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An active noise barrier with unidirectional secondary sources

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ABSTRACT

An active noise barrier with unidirectional secondary sources is investigated in this paper, where the unidirectional secondary source consists of two closely located loudspeakers with pre-adjusted phase difference. The secondary sound field of the unidirectional sources is adjusted to maximally match the primary sound field in the shadow zone behind the barrier. It is shown both numerically and experimentally that the noise reduction performance of the active noise barrier can be improved remarkably by replacing monopoles with the unidirectional sources. The mechanism for the improvement is also investigated.

Keywords: active noise barrier; unidirectional secondary source; phase adjustment

1. Introduction

Active noise control (ANC) techniques have been applied in noise barriers to improve its low frequency noise attenuation in the last few decades, and the resulting system is often called active noise barriers (ANB) [1]. Omoto et al. applied a multichannel control system to cancel the noise around a semi-infinite barrier top [2, 3], where he found that the control is effective and stable when the distance between the error sensors is less than half of the wavelength, and the sound reflections from the ground also have large influence on the performance of the ANB system. Afterwards, the influence of the ground reflection on the ANB system was studied in detail by Guo and Pan [4]. Berkhoff [5] proposed a control strategy with virtual errors for application in ANB system, where the signals of the error sensors in near-field are used to estimate the expected signals of the virtual error sensors in far-field. This method improved noise reduction performance and stability of the ANB system.

Ohnishi et al. established an ANB system along an expressway and it was the first time to realize a practical ANB system in engineering [6]. In their practice, the insertion loss of the barrier increased 1.6-3.1 dB in frequency range 315-1000 Hz due to the aid of active control. Niu et al. examined the potential optimal positions of the error sensors in an ANB system [7]. Han et al. used sound intensity as the cost function for active control to enhance the insertion loss of the ANB system [8]. Lau et al. pointed out that the method of controlling the pressure gradient is

more efficient than that of controlling the sound pressure [9]. The improved performance of the active noise barrier can be achieved using the new configurations of control loudspeakers and error sensing strategy.

In the previous studies mentioned above, all the secondary sources are omni-directional and can be regarded as monopoles in the low frequency range. Recent investigations indicate that secondary sources with specific directivity can improve the noise reduction of ANC system [10-12]. By adjusting the directivity of the secondary sources, the secondary sound field can reconstruct the primary sound field better so that more attenuation can be achieved. In this paper, based on the design method of Boone et al. [13], a kind of unidirectional secondary source is applied in an ANB system, and the mechanism of how such the directional secondary sources improve the performance of the ANB system is analyzed.

2. Theory

An ANB system is illustrated in Fig. 1a, where the primary source is on the left of the barrier. N_s secondary sources are placed evenly along the barrier top, and N_e error sensors are arranged along a line parallel to the barrier corresponding to each secondary source on the right of the barrier. In the absence of ground reflection, as the profile shown in Fig. 1b, the dotted lines at $\alpha = \pi - \theta_p$ and $\alpha = \pi + \theta_p$ subdivide the sound field into three separate regions according to the geometrical theory of diffraction. When the receiver is in region I, the total sound field is composed of the direct sound p_d from the primary source, the reflected sound p_r by the barrier, and the diffracted sound p_D along the edge of the barrier. When the receiver is in region II, the total sound field consists of p_d and p_D , while in the shadow zone (region III), only the diffracted wave p_D exists. The direct and reflected sounds are given by

$$p_d = \frac{j\omega\rho q_p}{4\pi R} e^{j(\omega t - kR)}, \quad p_r = \frac{j\omega\rho q_p}{4\pi R'} e^{j(\omega t - kR')}, \quad (1)$$

and the diffracted wave p_D can be calculated with the MacDonald solution [14]

$$p_D = -\sqrt{\frac{2}{\pi k R_{pr}}} A e^{j\pi/4} \left\{ \text{sgn}(\pi + \theta_p - \theta_r) \frac{e^{-jkR}}{\sqrt{k(R_{pr} + R)}} F[\sqrt{k(R_{pr} - R)}] \right. \\ \left. + \text{sgn}(\pi - \theta_p - \theta_r) \frac{e^{-jkR'}}{\sqrt{k(R_{pr} + R')}} F[\sqrt{k(R_{pr} - R')}] \right\}, \quad (2)$$

where $A = jZ_0 q_p$ with $Z_0 = k^2 \rho c_0 / 4\pi$ and q_p is the strength of the primary source. k is the

wave number, ω is the angular frequency, ρ is the air density and c_0 is the sound speed in the air. R and R' are distances from the receiver to the source and its image in the barrier respectively. $R_{pr} = r_p + r_r$ is the shortest distance from the primary source to receiver over the top of the barrier. $F(\mu) = \int_{\mu}^{\infty} e^{-ix^2} dx$ is the Fresnel integral.

When the ground reflections on both sides of the barrier are considered, the total sound pressure of the n th error sensor located at $\mathbf{r}_n$ can be determined by [14]

$$p_t(\mathbf{r}_n) = \sum_{i=1}^4 p_{pi}(\mathbf{r}_n) + \sum_{m=1}^{N_c} [Z_{sm}(\mathbf{r}_n) + Z_{sm}^i(\mathbf{r}_n)] q_m, \quad (3)$$

where the first term determines the total pressure produced by the primary source and its image sources, and q_m in the second term denotes the strength of the m th secondary source. $Z_{sm}(\mathbf{r}_n)$ and $Z_{sm}^i(\mathbf{r}_n)$ are the transfer impedances from the m th secondary source and its image in the ground to the n th error sensor respectively. The sum of the squared sound pressures at the error sensor positions is selected as the cost function, and the optimal strengths of control sources can be obtained [1]. The total pressure after control at any receiver point can then be calculated by Eq. (3), and the sound power flow from region II to region III can be written as [1]

$$W = \frac{1}{2} \int_s \text{Re}[p^*(r, t) u_n(r, t)] ds, \quad (4)$$

where s is the semi-infinite plane at $\alpha = \pi + \theta_p$, and $u_n(r)$ is the normal velocity on the plane and can be expressed as [1]

$$u_n(r, t) = -\frac{1}{\rho} \int \frac{\partial p(r, t)}{\partial r} dt. \quad (5)$$

As the normal intensity in the plane of $\alpha = \pi + \theta_p$ decreases with the increase of the distance between the point and the primary source, the infinite integral in Eq. (4) can be approximated with a finite integral in the calculation.

In order to improving the noise reduction performance of the ANB system, a kind of phase adjustment directivity source is introduced in Fig. 1a, which is constituted by two monopoles at up and low positions with a space of d . The complex strengths of the two elements are A_1 , A_2 respectively. The sound pressure p at a point in the free space can be expressed as

$$p = A_1 \frac{jk\rho c_0 e^{-jkr_1}}{4\pi r_1} + A_2 \frac{jk\rho c_0 e^{-jkr_2}}{4\pi r_2}, \quad (6)$$

where r_1, r_2 are respectively the distances from the measurement point to the two monopoles. According to the design method of Boone et al., the amplitude of the two elements can be written as [13]

$$A_1 = \frac{1}{2} Q \left(\alpha + \frac{2}{jkd} \right), \quad A_2 = \frac{1}{2} Q \left(\alpha - \frac{2}{jkd} \right), \quad (7)$$

where Q is a common source strength factor of the two elements, α is the parameter for phase adjustment. In the following active control, α corresponding to the largest noise reduction at the N_e error sensors at the specific frequency is selected as the optimal value, and the optimal directivity of the unidirectional source is then regulated. The directivity of the source approaches to that of a tripole when α equals to 1.0, and its directivity pattern is between tripole and monopole when α varies in the range of $[1, \infty)$.

3. Numerical analysis

3.1. Without the ground reflections on both sides of the barrier

As shown in Fig. 1, the height of the barrier is $h_b = 1.33$ m. A point primary source located at the position $(0, -4.0$ m, 0.16 m) with the strength of $q_p = 1.0$ m³/s. The frequency of the source is set to 160 Hz. Without considering the reflection of the ground, Fig. 2a displays the diffracted sound field in the yo z plane behind the barrier, where the dash lines denote pressure contours, and the arrows represent the sound intensity. With the increase of the distance from the receiver to the barrier, the angle between the intensity vectors and the horizontal direction decreases slowly. The intensity vectors are almost parallel to each other and point to the right down direction.

In ANB systems, monopoles are usually used as secondary sources. The secondary sound field distribution due to such a system is shown in Fig. 2b with $N_s = N_e = 16$, and $r_{ss} = r_{ee} = 0.6$ m. The locations of the secondary sources are $[(i_s - 8.5)r_{ss}, 0, h_b + 0.08]$ ($i_s = 1, \dots, 16$), and the error sensors are at $[(i_e - 8.5)r_{ee}, 2.2, 0.5]$ ($i_e = 1, \dots, 16$). Because monopoles are omni-directional, the intensity vectors in the figure are all along normal direction of the concentric circles centered at secondary source, and the vectors are almost along horizontal direction in far-field. The intensity distribution of the secondary sound field is quite different from that of the primary diffracted sound field on the right of the barrier. Therefore, even the ANB system can obtain high noise

reduction around the error sensors. The noise reduction in the other regions of the shadow zone cannot be maintained due to the fact that the secondary sound field produced by the monopoles cannot match the primary diffracted sound field well.

From the analysis above, it seems that the overall performance of the ANB system might be improved if the intensity distribution of the secondary sound field is similar to that of the primary sound field in the shadow zone. Replacing the monopole secondary sources by the unidirectional sources mentioned above and keeping other parameters invariant, the coordinates of the unidirectional sources are $[(i_d - 8.5)r_{ss}, 0, h_b + 0.08]$, $[(i_d - 8.5)r_{ss}, 0, h_b + 0.23]$ ($i_d = 1, \dots, 16$), and the optimal α equals to 2.0 at 160 Hz. The sound field distribution of the unidirectional secondary sources is shown in Fig. 2c. Comparing with that in Fig. 2a, the pressure contours and the intensity vectors produced by the unidirectional secondary source are more similar to that of the primary diffraction sound field. Therefore, the secondary sound field can match the primary diffraction sound field behind the barrier better. The ANB system with the unidirectional secondary sources can not only achieve high noise reduction at the location of error sensors, but also obtain better noise reduction performance in a large zone around the error sensors. For the case investigated here, the performance of the control system with unidirectional secondary sources is better than that of monopole secondary sources.

With α being 2.0, Fig. 3a shows the pressure directivities along a circle of radius 10 m centered at the top of the barrier in yoz plane. Where p_D is the diffracted wave produced by the primary source, p_M is the pressure produced by the monopole secondary sources and p_U is the pressure produced by the unidirectional secondary sources. $\Delta\Phi_M$ and $\Delta\Phi_U$ in Fig. 3b are the phase differences between p_D and p_M , p_U respectively. By observing the symmetry of the sound field, the region II can be divided into two parts, the left region of II ($\pi - \theta_p < \alpha \leq \pi$, abbreviated as IIL), the right region of II ($\pi < \alpha \leq \pi + \theta_p$, abbreviated as IIR).

In the region III, $\Delta\Phi_M$ and $\Delta\Phi_U$ are about 180° , p_D and p_M , p_U are almost out of phase, the total pressures after control in this region decrease. It is shown in Fig. 3a that the pressure directivity of unidirectional sources is more like the directivity of primary sound field than that of monopole sources. Therefore, larger noise reduction can be obtained in this region. In the region IIL, though p_D and p_M , p_U are also almost out of phase, large difference between their magnitudes makes the sum of p_D and p_M or p_U almost not decrease. In some cases, it may be even larger than p_D . In the regions I and IIR, p_D and p_M , p_U are almost in-phase, the sum of p_D and p_M or p_U is larger than p_D alone. Therefore, the mechanism of diffracted wave reduction in

region III seems that the diffraction energy in the shadow zone is reflected to other regions, resulting in a local quiet zone.

Fig. 4 shows the sound power flow from region IIR to region III as a function of frequency according to Eq. (4), where the integral surface is limited to $[-10 \text{ m}, 10 \text{ m}]$ in x direction and $[0, 40 \text{ m}]$ along the line $\alpha = \pi + \theta_p$ in Fig. 1b. Either with the monopole or the unidirectional secondary sources, the sound power flow from region IIR to region III with active control is always much less than that without active control. This might be considered as that the diffracted acoustic energy in the shadow zone is reflected to region IIR. Comparing the power flow of the unidirectional secondary source control system with that of the monopole secondary source in Fig. 4, though α is only an optimal value at 160 Hz, the control system with unidirectional secondary sources can reflect more energy from the shadow zone to region IIR than that of monopole secondary sources in a broader frequency range, accordingly, and larger noise reduction in the shadow zone can be obtained by the unidirectional secondary sources system.

3.2. *With the ground reflections on both sides of the barrier*

When the reflection of the ground is taken into consideration, the image of each source in the ground should be considered. The primary sound field and the secondary sound field become complicated; however, both primary source and secondary sources have image sources, the conclusions obtained above are still applicable for the occasion that the ground on both sides of the barrier is reflective.

As shown in Fig. 5a-c, the pressure contours of the sound field produced by the unidirectional sources is more similar to the primary diffraction field than that of the monopoles, but the difference of intensity distribution among the figures is not obvious. Fig. 5d shows the detail distribution of intensity vectors around an error sensor. The amplitude and direction of the intensity vectors produce by the unidirectional sources are more similar to that of the primary diffraction sound field. Hence, the noise reduction performance of the system with the unidirectional secondary sources might be better than that of the monopole secondary sources. Fig. 6 shows the sound power flow from region IIR to region III as a function of frequency according to Eq. (4), where the integral surface is the same as that in Fig. 4. It seems that the control system with the unidirectional secondary sources can obtain a little bit larger noise reduction than that of monopole secondary sources system in the shadow zone when the ground reflections are considered.

4. Experiments

4.1. The unidirectional source

Two loudspeakers with similar characteristics are used to constitute a unidirectional source. The cone diaphragm diameter of the unidirectional source element is 100 mm, and the loudspeaker is fixed on a box with inner dimensions of 200 mm $\times$ 140 mm $\times$ 130 mm. The thickness of the box wall is 10 mm. The distance between the centers of the two elements is about 0.15 m. The value of α is adjusted to 2.0 by using a phase shift circuit. The measured directivities of the unidirectional source on a circle with a radius of 1.0 m at 160 Hz and 300 Hz are shown in Fig. 7, where the unidirectional source exhibits a tripole-like pattern.

4.2. The experiments of ANB system with the unidirectional secondary sources

Fig. 8 shows the experimental setup carried out on an open roof of a building. The barrier is 8.0 m long and 1.33 m high. The surface density of the barrier is about 28.0 kg/m², and its transmission loss is no less than 31.0 dB above 160 Hz, so the sound transmission through the barrier wall can be ignored. There is no other high building around the roof, so the experimental site can be regarded as a semi-free acoustic field. The wind speed is about 2.0 m/s. Both the error microphones and the monitoring microphones are equipped with foam windshields. Seven secondary sources are on the top of the barrier. The diameter of the loudspeaker as the primary source is 320 mm and placed on the ground on the other side of the barrier. A microphone type B&K 4190 is used as the reference sensor 0.5 m in front of the center of the loudspeaker. The coordinate of the primary source, the distances between each adjacent secondary sources and error microphones are the same as the simulations in Section 3. When only the lower elements of the unidirectional sources are in active, the secondary sources of the control system can be regarded as monopoles. A 10 channels feedforward ANC controller (EZ ANC II from Causal Systems) using the Filtered-X LMS algorithm is applied. The measuring equipment is the B&K PULSE 3560D multi-channel analyzer with six monitoring microphones type B&K 4190.

All the monitoring microphones are fixed on a wooden support beam from 4 m to 6 m in the y direction with a space of 0.4 m. The beam is parallel to the ground. Move the beam to different altitudes so that the monitoring microphones at the height of 0.2 m, 0.6 m and 1.0 m in turn. The sound pressure level with and without active control at 18 monitoring points are obtained. The barrier is 8 m long but the length of the secondary source array is only 3.6 m. In order to reflect the theoretical results appropriately, only S_{yoz} plane is selected as the monitoring area, where

$$S_{yoz} = \{(y, z) | 4.0 \leq y \leq 6.0, 0.2 \leq z \leq 1.0\}. \quad (8)$$

The extra insertion loss achieved by the active control system in S_{yoz} can be calculated by

$$IL(\mathbf{r}_{i,j}) = 10 \log_{10} \left(\left| p_p(\mathbf{r}_{i,j}) \right|^2 / \left| p_t(\mathbf{r}_{i,j}) \right|^2 \right), \quad (9)$$

where $p_{p(i,j)}$ and $p_{t(i,j)}$ are, respectively, the sound pressures without and with active control at the location of $\mathbf{r}_{i,j}$ in the plane. Because the extra insertion loss behind the barrier varies with the spatial position, NR is introduced to assess the total performance of the active control system in S_{yoz} , which is defined as

$$NR = 10 \log_{10} \left(\sum_{i=1, j=1}^{i=N, j=M} \left| p_p(\mathbf{r}_{i,j}) \right|^2 / \sum_{i=1, j=1}^{i=N, j=M} \left| p_t(\mathbf{r}_{i,j}) \right|^2 \right), \quad (10)$$

The experimental results of extra insertion loss of the ANB system with the unidirectional secondary sources and the monopole secondary sources at 160 Hz in S_{yoz} are shown in Fig. 9a, b respectively. The contour distribution of the two figures is similar. The extra insertion loss difference between the unidirectional secondary source control system and the monopole secondary source control system is shown as contour plot in Fig. 9c. The difference is over 2.2 dB in most area in the plane, and the difference is large in the lower left of S_{yoz} plane. In the experiment, noise reduction at the position of each error microphone is about 20 dB.

The experimental results of NR in S_{yoz} plane are shown in Fig. 10b from 160 Hz to 300 Hz with 20 Hz interval, where it is clear that the noise reduction of the ANB system with the unidirectional secondary sources is larger than the one with monopole secondary sources throughout the frequency range, especially in the lower frequency range. With increasing of the frequency, the noise reductions of both control systems decrease. Comparing Fig. 10b with the numerical results in Fig. 10a, though the experimental noise reductions are smaller than that of numerical simulations, the trend of the experimental results is similar to the numerical one. The reason that the experimental results are much smaller than the simulation ones might be that the length of the barrier is limited (8 m long) when compared with the distance between the monitoring microphones and the barrier. The waves interfere in the space behind the barrier and the primary sound field is more complicated than that of theoretical model so the secondary sound field cannot match the primary sound field well as that in the theoretical analysis.

5. Conclusions

A type of unidirectional secondary source is proposed for use in the ANB system, which consists of two closely loudspeakers. The directivity of the unidirectional source is optimized accordingly by adjusting the phase difference of the two loudspeakers. Because the secondary sound field produced by the unidirectional sources matches the primary diffracted sound field

behind barrier better, the noise reduction performance of the ANB system can be improved. Both numerical and experimental results indicate that the ANB system with the unidirectional secondary sources can obtain better noise reduction performance than that of monopole secondary sources at the same number of control channels. Further study on how the locations of the primary source and error sensors affect on the optimal directivity of the unidirectional source will be carried out in future work.

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Figure Captions

Fig. 1. (a) Diagram of the ANB system. (b) The profile of the barrier system.

Fig. 2. Sound field distribution in the $yo\bar{z}$ plane behind the barrier at 160 Hz (without ground reflection). (a) Primary diffracted sound field. (b) Secondary sound field produced by monopoles. (c) Secondary sound field produced by the proposed unidirectional sources.

Fig. 3. (a) The pressure directivities along the circle with radius 10 m centered at the top of the barrier in $yo\bar{z}$ plane. p_D is the diffracted wave produced by the primary source, p_M is the pressure produced by the monopole secondary sources and p_U is the pressure produced by the unidirectional secondary sources. (b) Phase differences between p_D and p_M , p_U along the circle. Φ_D is the phase of p_D , Φ_M is the phase of p_M and Φ_U is the phase of p_U . $\Delta\Phi_M$ is the phase difference between Φ_D and Φ_M , $\Delta\Phi_U$ is the phase difference between Φ_D and Φ_U .

Fig. 4. The sound power flow from region IIR to region III (without ground reflection).

Fig. 5. Sound field distribution in the $yo\bar{z}$ plane behind the barrier at 160 Hz (with ground reflection). (a) Primary diffraction sound field. (b) Secondary sound field produced by monopoles. (c) Secondary sound field produced by the unidirectional sources. (d) The detail distribution of sound intensity around an error sensor; P: the sound intensity of primary sound field; M: the sound intensity produced by monopole secondary sources; U: the sound intensity produced by the unidirectional secondary sources.

Fig. 6. The sound power flow from region IIR to region III (with ground reflection).

Fig. 7. The directivity of unidirectional source at different frequencies with α equals to 2.0. (a) 160 Hz. (b) 300 Hz.

Fig. 8. Experimental setup of the ANB system.

Fig. 9. The IL distribution in $S_{yo\bar{z}}$ plane. (a) The ANB system with the unidirectional secondary sources. (b) The ANB system with the monopole secondary sources. (c) The distribution of the insertion loss difference between the control systems with the unidirectional secondary sources and the monopole secondary sources.

Fig. 10. The NR varies with frequency in $S_{yo\bar{z}}$ plane. (a) Numerical results. (b) Experimental results.

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Fig. 2. Sound field distribution in the yoz plane behind the barrier at 160 Hz (without ground reflection). (a) Primary diffracted sound field. (b) Secondary sound field produced by monopoles. (c) Secondary sound field produced by the proposed unidirectional sources.

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Fig. 4. The sound power flow from region IIR to region III (without ground reflection).

Fig. 5. Sound field distribution in the yoz plane behind the barrier at 160 Hz (with ground reflection). (a) Primary diffracted sound field. (b) Secondary sound field produced by monopoles. (c) Secondary sound field produced by the unidirectional sources. (d) The detail distribution of sound intensity around an error sensor; P: the sound intensity of primary sound field; M: the sound intensity produced by monopole secondary sources; U: the sound intensity produced by the unidirectional secondary sources.

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