\cdot)$ is the Hankel function of the first kind of order m.

The sound radiation power of a single ANC channel system consisting of one primary source and one secondary source can be formulated as [8]

$$W = A|q_s|^2 + q_s^* b + b^* q_s + c, \tag{2}$$

where q_s is the complex source strength of the secondary source, * denotes complex conjugation, $A = R_s/2$, R_s is the self-radiation resistance of the secondary source, $b = q_p R_{ps}/2$, R_{ps} is the mutual radiation resistance between the primary source and the secondary source, $c = |q_p|^2 R_p/2$, and q_p and R_p are the complex source strength and the self-radiation resistance of the primary source, respectively. The resistance can be obtained by using Eq. (1) as

$$R_i = \text{Re}\left[p(\mathbf{r}_i;\mathbf{r}_i)/q_i\right], \quad i = \text{p,s}, \tag{3}$$

$$R_{ps} = \text{Re}\left[p(\mathbf{r}_s;\mathbf{r}_p)/q_p\right], \tag{4}$$

where Re[·] denotes the real part of the quantity inside the square brackets.

The optimal secondary source strength and the sound radiation power under optimal control are [8]

$$q_{\text{s,opt}} = -\frac{R_{ps}}{R_s}q_p, \quad W_{\text{opt}} = \frac{1}{2}|q_p|^2\left(R_p - \frac{R_{ps}^2}{R_s}\right), \tag{5}$$

The noise reduction is defined as

$$NR \equiv -10\lg\left(\frac{W}{W_0}\right). \tag{6}$$

where lg means the common logarithm with the base 10 and the sound radiation power of the primary source on ground $W_0 = (\rho_{air}\omega k|q_p|^2)/(4\pi)$ is used as the reference. This defined noise reduction is 0 dB without active noise control if there are no additional reflecting surfaces around the system. For a constant volume primary source on ground, its sound radiation power (without ANC) varies after introducing reflecting surfaces near it. For example, the sound radiation power is increased by 3 dB when an infinitely large reflecting surface is introduced near the primary source at low frequencies [9]. Therefore, the noise reduction defined by Eq. (6) can then be nonzero (or even negative) without ANC when there are additional reflecting surfaces.

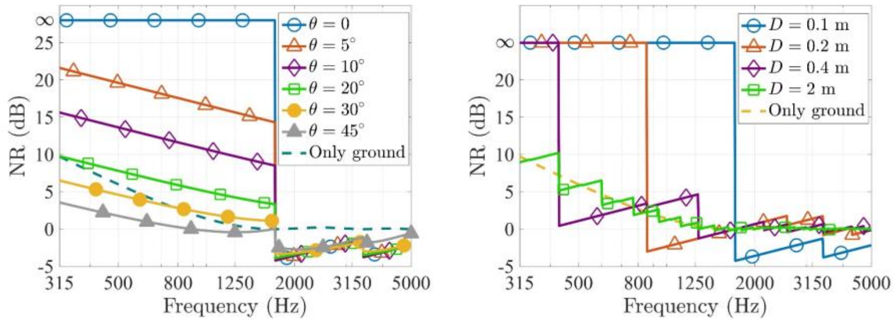
3 Numerical Results

In this section, the source interval, d, is set to 0.1 m throughout the simulations and the frequency of interest ranges from 315 Hz to 5 kHz. There are many geometric configurations of the sources and surfaces. For simplicity, only one case where the midpoint of the source line is on the middle line of the surfaces is considered. Then, the effects of the included angle between the source line and the normal line of the surfaces as well as the surface intervals are simulated and analyzed.

The noise reduction with different included angles when the surface interval D is set to 0.1 m is shown in Fig. 2(a). It can be observed that the noise reduction is significantly affected by the included angle. At the frequencies below 1715 Hz, which is the corresponding frequency when the surface interval equals to the half wavelength, the system with a smaller included angle has higher noise reduction. For example, the noise reduction at 500 Hz increases from 7.8 dB to 19.6 dB as the included angle decreases from 20° to 5°. The noise reduction is sensitive to the included angle. For example, the noise reduction is infinitely large when $\theta = 0°$ at 500 Hz, then it decreases to 19.6 dB when θ increases to 5°. It is noted that19.6 dB is larger (more than 13.6 dB) than that without any reflecting surfaces (only ground).

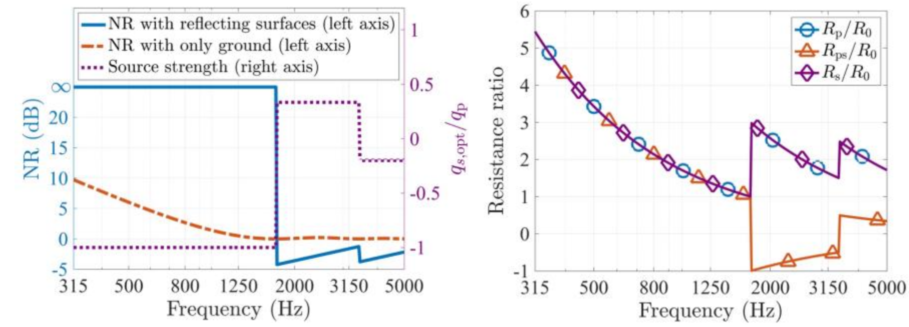
It should be noted that the noise reduction performance with the parallel reflecting surfaces can be worse than that without the surfaces (only ground) if the angle is large at low frequencies. For example, the noise reduction without the surface is 6.0 dB at 500 Hz, but it decreases rapidly to 1.8 dB if the included angle is 45°.

Figure 2(b) shows the effect of the surface interval D on the noise reduction of the ANC system when the included angle $\theta = 0°$. The noise reduction varies significantly from infinity to a finite value at 1715 Hz, 858 Hz and 429 Hz for the source interval D being 0.1 m, 0.2 m and 0.4 m, respectively. The turning frequency is defined as the frequency where the noise reduction varies from infinity to a finite value. The turning frequency is equal to $c_0/(2D)$ where c_0 is the sound speed in the air and it decreases as the surface interval increases. For the surface interval $D = 2$ m which is larger than the wavelength at 315 Hz (1.1 m) to 5 kHz (0.07 m), the noise reduction curve in Fig. 2(b) fluctuates around the one without any surfaces (only ground) because the surfaces are far enough away from the ANC systems. To have effects at high frequencies, the two surfaces need to be installed closely to each other.



(a) (b)

Fig. 2. Noise reduction of the ANC system on ground with two parallel reflecting surfaces: (a) with the fixed surface interval D = 0.1 m at different included angles θ; and (b) at the fixed included angle θ = 0° with different surface intervals D.



(a) (b)

Fig. 3. For D = 0.1 m, (a) noise reduction (left y-axis) and the ratio of the source strengths $q_{s,opt}/q_p$, (right y-axis) where $q_{s,opt}$ and q_p is the source strength of the secondary and the primary source respectively; and (b) the self-radiation resistances of the primary and secondary sources, R_p and R_s, and the mutual radiation resistance between the two sources R_{ps}, where $R_0 = (\rho_{air}\omega k)/(2\pi)$ is the self-radiation resistance of the primary source on ground without any surfaces.

The secondary source strength $q_{s,opt}$ and the self-radiation resistances of two sources and their mutual-radiation resistance are shown in Fig. 3 for the configuration with D = 0.1 m at θ = 0°. When the frequency is less than $c_0/(2D)$, which is 1715 Hz in Fig. 3, the secondary source strength is exactly opposite to that of the primary source and the mutual radiation resistance between sources R_{ps} and the self-radiation resistance of the secondary source R_s are exactly the same. Here only the zeroth normal mode exists inside the two parallel rigid boundaries. The radiation caused by the resistances at the primary (or secondary) source is exactly zero which means the overall sound power of the total system is zero. However, in real applications, the size of the reflecting surfaces can not be infinitely large which can deteriorate the noise reduction performance to a limited noise reduction.

4 Conclusions

This paper demonstrates that the noise reduction performance of a single channel active noise control system on ground can be significantly improved by introducing two vertically placed and parallel reflecting surfaces. If the reflecting surfaces are infinitely large, the sound radiation of the primary source can be completely suppressed in principle by a secondary source provided that the surface distance is less than the half wavelength. This is because only the zeroth normal mode exists inside the two parallel rigid boundaries, which can be completed cancelled if another source with 180 degrees phase is introduced. Future research includes exploring the noise reduction performance with finite size reflecting surfaces, the optimal geometrical shape and the optimal configurations of the error sensors and secondary sources for multiple channel ANC systems.

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