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A BRIEF REVIEW OF ACTIVE CONTROL OF ENVIRONMENTAL NOISE AND ITS APPLICATIONS

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Abstract

Although active noise control has been intensively explored for several decades, its practical and successful applications are still limited to a few specific areas. Active control of environmental noise has also received extensive attention for many years. Examples include active noise control in open spaces, active noise control in enclosed environments, and active noise control barriers. However, the application of active control to real environmental noise problems has not yet enjoyed much significant progress, even though environmental noise, especially low-frequency environmental noise, is becoming an important issue that raises increasing concerns from communities. This paper reviews the progress made so far from studies of active control of environmental noise, and discusses issues affecting their practical application. Future directions of active environmental noise control research and its applications are also discussed.

1. INTRODUCTION

Low-frequency noise (LFN) has been becoming one of the major environmental noise problems nowadays. This is partly due to the fact that the traditional noise control technologies are not effective for LFN. As a result, LFN is usually 'left over' when a noise control solution is implemented, making the LFN a more obvious environmental noise problem.

On the other hand, a new technology specifically developed for LFN - active noise control (ANC) - has been advanced dramatically due to rapid developments in control theory, computational acoustics, adaptive digital filters, and affordable digital signal processing devices. Although significant progress has been achieved theoretically and experimentally, the application of ANC to practical environmental noise problems is still very limited. This is largely because of the difficulties and complexities of environmental noise problems. Environmental noise is generally random, unstable, mobile, broadband frequency, and found in large unconfined spaces, which are all barriers to ANC application.

In this paper, the progress of ANC relevant to environmental noise problems is reviewed. The difficulties affecting their practical application are discussed. Some possible applications of ANC in near future that have been sought by the Western Australian Department of Environment and Conservation are also discussed.

2. ACTIVE NOISE CONTROL IN OPEN SPACES

Generally, approaches of active noise control in free space may be divided into global control and local control. The former adjusts the strength of the secondary source to minimize sound power output from the noise sources, while the latter minimises the total sound pressure at one or several positions in the space. Nelson and Elliott examined active noise control by a pair of point sources on the basis of sound energy analysis [1]. They developed a set of matrix equations for a number of primary and secondary point sound sources located in a free space [2] and presented the details of the global control [3]. Their work indicated that for a global control of noise, substantial reductions in total power output can be achieved only if the secondary sources are less than one half-wavelength away from the primary sources at the frequency of interest. In practical applications, the condition of short separation between primary and secondary sources may not always be satisfied. In the case where the global control is not achievable, to create quiet zones in some areas is an alternative approach.

Local control is to reduce the noise at some desired directions or in some desired areas. It has been found that when the local control strategy is used, the arrangement of primary source, secondary source and the point of cancellation (error sensor) becomes critical. The characteristics of the controlled sound field - such as the size of the quiet zone and the change of the total power output of the system - are determined by the configuration of the control system, such as the distance from primary source to secondary source and the distances from error sensor to primary and secondary sources.

Wright and Vuksanovic studied the active control of environmental noise based on an electronically controlled acoustic shadow system ("ECAS), as shown in Fig. 1. Their basic unit of ECAS consists of 3×3 equally spaced control sources and 3×3 equally spaced error microphones, and the system is arranged within a $15^0 \times 15^0$ control angle. Any arbitrary shadow are constructed by an addition of these unit ECAS [4], [5]. They further examined the applicability of their ECAS system to practical environmental noise, and demonstrated that the achievement of acoustic shadows was practically possible when the adaptive system was properly designed and operated [6], [7].

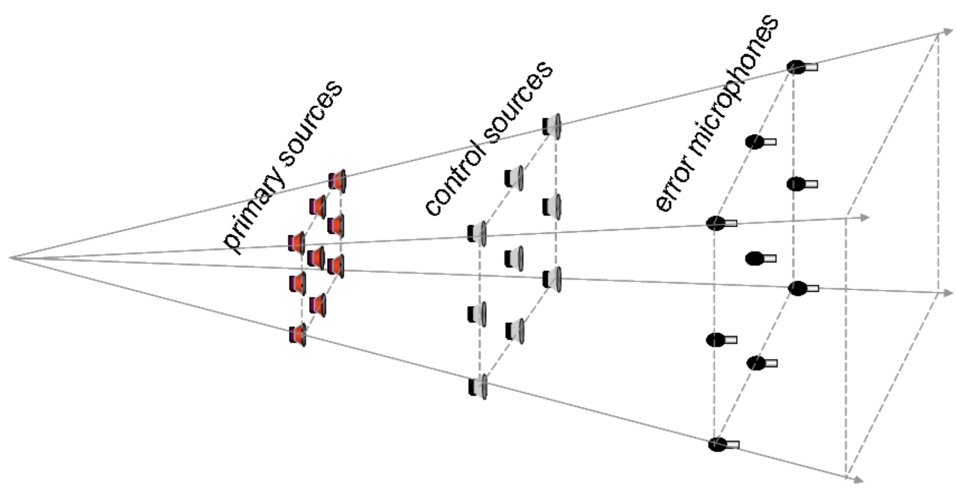

Fig. 1. A basic unit of Wright and Vuksanovic's ECAS system

Guo *et al.* investigated ANC in the free-field with a different approach. In their multi-channel local ANC system, same numbers of control sources and error microphones are equally spaced in two parallel arrays, as shown in Fig. 2. They have found an optimal configuration for this kind of multi-channel ANC system, which is the function of the number of control channels, the separations between the adjacent control sources and error microphones, the distances between the control source array and error microphone array, and the frequency of interest. With the optimal configuration, the total sound power output of the control system is minimised, while the size of the created ‘quiet zone’ is maximised [8].

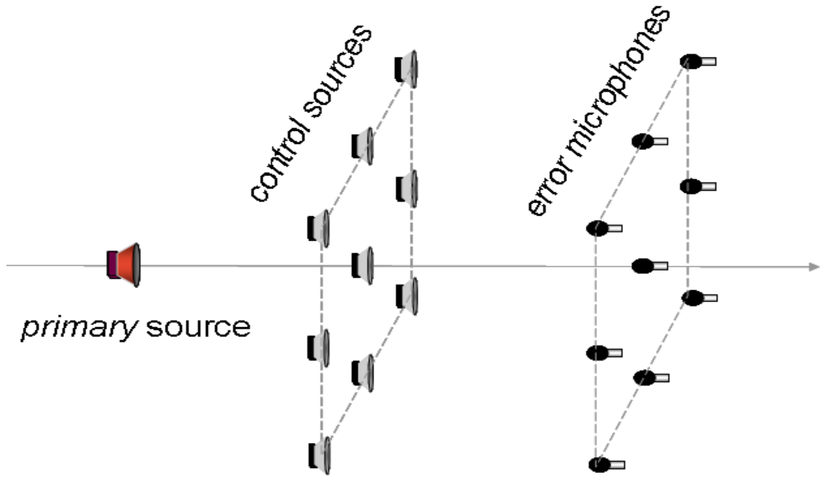

Fig. 2. Guo *et al.*’s multi-channel ANC system in free-space.

The performance of the multi-channel local control system in open space has also been examined with reflective ground, moving primary sources, and broadband noise. Results demonstrated that, with reduced efficiency, the system was still able to generate significant ‘quiet’ zones [9]-[11].

The multi-channel ANC systems discussed above are suitable to stable, compact and low frequency tonal noise sources. Further investigation is required to evaluate the effect of variation of environmental parameters such as change of wind speed, temperature and source characteristics.

3. ACTIVE NOISE BARRIERS

As discussed before, the number of environmental noise sources that meets the requirement of a good candidate for ANC is very limited. Most environmental noise sources are either broadband, or random, or mobile, or unstable. In such situations, ANC is better applied together with traditional noise control technologies, in order to improve the low-frequency performance of the noise control system. The active noise barrier is one of these applications.

According to the theory of diffraction, the strength of the diffracted field is proportional to the wavelength of the sound. In other words, while the barrier is effective at blocking high-frequency noise, it is less effective, or even useless, in the case of low-frequency noise, especially when the frequency of the noise is so low that its wavelength is comparable to the height of the barrier. The drawback of noise barriers in the case of low-frequency noise can be overcome by ANC.

Ise applied a single-channel adaptive control system to a 1:2 scale model of a passive barrier [12]. In his system, a loudspeaker acting as a monopole control source was positioned on the top of the barrier, and an error microphone was set in the desired area immediately behind the barrier. A "quieter" area around the error microphone was obtained at very low frequencies (125 Hz or lower).

Omoto took a different approach [13]. He used a multi-channel control system to cancel the noise around the barrier top, rather than the diffracted noise in the 'dark area'. For his specific configuration studied, Omoto concluded that when the separation distance between the error microphones on the diffraction edge is less than half of the wavelength, the active noise barrier works effectively. He further extended his work to barriers on reflective ground, and found that the efficiency of the control system was seriously affected by the reflective ground [14].

Guo *et al*. [15] applied their optimal multi-channel ANC system designed for open space to noise barriers, as shown in Fig. 3. They found that the optimally arranged active local control system significantly improved the performance of the noise barrier by creating a large (relative to the wave-length) area of noise attenuation in the 'dark area'. The extra insertion loss of the active noise barrier could be as high as 10 dB or more [16].

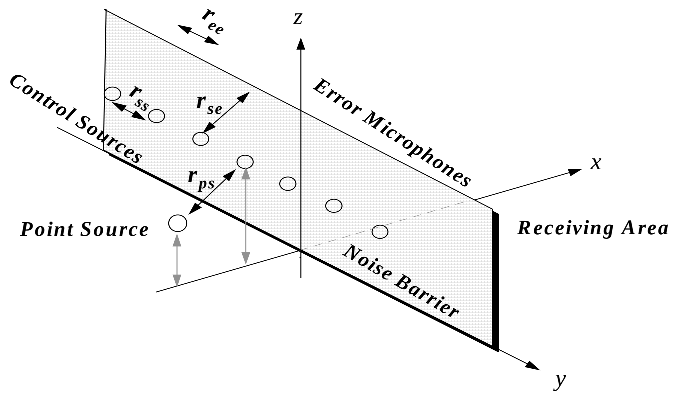

Fig. 3. A MIMO ANC noise barrier.

It can be seen that the efficiency of such an ANC noise barrier depends on the performance and robustness of the multi-channel control system - i.e. the multi-channel controller, control speakers and error microphones. This remains a problem in the real outdoor environment application. To overcome this difficulty, attempts have been made to simplify the multi-channel system into a multiple individual and localized system [17]. However, the extra insertion loss generated by the so-called ANC barrier with active controlled acoustical soft edge was not significant, making it not a very practical application.

4. ACTIVE NOISE CONTROL IN ENCLOSED ENVIRONMENTS

There are generally two approaches for applying ANC to enclosed environments such as rooms, based on the assumption that the enclosed sound field either has a low modal density or a diffuse sound field. In the first approach, the enclosed space is very small compared to the wavelength at the frequency of interest, and the sound field consists of only a few dominant modes. The sound energy can be significantly attenuated by suppressing the energy of each mode [18], [19]. This is the mechanism normally involved in active air-mufflers and in active noise control in small cabins [20].

When the enclosure is large, and the wavelength at the frequency of interest is smaller than the room dimensions, there will be too many modes to be controlled individually. The second approach then treats the enclosed sound field as diffuse. Studies with this approach have suggested that the noise can only be significantly reduced in a very small area inside the enclosure, which is of the order of one tenth of the wavelength at the frequency of interest [21]-[24]. This is normally too small for a practical use of ANC in such situation.

However, in many realistic enclosed environments, the low-frequency sound field is neither of low modal density, nor diffuse. Examples are workshops, offices, and classrooms. It has been demonstrated that an ANC local noise-control system is able to create relatively larger quiet zones in such non-diffuse enclosed sound field [25]. The size of the quiet zone is highly dependent on the configuration of the control system, the location of the primary source, the number of control channels, and the room characteristics, such as the dimensions and reflection coefficients of the surfaces. The efficiency of a local, active noise-control system can be improved by increasing the surface absorption and the number of control channels, and by optimally arranging the sources and error microphones [26], [27].

Another approach of ANC in enclosed environment is the study of active control of sound transmission into enclosed environment. Bao and Pan analytically and experimentally investigated the active control of noise transmitted through double walls into a room [28], [29]. Their results demonstrated that the noise transmission into the room could be significantly reduced either by the active noise control in the cavity between the two walls, or by the active vibration control of the surface panels. When the double panel was the only noise transmission path, active control of noise transmission into the room was more effective than the active control of the noise inside the room. Similarly, active control of noise transmitted through windows or double windows have also been investigated [30], [31]. A recent feasibility study conducted by Naticchia and Carbonari concluded that an active structural acoustic control system is possible to strongly improve the sound transmission loss of windows and walls at low frequency, and increase the acoustic comfort in buildings [32].

5. ACTIVE CONTROL OF AIRPORT RUN-UP NOISE

Airport run-up noise seems to be another good candidate for ANC. Due to its strong low-frequency components, aircraft run-up noise is able to travel into residential areas several kilometres away, making it one of the major sources of noise annoyance in urban environment. Because of its low-frequency content, the traditional noise control measures for jet engine tests, such as jet pens, hush houses and enclosures are not effective.

Smith *et al*. experimentally investigated the use of ANC to reduce low-frequency jet engine exhaust noise from a military jet engine test facility – a hush house [33]. The hush house is able to achieve considerable noise reduction at mid and high frequencies. However, a jet engine exhaust contains a very strong low-frequency component, which becomes dominant in the far field. Both single channel and multi-channel control systems were implemented and tested in small-scale experiments, and both systems demonstrated the ability to generate a low-frequency noise reduction zone in an extended sector. The experiments indicated that more control channels and smaller spacing between the control source/sources and the hush house generated a larger area of noise attenuation. This study concluded that when implementing the ANC in larger-scale jet engine test facilities, further study of the control sources with higher sound power output at low-frequencies was required.

The attempt to use ANC to reduce the propeller aircraft run-up noise has been investigated at Vancouver International Airport [34]. Unlike the broadband jet engine noise, propeller engine noise is dominated by pure-tone components starting from about 100 Hz. Due to the fact that high-frequency noise suffers higher loss during long range transmission, the run-up noise at the affected communities several kilometres away is dominated by low-frequency pure-tone components, making it a good candidate for ANC. As shown in Fig. 4, in the residential area most noise energy was concentrated in three low-frequency harmonics. It is clear that control of these three low-frequency harmonics will achieve significant noise reduction at the annoyed community.

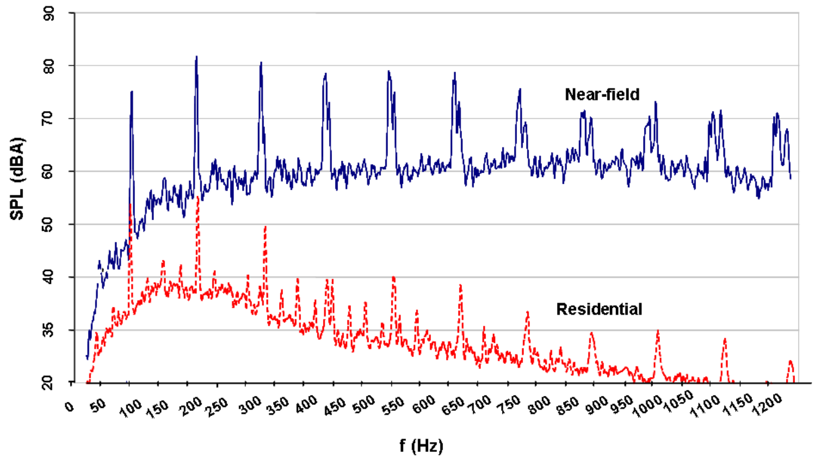

Fig. 4. Run-up noise spectra in the near-field and in the far-field residential area.

Both theoretical analyses and experimental investigations demonstrated that an optimally arranged ANC system was able to achieve 10 dB or more of sound-level attenuation over areas (called ‘quiet zones’) large enough to cover the complainant receiver locations. The performance of the ANC system was improved when combined with the existing run-up blast fence, as illustrated in Fig. 5 [35].

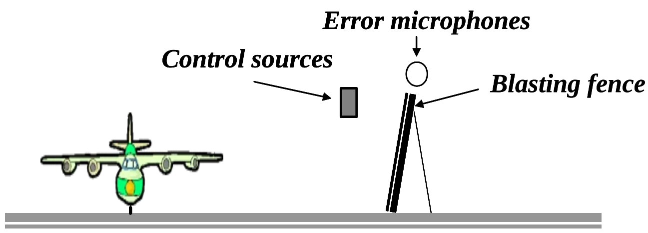

Fig. 5. Combining the ANC system with the existing blast fence.

This study also found that the practical implementation of ANC system to the run-up noise depended on the further understanding of the run-up noise characteristics and run-up noise propagation in large range, and the development of powerful ANC controller and control sources [36], [37].

6. DISCUSSION OF NEAR FUTURE APPLICATIONS

As discussed above, wider practical application of ANC still relies on further studies of ANC and developments of control theories and controllers. Although low-frequency noise is one of the major environmental noise problems, most environmental noise sources - such as road traffic noise, aircraft noise, music entertainment noise - are either with broad frequency band or random in nature. Direct application of ANC to these noise problems may not be able to achieve significant overall noise reduction at this stage. However, use of ANC systems to improve the low-frequency performance of a traditional noise control system is a practical approach that makes the application of ANC to environmental noise problems possible.

One example of the possible application of ANC to environmental noise is to use ANC to reduce the mining refinery noise inside residential homes. Some residents about 2 km away from the refinery are exposed to noise up to 10 dB above the noise standard for the area during the night time. Although the noise inside the refinery was broadband, the noise measured at the residents showed a very strong tonal component, as shown in Fig. 6. Because the problem was not fixed after implementing various engineering noise controls, the refinery took several noise management actions, including offering the acoustical treatment of the residential houses. Several affected residents took the offer of acoustic upgrade of their houses, which included the acoustic treatment of windows, walls, roof, eaves and floor. Interestingly, the residents started to complain about the refinery noise again, not long after they expressed their satisfaction with the house upgrade when it was completed. The residents claimed that they could hear the low-frequency refinery noise more clearly after the acoustic upgrade, as it reduced the high-frequency masking background noise inside the house.

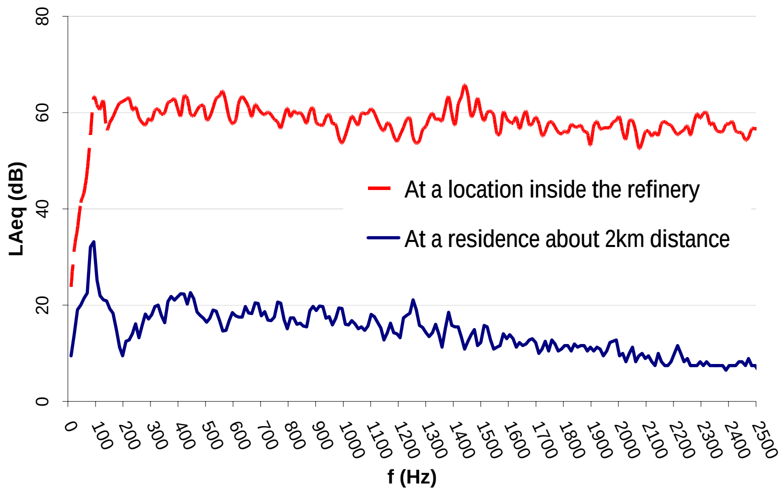

Figure 6. Noise spectra inside the refinery and at a residence about 2km away.

It is obvious that the improvement of acoustic quality inside those residential houses depends on the low-frequency attenuation or insulation. The Western Australian Department of Environment and Conservation sees the potentially successful application of ANC to this low-frequency noise problem. A similar possible ANC application is the acoustic renovation of residential houses under the aircraft flying paths. Due to the fast expansion of urban areas in Perth and the lack of residential land, there has been a push to develop lands reserved for aircraft flying paths near the airport. Low-frequency noise is always a problem for those traditional acoustic treatments of houses. Successful application of ANC in this aspect will make the use of those lands under the aircraft flying paths possible.

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