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Progress of research on active noise radiation control with reflecting surfaces

Tao, Jiancheng[1]
Key laboratory of Modern Acoustics and Institute of Acoustics, Nanjing University
No. 22, Hankou road, Nanjing, China, 210093

Xue, Jinpei[2]
Key laboratory of Modern Acoustics and Institute of Acoustics, Nanjing University
No. 22, Hankou road, Nanjing, China, 210093

Zhong, Jiaxin[3]
Centre for Audio, Acoustics and Vibration, Faculty of Engineering and IT, University of Technology Sydney
32-34 Lord Street, Botany, NSW 2019, Australia

Qiu, Xiaojun[4]
Centre for Audio, Acoustics and Vibration, Faculty of Engineering and IT, University of Technology Sydney
32-34 Lord Street, Botany, NSW 2019, Australia

ABSTRACT

The effect of reflecting surfaces on the peformance of active noise radiation control attracted attentions more than 20 years ago and there has been a lot of research on the area since then; however, successful applications are rarely reported. This paper first reviews the history of the research on active noise radiation control with reflecting surfaces, and then introduces recent progresses on this area at Nanjing University. The first progress is that the mechanism of noise reduction enhancement by introducing a refecting surface against the primary source in a multi-channel active sound radiation control system is analyzed. The second progress is that the noise reduction improvment by introducing an extra vertical reflecting surface to an active noise radiation control system near one existing horizontal surface is studied and the effects of the system orientation and the primary source location are discussed. The last progess is on increaseing the noise reduction by employing a finite size reflecting surface for the primary source on ground.

Keywords: Active noise radiation control, reflecting surface
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[1] jctao@nju.edu.cn
[2] xuejinpei@nju.edu.cn
[3] jiaxin.zhong@student.uts.edu.au
[4] xiaojun.qiu@uts.edu.au

1. INTRODUCTION

The effect of reflecting surfaces on the peformance of active noise radiation control is of great concern for practical noise sources, such as the power transformer with vertical fire proof wall on the ground. Early investigations on multipole sound radiation indicate that 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.[1] The feasiblity of enhancing the noise reduciton or reducing the complexity of active noise control systems by introducing reflecing surfaces is worth studying.[2]

The impact of the presence of a nearby reflective plane on the active control of sound radiated by point sources has been stuided by using the image source model. The analytical formulae of the optimal secondary source strength and the noise reduction were derived and both rigid and sound release boundaries were considered. It was found that the effect of the reflective plane is highly dependent on the source configuration and closeness of the sources to the plane. For sources in a line vertical to a nearby horizontal plane, the achived noise reduction can be greatly improved.[3]

The effect of a rigid plane on the active noise control of an acoustic source with characteristic dimensions comparable to the acoustic wavelength has also been investigated based on the boundary element models. The primary noise source is the vibrating upper surface of a box with the dimension of 760 mm × 610 mm × 457 mm, and 6 squre elements on the side walls were assumed as the secondary sources. For two basic plane orientations, it was shown that the plane can significantly affect the active noise control when the geometric center of the source is within 1/5 wavelength from the plane at the lower frequency. For the specific cases, the rigid plane still affects greatly when it is one-half and one-quarter wavelengths away.[4]

The mechnism of the peformance improvement due to a nearby reflecting surface has been discussed based on the analytical derivation and experiment validation. It was found that the noise reduction is dependent upon the system orientation angle. Based on the mechanism that the reflecting surface can convert a dipole vertical to the surface into a longitudinal quadrupole, it was proposed that if a monopole type of primary source is located near a reflecting surface, the secondary control source should be arranged to make the control system vertical to the surface.[5,6]

The effects of spherical reflecting sufaces has also been investigated in different applications. It has been demonstrated that rigid sphere can increase global sound radiation control performance after optimizing the locations of secondary in active control of radiation from a piston set in a rigid sphere.[7] The human head in a three 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.[8]

All the previous work has demonstrated the potential of increasing the noise reduction of active noise radiation control systems by employing reflecting surfaces; however, successful applications of this technology are still rare. This paper will report three recent progresses on this area at Nanjing University, and discuss future directions and implementation issues for active control of transformer noise systems. The first progress is on the noise reduction enhancement by introducing one reflecting surface against the primary source for multi-channel ANC system,[9,10] the sencond is on the influence of an extra vertical reflecting surface on the active radiation cotrol sytem near an existing horizontal surface,[11] and the last is on improving the noise reduction pefromance by employing a finite size reflecting surface.[12]

2. ONE REFLECTING SURFACE

Figure 1 shows a multi-channel active noise radiation control system, where the primary sound source locates on an infinitely large rigid plane z = 0 and the secondary sources are placed on a semi-sphere surface with a radius of l. The distance between the ith secondary source and the image of jth secondary source is $d_{ij'}$ and the distance between the jth secondary source and the image of ith secondary source is $d_{i'j}$.

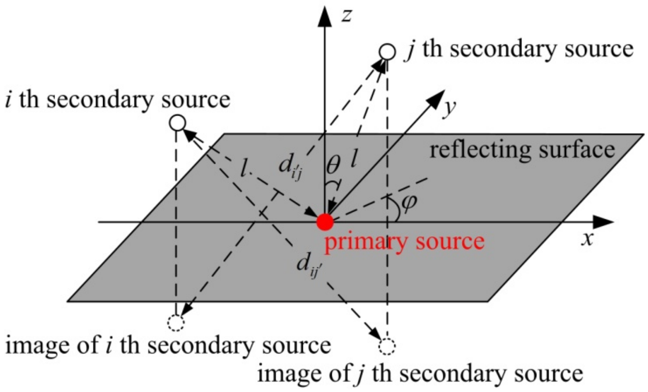


Figure 1. A multi-channel active noise radiation control system for a primary source on an infinitely large rigid surface (only two secondary sources are shown in the figure)

The sound radiation power of such a system can be formulated as[13,14]

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

where **Q** is the strength vector of the secondary sources, **A** is a matrix composed by the radiation resistances between two corresponding secondary sources, **b** is a 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. The matrix elements in Equation 1 are $A_{ij} = 0.5Z_0[\text{sinc}(kd_{ij})+\text{sinc}(kd_{i'j})]$, $b_i = Z_0 q_{\text{p}}\text{sinc}(kl)$, $c = Z_0 q_{\text{p}}^2$, 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, and q_{p} is the strength of the primary source.

Substituting the optimal secondary source strength $\mathbf{Q}_{\text{opt}} = -\mathbf{A}^{-1}\mathbf{b}$ in to Equation 1, the sound radiation power with active control is[13,14]

$$W_{\text{opt}} = c - \mathbf{b}^{\text{H}}\mathbf{A}^{-1}\mathbf{b}\,. \tag{2}$$

It can be seen that the sum of the first two terms on the right hand side of Euation 1 equals to zero with the active noise control, which 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. The mutual radiation power of the primary source from the secondary sources can be formulated as $0.5\,\text{Re}\{p_{\text{S}}^{*}q_{\text{p}}\}$, 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. In other words, the sound power with active control decreases with the sound pressure generated by the secondary sources at the primary source.

The noise (sound radiation power) reduction is defined as

$$NR = -10\log\left(\frac{W_{\text{opt}}}{W_{\text{off}}}\right), \tag{3}$$

where W_{off} is the sound power without active control. Considering Equations 2 and 3, the noise reduction is inversely proportional to the matrix **A**. For sufficiently low frequency, A_{ij} depends on the distances $d_{i'j}$ and $d_{ij'}$. The larger these two distances are, the smaller the value of A_{ij} will be. Therefore, the maximal noise reduction can be obtained by searching the optimal location of secondary sources to minimize the value of matrix **A**.

Figure 2(a) shows the optimal zenith angle of two secondary sources labelled as S1 and S2 in a 2-channel system for a monopole primary source, where the optimal zenith angle remains 45° first and then increases with the frequency. Figure 2(b) shows the sound pressure level generated by the secondary sources at the primary source and the noise reduction with different zenith angles at 800 Hz. It is clear that the noise reduction corresponds to the increase of the sound pressure p_S and its maximum occurs when the zenith angle is 45°, which validates that mechanism for the noise reduction improvement is due to the increased sound pressure generated by the secondary sources at the primary source location.

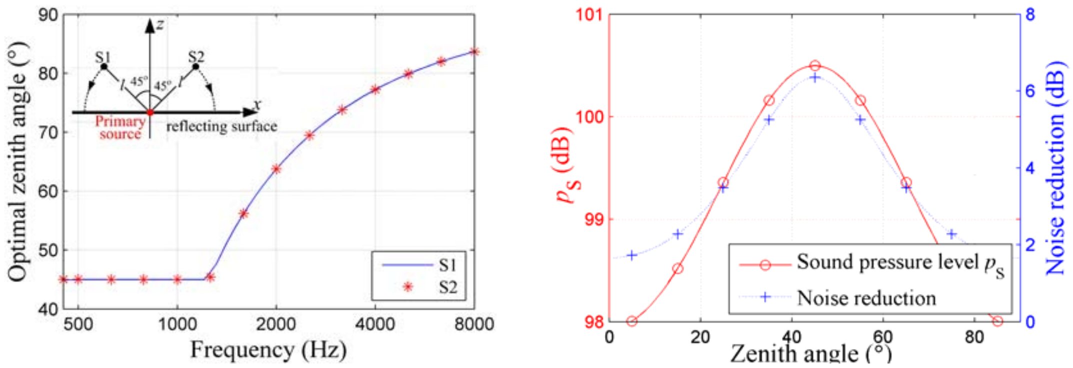


Figure 2. (a) optimal zenith angle of secondary sources (b) noise reduction and the sound pressure generated by the secondary sources at the primary source of a 2-channel ANC system

Figure 3 shows the optimal noise reduction with and without the reflecting surface, where the optimal noise reduction decreases with the frequency first and then converges to a constant value, which is −3 dB and 0 dB respectively. The reason for the 3 dB difference is that the sound radiation power of the primary field is doubled when a reflecting surface is placed against the primary source. It is also found that the noise reduction with the reflecting surface is higher when the frequency is below 1000 Hz. Futher derivation shows that compared to the free field, the maximal improvement of the noise reduction with a reflecting surface is 3 dB for the 2-channel ANC system when the frequency decreases to 0. The noise reduction can be improved by introducing a reflecing surface against the primary source in low frequency range.

Defining the minimal frequency that the optimal noise reduction with a reflecting surface equals to that in free field as the cross frequency. Figure 4(a) shows that the cross frequency increases with the number of secondary sources and converges to the "half-wavelength frequency" $c_0/2l$ (1387 Hz in the simulations). Experimental results in Figure 4(b) show that the cross frequency is 800 Hz and 850 Hz respectively for the 2-channel and 3-channel system, which validates the variation rule of the cross frequency.

The optimal noise reduction of an ANC system typically increases with the number of system channels, therefore the noise reduction curves of the ANC system with $n + 1$ channels should locate above the corresponding curves of the system with n channels and the intersection of the noise reduction curves with and without a reflecting surface (which corresponds to the cross frequency) must occur at a higher cross frequency when the number of system channels increases.

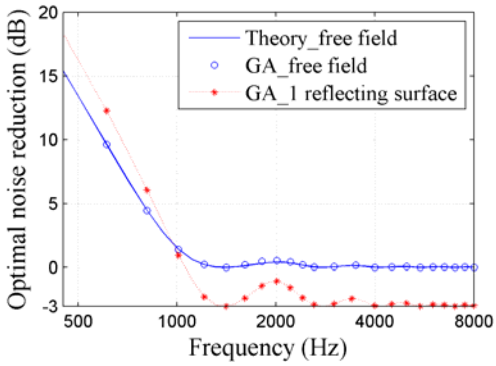


Figure 3. Optimal noise reduction of the 2-channel system with and without the reflecting surface

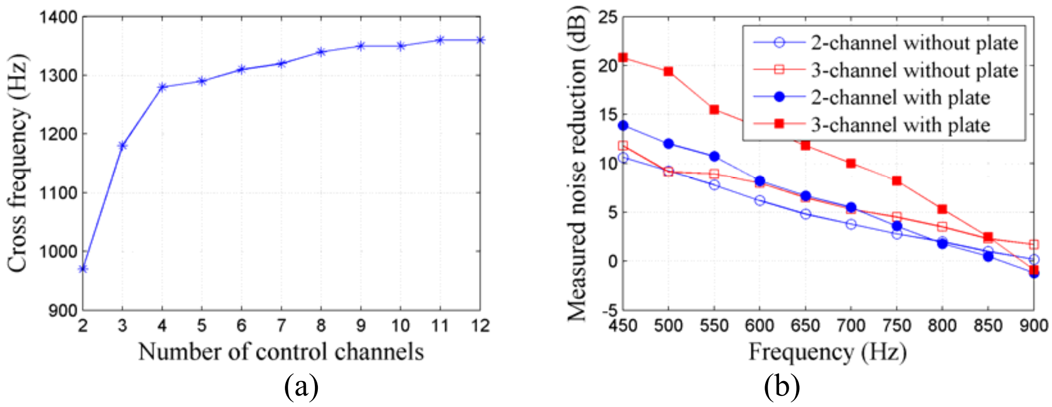


Figure 4. The cross frequency as a function of channel (secondary source) number of the ANC system when the primary source is on a reflecting surface

This section demonstrates that the noise reduction of a multichannel active sound radiation control system at low frequencies can be improved by introducing a reflecting surface against the primary source after optimizing the location of the secondary sources. The mechanism for the performance improvement is due to the increased sound pressure generated by the secondary sources at the primary source location. If more secondary sources are adopted, the noise reduction improvement by introducing a reflecting surface will be larger, and the beneficial frequency range will extend to the half-wavelength frequency, which is determined by the distance between the secondary sources and the primary source.

3. TWO REFLECTING SURFACES

Figure 5 shows a single channel active noise radiation control system with two reflecting surfaces, where the primary source with the strength of q_p, the secondary source with the strength of q_s and their images are labeled from 1 to 8. The horizontal surface (surface 1) always exists and the vertical surface (surface 2) is defined as an “introduced surface”. The distances between the midpoint of the two point sources and surface 1 and surface 2 are h and d, respectively and the distance between the ith and jth sources is d_{ij}.

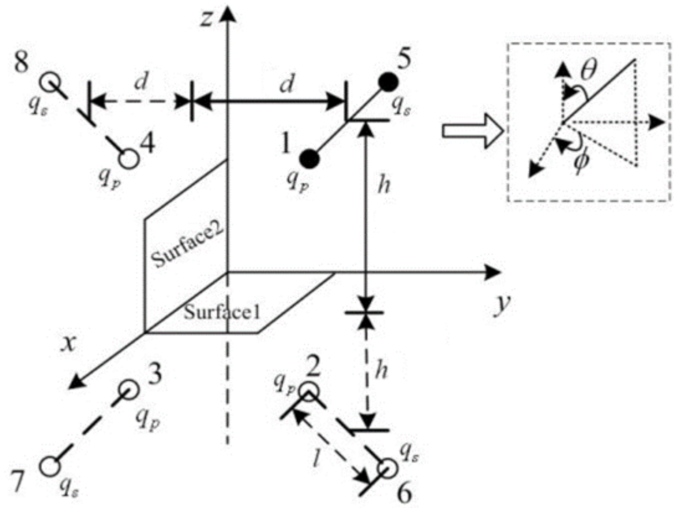


Figure 5. Active control system consisting of one primary source, one secondary source and two rigid reflecting surfaces

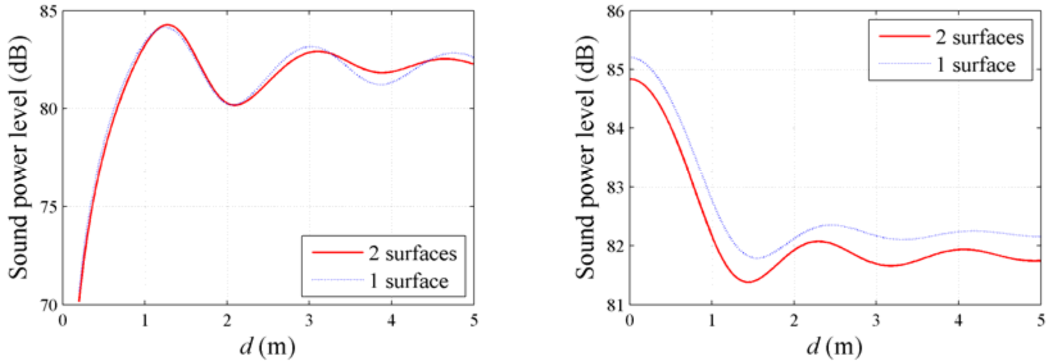
From Equations 1 and 2, the radiatied sound power without and with control is[13,14]

$$W_{\text{off}} = W_0 \sum_{i=1}^{4} \operatorname{sinc}(kd_{1i}), \tag{4}$$

and
$$W_{\text{opt}} = W_0 \sum_{i=1}^{4} \operatorname{sinc}(kd_{1i}) - W_0 \frac{\left[\sum_{i=5}^{8} \operatorname{sinc}(kd_{1i})\right]^2}{\sum_{i=5}^{8} \operatorname{sinc}(kd_{5i})}. \tag{5}$$

Figure 6 compares the sound power level with and without the introduced surface (surface 2) at 100 Hz, where the radiation power of the primary frequency is 90 dB and the interval l is 0.4 m. Figure 6(a) shows that the sound radiation is nearly the same with and without the introduced surface when the primary and secondary sources are arranged in a line perpendicular to surface 1 and parallel to surface 2. Figure 6(b) shows that when the line determined by the primary and secondary sources is parallel to both surfaces, the sound power level can be reduced by the introduced surface. The effect of the introduced reflecting surface is determined by the orientation of the active noise radiation control system.

Figure 7 shows the optimal zenith angle of the secondary source to achieve the maximal noise reduction when the primary source is 0.005 m, 0.05 m and 0.5 m high. It is seen that the optimal zenith angle converges to 0° when the distance between the primary source and the introduced surface increases, and the covegence progress becomes intense with the height of the primary source. Simulations also show that the optimal azimuth angle is either 90° or −90°. The optimal location of the secondary source moves to the point right above the primary source when the introduced reflecting surface becomes far away from the primary source when the primary source is sufficiently close to the horizontal surface.



(a) (b)

Figure 6. Sound power level of the ANC system with and without the introduced reflecting surfaces (a) when two point sources are arranged in a line perpendicular to surface 1 and parallel to surface 2 (b) when the two point sources are arranged in a line parallel to both surfaces 1 and 2

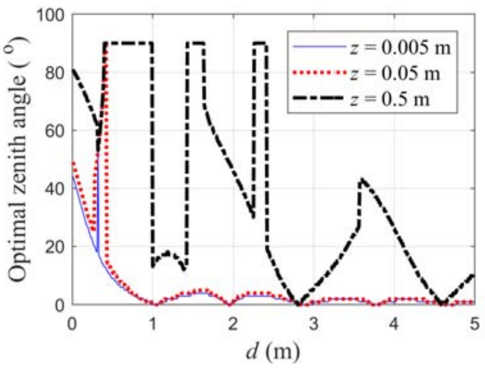
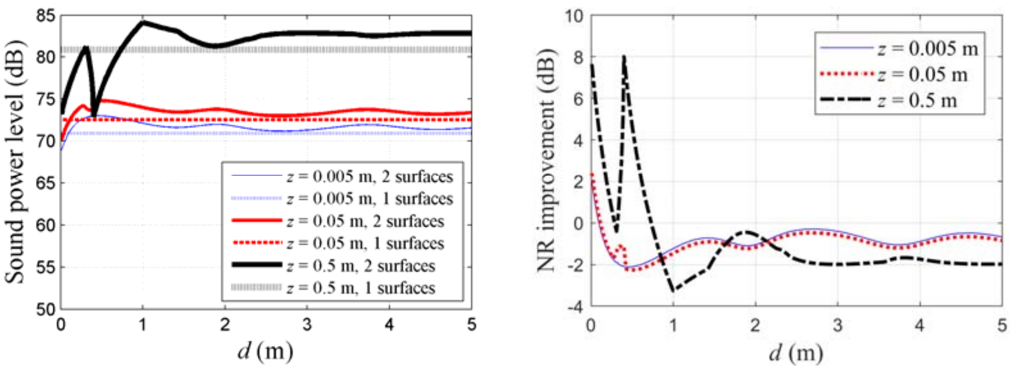


Figure 7. Optimal zenith angle of the secondary source when the primary source is at different heights



(a) (b)

Figure 8. (a) The sound power level and (b) the extra noise reduction when the introduced surface is placed at different locations

Figure 8 shows the sound power level and noise reduction when the primary source is located at different heights and the location of the secondary source is optimized. In the case with one surface, the secondary source locates right above the primary source and the sound power level increases with the height of the primary source. It is seen that the sound power can be reduced by introuding the vertical reflecting surface (surface 2) near the primary source. The maximum achievable power reduction is less than 3 dB by introducing one more surface when the height of the primary source is 0.005 m and 0.05 m. However, when the noise source is 0.5 m above the ground, a 8 dB additional sound power reduction can be achieved.

In this section, the formula for the power radiation of the single channel active noise radiation control system near two reflecting surfaces is derived. The noise reduction can be improved by introducing one more vertical surface if the distances between the midpoint of the two point sources and the introduced surfaces is suitablely selected and the location of the secondary source is optimized. Furthermore, the extra noise reduction induced by the introduced surface, as well as the total sound power level, increases with the height the primary noise.

4. ONE FINITE SIZE VERTICAL SUFACE ON GROUND

Figure 9 shows an active noise radiation control system on ground with a vertical semicircular rigid disk with the radius of a in the plane $x = 0$. The distance between the primary and secondary sources is l, and the distance between the secondary source and the center of the disk is r. The semicircular rigid disk vertical to the ground can be treated as a whole rigid disk using the image source method and its sound radiation can then be calculated based on the disk scattering model.

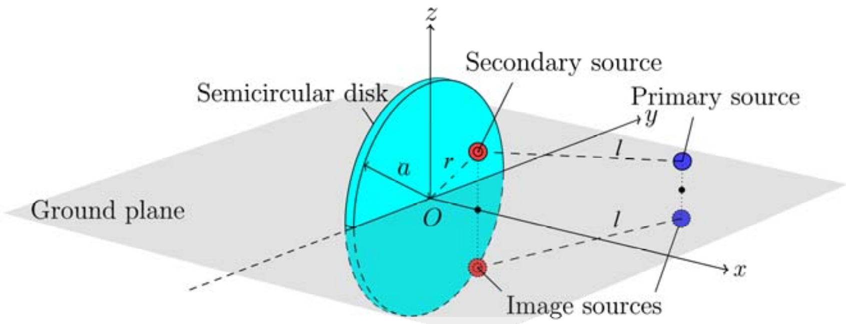


Figure 9. Active radiation system with a vertical semicircular rigid disk on ground

The Cartesian coordinates (x, y, z) can be transformed to the oblate coordinates (η, ξ, φ) as[15]

$$\begin{aligned} x &= a\eta\xi \\ y &= a\sqrt{(1-\eta^2)(1+\xi^2)}\cos\varphi\,, \\ z &= a\sqrt{(1-\eta^2)(1+\xi^2)}\sin\varphi \end{aligned} \tag{6}$$

and the total sound pressure at a field point (η, ξ, φ) radiated by a monopole source with the strength q at $(\eta_S, \xi_S, \varphi_S)$ with source strength q can be calculated as[15]

$$\begin{aligned} p(\eta,\xi,\varphi) = {} & \frac{\rho_0\omega kq}{4\pi}\sum_{m=0}^{\infty}\sum_{n=m}^{\infty}\frac{2\varepsilon_m}{N_{mn}(-\mathrm{j}ka)}S_{mn}(-\mathrm{j}ka,\eta)S_{mn}(-\mathrm{j}ka,\eta_S)\cos[m(\varphi-\varphi_S)] \\ & \times\left[\begin{aligned} & R_{mn}^{(1)}(-\mathrm{j}ka,\mathrm{j}\xi_<)R_{mn}^{(3)}(-\mathrm{j}ka,\mathrm{j}\xi_>) \\ & \quad -\frac{R_{mn}^{(1)'}(-\mathrm{j}ka,\mathrm{j}\xi_b)}{R_{mn}^{(3)'}(-\mathrm{j}ka,\mathrm{j}\xi_b)}R_{mn}^{(3)}(-\mathrm{j}ka,\mathrm{j}\xi)R_{mn}^{(3)}(-\mathrm{j}ka,\mathrm{j}\xi_S) \end{aligned}\right], \end{aligned} \tag{7}$$

where ε_m is the Neumann factor ($\varepsilon_m = 1$ for $m = 0$ and $\varepsilon_m = 2$ for $m \neq 0$), $S_{mn}(-\mathrm{j}ka, \eta)$ is the angular oblate spheroidal wave function, $N_{mn}(-\mathrm{j}ka)$ is the normalization factor of $S_{mn}(-\mathrm{j}ka, \eta)$, and $R_{mn}^{(i)}(-\mathrm{j}ka, \mathrm{j}\xi)$ and $R_{mn}^{(i)'}(-\mathrm{j}ka, \mathrm{j}\xi)$ represent the ith kind of the radial oblate spheroidal wave functions and their derivatives with respect to ξ, i = 1, 3,$\xi_<$ = min(ξ, ξ_s) and $\xi_>$ = max(ξ, ξ_s).

When the radial coordinate $\xi = \xi_b = 0$, the oblate represents an infinitely thin disk with a radius of a in the plane y = 0. The self-radiation resistance of the primary and secondary source, Z_p and Z_s, the mutual radiation resistance between two sources Z_{ps} can be calculated by employing Equation 7, and the noise reduction can be written in terms of the resistances as

$$\mathrm{NR} = -10\lg\left(\frac{2\pi}{\rho_0\omega k}\frac{Z_p Z_s - Z_{ps}^2}{Z_s}\right), \tag{8}$$

where the noise reduction increases as the term $(Z_p Z_s - Z_{ps}^2)/Z_s$ decreases. According to the reciprocity theorem, the value of $(Z_p Z_s - Z_{ps}^2)$ does not change if the location of the primary and secondary sources is exchanged, but the value of Z_s might change after the exchanging operation. This implies that higher noise reduction can be obtained if the secondary source is placed in a place where it has higher self-radiation resistance. Therefore, when a reflecting surface is introduced near a single channel active control system, the surface should be placed close to the secondary source to increase the self-radiation resistance of the secondary source.

Figure 10 shows the noise reduction when the disk radius is a = 0.1 m and the interval between the primary and secondary source is 0.1 m. The noise reduction of all cases approaches 0 when the frequency is suffciently high, and better noise reduction is achieved by introducing the disk closer to the secondary source in the low frequency range. For example, the noise reduction with the disk is higher at frequencies below 900 Hz and 1250 Hz when the distance between the vertically placed disk and the secondary source is 0.1 m and 0.05 m, respectively.

Figure 11 shows the noise reduction of the active control system when the disk is placed against the secondary source and the noise reduction. It is found that the noise reduction is significantly enhanced in the low frequency range after introducing the reflecting disk. For example, the noise reduction is 6.0 dB at 500 Hz without the disk (i.e. only the ground), and it increases up to 17.5 dB when a rigid disk with a radius of 0.3 m is introduced. It is also found that the noise reduction with the infinitely large reflecting surface is lower than that with a finite size disk at some frequencies although it is larger at most frequencies. For example, a disk with a radius of 0.3 m brings extra 2.3 dB noise reduction at 440 Hz compared with that with an infinitely large one.

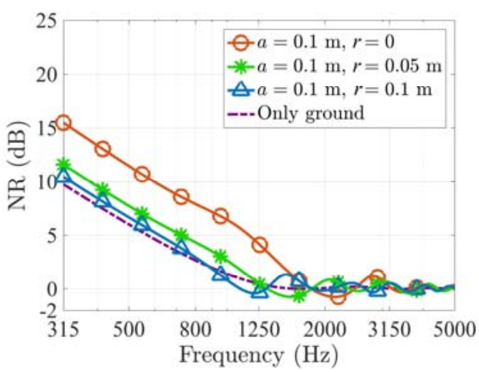


Figure 10. Noise reduction of the ANC system with a vertically placed semicircular rigid disk at distance r from the secondary source

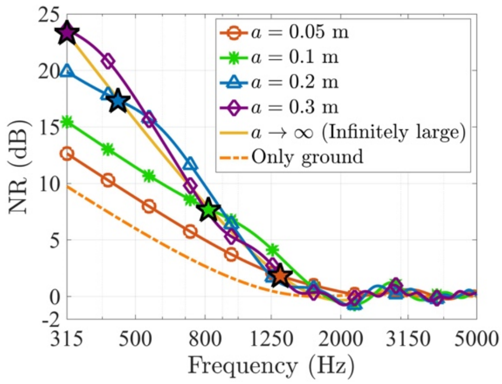


Figure 11. Noise reduction of the active control system after introducing a vertical disk

Figure 12 shows the noise reduction of the active control system as a function of a/λ and d/λ, where λ is the wavelength. It is found that the maximal noise reduction is achieved near the line of $a = 0.35\lambda$ for a fixed source distance d/λ. The sound pressure at the primary source location generated by the secondary source consists of the direct wave and the diffraction wave of the edge of the disk, and the latter one has the maximal constructive effects with the direct wave (even greater than that caused by an infinitely large reflecting surface) when the radius of the disk $a \approx 0.35\lambda$.[16] Therefore, the sound pressure at the primary source location generated by the secondary source with a disk with a radius of 0.35λ is the largest, which is even larger than than that with the infinitely large one. Therefore, the appropriate radius of the disk can be determined according to the frequency of interest in practical applications. For example, if the frequency is 100 Hz ($\lambda = 3.43$ m) for transformer noise control and the in situ source distance l is 0.5 m (0.145λ), the maximal noise reduction of the active control system without the reflecting surface is 6.0 dB. With an infinitely large reflecting surface placed vertically on ground, the noise reduction can be increased up to 15.6 dB, but if the radius of the vertically placedsemicircular rigid disk is optimizedto 1.2 m (0.35λ), the noise reduction can be increased up to 17.7 dB.

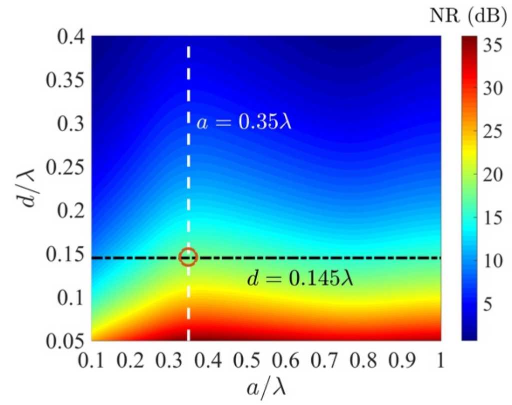


Figure 12. Noise reduction of the active control system as a function of the normalized radius of the semicircular rigid disk and the normalized source distances

This section demonstrates that the noise reduction performance of a single channel active noise control system on ground can be further increased by introducing a finite size rigid disk vertical to the ground after optimizing the distance between the secondary source and the disk and the size of the disk. The mechanism for the performance improvement caused by the finite size disk is due to the increased sound pressure diffracted by the edge of the disk at the primary source location generated by the secondary source. To maximize the noise reduction performance, the vertical reflecting surface should be placed as close as possible to the secondary source and the radius of the disk should be set to 0.35λ where λ is the wavelength of the noise to be controlled.

4. CONCLUSIONS

The effect of reflecting surfaces on active noise radiation control system is investigated, and it is shown that the mechanism of the noise reduction improvement is that the sound pressure generated by the secondary source at the primary source increases when the location of the reflecting surfaces and secondary source is optimzied. The noise reduction of the active noise radiation control system with one horizontal reflecting surface can be further improved by introducing an extra vertical reflecting surface, and the corresponding improvement also depends on the height of the primary source. To maximize the noise reduction performance, the vertical reflecting surface should be placed as close as possible to the secondary source and the radius of the disk should be set to 0.35λ where λ is the wavelength of the noise to be controlled. Future researh directions includes exploring the optimal size of a finite size rectangular reflecting surface and investigating the peformance of multi-channel active control systems.

5. ACKNOWLEDGEMENTS

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