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A Review of the Effect of Reflective Surfaces on Power Output of Sound Sources and on Actively Created Quiet Zones

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Summary

It is known that active noise control systems behave differently in free space and half space. However analysis of active noise control applications has generally neglected the presence of a reflective surface. The objective of this paper is to review the effect of a reflective plane on an active noise control system. This effect is subject to the characteristics and configurations of the noise sources, control sources, sensors and the reflective plane itself. These configurations include the directivity pattern of sources, distance of sources from the plane, orientation angle of sources to the plane, number of control sources, and frequency of the primary noise. It is shown how the power output and the size of the quiet zone depend on these factors. The research papers dealing with reflective planes are reviewed and discussed. Recent trends of active noise control systems in free field conditions with respect to the control performance are also highlighted. Some applications of active noise control technology are given and recent progress in the field outlined. Finally, research directions in this particular area are suggested.

PACS no. 43.50.-x, 43.55.-n

1. Introduction

Active noise control is a technique based on the principle of destructive interference whereby an 'anti-noise' of the same amplitude as the noise source but opposite in phase is combined with the primary noise resulting in the cancellation of both noises. Active noise control has been the subject of research since a long time [1] and with the advent of microprocessors and subsequently Digital Signal Processors, research in this area has been very extensive. There are two major approaches to active noise control, namely global control and local control. In global control, the strengths of the control sources are adjusted in order to achieve minimization of the total power output of the control system [2]. The aim is to reduce the sound pressure at all points in a particular space. For local control, a quiet zone is generated in an area, without taking into account what happens in other areas [3]. A quiet zone is defined as an area where the sound pressure has been attenuated by at least 10 dB [2]. These two strategies are applicable in free space as well as in half space. In free space, the sound may propagate free from any form of obstruction. The total power output and the size of the quiet zone are mainly determined by the relative positions of the sources and sensors of the active noise control system. However, in half space, the presence of the reflective plane affects both the total power output of the system and the size of the quiet zone generated. A reflective plane is usually considered to have infinite acoustic impedance i.e. where the sound waves incident on the rigid plane are totally reflected and not absorbed. The analysis of the system is different in free field and half space. In this paper, active noise control in free field is first reviewed and then the different configurations involving the reflective plane and the control system are analysed. Active control systems have various applications and the most popular ones are active headsets in the transportation industry. Other applications also include air conditioning ducts, power generators, noisy plants, compressors, and aircraft cabins.

Most research papers addressing active noise control in an open space assumes free field conditions. However, free field conditions seldom exist in practical applications and half space is more realistic. It has been observed that research on the effect of a reflective surface is lacking in the literature. As a matter of fact, this paper will try to address the effect of a reflective surface in practical applications with emphasis on the configurations of the reflective surface and the control system. The effect of a reflective surface is a very important parameter in designs of acoustic systems of halls, theatres, gymnasiums and even in cars. In the work by Pan *et al.* [4], it is even mentioned that acous-

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ticians may use the acoustical features of the surrounding systems to improve the control performance of an active noise control system. Practical applications include a transformer fixed on a rigid plane, the active control of human speaking using the principle of a piston set in a rigid sphere, and even using a short duct at the outlet of an axial fan. For completeness, this review paper will initially highlight the main results obtained from recent trends in active noise control system in free field.

2. Control performance in free field

For active noise control systems in free field, many methods have been used with the primary aim to enlarge the size of the quiet zone whilst allowing the least increase in sound pressure level elsewhere. The first attempts to control sound in free space were aimed at controlling tonal noise radiated by large transformers [5]. Since then, active control of free field sound radiation has evolved. In this section, a brief overview of free field sound control will be given followed by some of the recent techniques used to improve the size of the quiet zone in free field.

2.1. Active control of free field sound radiation

The most basic active noise control problem involves the minimization of sound radiated by an acoustic monopole by a secondary acoustic monopole in three dimensional space. The resulting sound will produce a decrease in sound pressure level in some areas and an increase in other areas due to the destructive and constructive interference respectively. The number of secondary sources all around the primary source can be extended as shown in Figure 1 where each secondary source is at equal distance d from the primary source [6]. A practical situation may be the case of an array of loudspeakers all around the end of an engine's exhaust pipe in open air.

The attenuation in total acoustic power radiated in free field by a primary monopole for different number of secondary sources is shown in Figure 2. It is seen that the number of secondary sources required to achieve a given attenuation increases as the square of the normalized distance d/λ [6].

It has also been shown that the power output of all secondary sources is equal to zero when controlling a single primary source [6]. This indicates their reactive capacity in absorbing the power. Another parameter which is important in the control of acoustic power in free space is the quiet zone. The size and shape of the quite zone is determined by the distance between the secondary source and the cancellation point. For a configuration, of one secondary source, if the distance is very small compared with the acoustic wavelength, then the shape of the quiet zone is a shell all around the secondary source. If however, that distance is not small compared to the wavelength, then the quiet zone is spherical in shape centered around the cancellation point.

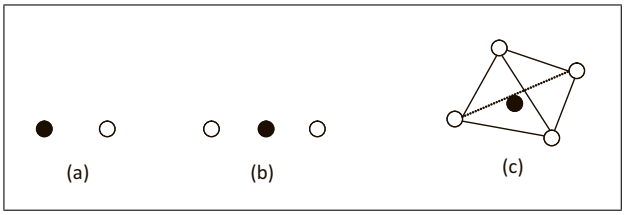


Figure 1. Arrangement of primary (solid sphere) and secondary acoustic monopoles (open spheres) in free space, (a) one secondary source (b) two secondary sources (c) four secondary sources, at equidistant d from the primary source.

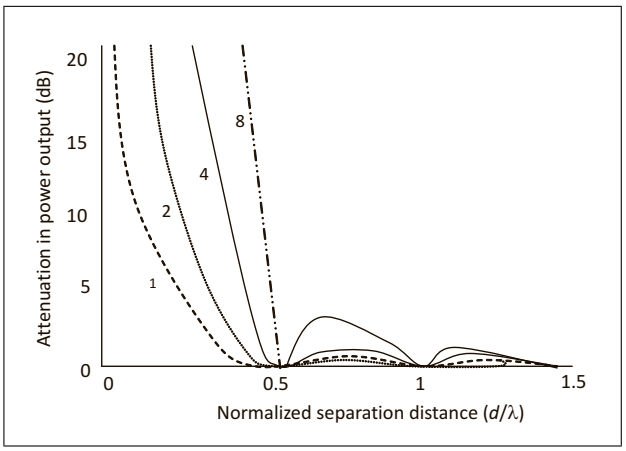


Figure 2. Attenuation in the total acoustic power radiated into free space by a primary monopole source when optimally controlled by one, two, four, and eight secondary monopole sources, as a function of the distance d, from the primary to the secondary sources, normalized by the acoustic wavelength λ [6].

2.2. Effect of directivity in free field

In the field of active control system, the directivity of secondary sources is an important parameter which determines the overall performance of the system. The directivity pattern represents the angular distribution of the sound field radiated by an acoustic monopole, dipole or quadrupole [7].

Qui and Hansen [8] worked on the comparison of whether using single secondary multipoles or an array of monopoles was better in a control system. Their experiment was based on using a small, baffled and simply supported plate. From their results, it has been found that the selection of the secondary sources depends on the primary field characteristics. They have shown that if the primary sound field is varying with time and too complex, then an array of monopoles gives better results due its robustness and generality. On the other hand, if the primary source is stable and well defined, using a secondary multipole is better due to the number of control output channels. Another work related to directivity, was carried out by Gerard *et al.* [9], which consists of the investigation of the effect of using a single loudspeaker in front of a fan for the control of tonal noise. For a single control source, its spatial directivity shall be similar to that of the primary source and also be physically close to the latter. At this configuration, signif-

icant attenuation can be achieved. Experiments were performed related to a symmetric six-bladed fan and a non-symmetric seven bladed fan. For the six bladed fan with equal pitches, the rotational speed was adjusted to 50 Hz such that the first two disturbing tones are at 300 Hz and 600 Hz. Figure 3 shows the results with and without active noise control. From the results, it is noted that the tones at 300 Hz and 600 Hz are attenuated significantly. The tone at 900 Hz remains as the control system is limited by the number of filter coefficients and low-pass filtering (which was set at 800 Hz in this case).

Using the seven bladed fans, the speed was set at 48.5 Hz, such that the first two disturbing tones are at 340 Hz and 680 Hz. This time, it is found that the highest energetic peak (i.e. at 340 Hz and 680 Hz) are attenuated but has little effect on other peaks at the multiples of the rotational speed of the fan. In fact, the effect of the irregular blade spacing is that the acoustic energy is spread over the entire integer multiples of the rotational speed. The resulting radiation pattern after control is a quadrupole just as for the six bladed fan. From their results, it has been found that the more the primary and secondary source directivities are similar, the level of control is better [9].

2.3. Control of sound radiation in free space by an active noise barrier

As previously mentioned, one of the first attempts to control noise in free space was to use an array of loudspeakers all around the transformer to control tonal noise [5]. In many situations, unwanted noise is propagated in the far field. By surrounding the noise with a layer of secondary sources, the sound radiation can be suppressed. This ANC technique is known as an active noise barrier [10]. By using this technique, environmental noise in local areas may be reduced. Transformer noise produce even numbered harmonics of the power frequency. Experiments have been carried out using three controllers, three microphones and three loudspeakers [11] and significant reduction in sound pressure level (>10 dB) has been achieved. However, there are many difficulties in the control of transformer noise due to effectiveness, robustness and cost of the ANC system relating to the algorithm especially. Also since transformer noise contains more than one frequency component, active methods should be combined with passive methods for better performance. More recently in the paper by Qui *et al.* [12], ANC solutions have been proposed for the control of transformer noise. For a transformer in free space, a significant number of loudspeakers can be mounted all around the transformer to reduce its total radiation. Generally, more than 10 dB attenuation can be achieved at 100 Hz [12]. This method can be extended to active noise barrier systems where they are used with passive barriers for better efficiency.

2.4. Configuration of multi-channel active noise control systems

In an active noise control system, the location and number of sources and sensors, is determinant to the control

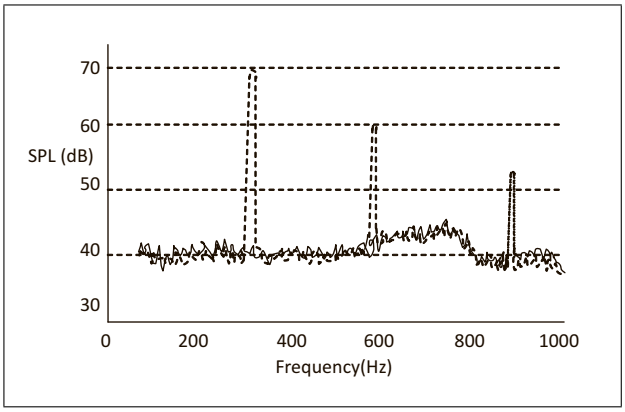


Figure 3. Power spectrum of the sound pressure at the error position for a six-bladed fan (equal pitches) automotive fan noise, with (solid line) and without (dashed line) active control [9].

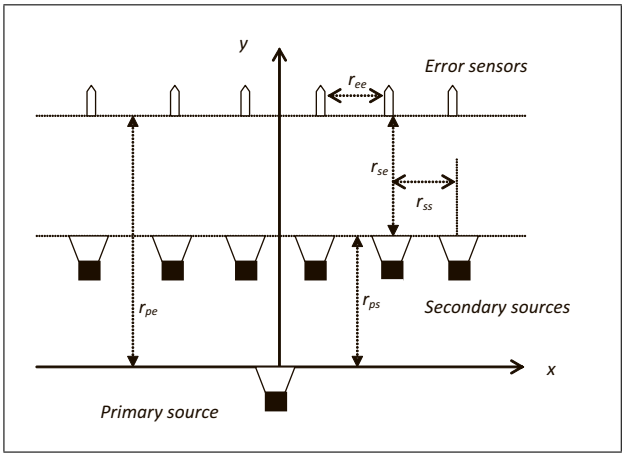


Figure 4. Typical arrangement of control system with multiple secondary sources [13].

performance of the system. Guo *et al.* [13] worked on actively created zones by multiple control sources. In their work, they showed that the overall quiet zone is not only the summation of quiet zones created by individual control sources but is rather dependent on the configuration of the system. It is important to note that while increasing the quiet zone, there is no large increase of sound pressure elsewhere. The configuration used by Guo *et al.* [13], consists of multiple secondary sources and multiple error sensors equally spaced in two parallel lines as shown in Figure 4.

Based on that particular configuration, it has been shown that there exists a range of optimal solution whereby the largest quiet zone corresponds with the least increase in total power output. For that optimal solution, the size of the quiet zone is directly proportional to the ratio of r_{se} to r_{ps} and is also directly proportional to the number of control sources and error sensors. However, even if the use of many secondary sources and error sensors may produce larger quiet zones, the distribution is overall complex and untidy.

In multi-channel systems, the distance between the error sensors must be smaller than the radius of the quiet

zone created by each error sensor such that there is no amplification between sensors [14]. Lopes [14] worked on a system that does not need the extra number of error sensors. The technique used is to band-limit the anti-noise by using special algorithms such as the MFx-LMS. Simulation results given in the paper by Lopes [14] proved that the method works. Another study in multi-channel systems is by Chen *et al.* [15]. Their work consists of replacing monopole secondary sources by a compound secondary source. The compound secondary source consists of two closely located monopole sources being separated by a distance much smaller than a wavelength. More precisely, the compound secondary source comprises two well matched loudspeakers with different gain and opposite phase [15]. The use of compound secondary sources instead of monopole sources can be used to reduce the number of control channels. Their experimental set up was carried out in an anechoic chamber with the use of the Fx-LMS algorithm. In their experiment, they have used eight error microphones and four compound secondary sources. The results are shown in Figure 5. From the results, it is noted that the noise reduction of the compound secondary sources is larger than that of monopole secondary sources of a control system in the frequency range of interest of 250–500 Hz. In the interval 350–500 Hz, the noise reduction is almost 10 dB higher. The reason for the difference between the compound secondary sources and monopole sources is due to the directivity of the compound secondary sources.

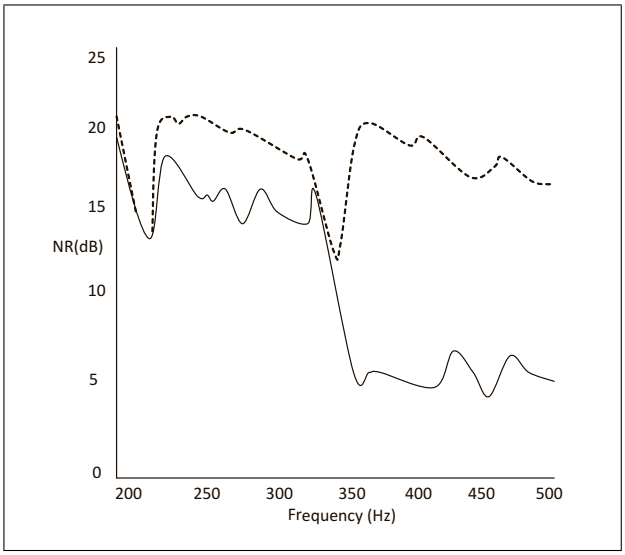


Figure 5. Noise reduction of monopole (solid line) and compound (dashed line) secondary source [15].

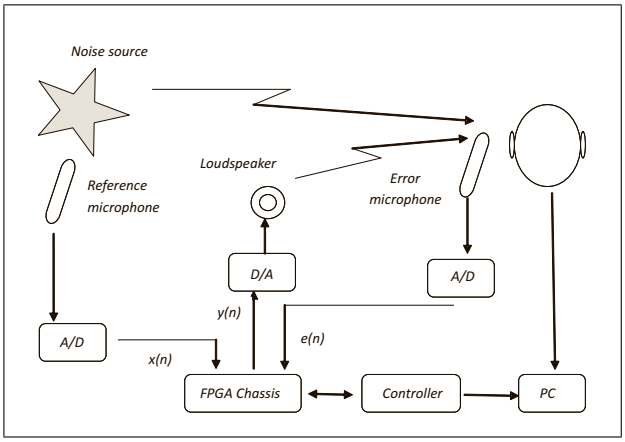


Figure 6. Schematic diagram of the implemented adaptive ANC system [17].

2.5. Adaptive control in free field

Adaptive control deals with the adjustment of the ANC controller by using the impulse response of the secondary path. The digital control structure consists of two separate parts namely the programmable digital filter (ANC controller) and an adaptation algorithm for the adjustment of the controller [16].

The algorithm used for most ANC systems is the Fx-LMS which has also some variants. But the problem with the Fx-LMS algorithm is the slow convergence rate especially when there is a large number of filter weights. Other modified Fx-LMS algorithms were developed to have faster convergence rate but they involve matrix computation and real time realization is not effective. The performance of the Fx-LMS algorithm is governed by the physical plant characteristics i.e the secondary path impulse response and the acoustic bandwidth. For the electronic control system, the factors limiting the performance are the length of the filter and the adaptation step size μ. The length of the filter is the most important parameter. Increasing the filter length gives better steady state response but affects the convergence rate. Setting the value of μ is also important as there is a maximum value of μ for which the system becomes unstable.

Conventional adaptive ANC algorithms have been developed to be efficient in acoustic ducts and headphones as they have been designed for the minimization of sound fixed at a single point where the error microphone is located. However, propagation of sound in free air is more complex and requires special adaptive algorithm which needs to cope with changes in the environmental characteristics. Ardekani and Abdullah [17] worked on an adaptive ANC algorithm for free field noise. Their set up as shown in Figure 6 was tested in a free space environment. Their proposed solution is based upon consideration of the sound field in a volumetric space around the error microphone. In the derivation of their solution, it was assumed that the secondary source is much closer to the error microphone than the noise source. The results shown in Figure 7 prove that their proposed optimal solution is better. When using the conventional algorithm, the system diverges after a short period. When the radius of interest (distance from the error microphone) is set to 2 cm, the noise reduction is nearly 15 dB after 250 ms. At a radius of 5 cm, the maximum noise reduction is 10 dB as the region of interest is larger.

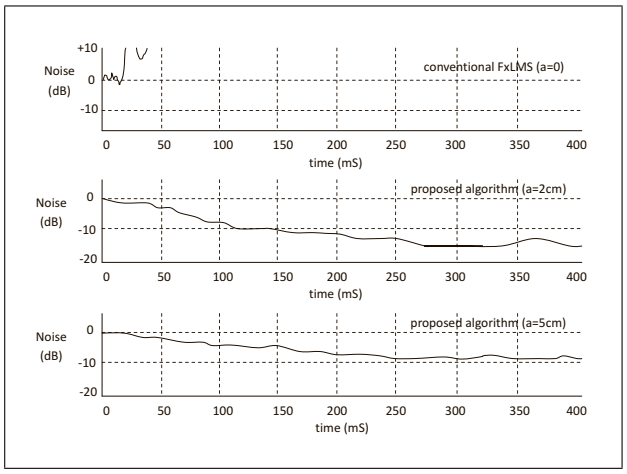


Figure 7. Experimental Results showing the overall noise level for the respective algorithm [17].

2.6. Virtual sensing techniques

Active Noise Control systems aim to create a zone of quiet at the error microphone by minimizing the acoustic power at the location of the error microphone. However, the quiet zone formed is limited in size and hence this will require the error sensor to be located at the exact desired location which is often inconvenient [18]. To overcome this problem, virtual sensing methods have been developed. This is based on the estimation of the error signal at a location different to that of the physical sensor which is referred to as the virtual location. The virtual microphone arrangement is one of the sensing methods and is based on the assumption that the primary sound pressure at the physical and the virtual location is the same. Garcia- Bonito *et al.* [19] worked on these investigations and stated that at low frequencies, the acoustic pressure may be assumed the same at both the locations since the spatial rate of pressure change due to the primary field is small. However, at higher frequencies this assumption no longer holds due to a decrease in wavelength.

A virtual sensing algorithm is used to estimate the pressure at a fixed virtual location using the physical error signal. In fact, the active noise control system minimizes the estimate pressure at a virtual location, thereby creating a quiet zone at that location instead of the physical error sensor location. Figure 8 shows the difference in a local active noise control system between the physical sensor and the virtual sensor.

The performance of a local active headrest has been investigated by Garcia-Bonito *et al.* [19], at virtual microphones located 2 cm from ears of a manikin and at 10 cm from the physical microphone. Their results show that at low frequencies (<500 Hz), a 10 dB zone of quiet is generated at the virtual microphone. At higher frequencies (>500 Hz), limited attenuation is obtained for reasons mentioned above. Virtual sensing techniques have applications especially in consumer electronics and medical instruments where it is important to have quiet zones at desired virtual locations for optimum performance [20].

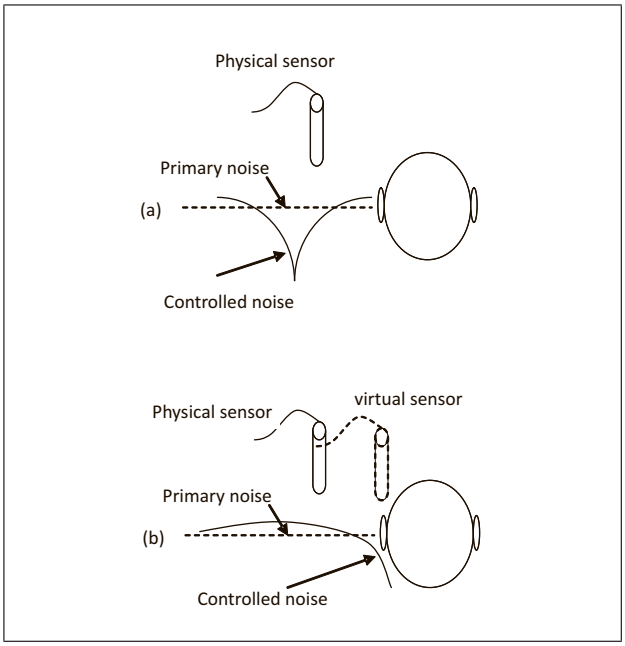


Figure 8. Comparison in a local active noise control system between the physical sensor and the virtual sensor [18].

2.7. Directional secondary loudspeaker

Conventional ANC systems normally use omni-directional loudspeakers as secondary sources. However, recently, there has been a growing interest to use highly directional loudspeakers such as parametric loudspeakers. The working principle of parametric loudspeakers is to modulate an audible sound signal onto an ultrasonic carrier and project the modulated signal by special types of ultrasonic emitter to generate a non-linear acoustic effect in air [20]. The advantage of directional loudspeakers is to reduce the primary noise in a very confined area of quiet zone, with little spill outside the zone. This is achieved by the fact that these loudspeakers project highly directional sound sources.

However the major drawback with directional loudspeakers is that they can't control efficiently noises of frequency lower than 500 Hz, as they have very poor frequency response at low frequencies. Ye *et al.* [21] have worked on actively created quiet zones using parametric loudspeakers as secondary sources. In their work, comparison has been made between omni-directional loudspeakers and parametric loudspeakers. It has been found that the quiet zone created by omni-directional loudspeakers is larger than that by directional loudspeakers but the sound pressure levels in other areas for conventional loudspeakers increase significantly as shown in Figure 9. Parametric loudspeakers help in creating a confined quiet zone along the sound beam direction of the loudspeakers without creating increase in sound levels in other areas. Tanaka *et al.* [22] also worked on experiments in factory using parametric loudspeakers. Their idea was based on the fact that it will minimize interferences and cross talk in multichannel systems and also proposed an ANC system that will control independently every channel. These multi-

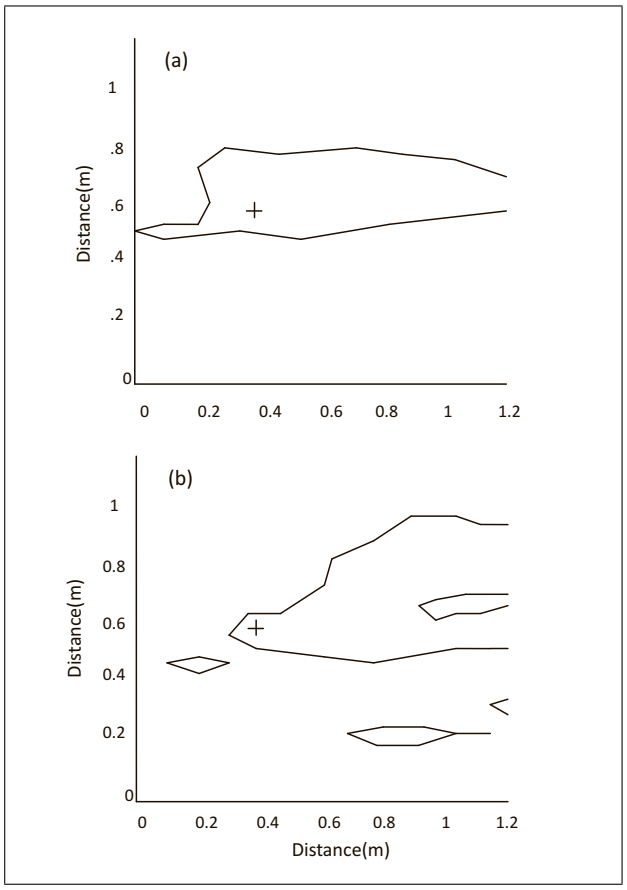


Figure 9. Quiet zone created with 10 dB sound pressure reduction created by parametric loudspeaker (a) and omnidirectional loudspeaker (b) [21].

channel systems configuration consist of one reference microphone, two secondary sources and two error microphones, referred to as Case (1,2,2) [22]. In their work, the results have shown that their proposed ANC system can efficiently reduce factory noise about 15 dB, but for frequencies below 500 Hz.

3. Classification of parameters affecting the control performance in the presence of a reflective plane

Whereas active noise control in free field has been given a lot of attention in past research the effects of a reflective plane on the control system performance has not been thoroughly researched. In this section a review of the main results considering the effects of a reflective plane is carried out with respect to known free field results. The effect of a reflective surface is governed by certain parameters. These factors determine to what extent the reflective surface affects the power output and quiet zone, and are listed below.

1. Directivity pattern of sources,
2. Distance between reflective plane and sources, and between sources,
3. Angle of orientation between rigid plane and sources,
4. Control performance when using single and multiple control sources,
5. Frequency of the primary source.

The research papers dealing with the above parameters will be analysed and reviewed. Comparisons will be made in terms of the power radiated for different configurations. The size of the quiet zone generated in some cases will also be outlined. The experiments that have been conducted in the different research papers to show the effect of the above, consist basically of an active noise control system including microphones (as sensors), loudspeakers (as actuators), and a Digital Signal Processor to implement the controller. Practically, all the experiments have used the FXLMS algorithm for the active control system. A detailed analysis of each factor is given next.

3.1. Directivity pattern of sources

Directivity patterns are analysed differently in the presence of a reflective plane. In this section, a description will be given of how the sound source is affected by a reflective plane. The analytical expressions for the ratio of the total radiated power in the presence of the field to the total power radiated in free field, for each type of sound field will also be outlined. This is important to consider since when an active noise control system is in the presence of a reflective plane, the directivity pattern newly formed may have a bearing on the system performance.

3.1.1. Acoustic monopole

A monopole is a sound source which radiates sound well in all directions (e.g. boxed loudspeaker). In the presence of a rigid plane, the ratio of the total radiated power in the presence of the field (W) to the total power radiated in free field (W_0) is equal to the analytical expression [23]

$$W/W_0 = 1 + \operatorname{sinc} z, \tag{1}$$

where $\operatorname{sinc} z = \sin z/z$, and $z = 2kh$, ($k = 2\pi/\lambda$, h is the distance of source from the plane, and λ being the wavelength).

Simulation results for the amplification factor W/W_0 as a function of z are shown in Figure 10a for a monopole. Lim [24] obtained the same equation for a reflecting plane of infinite extent and his work complies with that of Ingard and Lamb [23].

3.1.2. Acoustic dipole

An acoustic dipole (Figure 11) can be represented as two monopoles of equal strength but opposite in phase, and separated by a small distance compared with the wavelength of the sound (e.g. unboxed loudspeaker). In the presence of a rigid plane, a dipole behaves differently depending on whether it is horizontal or vertical to the plane [4, 25].

For a horizontal dipole, the analytical expression for the amplification factor is given as [23],

$$\frac{W}{W_0} = 1 + \frac{3}{z}\left(\frac{\sin z}{z} - \frac{\cos z}{z}\right). \tag{2}$$

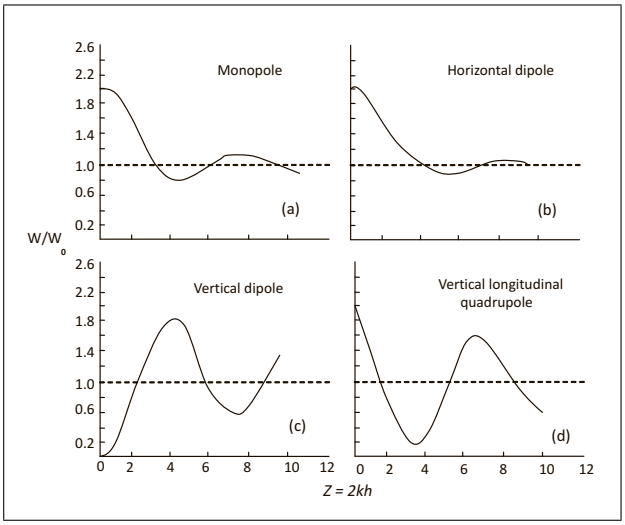


Figure 10. Simulation results for the amplification factor as a function of source height above boundary [23].

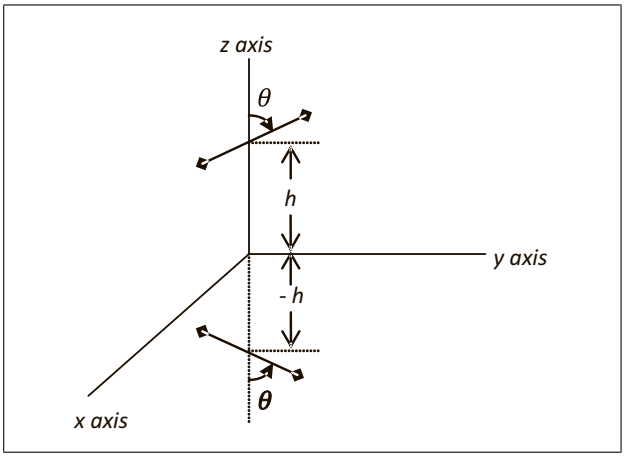


Figure 11. Geometry for a dipole source [26].

For a vertical dipole, the expression is given by

$$\frac{W}{W_0} = 1 - \frac{3}{z}\left[\left(1 - \frac{2}{z^2}\right)\sin z + 2\frac{\cos z}{z}\right]. \qquad (3)$$

For equations (2) and (3), z is defined as in equation (1).

The simulation results for the horizontal and vertical dipoles are shown in Figure 10b and Figure 10c respectively. Comparing these results, it is noted that the system is much less affected by a horizontal dipole than for a vertical dipole. The vertical dipole is a more efficient radiator than a horizontal dipole configuration. In the analysis by Bies [26], for a distribution of randomly oriented dipoles, it was found that the average is closer to unity over the entire frequency range. Hence for an arbitrarily oriented dipole, the radiated sound power is much less affected by the reflective plane.

3.1.3. Acoustic quadrupole

A quadrupole consists of two identical dipoles with opposite phase and separated by a small distance. A quadrupole can be either a lateral quadrupole where the dipole axes do not lie along the same line, or a longitudinal quadrupole where the dipole axes lie along the same line.

The analytical expression for the radiated power ratio given by Ingard and Lamb [23] is

$$\frac{W}{W_0} = 1 + \frac{5}{z}\left[\left(1 - \frac{12}{z^2} + \frac{24}{z^4}\right)\sin z + \left(\frac{4}{z} - \frac{24}{z^3}\right)\cos z\right], \qquad (4)$$

where $z = 2kh$, ($k = 2\pi/\lambda$, and h is the distance of source from the plane). The simulation results are shown in Figure 10d.

For arbitrarily oriented quadrupoles considered by Bies [26], it has been shown that the effect of a rigid plane on the total radiated power is insignificant when the source is more than half a wavelength from the plane. Compared to a multipole, when averaging arbitrarily oriented quadrupoles over the orientation angle, the effect is a decrease in fluctuation of the power output.

It is worth noting that in all the experiments carried out by Ingard and Lamb [23], Bies [26] and M. K. Lim [24], there is only the primary source (with no control source). Hence the primary concern was to study the radiation efficiency at various simple sources in the presence of a reflective plane.

In a more recent work by Pan *et al.* [4], the power radiated by two monopoles near a reflective surface when one monopole is actively controlled, was evaluated. It has been shown that the power output for this case is dependent on the orientation angle. But more importantly, it was found that to achieve maximum reduction in sound power, the secondary control source should be arranged in such a way that the control system is vertically placed with respect to the plane, to form a longitudinal quadrupole as shown in Figure 11 for $\theta = 0$. Tarabini *et al.* [27] compared monopole and dipole control sources in their work which involves the use of a diagonal active barrier to increase the isolation of an enclosure wall. In their experiment, the error microphones were placed and kept near the actively controlled surface as shown in Figure 12. With monopole control sources, a better performance was obtained when the secondary sources were placed near the error microphones. On the other hand, with dipole control sources, better results were obtained when the secondary sources are placed relatively far from the perimeter wall.

3.1.4. Analysis of findings

All directivity patterns are affected in some way by a reflective plane. For a single control source system, a longitudinal quadrupole, formed by a vertically arranged control system can help to achieve good performance in noise reduction. When using an array of secondary sources, such as in the work by Tarabini *et al.* [27], it was found that the control performance is more significantly affected by the distance between the secondary control sources and the error microphones, and the directivity of these secondary sources. In the configuration they used, they found that

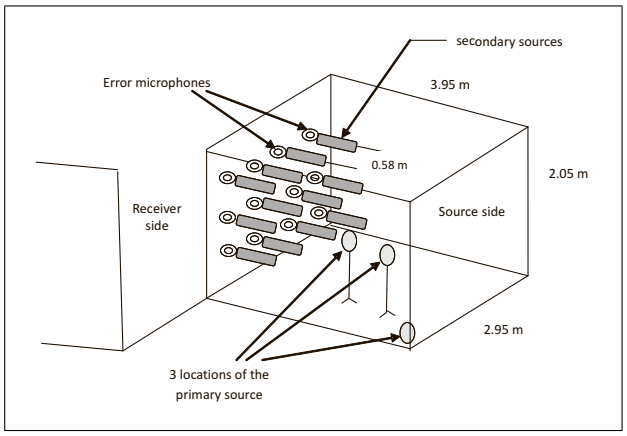


Figure 12. Diagonal active barrier to increase isolation of an enclosure wall [27].

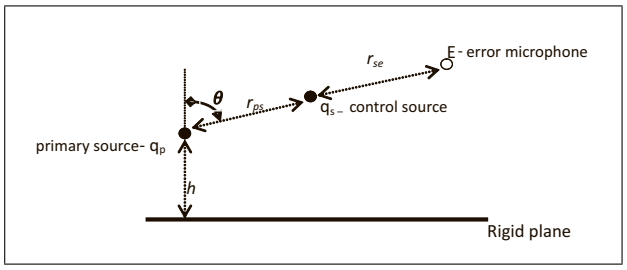


Figure 13. Monopole primary and secondary source over a rigid plane.

in general, better results are obtained when the secondary control sources are dipoles.

3.2. Distance between reflective plane and sources, and between different sources

The parameter which is most determinant to the effect of a reflective plane on the performance of an active control system is that of the distance between the different sources, actuators and the reflective plane. It is a fact that when the sources are far away (or many wavelengths) from the reflective plane, the effect of the latter is negligible. However, the reflective plane may significantly alter the radiation impedance presented to the source if the reflector is less than a few wavelengths from the source [26]. For a horizontal quadrupole configuration, the limiting distance where the reflective plane will affect the source is as little as one half wavelength [26]. In the work by Cunefare and Shepard [25], it was shown that if the sources are in a parallel configuration to the plane, then the latter has negligible effect on noise reduction, and that free space solutions can be used as an approximation to half space equations. However, in a configuration of the control sources perpendicular to the plane, then there is subsequent power reduction. Significant reduction in sound power levels can be achieved when the control sources are in close proximity to the plane. When the control sources are within half of a wavelength to the plane, there is still reduction in noise level. Shepard and Cunefare [28] considered the active control of extended acoustic sources in half space where the effect of a rigid plane on the active noise control of extended three-dimensional sources has been analysed. It was shown that the plane can significantly affect the active noise control system when the "geometric centre of the source is within one fifth of a wavelength to a plane at lower frequency". Guo and Pan [2] used the schematic shown in Figure 13 to assess the effect of the reflective plane on the total power output and it was shown that this effect

- decreases when h increases;
- decreases when r_{ps} increases;
- decreases significantly when r_{se} decreases,

where h is the distance between the sources and the plane, r_{ps} is the distance between the primary and the secondary source and r_{se} is the distance between the secondary source and the error microphone.

Their work also showed that a reflective plane not only affect the power output of the active noise control system, but also the size of the quiet zone. However, this will be dependent on the configuration of the sources and the plane. For parallel configuration to the plane, the quiet zone will always be smaller when the sources are greater than a critical height, h_c, from the plane. When the sources are less than h_c from the plane, the size of the quiet zone can increase. For perpendicular configuration, the size of the quiet zone may increase provided the distance between the primary source and plane is less than one wavelength (λ), and that the distance between the primary and the secondary source is less than λ. Tarabini and Roure [3] worked on the influencing parameters of an active noise control system on an enclosure wall. Their work comprises an array of error microphones and secondary sources as an active noise barrier to minimize the sound pressure. They showed that the distance between the array of error microphones and the wall is less important compared to other factors such as distance between control sources and error microphones, and directivity. Good performances are obtained when using monopole sources close to the error microphones or using dipole sources relatively far from the error sensors.

Table I summarises the impact of distance of sources and microphones from the rigid plane.

A diffracting sphere also has an effect on the performance of an active noise control system. The purpose of studying the effect of a diffracting sphere is because the latter can be used as a model of the human head. In the work by Lin *et al.* [29], the noise reduction as a function of distance between the control source and the sphere centre was studied with and without the rigid sphere. Their results show that in the presence of the rigid sphere, the noise attenuation is larger. Zou and Qiu [30] used the configuration shown in Figure 14 to demonstrate the effect of the rigid sphere. In general, a rigid sphere, placed inside an array of control sources and microphone has a positive effect on the performance of the control system. Another important issue worth considering is the movement of the rigid sphere in the system, representing the movements of the human head. It has been shown that when the rigid

Table I. Effect of rigid plane with respect to distance.

Effect on Total power output
Bies [26]: For arbitrarily oriented multipole, limiting distance is $\lambda/2$ for horizontally placed quadrupole with respect to plane.
Cunefare and Shepard [25]: (i) parallel configuration: negligible impact by reflective plane (ii) perpendicular configuration: impact for distance less than $\lambda/2$. Significant impact for distance less than $\lambda/3$.
Shepard and Cunefare [28]: For extended sources, when distance is greater than λ, effect can be neglected. Plane affect system when geometric centre of the source is within $\lambda/5$ of the plane at the lower frequency.
Guo and Pan [2]: Effect of the plane (i) decreases when h increases (ii) decreases when r_{ps} increases (iii) decreases significantly when r_{se} decreases.
Tarabini and Roure [3]: Distance between error sensors and plane less important factor than distance between control sources and error sensors or directivity.
Size of quiet zone
Bies [26]: No control source considered.
Cunefare and Shepard [25]: No control source considered.
Shepard and Cunefare [28]: No control source considered.
Guo and Pan [2]: (i) parallel configuration: size of quiet zone is always smaller provided plane is less than a critical height whereby the size is unaffected. (ii) perpendicular configuration: the quiet zone may increase provided h is less than λ, and that r_{ps} is less than λ.
Tarabini and Roure [3]: Not considered.

sphere is moved away from the centre of the system, the performance of the control system decreases.

Table II gives a comparison of the work by Lin *et al.* [29], and Zou and Qiu [30] for the effect of a diffracting sphere.

3.2.1. Analysis of findings

For a rigid plane, comparison of the findings (Table I) shows that there is a limiting distance whereby the plane will affect the system. For the parallel configuration, the effect is insignificant whereby an approximation to free field solutions may be considered. In fact, there is a critical height ($h_c = 0.4\lambda\sqrt{r_{se}/\lambda}$) whereby the size of the quiet zone will not be reduced if the distance of the control source from the reflective ground is less than h_c [2]. For the perpendicular configuration, there can be a positive effect on the system provided distances between sources are respected. Also, for an array of control sources and error

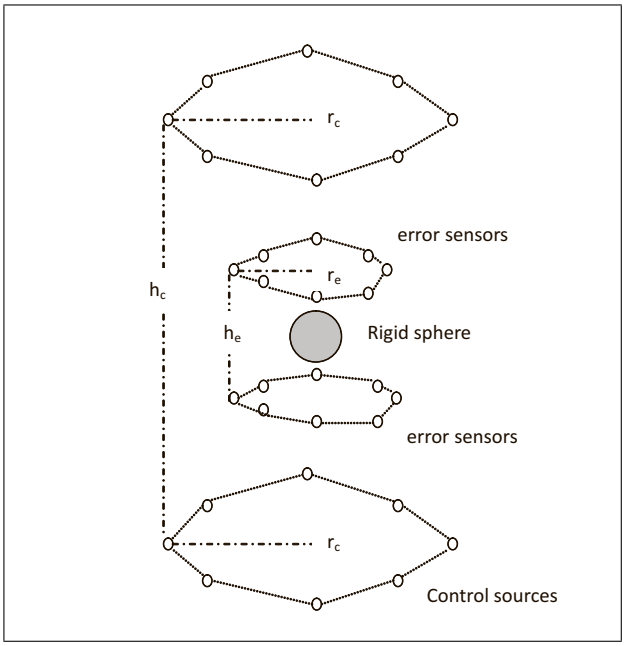


Figure 14. Control system in a diffracting sphere [30].

Table II. Effect of rigid sphere on the control system.

Effect on Total power output
Lin *et al.* [29]: (i) Effect can be neglected when control source is more than $\lambda/2$ from the sphere centre. (ii) Nearer the control source is to sphere centre, the better the attenuation.
Zou and Qiu [30]: (i) when distance between error sensor and sphere centre increases, the system performance deteriorates (ii) when error sensor is very close to the sphere, system is better without the rigid sphere.
Size of quiet zone
Lin *et al.* [29]: Presence of rigid sphere beneficial to system.
Zou and Qiu [30]: (i) Generally, rigid sphere gives larger quiet zone. (ii) when sphere moved away from centre of system, performance deteriorates.

sensors, some factors are more determinant especially the distance between the error microphones and loudspeakers and directivity, than others [3].

For a diffracting sphere, it is also found that in general (Table II), there is a positive effect on the system. In the study by Lin *et al.* [29], for a distance of 0.1 m of the source from the sphere centre (at a frequency of 500 Hz), the attenuation is 33 dB with the rigid sphere and 21.2 dB without the rigid sphere. In the work by Zou and Qiu [30], the control performance at 500 Hz with respect to the distance of the error sensor from sphere centre (r_e) for a fixed value of r_c (defined in Figure 14), has been analysed and is shown in Figure 15. It is found that there is a limiting value of r_e whereby the system is worse with the rigid

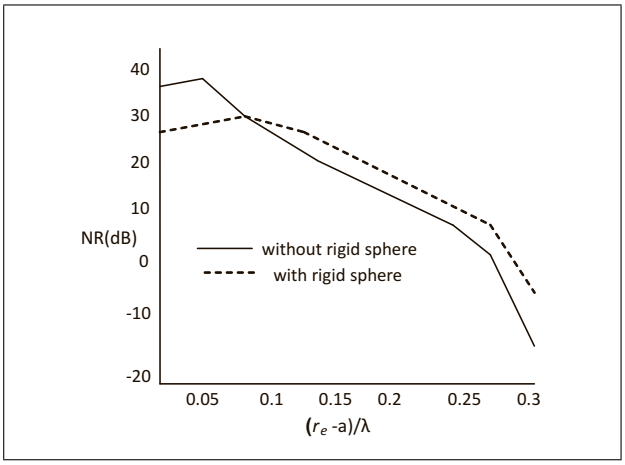


Figure 15. Simulation results with respect to r_e, when using a 16-channel cylindrical virtual sound barrier with a rigid sphere [30].

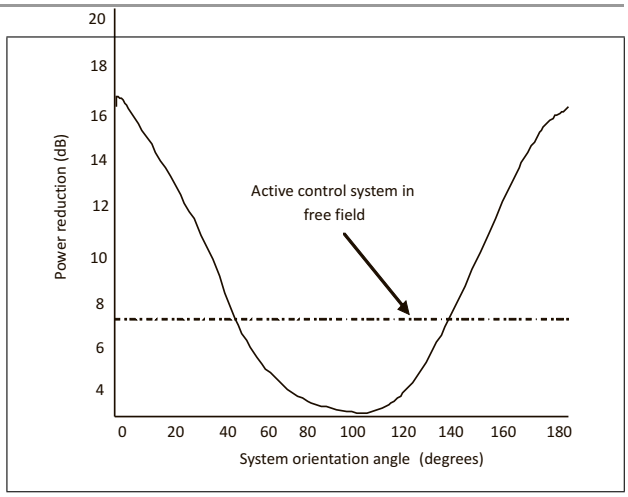


Figure 16. Reduction in total power radiated with respect to angle of orientation [4].

sphere (approximately $r_e - a = 0.09\lambda$, a being the radius of the sphere). The maximum difference can be around 9 dB. When r_e is greater than that threshold, the system performance improves in the presence of the rigid sphere.

3.3. Angle of orientation between sources and rigid plane

Another factor in the configuration of the control system, which affects the system performance, is that of the angle of orientation of the control sources with the rigid plane. This is an important parameter to consider when designing systems to achieve good quiet zones. Studies have shown that the total power output and the size of the quiet zone, for different orientation angle, can be quite diverse and will be discussed next.

Cunefare and Shepard [25] considered two configurations for the effect on power reduction namely when the line of control sources are parallel to the plane (for θ = 90 degrees in Figure 13) and when they are perpendicular to the plane (for $\theta = 0$ in Figure 13). The analysis has been performed using both the free space solution and the half space solution and the results compared. For the parallel configuration, the difference obtained when using the free space solution and the half space solution is at most 0.25 dB, which is relatively low. Consequently, it can be concluded that for configuration of sources in a line parallel to a rigid plane, the presence of the plane has negligible impact on the noise reduction. Guo and Pan [2] also considered the effect on total power output. For the parallel configuration they showed that it is dependent upon the height of the sources and the error sensor above the plane, and also on the distances between the primary and secondary sources (r_{ps}) and that between the secondary source and the error sensor (r_{se}). In this configuration, the noise reduction is much more affected by r_{se}, whereby it increases when r_{se} increases.

In the work by Pan *et al.* [4], the power reduction has been compared against the system orientation angle (from 0 to 180 degrees) and is shown in Figure 16. It has been noted that for the parallel configuration (i.e. for an orientation angle of 90 degrees), the rigid plane has a negative effect on the control system, where the power reduction is lesser than in the absence of the rigid plane, i.e. in free field conditions. In fact for a range of angles between 40° and 140°, the system is worse in the presence of the rigid plane where the noise reduction is less as shown in Figure 16. This is because the mechanism of the active control system is characterized by the parallel dipole configuration [4]. For sources in a line perpendicular to the plane, the noise reduction analysis carried out by Cunefare and Shepard [25] used both the free space and half space solution. However, this time, comparison of the results has shown a difference varying between 3 dB and 8 dB which is quite significant. Hence for sources in a line perpendicular to the rigid plane, the sound pressure levels are largely affected by the presence of the plane. This has been confirmed in the work by Pan *et al.* [4] where a significant increase in power reduction is observed at angles of 0 and 180 degrees as shown in Figure 16. In this situation, the active control system is dominated by a vertical dipole configuration. Therefore, when a primary monopole source is located near a rigid plane, the secondary source shall be arranged in such a way that the control system is vertically oriented to the plane in order to achieve a significant reduction in total sound power. This arrangement allows the vertical dipole and its image from the rigid plane to form a longitudinal quadrupole, which radiates much less power than a vertical dipole in free field conditions [4].

Hart and Lau [31] studied the minimization of the squared acoustic pressures with a linear array of control sources and a perpendicular linear array of error sensors placed above the top of a noise barrier as shown in Figure 17. They found that for a distance between control sources and error sensors much less than a quarter of a wavelength of the primary noise disturbance, the orientation angle of the combined linear control source and sensor arrays, has little effect on the noise reduction. This means that, for that particular configuration, i.e. distance being

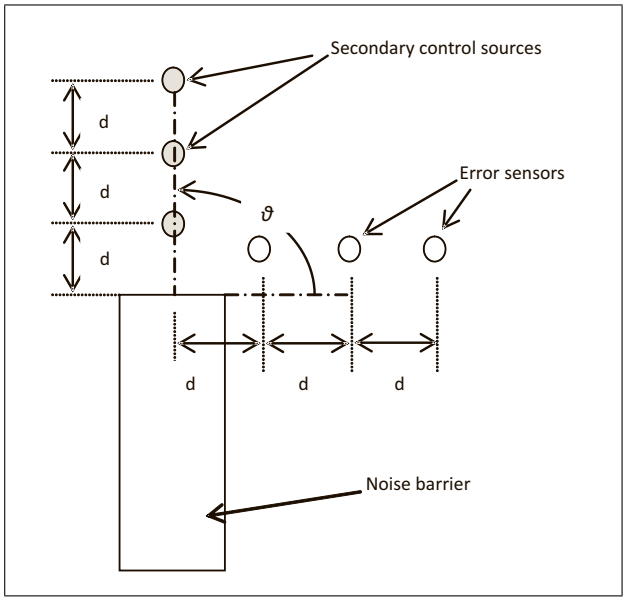


Figure 17. Control sources above a noise barrier with perpendicular linear array of error sensors (θ being the orientation angle) [31].

less than $\lambda/4$, any angular orientation will give the same noise attenuation.

The rigid plane not only affects the total power output but also impacts on the size of the quiet zone. In the work by Guo and Pan [2], it was shown that when the control system is in a line parallel to the reflective plane, the quiet zone created is always smaller than that created in free field, when the height of the control source from the plane is larger than a critical value, h_c. For a height smaller than h_c, the quiet zone created may be greater. For a control system in a line at an angle to the plane, the size of the quiet zone is always smaller than that for the free field conditions except for an angle of 0°. At this angle, the control system is perpendicular to the rigid plane. The size of the quiet zone may increase but subject to the distance r_{ps}, and height h.

Table III. Effect of orientation angle on control performance.

Effect on Total power output
Cunefare and Shepard [25]:
Paralell configuration: Very little effect on total power output. Free space solutions can be used as an approximation to half space solutions.
Perpendicular configuration: Free space error significant. Must determine appropriate form of impedance relationships for analysis.
Guo and Pan [2]:
Parallel configuration: Power output dependent upon h, r_{ps}, and r_{se}. Much more affected by r_{se}.
Pan *et al.* [4]:
Other angles except perpendicular configuration: For system angles 40° to 140° (parallel configuration: 90°): system worse than in absence of plane.
Perpendicular configuration: Positive effect on system. Large difference in power reduction between vertical and horizontal configuration.
Hart and Lau [31]:
For distance between array of loudspeakers and error microphones less than $\lambda/4$, orientation angle has negligible effect on the control performance.
Effect on Quiet zone
Cunefare and Shepard [25]:
Not considered.
Guo and Pan [2]:
Paralell configuration: Quiet zone may be greater provided system is less than critical height, h_c (as defined in section 3.2). When height is greater than h_c, quiet zone always smaller.
Other angles: Quiet zone always smaller except for perpendicular configuration where it may increase. For this configuration, quiet zone size is a function of h and r_{ps}.
Pan *et al.* [4]:
Not considered.
Hart and Lau [31]:
Not considered.

3.3.1. Analysis of findings

From Table III, it seems that there is a significant difference for power output for the parallel and perpendicular configurations. For the parallel configuration, research work shows convergence such that the reflective plane has little or even adverse effect on the system. For good performance, the perpendicular configuration is a better solution though it is difficult to implement that configuration in practice. Also, the orientation angle has little effect on the system for close distance (less than $\lambda/4$) between the error sensor array and control loudspeakers.

3.4. Control performance when using single and multiple control sources

In an active noise control system, the use of one secondary source can achieve some quiet zone. However, in order to increase the performance of the control system, more than one control source is necessary. The effect of a reflecting surface on the control system comprising of multiple control sources results in a decrease in the acoustic radiation.

Lin *et al.* [29] considered the effect of a rigid sphere on the control system by making use of a geometrical arrangement of monopole sources all around the sphere. The location of these control sources and error sensors is of utmost importance to achieve maximum noise reduction. In their work, they used practical set ups involving two, three, four and six control sources and determined their noise reduction. They showed that the maximum noise reduction does not increase significantly when the number of control sources is greater than 3. Also, the configuration of these three control sources may be the best arrangement for practical applications as it involves few control sources and give relatively high noise reduction. Lin *et al.* [29] also used a genetic algorithm method to determine the optimum number and best locations for control sources and error

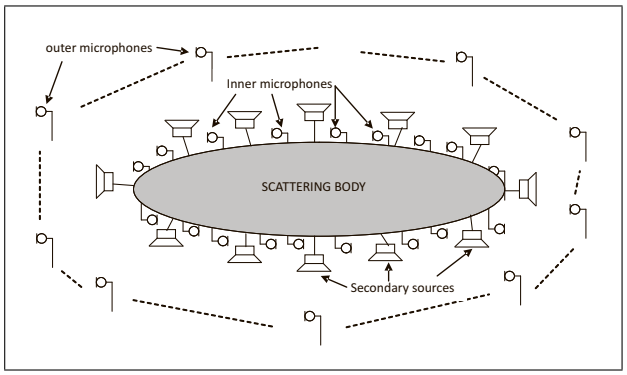


Figure 18. Arrangement of actuators and sensors for real-time reduction of scattered radiation [32].

sensors and compared the results with their practical set ups. They found that the genetic algorithm is comparable to their set ups implemented for a few control sources (less than four).

Zou and Qiu [30] studied the performance of a virtual sound barrier with a diffracting sphere. The distribution of the control sources was in two parallel arrays below and above the sphere, arranged in a circle as shown in Figure 14. Sixteen control sources were used in total with the same number of error sensors. When the radius of the distribution of the control sources (r_c) was increased, the noise reduction increases rapidly but then stabilizes depending upon the distribution of the error sensors, which are placed inner to the centre of the sphere. After a certain value of r_c, the sphere does not have any effect on the control system. Friot and Bordier [32] introduced a control strategy to reduce scattered acoustic radiation from a reflecting body in real time. Applications can be to render submarines or underwater mines invisible to detection from sonar systems, which is of interest for military purposes. They showed that in order to control the scattered radiation from the reflecting body in all directions, the secondary sources shall be placed at the body surface all around the body as shown in Figure 18. It is clear that a single control source won't be able to achieve the required control performance for that particular application. Moreover, in their work, they found that a minimum number of sensors is required at the body boundary for an accurate estimation of the scattered noise. But, the control strategy proposed is limited by the number of sensors and actuators. Tarabini *et al.* [27] considered the noise control in an adjacent room through an array of secondary sources as shown in Figure 9. In their work, an array of 12 secondary sources was used on the wall partition in the source side. However, it is to be noted that the larger the surface of the partition, the higher will be the number of control sources.

3.4.1. Analysis of findings

Using multiple control sources definitely helps to increase the performance of the control system but too many control sources is not practical due to complexity, computational burden and cost. However, most importantly it is the arrangement of the control sources which mostly affects the system as shown in Table IV. The use of a genetic algorithm [33] is one of several stochastic optimization procedures to find the best number and locations of the loudspeakers.

Table IV. Effect of multiple control sources on overall performance of system.

Effect on Overall performance
Lin et al [29]: Considered geometrical arrangement of monopole sources all around a diffracting sphere. Noise reduction does not increase much for systems greater than 3 control sources. Genetic algorithm used to determine optimum number and location of control sources.
Zou and Qiu [30]: Studied performance analysis of a virtual sound barrier with a diffracting sphere. Control sources placed above and below sphere. Overall noise reduction increases rapidly and then stabilizes when r_c is increased.
Friot and Bordier [32]: To control scattered radiation from a reflecting body in all directions, secondary sources placed on the body surface. Minimum number of sensors is required for an accurate estimation of scattered noise. Control strategy limited by number of sensors and actuators.
Tarabini *et al.* [27]: Noise control in an adjacent room through an array of secondary sources. The larger the surface of partition, the greater will be number of control sources.

3.5. Effect of reflecting planes on different frequencies of the primary source

In the presence of a reflective plane, the reduction in total sound power output for different frequencies varies. Lin *et al.* [29] analysed the active control of acoustic radiation from a piston set in a rigid sphere with respect to frequency. The graph of noise reduction versus frequency follows the same shape in the absence and in the presence of the rigid sphere as shown in Figure 19. However, in the presence of the rigid sphere, the attenuation is larger than that without the rigid sphere. The noise attenuation is high for low frequencies (up to 500 Hz), where the value of the noise reduction then stabilises. So, the presence of the rigid sphere is more effective at low frequencies than at high. In the work by Zou and Qiu [30], the effect of the rigid sphere on noise reduction is again analysed. It is seen that the value of the noise reduction falls when the frequency of the noise is increased. When the frequency is higher than 100 Hz, the performance of the system is better with the rigid sphere as shown in Figure 20. However, for frequencies lower than 100 Hz, the rigid sphere has a negative impact on the system. Hence control in the presence of the rigid sphere depends on the frequency and the sphere has a positive effect on the system for frequencies between 100–600 Hz.

In the work by Friot and Bordier [32], a removable tap has been inserted in a duct to simulate the effect of a

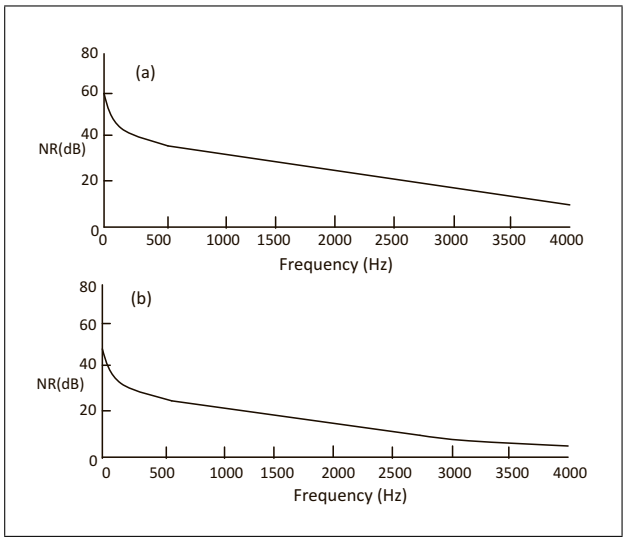


Figure 19. Noise reduction as a function of frequency: (a) with the rigid sphere and (b) without the rigid sphere [29].

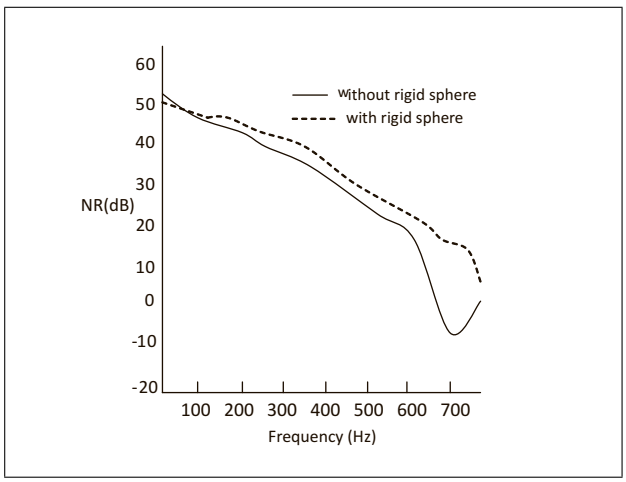


Figure 20. Simulation result of the control performance with respect to the frequency of the noise signal [30].

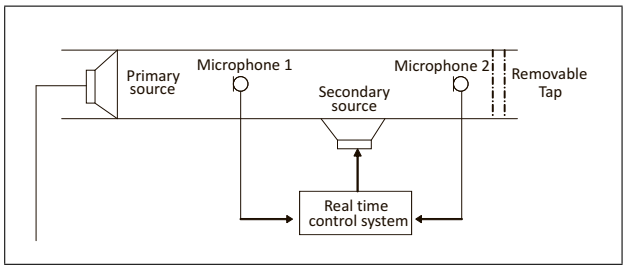


Figure 21. Duct with a removable tap for real time control [32].

scattering body as shown in Figure 21. The input to the primary source is a 0–800 Hz band white noise. The effect of the scattering body over the range of frequencies is quite similar to the above case. For very low frequencies (below 80 Hz), there is practically no effect as the secondary sources used are inefficient at these very low frequencies. The highest efficiency in noise reduction is obtained in the range 100–350 Hz. For frequencies higher than 350 Hz, the change in noise reduction stabilizes. The scattered noise can be reduced by about 10–30 dB, in the frequency range of interest by using that type of control.

Table V. Effect of frequency on the control performance.

Effect on Total power output
Lin *et al.* [29]: Frequency curve same shape with/without rigid sphere. Attenuation is better in presence of rigid plane. Attenuation high for low frequencies and falls gradually as frequency increases.
Zou and Qiu [30]: General trend is that attenuation falls as frequency increases. But at very low freq (<100 Hz), system better without the rigid sphere.
Friot and Bordier [32]: For very low frequencies (<80 Hz), practically no effect. Best efficiency occurs in range 100-350 Hz. After 350 Hz, system stabilizes.
Tarabini *et al.* [27]: Ineffective at low frequencies (<80 Hz). Best performance occurs in range 80-200 Hz. Higher than 200 Hz, noise reduction falls as frequency rises.

In the work by Tarabini *et al.* [27], where the active control of noise on the source side of a partition to increase its sound isolation has been investigated (Figure 12), the effect on frequency has been studied over a frequency band of 50–300 Hz. Here also, it has been found that the control system is ineffective at very low frequencies (<80 Hz), and the control was better for frequencies 80–300 Hz. The frequency limitation of 80 Hz is mainly due to the limited efficiency of loudspeakers in the low frequency range. Table V summarises the effect of the frequency on the control performance.

3.5.1. Analysis of findings

In general, it can be stated that there is better control for lower frequencies than high frequencies. However, there seems to be a lower limit of frequency whereby the control performance is better without the reflective body. The frequency band where the control system works well is in the range 100–600 Hz for the set ups implemented. Outside this range, either appropriate secondary sources (<100 Hz) or a hybrid control system making use of passive control methods (>600 Hz) can be used.

4. Comparison matrix showing the effect of each parameter on the control performance

In the previous section of this paper, the extent by which a reflective plane affects the control performance has been given for each parameter. However, it is important to have a global picture of the research attained so far, and in what areas there is still work to be achieved. Table VI gives a comparison matrix outlining the effect of a reflective plane

on power output and quiet zone in relation to each parameter.

From Table VI, it has been found that there has been little ongoing research on the effect of reflective surfaces on the performance of active noise control systems. Moreover, in some areas, there is a lack of focus especially in terms of the extent of the quiet zone. Further research work can still be carried out addressing the effect of multiple control systems, and that of frequency on the size of the quiet zone. Also, it is found that the effect of directivity of the control sources is lacking in research.

5. Conclusions and future work

In this paper, factors by which a reflecting plane affects an active noise control system have been outlined. It has been shown that the extent, by which these parameters influence the control system, is dependent on the configuration of the system itself. Also, there are factors which affect the control system more than others as pointed out by Tarabini *et al.* [27] in their work. The latter used a factorial design of experiments to determine the influence of each parameter. In their configuration, they showed that the loudspeaker directivity and the distance between loudspeakers and error microphones are more significant on the overall performance of the system than the distance between the error microphones and the rigid wall or the characteristics of the wall. Furthermore, in the work by Hart and Lau [31], it was found that the performances of the control system are independent from the orientation angle when the separation between the control sources array and error microphone array is less than a quarter of a wavelength. This gives an advantage on the practical arrangement of the control system. In general, a reflective plane has a positive effect on an active control system. However, to optimize the presence of the reflective body in terms of the control performance, a study of the system needs to be carried out to determine the influence of each parameter.

In free field conditions, there are also certain parameters that governed the overall control performance. Some of the recent techniques have been outlined in this paper. Multichannel systems are bulky in terms of practical arrangement but may give a larger quiet zone but this may not be practical or cost effective. Methods to reduce the complexity of multi-channel systems have been developed such as band-limiting the highest frequencies of the anti-noise [14] or replacing monopole sources by compound secondary sources which have proved useful. Adaptive control has also proved to be worthwhile as it adapts itself to changes in the environmental characteristics. Virtual sensing techniques are very useful especially when we want to achieve quiet zones at very precise locations in complex arrangements. Directional loudspeakers are efficient in reduction of sound pressure levels by minimizing interferences and cross-talk in multi-channel systems but have their limitations at low frequencies.

In this field of research when considering the effects of reflective plane, there is still work to be done especially on the extent of quiet zone. Further research work needs to be carried out to assess the impact of multiple control systems on the size of the quiet zone. Comparative experiments can be implemented with multiple channel systems using an array of loudspeakers and microphones. These setups can be mounted using either feedback or feed-forward configurations with the Fx-LMS algorithm. The effect of the frequency of the primary noise on the size of the quiet zone is also lacking in research. Here also, this can be analysed with multiple control sources systems, using specific low frequency loudspeakers, and different arrangements of the

Table VI. Effect of rigid plane on power output and quiet zone with respect to each parameter.

Effect on Total power output
Directivity pattern of sources: Maximum reduction in power output when control system vertically placed to plane to form a longitudinal quadrupole. For multiple control source system used to form a diagonal active barrier, better performances with dipoles.
Distance between plane and sources: For parallel configuration: practically no effect. For perpendicular configuration, there is a limiting distance. Effect of plane (i) decreases when h increases (ii) decreases when r_{ps} increases (iii) decreases significantly when r_{se} decreases. Presence of rigid sphere is positive to performance.
Angle of orientation between plane and sources: System worse for parallel configuration or close to parallel configuration. For perpendicular configuration, positive effect on system where reduction in power output is significant.
Using single or multiple control sources: Using multiple control sources has a positive effect on system but noise reduction stabilizes after a certain number of control sources. System limited by practical implementation of sensors and actuators.
Frequency of the primary source: System performance is worse for very low frequencies (<100 Hz). Best performance occurs for range 100-600 Hz. For higher frequencies, hybrid control methods need to be used.
Effect on quiet zone
Directivity pattern of sources: Research not directly centered on size of quiet zone.
Distance between plane and sources: For parallel configuration, size of quiet zone is always smaller provided plane is less than a critical height whereby the size is unaffected. For perpendicular configuration, the quiet zone may increase provided h is less than λ, and that r_{ps} is less than λ.
Angle of orientation between plane and sources: Only perpendicular configuration gives a definite bigger quiet zone.
Using single or multiple control sources: Lacking in literature.
Frequency of the primary source: Lacking in literature.

sensors. Moreover, the effect of impedance of the reflecting surface should also be studied in its own right. Finally, since the directivity of sources is a leading parameter in multiple control sources systems, practical arrangement of loudspeakers is challenging and the design of small secondary sources will be an advantage.

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