Application of Active Noise Control to Noise Barriers

Jingnan Guo and Jie Pan
Department of Mechanical and Materials Engineering
University of Western Australia, Nedlands, WA 6907

This paper is based on the 1996 PRESIDENT'S PRIZE. This prize, established in 1990 by the Australian Acoustical Society, is awarded to the best technical paper presented at the Australian Acoustical Society Conference.

ABSTRACT: Previous work has shown that active noise control technology may improve the low frequency performance of noise barriers. In this paper, such a possibility is confirmed. A multi-channel active control system has been used to create quiet zones on the top of a barrier in order to reduce the diffraction along the top, and to increase the insertion loss of the barrier. Both the simulation and experimental results obtained showed that a barrier assisted with an active noise control device achieves extra noise attenuation when the control system is optimally arranged. The results also demonstrate that active noise control is particularly effective at low frequencies in increasing the insertion loss of a noise barrier. This feature of active noise control overcomes the weakness of noise barriers at low frequencies.

1. INTRODUCTION

Barriers are classical devices in the field of noise control. When a noise barrier is interposed between the noise sources and the receivers, the direct sound wave will be blocked. Only the diffracted sound wave will contribute to the noise level in the area behind the barrier. Behind the barrier, the contribution of the diffracted field is relatively weak compared with that from the original direct field. Therefore, an area of quiet, or a 'dark' area, can be created.

The effectiveness of a barrier in blocking the noise depends upon many factors such as the characteristics of the noise source, the shape and dimensions of the barrier, and environmental conditions. It has been found that while the barrier is very effective in attenuating high frequency noise, it becomes ineffective at low frequencies where the wavelength of the noise is comparable with the height and length of the barrier. Increasing the height of the barrier can improve the low-frequency performance of the barrier, but it is usually not practical. As a result, the improvement in the performance of a barrier, especially in the low-frequency range, has been a research topic in the field of acoustics for more than 20 years.

Although the concept of using noise to cancel noise is not new [1], the recent developments of the control technique have made the implementation of active noise control practically possible. Since active noise control (ANC) is very effective in attenuating low frequency noise [2], it is reasonable to believe that the low-frequency performance of a barrier can be improved by this technique.

Ise [3] applied an adaptive control system into a half-scale model of a passive barrier. In Ise's system, a speaker was used as a monopole control source and positioned on the top of the barrier. The error microphone was set in the desired space behind the barrier. He was able to create a quieter area around the error microphone at very low frequencies (125 Hz or lower). Omoto [4] used a multiple channel adaptive controller in his control system. In a different approach from Ise's arrangement, Omoto put all the error microphones on the top of the barrier. As the sound pressure at the top behaves like virtual sources of the diffracted field, the mechanism of this arrangement was to cancel the sources of the diffractive noise around the top of the barrier. For his specific configuration, Omoto concludes that when the interval of the error microphones on the diffraction edge is less than half of the wavelength, the active noise barrier works effectively.

The present authors [5,6] have thoroughly investigated active noise control in open space. It is found that a large volume (in terms of the wavelength) of noise attenuation can be obtained when the control system is optimally arranged. In this paper, we apply our findings about active noise control in open spaces to a noise barrier, and illustrate the effectiveness of ANC in improving the low-frequency performance of noise barriers.

2. INSERTION LOSS OF NOISE BARRIER

Many theories may be used to predict the sound insertion loss of noise barriers. The basic ones are the Huygen's principle and the Kirchhoff's diffraction formulation [7, 8]. For the reflective noise barrier shown in Fig. 1, and using a point noise source with pressure field of

$$P_0 = \frac{A}{kr} e^{ikr} , \tag{1}$$

the diffracted field can be approximately expressed as [9]

$$P_d = -\sqrt{\frac{2}{\pi k R_1}} A\, e^{-i\pi/4} \{ \mathrm{sgn}(\pi + \alpha - \phi) \frac{e^{ikR}}{\sqrt{k(R_1 + R)}} F\left[\sqrt{k(R_1 - R)}\right] + \mathrm{sgn}(\pi - \alpha - \phi) \frac{e^{ikR'}}{\sqrt{k(R_1 + R')}} F\left[\sqrt{k(R_1 - R')}\right] \} \tag{2}$$

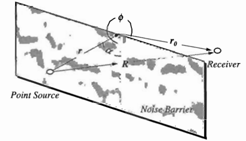

Figure 1. Schematic of a noise barrier.

for $kR_1 >> 1$, where k is the wave number of the sound, R and R' are respectively the distances from the receiver directly to the source and to the source mirror image in the barrier. $R_1 = r + r_0$ is the shortest distance from the source to the receiver over the barrier top, $A = -iZ_0 q$ where q is the source strength, $Z_0 = \omega^2 \rho_0 / 4\pi c_0$, and

$$F(\mu) = \int_{\mu}^{\infty} e^{i\chi^2} d\chi \qquad (3)$$

is the Fresnel integral. The symbol sgn is the sign function, and α and ϕ are the angles defined in Fig. 1.

The sound insertion loss caused by the barrier then can be given by

$$\Delta L = 20 \log_{10}(|P_d / P_0|), \qquad (4)$$

where P_0 is the sound pressure at the receiver's position when the barrier is absent, as expressed by Eq. (1). A widely used engineering approximation for the sound insertion loss of the barrier is Maekawa's asymptotic expression [10]

$$\Delta L = -10 \log_{10}(3 + 20N), \qquad (5)$$

where N is Fresnel's zone number of the barrier, expressed as

$$N = \frac{2}{\lambda}\delta, \qquad (6)$$

where $\delta = r + r_0 - R$ is the path difference and λ the wavelength of the diffractive sound.

The insertion losses of the barrier described by Eqs. (4) and (5) are shown as a function of frequency in Fig. 2 for a typical noise barrier of height of 1 m. Located on different sides of the barrier, the noise source and receiver are both 0.5 m high, and both at a distance of 2 m away from the barrier.

It is shown in Fig. 2 that the sound attenuation of the barrier at a point in the quiet area is only 5 dB at the low frequencies, while the insertion loss at the high frequencies is more than 10 dB. These indicate that the effort of improving the performance of the noise barrier should be focused on the low frequency range.

3. ACTIVE NOISE CONTROL IN OPEN SPACE

Active noise control in an open space can be implemented by either global control or local control. It has been found that global control can only be achieved when the control sources and the primary sources are closely located. In many practical applications, this condition may not be satisfied, in which case, the local control strategy seems to be the only choice.

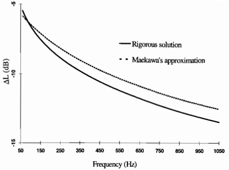

Figure 2. Sound insertion loss of a specific barrier as a function of frequencies.

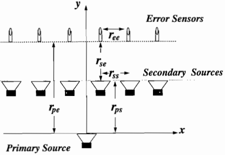

Figure 3. A typical arrangement of a multi-channel active noise control system in open space.

It has been shown [5] that the total sound power output of the local control system usually increases after control, which means that while a 'quieter' area can be created in some places, there must be other areas with an increase in sound pressure. The objectives of local control of the sound pressure field are (1) to create large quiet zones at required positions (where error sensors are located), and (2) to minimise the increase of the sound pressure at other locations (or to minimise the increase in the total power flow from all sources). The quiet zone is defined as the area where the primary sound pressure level is attenuated by more than 10 dB.

Figure 3 is a typical control system configuration, where the equally spaced N secondary sources and N error sensors are placed in two parallel lines. A monopole primary source is located on the central axis of the arrays of secondary sources and error sensors. The distance between the primary source and the secondary source array in the y direction is r_{ps}, and that between the secondary source array to the error sensor array is r_{se}. The secondary sources and the error sensors are separated respectively by r_{ss} and r_{ee}, with $r_{ss} = r_{ee}$ in this arrangement. The sum of the squared sound pressures at the microphone positions is selected as the cost function. Our research on this control system has found that when both the distances from the noise source to the control sources, and from the control sources to the error microphones are given, there exists an optimal range of intervals among the adjacent

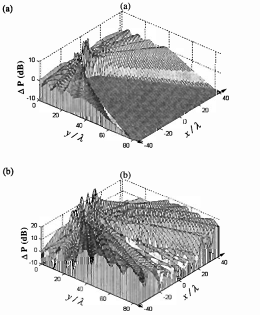

Figure 4. Sound pressure attenuation of a control system with 21 secondary sources and 21 error sensors when r_{ps}=5λ, r_{se}=5λ, and (a) r_{ss}=0.715λ, and (b) r_{ss}=0.88λ.

control sources and error microphones. Within this range, the increase of the total sound power output is minimised, and the largest area of quiet zone can be obtained, which resembles a wedge with its edge along the error microphones. The upper and lower limits of this range are expressed [6] as

$$r_{ss-max} = \begin{cases} \frac{\lambda}{2}\sqrt{1+\frac{4r_{se}}{N\lambda}}, & N = 2,\ 4,\ 6,\cdots, \\ \frac{\lambda}{2}\sqrt{1+\frac{N+1}{N-1}\frac{4r_{se}}{N\lambda}}, & N = 3,\ 5,\ 7,\cdots, \end{cases} \tag{7}$$

and

$$r_{ss-min} = \begin{cases} \frac{5\lambda}{2}\exp\left\{-\left[\frac{3(\lambda+0.04r_{ps})}{2r_{se}-\lambda}+\frac{20\lambda}{15\lambda+r_{ps}}\right]\right\}, & N = 4,\ 6,\ 8,\cdots, \\ \frac{3\lambda(N+1)}{N}\exp\left\{-\left[\frac{\lambda+2r_{ps}}{2(2r_{se}-\lambda)}+\frac{12\lambda}{5\lambda+r_{ps}}\right]\right\}, & N = 3,\ 5,\ 7\cdots. \end{cases} \tag{8}$$

It has also been found that for the configuration with the intervals outside the above range of limits, the system is not able to create a large area of quiet zone, and a large sound power output is often observed.

Figure 4 gives examples of quiet zones actively created in free space (no barriers) by a multiple control system with 21 control sources and 21 error microphones. The system is arranged with the primary source at the position (0, 0, 0), the 21 secondary sources at (5λ, $(i-11)r_{ss}$, 0) (i=1,2...,21), and the 21 error sensors at (10λ, $(i-11)r_{ss}$, 0) (i=1,2...,21), where r_{ps}=5λ and r_{se}=5λ. The upper limit and the lower limit for optimum performance of the system can be calculated by Eqs.

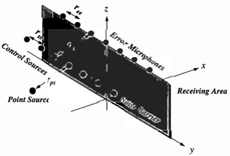

Figure 5. Active noise control system on a noise barrier.

(7) and (8) to correspond to r_{ss}-min=0.5λ and r_{ss-max}=0.715λ. Fig. 4(a) is the configuration within the optimal range (r_{ss}= r_{ss-max}) and Fig. 4(b) is the configuration outside the optimal range (r_{ss}=0.88λ> r_{ss-max}).

It can be seen that the quiet zone created by the optimal configuration is quite large, with no significant increase of sound pressure level outside the quiet zone (except for the area close to x=0 and y=0, where the secondary sources are located). For the configuration just outside the limits, there is hardly any evident quiet zone, and most of the areas suffer from a large increase of sound pressure level, as shown in Fig. 4(b). It can also be seen that the area of quiet zone created by the optimally arranged control system is scaled in terms of the wavelength of the noise, which means, in a practical application, the lower the frequency of the noise, the larger the area of quiet zone.

4. ACTIVE NOISE BARRIER

As the sound around the top of the barrier contributes a diffracted sound field in the quiet area behind the barrier, it is reasonable to believe that if the sound over the top can be cancelled, the diffracted sound in the quiet area behind the barrier should also be attenuated. This approach should have the equivalent effect to an increase of height of the noise barrier. Consequently the insertion loss of the barrier can be increased.

The multi-channel system used for open space noise control is applied here to a noise barrier. The control system consists of N control sources and the same number of error microphones, as shown in Fig. 5. The control sources and error microphones are equally spaced in two parallel lines. The array of error microphones is located just on the top of the barrier. The control source array is located between the primary source and error microphone array, and in the same plane containing both primary source and error microphone array.

When the ANC system is on, the sound pressure at the error microphones is cancelled, and a quiet zone along the top of the barrier is then created. This also increases the noise attenuation in the receiving area behind the barrier. The total diffracted sound pressure becomes

$$P = P_{pd} + \sum_{i=1}^{N} P_{sd}^{(i)}. \tag{9}$$

P_{pd} is the diffraction caused by the primary noise source only, which also represents the diffractive sound while the active control system is off, and $P_{sd}^{(i)}$ the diffraction caused by the i control source. Both P_{pd} and $P_{sd}^{(i)}$ are expressed in the form of Eq. (2). The extra sound insertion loss created by the active multiple control system can then be described as

$$\Delta L = 20\ \log_{10}(|P/P_{pd}|). \tag{10}$$

When applying the multi-channel active noise control system to the noise barrier, the configuration of the control system, such as the intervals of the adjacent control sources and the adjacent of the error microphones, is extremely important. It has been found that the optimal configurations of the control system in open space also apply to the active noise barrier shown in Fig. 5. The specific active noise barrier used in this analysis is 1 m high and located along the y axis. The location of the primary source is (-1.376, 0, 0.5) and the control sources are located at (-0.688, $(i-(N+1)/2)r_{ss}$, 0.75). The error microphones are located at (0, $(i-(N+1)/2)r_{ss}$, 1). For the control system with 3 control sources and 3 error microphones and an operating frequency of 500 Hz, the optimal range of r_{ss} is [0.22λ, 0.98λ] according to Eqs. (7)-(8). The extra sound attenuations of two configurations (one with r_{ss} within the limits as r_{ss}=0.75λ, another with r_{ss} outside the limits as r_{ss}=1.75λ) are given in Fig. 6. For this case, the ground on both sides of the barrier is assumed to be non-reflective.

It is clear that an active noise control system can effectively improve the insertion loss of the barrier if the system is optimally arranged. When the intervals of the control sources are within the optimal range, the extra sound attenuation of the barrier due to the control system can be more than 10 dB in the area behind the barrier, as shown in Fig. 6(a). If the intervals of the control sources are outside the optimal range, the large extra sound attenuation may not be achieved, and the control system may degrade the insertion loss of the barrier, as shown in Fig. 6(b). These examples demonstrate that the configuration of the control system is most important for the active noise barrier.

Although the above conclusions are made from the observation of a simple case of multi-channel active control system (3 control sources and 3 error microphones are used in this simulation), it can be shown that they are also applicable to the cases of more control sources and error microphones.

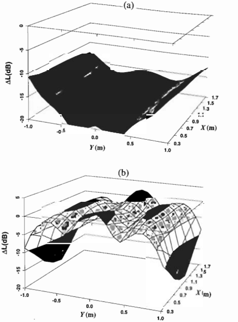

Figure 6. Extra sound attenuation due to the active noise control system when (a) r_{ss}=0.75λ and (b) r_{ss}=1.5λ.

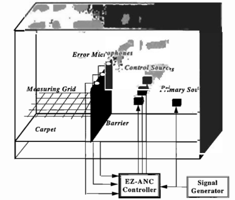

Figure 7. Experiment setup in an anechoic chamber.

5. EXPERIMENTS

Experiments were carried out in an anechoic chamber with the size of 4.2m×4.2m×4.2m. The barrier consists of 2 pieces of plywood plates sandwiching a foam. The barrier of size 0.05m thick, 1.0m high and 4.2m long, was put on the suspended metal grid floor of the anechoic chamber. To prevent the sound propagating underneath the barrier, and to prevent reflection from the floors on both sides, the metal grid floor was covered with thick carpet. The primary noise source was about 1.4 m away from the barrier, 0.5 m above the floor and on the central line of the chamber. The control system consists of 3 half-enclosed speakers as control sources, 3 microphones as error sensors, and a multi-channel EZ-ANC as the controller. The arrangement of the control system is shown in Fig. 7. The sound signal used in the experiment was a pure tone of 500 Hz. The pure tone signal was fed into the primary source directly, and was also provided to the controller as a reference signal. Three control channels of the controller were used to cancel the total sound pressure at the position of 3 error microphones.

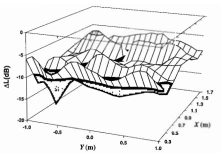

Figure 8. Insertion loss of the barrier from experimental measurement.

The experimental insertion loss of the noise barrier without active control in a measuring plane (0.5 m above the floor) is shown in Fig. 8. It can be seen that due to the reflections from the floor carpet and the walls of the anechoic chamber, the insertion loss of the barrier is not as large and smooth as predicted by the theory. It will be shown later that these reflections also decrease the effectiveness of the active noise barrier.

The coordinates of the control sources and error microphones are the same as in the computer simulation discussed previously [(-0.688, $(i-(N+1)/2)r_{ss}$, 0.75) and (0, $(i-(N+1)/2)r_{ss}$, 1) respectively, where i=1,2,3, and N=3]. Two different intervals of the control sources were used to test the effectiveness of the active noise barrier. One was within the optimal range at $r_{ss}=0.75\lambda$, and the other was outside the optimal range at $r_{ss}=1.75\lambda$. The extra sound attenuation achieved by these two configurations of active noise control system is chosen in Fig. 9.

Figure 9 shows a significant difference in the extra sound attenuation of the active noise barrier for the different configurations of the control system. When the system is optimally arranged, the extra sound attenuation has been achieved at every position in the measuring plane, as shown in Fig. 9(a). When the system is arranged outside the optimal range, the active noise control system may even decrease the insertion loss of the passive barrier in some locations, as shown in Fig. 9(b).

Comparing Fig. 9 with Fig. 6, it can be easily seen that the extra sound attenuation of the active noise barrier in the experiments is not as significant as that of the theoretical analysis. This is due to the reflection from the carpet, as well as from the walls of the anechoic chamber. Practical situations such as a highway barrier and an industrial barrier often have the reflections from the grounds and nearby reflective objects. It is expected that the characteristics of the quiet zone and the optimal arrangement of control sources will relate to the ground impedance and properties of the nearby reflective objects. Further investigation in those aspects is under way.

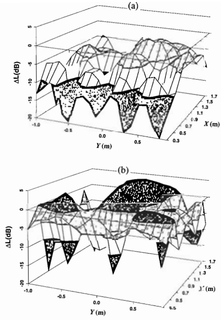

Figure 9. Extra attenuations due to the active noise control system when (a) $r_{ss}=0.75\lambda$ and (b) $r_{ss}=1.5\lambda$.

6. CONCLUSIONS

The effectiveness of applying active noise control system to improve the sound insertion loss of the barrier has been demonstrated in this paper. To create a large area of quiet zone around the diffraction edge of the barrier is a good approach to increase the sound insertion loss of the barrier. An optimal multi-channel active control system developed for active noise control in free space can be successfully applied to the barrier. Similar to the cases of ANC in open space, the configuration of the active noise control system used with noise barriers is extremely important in terms of optimising performance. The extra sound attenuation due to the active noise control system can be significant only when the system is optimally arranged, otherwise, the active control system may be ineffective or even reduce the insertion loss of the barrier.

The size of the improved quiet area is proportional to the number of control channels used in the active control system. As the size of the improved quiet area is scaled in terms of the wavelength of the sound, it can be concluded that the active noise barrier is more useful in the low frequency range where the passive noise barrier is not as effective.

Although the results of the analysis presented in this paper are explained in terms of single frequency sound waves, the optimal arrangement discovered can be used for the design of a control system for practical source with multiple frequency components (such as those from power transformers). Taking the steady state primary sources as an example, the optimal separation distance between control sources is determined by the shortest wavelength of the noise component to be controlled and it is also important to arrange control system so that wavelength of the dominant frequency component is within the optimal range. For those frequency components with wavelength outside the optimal range, band-pass filtering can be used to avoid the effect of control on these components and consequent unnecessary increase of sound level.

In this research, a good coherence between the primary source signal (reference signal) and the error signal is assumed. In all the practical applications of ANC, this is the basic requirement for achieving any significant noise reduction. In the case when the coherence time of wave trains is not very long, spatial causality will set a limit to the arrangement of the control sources and to the processing time of the controller [11].

REFERENCES

1. P. Lueg, *Process of silencing sound oscillations,* U.S. Patent 2043416, 1936.
2. P.A. Nelson and S.J. Elliott, *Active Control of Sound,* Academic Press, San Diego, 1992.
3. S. Ise, H. Yano and H. Tachibana, "Basic study on active noise barrier", *J. Acoust. Soc. Jpn.* **12**, 299-306 (1991).
4. A. Omoto and K. Fujiwara, "A study of an actively controlled noise barrier", *J. Acoust. Soc. Am.* **94**, 2173-2180 (1993).
5. J. Guo and J. Pan, "Analysis of active noise control in a free field", *Proc. Active* **95**, Newport Beach, California, pp. 649-660, 1995.
6. J. Guo, J. Pan and C. Bao, "Actively created quiet zones by multiple control sources in free space", *J. Acoust. Soc. Am.* **101** 1492-1501, 1997.
7. A. Sommerfeld, *Optics,* Academic Press, New York, 1954.
8. M. Born and E. Wolf, *Principles of Optics,* Pergamon Press, London, 1959.
9. J. J. Bowman, T. B. A. Senior and P. L. E. Uslenghi, *Electromagnetic and Acoustic Scattering by Simple Shapes,* North-Holland, Amsterdam, 1969.
10. Z. Maekawa, "Noise reduction by screens", *Applied Acoustics.* **1**, 157-173 (1968).
11. D. G. Pederson and T. A. Laak, "Method for optimizing error filtering based on coherence", *Proc. Active 95*, Newport Beach, California, pp. 649-660, 1995.