Journal of Sound and Vibration (2002) **251**(3), 457–475
doi:10.1006/jsvi.2001.3994, available online at http://www.idealibrary.com on IDEAL®

ACTIVE CONTROL OF A MOVING NOISE SOURCE—EFFECT OF OFF-AXIS SOURCE POSITION

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(*Received* 8 *March* 2001, *and in final form* 4 *September* 2001)

An optimally arranged multiple-channel active-control system is known to be able to create a large quiet zone in free space for a stationary primary noise source. When the primary noise source moves, the active control of the noise becomes much more difficult, as the primary noise field changes with time in space. In this case, the controller of the control system must respond fast enough to compensate for the change; much research has been focused on this issue. In this paper, it is shown that a moving source also causes difficulties from an acoustical perspective. A moving source not only changes continuously the strengths and phases of the sound field in the space, but also changes the wavefront of the primary sound field continuously. It is known that the efficiency of active noise control is determined mainly by the wavefront matching between the primary and control fields. To keep the control system effective in the case of a moving source, the wavefront of the control field needs to change, in order to continuously match the primary-wavefront change. This paper shows that there are limitations to the control-wavefront change. An optimally pre-arranged, multiple-channel control system is not able to construct a matching wavefront when the primary source moves outside a certain range. In other words, the control system is still able to create a large quiet zone only when the primary source moves within a range around the central axis of the control system. Both the location and the size of the quiet zone change with the location of the primary source.

1. INTRODUCTION

Research on active noise control in open space, and its application, has attracted more and more attention and made great progress recently. There are two major approaches to active noise control in open space, or in outdoor environments; global control and local control. The global-control strategy is to reduce the total sound-power output, thus attenuating the sound pressure over the whole space. The deficiency of this approach is that it requires the control sources to be located very closely to the primary sources—less than half wavelength [1–3]. Therefore, for many practical problems of interest, such a goal is unachievable. The local-control strategy, on the other hand, is to attenuate sound pressure in certain directions or in certain desired regions. It is a more practical option when global control is not achievable [4, 5]. Furthermore, in many applications, the reduction of the sound pressure over the whole space is not necessary; it is sufficient to create quiet zones in some desired areas.

It has been found that, for both control strategies, the control efficiency depends strongly on the configuration of the control system, i.e., the geometrical arrangement of the control sources (and error microphones) in relation to the characteristics and locations of the primary sources [1–6]. This means that a system arrangement may be effective for a specific noise source in a specific position, but may become useless, or even increase the primary sound field, for other noise sources in other locations. The important role of the geometrical arrangement of the system to the control efficiency is more obvious for a multi-input/multi-output (MIMO) local-control system, in which the performance of the control system is very sensitive to the control sensor/actuator arrangement. The optimal arrangement of the control sensor/actuator arrays gives rise to the best control efficiency [5, 6]. It should be noted that, in the previous research, the optimal control-system strategies and configurations were investigated for arrangements for which the primary source was always fixed at the centre, or on the central axis, of the control system.

In practical applications, there are cases when the primary noise source is not fixed at a specific location, but moves around. The application of an active noise-control system to moving noise sources has been attracting research interest [7–10]. When the noise source moves, both the frequency and the wavefront of the primary field change with the speed and the direction of the movement [11]; this increases the difficulty in actively controlling the noise dramatically. Generally speaking, there are two major difficulties which arise when using an active noise-control system to attenuate the noise from moving sources. The first difficulty relates to the controller. When the noise sources move, the primary paths of the control system change all the time. These changes are proportional to the speed of the motion of the primary sources. The frequency of the noise may also change due to the Doppler effect. The performance of the control system in the case of moving noise sources depends on how fast the controller can respond to these changes, i.e., the tracking ability of the controller with respect to the moving primary sources.

The second difficulty relates to acoustical limitations of the control system. The efficiency of the control system is mainly determined by wavefront matching, or the coupling between the primary sources and control sources; for this, the relative locations of the sources are critical to the efficiency. When the primary source moves, it is impossible to keep the primary source fixed at the centre, or on the central axis, of the control system, unless the control system moves with the primary source (this case is not discussed here). The primary noise source changes its position relative to the control system all the time. As revealed by previous research, the configuration of the control system with respect to the characteristics and location of the primary source plays an extremely important role in the control efficiency. An optimally arranged control system for a specific noise source at one position may become less effective, or even useless, for the same source at another location. For a pre-arranged control system, its control efficiency is limited by the physical nature of the wave interference of the primary and secondary sound fields, which is determined by the position of a moving source relative to the control system.

There have been recent attempts to control the moving primary source by using an active noise-control system. Omoto *et al.* [7] examined the behaviour of an adaptive controller with a moving primary source. The convergence properties of a controller with multi-channel filtered-x LMS were examined in both the frequency and time domains via numerical simulations. Their results indicated that the controller might adapt to the changes resulting from the movement of the primary source. Duhamel and Sergent [8] studied the possibility of active control of traffic noise by analyzing an incoherent line source, which was regarded as a good model for the noise radiated from dense road traffic or a train. The efficiency of active control by multiple point sources was calculated for finite- and infinite-length primary sources. The computer simulations demonstrated that it was still possible to create a quiet zone, even when the primary source was infinitely long, though the zone was quite small, with dimensions of only a fraction of a wavelength. The control efficiency was considerably improved for the limited source length assumed. Uesaka *et al.* [9], on the other hand, investigated the active control of noise from a moving source through experiments in an anechoic chamber and in an outdoor environment. In their indoor experiments, nine loudspeakers were placed in a line parallel to the control system, at intervals of 1 m. Each of these nine sources worked in turn to simulate a moving primary source at speeds of 30 and 50 km/h. Both single-channel and multi-channel control systems, and both fixed-FIR and adaptive, filtered-x LMS algorithms, were examined. In their outdoor experiments, a loudspeaker was mounted on a car that ran at 30 km/h, and the six-channel control system was placed on the top of a noise barrier. They obtained sound-pressure attenuation of about 5 dB at several measurement points for the indoor experiments, and of about 5–9 dB at the error microphones for the outdoor testing. They also found that the sound reduction varied with different locations of the primary source; i.e., the reduction became large when the primary source passed in front of the control system. Martin [10] investigated numerically the effect of a moving noise source on the noise attenuation in a small domain, and found that shifting the drive from one secondary source to another according to the movement of the primary noise source can lead to a good performance of the active noise-control system.

As the efficiency of the active control system to a moving noise source is limited by both the controller and the acoustical characteristics of the control system, it is necessary to distinguish between these two limitations and investigate them separately. In this paper, the acoustical limitations of an MIMO local-control system to a moving noise source are studied by examining whether an optimally arranged control system is still effective at creating a large area of quiet zone when the primary source shifts to different locations. In the following discussion, the controller of the control system is assumed to be able to adapt to the change in the primary sound field. The speed of the movement is assumed to be much less than the sound speed, and the Doppler effect and other dynamic changes due to the movement of the noise source are not considered. The efficiency of the control system is examined with respect to two measures: the total power-output increase and the size of the quiet zone. Quiet zone is defined as the area in space over which the sound pressure has been attenuated by 10 dB or more [12].

2. SYSTEM DESCRIPTION

Two multi-channel active local-control systems in open space are shown in Figures 1 and 2. While an optimally arranged System I is able to create a large quiet zone in the area behind the control system in the shape of a wedge [5], System II can significantly increase the quiet zone in z direction [6]. System I, shown in Figure 1, is arranged such that the N secondary sources and N error microphones are equally distributed in two parallel lines, while System II, shown in Figure 2, is such that the $N \times N$ control sources and $N \times N$ error microphones are equally placed in two parallel planes. The spacings of the control sources and error microphones are equal—i.e., $r_{ss} = r_{ee}$—for both control systems. The sound pressures at the error microphones can be minimized (theoretically, to zero) if the strengths of the N (or $N \times N$ for System II) control sources are chosen as

$$\mathbf{q}_{s0} = -\mathbf{Z}_{se}^{-1}\mathbf{Z}_{pe}q_p, \tag{1}$$

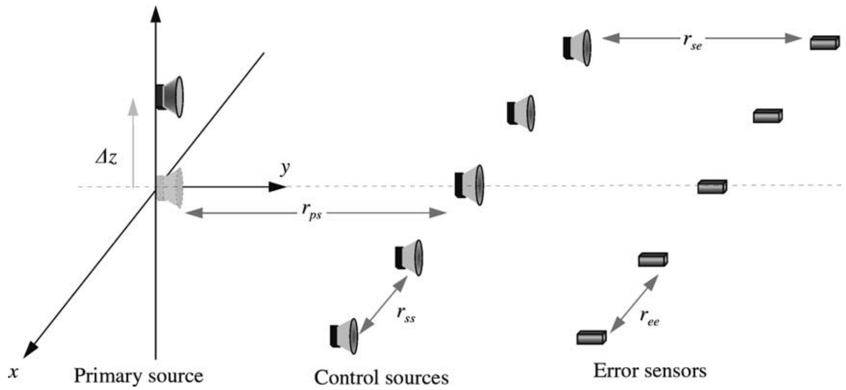


Figure 1. MIMO local-control system arranged in two parallel lines (System I).

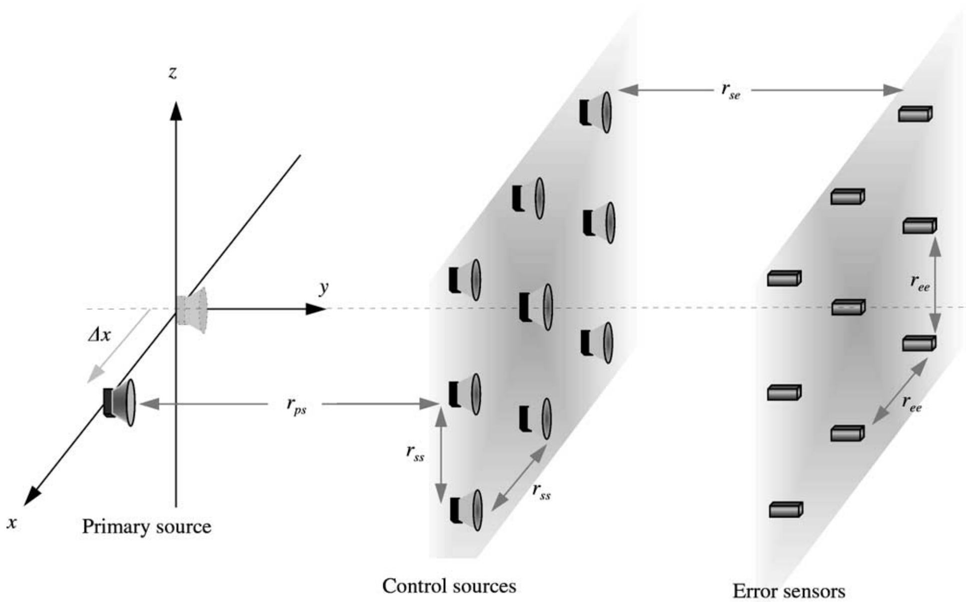


Figure 2. MIMO local-control system arranged in two parallel planes (System II).

where q_p is the strength of the primary source, $\mathbf{q}_s$ is a column vector of source strengths for the N (or $N \times N$ for System II) control sources, $\mathbf{Z}_{se}$ is an $N \times N$ (or $(N \times N) \times (N \times N)$ for System II) matrix of acoustical transfer impedances from the N (or $N \times N$ for System II) control sources to the N (or $N \times N$ for System II) error microphones, and $\mathbf{Z}_{pe}$ is a column vector of acoustical transfer impedances from the primary source to the N (or $N \times N$ for System II) error microphones. Then, the total radiated acoustical power from the primary and secondary sources can be written as

$$W_T = \tfrac{1}{2}\left\{|q_p|^2 Z_0 + \mathbf{q}_s^{\mathrm{H}}\,\mathrm{Re}(\mathbf{Z}_{ss})\mathbf{q}_s + q_p^*\,\mathrm{Re}(\mathbf{Z}_{ps}^{\mathrm{T}})\mathbf{q}_s + q_p\mathbf{q}_s^{\mathrm{H}}\,\mathrm{Re}(\mathbf{Z}_{ps})\right\}, \tag{2}$$

where $Z_0 = \omega^2\rho_0/4\pi c_0$, $\mathbf{Z}_{ss}$ is an $N \times N$ (or $(N \times N) \times (N \times N)$ for System II) transfer-impedance matrix among the N (or $N \times N$ for System II) control sources, and $\mathbf{Z}_{\mathbf{ps}}$ is the column vector of transfer impedances between the primary source and the N (or $N \times N$ for System II) control sources. The principle of acoustical reciprocity applies in this discussion, i.e., $\mathbf{Z}_{sp} = \mathbf{Z}_{ps}^{\mathrm{T}}$. For active local-control strategies in free space, the total power output of the system always increases after the control. This means that the control sources generate the sound power required to control the primary sound field locally. As a result, while the control system creates quiet zones in some desired areas, it increases the sound pressure in other areas. The optimal design of the local-control system involves arranging the control system to create the largest quiet zone, but at the same time to undergo the least increase of total-power output. The optimal design has been found to be very sensitive, and also very important, to the control efficiency of the system [5, 6].

It has been found that, when the primary source is on the central axis of the control system—i.e., at the origin in Figures 1 and 2—there always exists an optimal range of spacing between adjacent control sources and adjacent error microphones of the control system. When the system is designed within this optimal range, it can create the largest quiet zone with the least increase of total sound-power output. When $r_{ss} = r_{ee}$, the upper limit of the optimal range for both Systems I and II is given by [5, 6]

$$r_{ss-\max} \cong \begin{cases} \dfrac{\lambda}{2}\sqrt{1 + \dfrac{4r_{se}}{N\lambda}}, & N = 2,\ 4,\ 6,\ \dots, \\[2ex] \dfrac{\lambda}{2}\sqrt{1 + \dfrac{N+1}{N-1}\dfrac{4r_{se}}{N\lambda}}, & N = 3,\ 5,\ 7,\ \dots, \end{cases} \tag{3}$$

while the lower limits of the range for Systems I and II are given, respectively, by [5]

$$r_{ss-\min} \cong \begin{cases} \dfrac{5\lambda}{2}\,\mathrm{e}^{-[3(\lambda + 0{\cdot}04r_{ps})/(2r_{se}-\lambda) + 20\lambda/(15\lambda + r_{ps})]}, & N = 4,\ 6,\ 8,\ \dots, \\[2ex] \dfrac{3\lambda(N+1)}{N}\,\mathrm{e}^{-[(\lambda + 2r_{ps})/2(2r_{se}-\lambda) + 12\lambda/(5\lambda + r_{ps})]}, & N = 3,\ 5,\ 7,\ \dots, \end{cases} \quad \text{(System I)} \tag{4}$$

and [6]

$$r_{ss-\min} \cong \begin{cases} \dfrac{1{\cdot}4\lambda}{20}\left(\ln\left(\dfrac{r_{ps}}{\lambda} + \dfrac{1}{2}\right) + 0{\cdot}5\right)\ln\left(\dfrac{r_{se}}{\lambda} + \dfrac{1}{2}\right) + \dfrac{\lambda}{3}, & N = 2,\ 4,\ 6,\ \dots, \\[2ex] \dfrac{(N+1)\lambda}{20(N-2)}\left(1{\cdot}25\ln\left(\dfrac{r_{ps}}{\lambda} + \dfrac{1}{2}\right) + 0{\cdot}7\right)\ln\left(\dfrac{r_{se}}{\lambda} + \dfrac{N+1}{4(N-1)}\right) + \dfrac{\lambda}{3}, & N = 3,\ 5,\ 7,\ \dots, \end{cases} \quad \text{(System II)}. \tag{5}$$

In the above, r_{ps} is the distance between the primary source and the secondary source array, r_{se}, is the distance between the secondary-source array and the error-sensor array, and λ is the wavelength of the noise to be controlled. A system arranged outside this optimal range becomes inefficient at creating quiet zones, or even greatly increases the primary noise field over the whole space. In other words, the performance of the control system is very sensitive to the sensor/actuator configuration. Therefore, these optimal configurations need to be strictly observed when designing a multiple-channel local-control system in free space.

For practical applications, the control system is usually pre-designed and fixed at a location in front of the desired quiet areas. A moving primary source can no longer be kept on the central axis of the stationary control sensor/actuator arrays. In the following sections, the performance of the control system will be examined for the case of a primary source shifting away from the position of the central axis of the control system. The control efficiency of the system corresponding to the primary-source shifts will be investigated by way of two measures: the total power-output increase and the size of quiet zone.

3. EFFECT ON TOTAL POWER OUTPUT

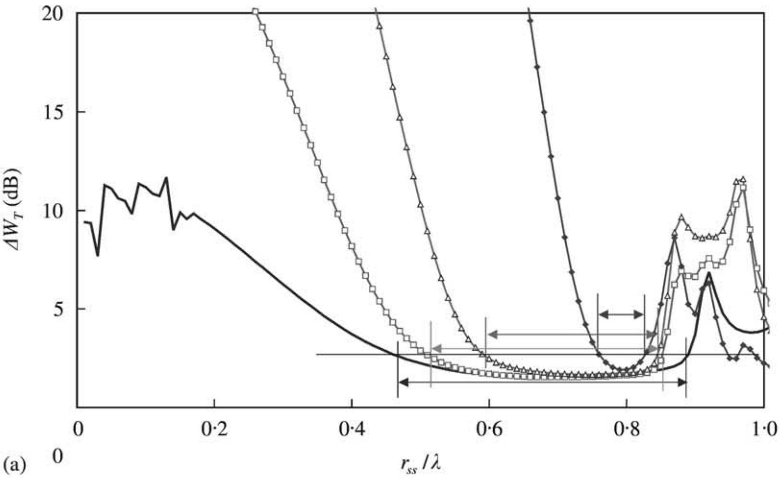
The increase of noise power output due to the introduction of the control system is one of the most important indicators of the control system performance. An optimal local control system always corresponds to the configurations where the total noise power output increase is minimum [5, 6]. The total power output of the multiple-channel control system can be calculated using equation (2); it is obviously a function of the control-system configuration, the wavelength of the noise, and the location of the primary noise source with respect to the control system. The total sound power output increase after control is defined as, $\Delta W_T = 10\log(W_T/W_0)$. An examination of the total power-output increase has been done for both Systems I and II with various system configurations, and with various primary-source shifts away from the central axis. Numerous numerical-simulation results indicate that there always exists an optimal range, or a range of lower power-output increase, even when the primary source shifts away from the original position. This optimal range varies with the primary-source shift.

3.1. SYSTEM I

For the system shown in Figure 1, the primary source has shifted some distance in the x direction and/or the z direction. The shifts are referred to as Δx and Δz. A typical control system with 11 control sources and 11 error microphones is illustrated as an example. The distance from the primary source to the control-source array is $r_{ps} = 2\lambda$; the distance between the control-source array and the error-microphone array is $r_{se} = 5\lambda$. Figure 3 shows the change in the increase of total sound-power output caused by the control system with respect to the spacing of the control sources r_{ss} for different primary-source shifts. The power-output increase for the system without primary-source shift (corresponding to $\Delta x = 0$ and $\Delta z = 0$), which has an optimal spacing range from $0{\cdot}45\lambda$ to $0{\cdot}89\lambda$ according to equations (3) and (4), is also given for comparison.

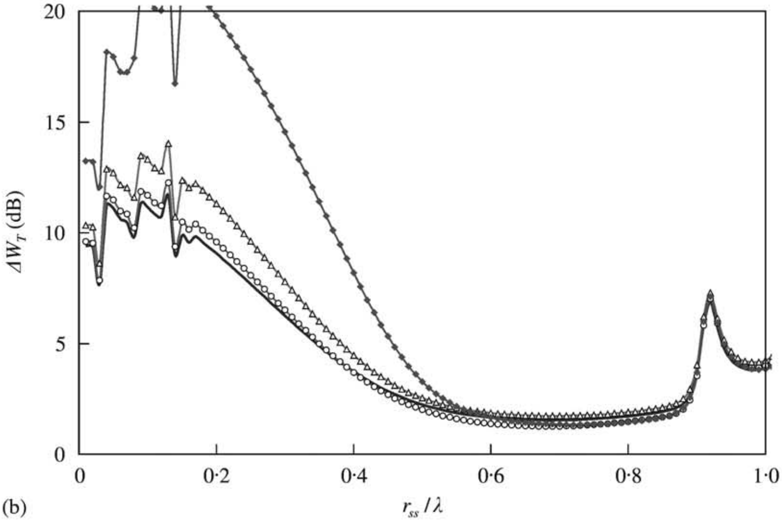
Figure 3 shows that there still exists a range of low power-output increase, though it varies with the primary-source shift. When the primary source shifts some distance in the x direction away from the central axis of the control system, both the upper and lower limits of the optimal range change. Figure 3(a) shows this change for three primary-source shifts; $\Delta x = \lambda$, 2λ and 5λ. The optimal ranges are reduced in comparison with the case without the shift, $\Delta x = 0$. The optimal range recedes at both the upper and lower ends, but mostly at the lower end. The greater the primary-source shift, the narrower the optimal range becomes. When the primary-source shift is $\Delta x = 5\lambda$, the optimal range becomes very narrow, around $r_{ss} = 0{\cdot}8\lambda$. On the other hand, the optimal range remains about the same for the case when the primary-source shift is in the z direction only, as shown in Figure 3(b). The range of low

Figure 3. Total power-output increase of the control system with primary-source shifts in (a) x direction only: —, $\Delta x = 0$; –□–, $\Delta x = \lambda$; –△–, $\Delta x = 2\lambda$; –●–, $\Delta x = 5\lambda$; (b) z direction only: —, $\Delta z = 0$; –○–, $\Delta z = \lambda$; –△–, $\Delta z = 2\lambda$; –●–, $\Delta z = 5\lambda$; and (c) both x and z directions: —, $\Delta z = \Delta x = 0$; –○–, $\Delta z = \Delta x = \lambda$; –△–, $\Delta z = \Delta x = 2\lambda$; –●–, $\Delta z = \Delta x = 5\lambda$.



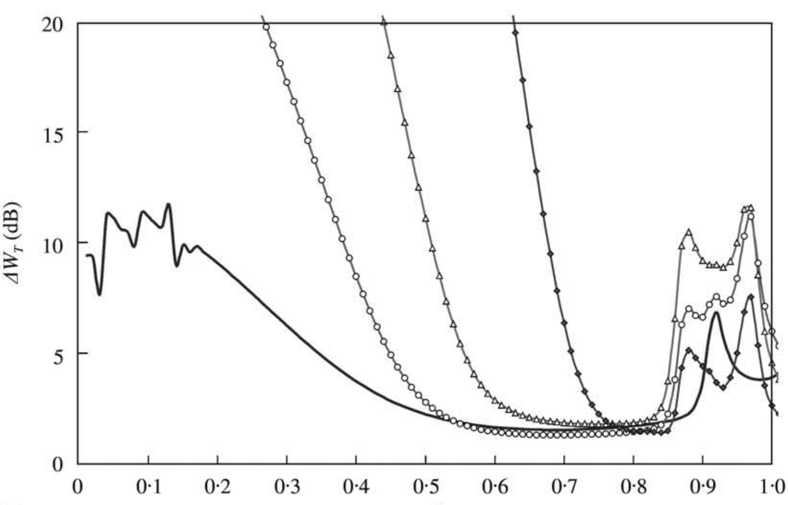
ΔW_T (dB)
r_{ss}/λ

(a)



ΔW_T (dB)
r_{ss}/λ

(b)



ΔW_T (dB)
r_{ss}/λ

(c)

increase of power output decreases when the primary source shifts in both the x and z directions. Figure 3(c) shows that the range reduction is very similar to that in the case of Figure 3(a), which implies that the effect of primary-source shift on the power-output increase results mainly from the primary-source shift in the x direction for System I.

3.2. SYSTEM II

Similar to the previous analysis for System I, results for a system with 11×11 secondary sources and 11×11 error microphones arranged in two parallel planes are shown as an example. The distance from the primary source to the control-source array is $r_{ps} = 2\lambda$, and the distance between the control-source array and the error-microphone array is $r_{se} = 5\lambda$. This system is symmetrical with respect to the x- and z-axis, and the analysis pertains to a primary-source shift in the x direction only, and equally in both the x and z directions. Figure 4 shows the change of increase of total sound-power output caused by the control system, with respect to the spacing of the control sources r_{ss} for different primary-source shifts. The power-output increase for the system without primary-source shift (corresponding to $\Delta x = 0$ and $\Delta z = 0$), which has an optimal spacing range from $0{\cdot}54\lambda$ to $0{\cdot}89\lambda$ according to equations (3) and (5), is also given for comparison.

Figures 4(a) and 4(b) also show the reduction of the low power-output-increase range due to the primary-source shift. The further the primary source shifts, the narrower the range becomes. The increase of total sound-power output due to the control system is very large outside this range.

Optimal local-control systems are those that can create large quiet zones with low power-output increases [5]. It has been found that, when the primary source is on the central axis of the control system, the control system can create a large quiet zone if it is designed within the low power-output-increase range shown in Figures 3 and 4. This low power-output-increase range is also called the “optimal” range [6]. The following section shows that when the primary source shifts from the central axis, the low power-output-increase range may not necessarily be an optimal range. Even when the control system is arranged within the low power-output-increase range, the control system may not be able to create a large quiet zone if the primary source moves outside a certain range. Furthermore, it has been found that the width of the optimal range determines an effective frequency range [13]; a narrower range for the moving primary source also means a narrower effective frequency band.

4. EFFECT ON THE QUIET ZONE

The quiet zone created by the control sources depends mainly on the wavefront matching between the primary field and the control field. When the primary source moves, the wavefront matching between the primary and control fields changes; so do the size and location of the quiet zone created by the control system. Analysis of the power-output increase indicates that the low power-output-increase range still exists when the primary source shifts, though it may become very narrow as the primary source moves further away from the central axis. However, it is shown in this section that, when the primary source shifts to a certain distance from the central location in a certain direction, the control system may not be able to create a quiet zone even if it is still arranged in the low power-output-increase range. The large area of wavefront matching between the primary field and the field generated by the control-source array cannot be obtained when the primary-source shift is too large.

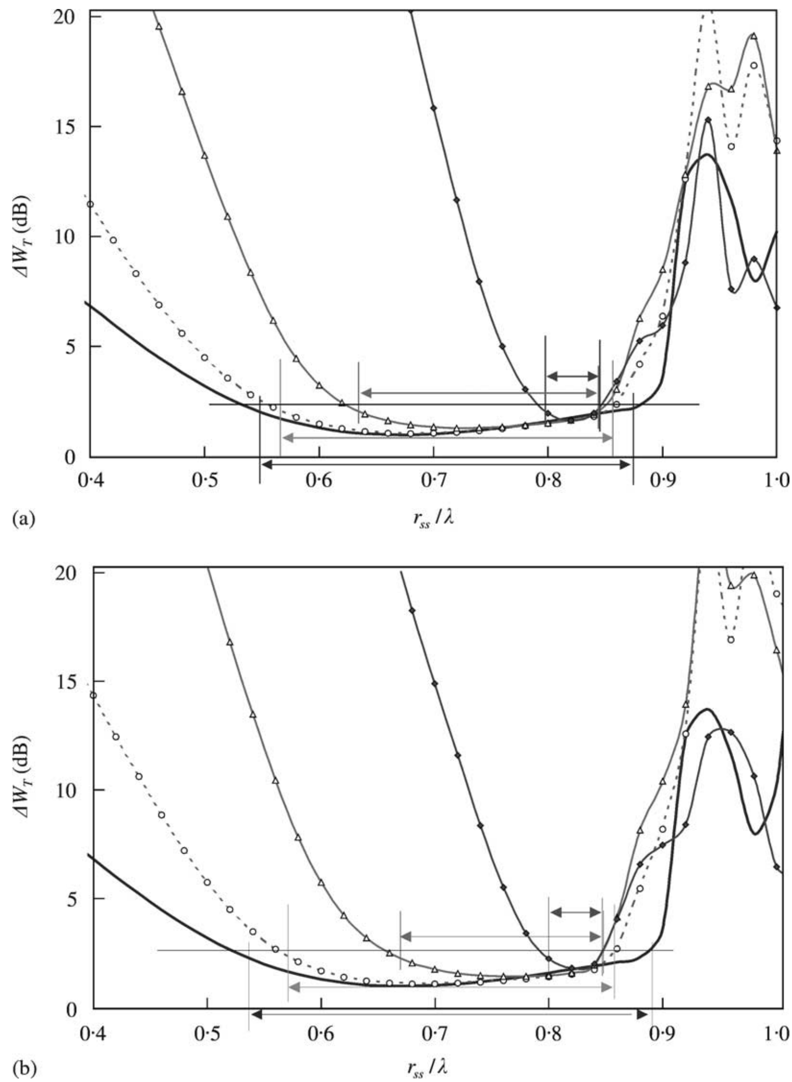


Figure 4. Total power-output increase of the control system with primary-source shifts in (a) x direction only: —, $\Delta x = 0$; –○–, $\Delta x = \lambda$; –△–, $\Delta x = 2\lambda$; –●–, $\Delta x = 5\lambda$; and (b) both x and z directions: —, $\Delta x = \Delta z = 0$; –○–, $\Delta x = \Delta z = \lambda$; –△–, $\Delta x = \Delta z = 2\lambda$; –●–, $\Delta x = \Delta z = 4\lambda$.

The sound-pressure attenuation in the space resulting from the control system is defined as $\Delta P = 20 \log(|P_T|/|P_0|)$, where P_T is the total sound pressure in the space after the control, and P_0 is the sound pressure generated by the primary source only when the control system is off. The effect of the primary-source shift on the quiet zone is discussed separately for the previous two systems.

4.1. SYSTEM I

The previous control system with 11 channels is again taken as an example to demonstrate the effect of primary-source shift on the quiet zone. The spacing of the control sources and the error microphones is chosen as $r_{ss} = 0{\cdot}8\lambda$, which corresponds to the lowest total power-output-increase arrangement, as shown in Figure 3(a). The effect of the primary-source-shift on the quiet zone will be discussed for three conditions: primary-source shift in the x direction only; in the z direction only; and in both the x and z directions.

4.1.1. *Primary-source shift in x direction only*

The quiet zones created by the system with three different primary-source shifts in the x direction only—$\Delta x = 2\lambda$, 4λ, and 5λ—are presented in the x–y plane containing the control system ($z = 0$). For the purpose of comparison, the one corresponding to zero shift is also given as a shaded area, as shown in Figure 5.

Figure 5 illustrates that the primary-source shift in the x direction not only reduces the size of the quiet zone, but also causes the quiet zone to shift in the opposite direction of the primary-source shift. The larger the primary-source shift, the smaller the quiet zone becomes, and the further the quiet zone shifts in the opposite direction. When the shift is larger than a critical distance ($\Delta x > 4\lambda$ in this example), the quiet zone disappears, even though the spacings of the control sources and error microphones are within the low power-output-increase range.

For the demonstrated control system, the control sources are all placed in a line parallel to the x-axis, in the x–y plane, over the range $-4\lambda \leqslant x \leqslant 4\lambda$. Note that the critical distance for the primary-source shift is 4λ for the control system; it seems that the critical distance of the primary-source shift is half the width of the control-source array. Computational analysis has been conducted for various control systems ($N = 2, 3, \ldots, 21$) with various system configurations. The results lead to the conclusion that the distance between the primary source and the control-source array r_{ps} also contributes to the critical primary-source shift; this can be summarized approximately as

$$\Delta x_C \cong w_{1/2}\left(1 + \frac{r_{ps}}{20\lambda}\right), \tag{6}$$

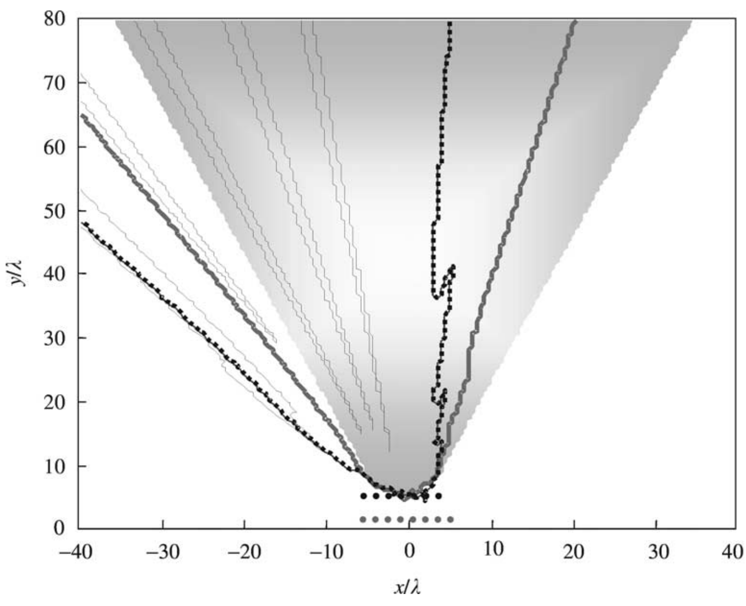


Figure 5. Quiet zones in an x–y plane created by the 11-channel control system with primary-source shifts of $\Delta x = 0$; 2λ; 4λ; and 5λ: (shaded), $\Delta x = 0$; ——, $\Delta x = 2\lambda$; ••••••, $\Delta x = 4\lambda$; ——, $\Delta x = 5\lambda$.

where $w_{1/2} = (N-1)r_{ss}/2$ is half the width of the control-source array. This means that the control system is still effective at creating a quiet zone when the primary-source shift is within the range defined by the critical primary-source shift, i.e., $-\Delta x_c \leqslant \Delta x \leqslant \Delta x_c$.

Contour plots of the quiet zones in an x–z plane show this primary-source-shift limitation more clearly. Figure 6 shows the effect of the distance between the primary source and the control-source array r_{ps} on the primary-source-shift limitation. For the above 11-channel control system with $r_{se} = 5\lambda$ and $r_{ss} = 0{\cdot}8\lambda$, three distances between the primary source and the control-source array—$r_{ps} = 2\lambda$, 5λ and 10λ—are examined in an x–z plane 20 wavelengths behind the primary source ($y = 20\lambda$), as shown in Figures 6(a), 6(b) and 6(c) respectively.

Figure 6(a) indicates that the control system is still able to create a large quiet zone when the primary source shifts as much as $\Delta x = 4\lambda$, though the quiet zone shifts to the opposite direction of the primary-source shift. The quiet zone disappears when the primary-source shift is larger than 4λ, as shown for the case of $\Delta x = 5\lambda$. The longer distance between the primary source and the control-source array extends the effective range of the primary-source shift. The effective range of the primary-source shift that extends to $\Delta x = 5\lambda$ and $\Delta x = 6\lambda$, respectively, as described by equation (6), is shown in Figures 6(b) and 6(c).

4.1.2. *Primary-source shift in z direction only*

While the control system is still able to create a quiet zone with the primary-source shift in the x-axis, the quiet zone disappears very quickly when the primary source shifts in the z direction. The contour plots of the quiet-zone reduction resulting from the primary-source shifts are shown in Figure 7, in which the primary source shifts to $\Delta z = \lambda$, 2λ, and 4λ. It can be seen that a large area of quiet zone is replaced by several narrow quiet zones in the space, and that these narrow quiet zones are separated in the z direction.

4.1.3. *Primary-source shift in both x and z directions*

The contour plots of quiet zones created by the control system with primary-source shifts in both the $+x$ and $+z$ directions are shown in Figure 8. Three shifts—$\Delta x = \Delta z = \lambda$, $\Delta x = \Delta z = 2\lambda$ and $\Delta x = \Delta z = 5\lambda$—are discussed as examples. Similar to the case of primary-source shifts in the z direction only, a large quiet zone is now replaced by several narrow quiet zones, even though the shift is small—say, only one wavelength away. Unlike the case of primary-source shifts in the z direction only, these narrow quiet zones also shift in the $-x$ direction.

4.2. SYSTEM II

The same control system with 11×11 channels, analyzed in the previous section, is discussed as an example. The control system is also arranged with $r_{ss} = 0{\cdot}8\lambda$, which is shown in Figure 4 as the low power-output-increase range of the system with a primary-source shift. The halfwidth of the control-source array is also $w_{1/2} = 4\lambda$. For the control system with control sources and error microphones arranged in two parallel planes, the analysis in the x-axis and the z-axis should be uniform; therefore, the discussions below are limited to primary-source shifts in the x direction only and in both the x and z directions.

4.2.1. *Primary-source shift in x direction only*

The critical primary-source shift expressed by equation (6) also seems to be applicable for System II. The contour plots in an x–z plane, of the quiet zones created by the control system with primary-source shifts in the $+x$ direction, are shown in Figure 9. The quiet

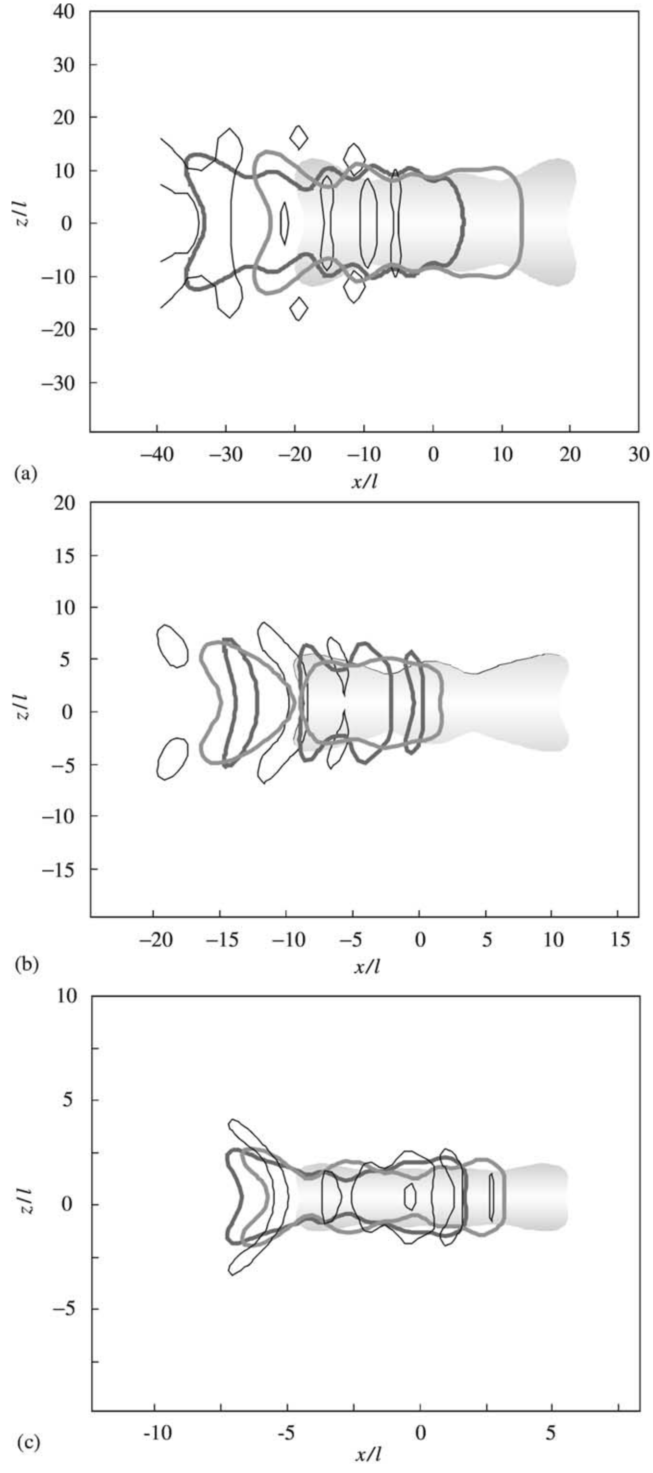


Figure 6. Quiet zones in an x–y plane created by the 11-channel control system with primary-source shifts in x-axis only when (a) $r_{ps} = 2\lambda$: ▬, $\Delta x = 0$; ——, $\Delta x = 2\lambda$; ▬, $\Delta x = 4\lambda$; ——, $\Delta x = 5\lambda$; (b) $r_{ps} = 5\lambda$: ▬, $\Delta x = 0$; ——, $\Delta x = 4\lambda$; ▬, $\Delta x = 5\lambda$; ——, $\Delta x = 6\lambda$. and (c) $r_{ps} = 10\lambda$: ▬, $\Delta x = 0$; ——, $\Delta x = 4\lambda$; ▬, $\Delta x = 6\lambda$; ——, $\Delta x = 7\lambda$.

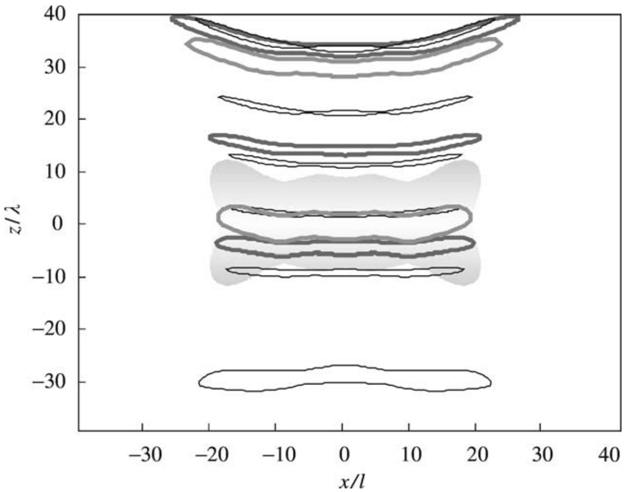


Figure 7. Quiet zones created by the 11-channel control system with primary-source shifts in the z direction only: ▬▬, $\Delta z = 0$; ——, $\Delta z = \lambda$; ▬▬, $\Delta z = 2\lambda$; ——, $\Delta z = 4\lambda$.

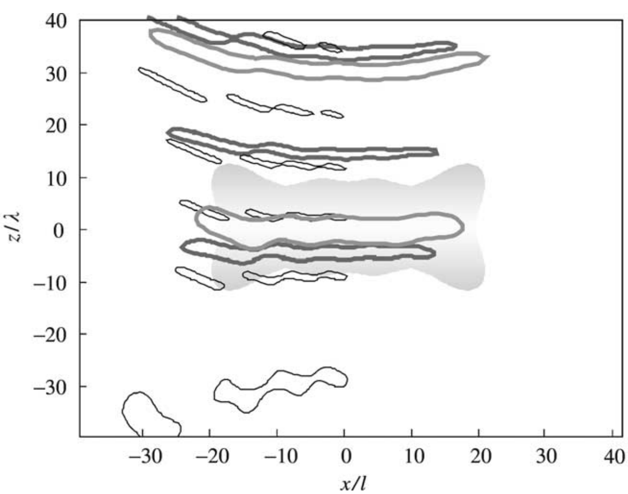


Figure 8. Quiet zones created by the 11-channel control system with primary-source shifts in both the x and z directions: ▬▬, $\Delta x = \Delta z = 0$; ——, $\Delta x = \Delta z = \lambda$; ▬▬, $\Delta x = \Delta z = 2\lambda$; ——, $\Delta x = \Delta z = 4\lambda$.

zone created by the control system without primary-source shifts is also plotted for comparison; it resembles a square (shaded area). Three different distances between the primary source and control-source array—$r_{ps} = 2\lambda$, 5λ and 10λ—are examined.

It can be seen that the critical primary-source shifts, corresponding to these three configurations of the system, are 4λ, 5λ, and 6λ, respectively; these are the same as those obtained for System I with primary-source shifts in the x direction only. The quiet zone also moves in the opposite direction of the primary-source shift (-x direction).

4.2.2. *Primary-source shift in both x and z directions*

The configuration of the system for the demonstration is the same as that for Figure 9(a), i.e., $r_{ps} = 2\lambda$. Now the primary noise source moves in both the $+x$ and $+z$ directions. The

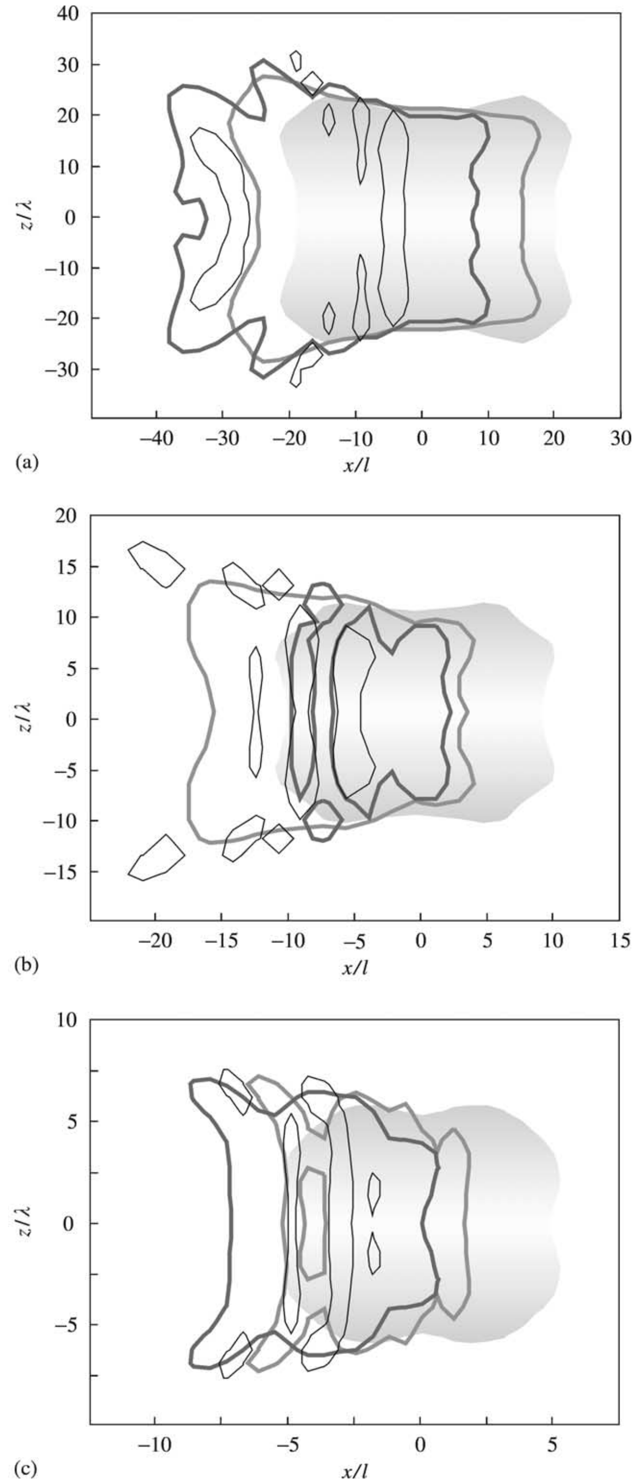


Figure 9. Quiet zones created by System II with primary-source shifts in the x direction only when (a) $r_{ps} = 2\lambda$: , $\Delta x = 0$; , $\Delta x = 2\lambda$; , $\Delta x = 4\lambda$; , $\Delta x = 5\lambda$; (b) $r_{ps} = 5\lambda$: , $\Delta x = 0$; , $\Delta x = 4\lambda$; , $\Delta x = 5\lambda$; , $\Delta x = 6\lambda$; and (c) $r_{ps} = 10\lambda$: , $\Delta x = 0$; , $\Delta x = 4\lambda$; , $\Delta x = 6\lambda$; , $\Delta x = 7\lambda$.

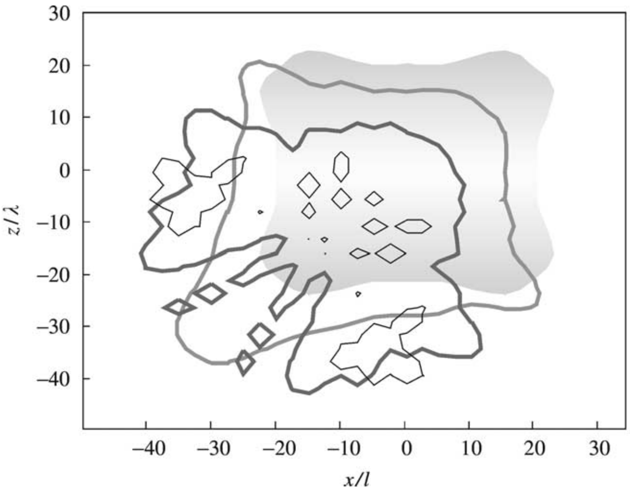


Figure 10. Quiet zones created by System II with primary-source shifts in both the x and z directions: ——, $\Delta x = \Delta z = 0$; ——, $\Delta x = \Delta z = 2\lambda$; ——, $\Delta x = \Delta z = 4\lambda$; ——, $\Delta x = \Delta z = 5\lambda$.

quiet zone in this case shifts in both the $-x$ and $-z$ directions, again the opposite direction of the primary-source shift, as shown in Figure 10. The large area of quiet zone disappears when both $\Delta x > 4\lambda$ and $\Delta z > 4\lambda$. This suggests that the critical primary-source shift described by equation (6) may also be applicable for System II when the primary-source shift is in both the x and z directions.

As stated previously, the mechanism involved in the quiet zone is the wavefront matching between the primary source and the control sources. Figure 11(a) shows the wavefront matching in an x–y plane for the 11-channel control system without the primary-source shift. It can been seen that, when the spacing of the control sources and error microphones are optimally arranged, the control-source array constructs a wavefront that matches the wavefront of the primary point source over a very large area just behind the control sources. A quiet zone in the shape of a wedge that extends over a very long distance is then created. When the primary source moves to a position $\Delta x = 3\lambda$, the control-source array is still able to construct a large area of wavefront matching that of the primary source, as shown in Figure 11(b). With this primary-source shift, the wavefront-matching area shifts by an angle opposite to the primary-source shift, which corresponds to the quiet-zone shift, as demonstrated above. When the primary source moves further away from the central axis—say $\Delta x = 6\lambda$ for the same control system—the control-source array is not able to construct a wavefront that matches the new wavefront of the primary source, as shown in Figure 11(c). Then, the large area of quiet zone disappears.

5. EXPERIMENTAL VERIFICATION

Experiments were conducted to demonstrate how the control efficiency, and the quiet zone are affected by the primary shift, and to validate the computer simulations. An ANC system involving three channels was set-up in an anechoic chamber in the Department of Mechanical Engineering at the University of British Columbia, simulating free-field conditions. The chamber measured $4{\cdot}7 \times 4{\cdot}3 \times 2{\cdot}3$ m^3. Previous tests showed the chamber to be highly anechoic at frequencies above about 200 Hz. The experimental set-up is shown in Figure 12. An EZ-ANC multi-channel active noise controller was used in the experiment.

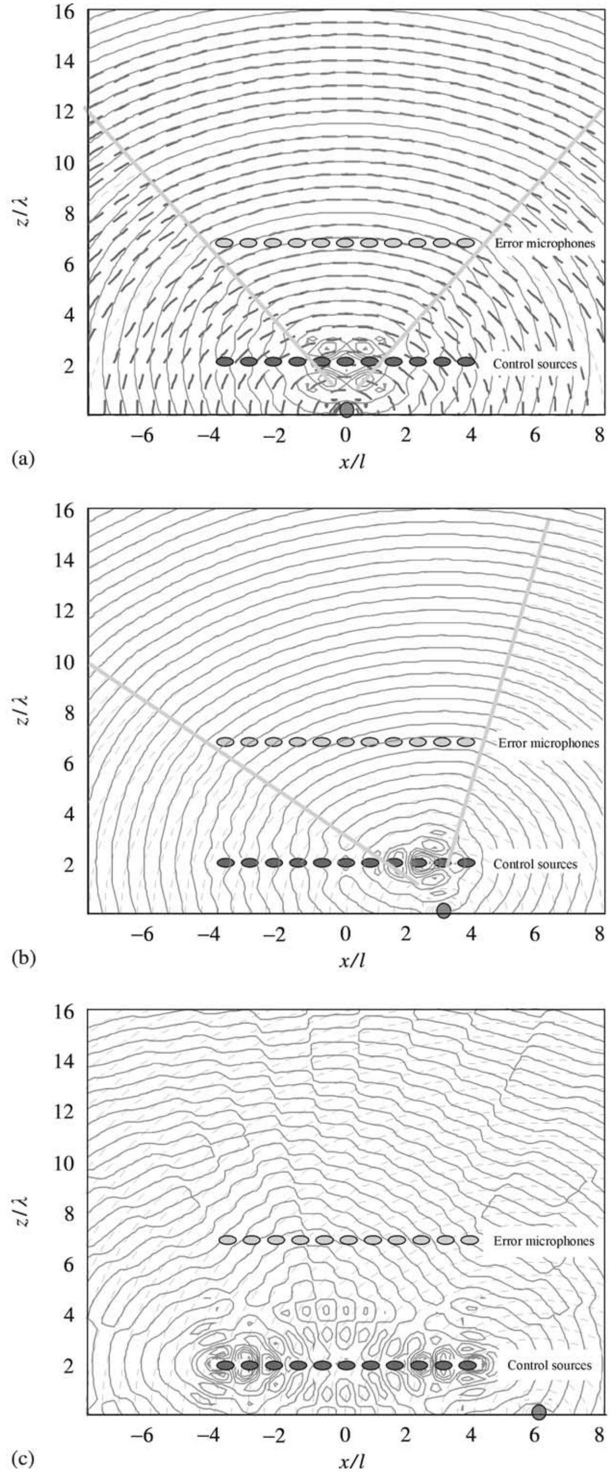


Figure 11. Wavefront matching between the sound fields radiated by the primary source (dotted curve) and the control-source array (solid curve) with primary-source shifts: (a) $\Delta x = 0$; (b) $\Delta x = 3\lambda$, and (c) $\Delta x = 6\lambda$.

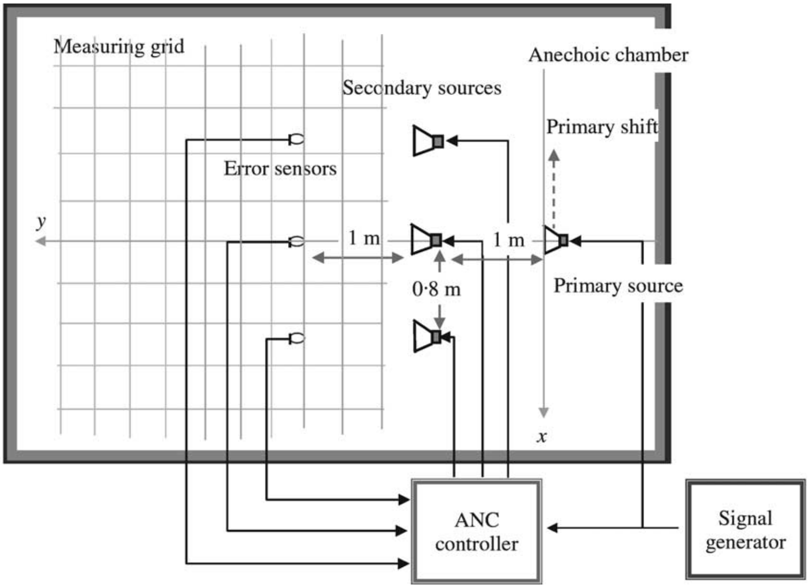


Figure 12. Experimental set-up.

Three control loudspeakers were located at (− 1, − 0·8), (− 1, 0) and (− 1, 0·8), and three error microphones were at (0, 0·8), (0, 0) and (0, 0·8). The sound attenuation was measured in the area behind the control sources. The sound-pressure attenuations for three primary-source positions—an on-axis position at (− 2, 0), and off-axis positions at (− 2, − 0·4) and (− 2, − 0·8)—were measured. The test frequencies were 300 and 400 Hz.

As the control system was arranged within the optimal range defined by equation (3), a large quiet zone was created in the area behind the control system when the primary source was at the on-axis position, as demonstrated in Figure 13. However, the quiet zone shifted to the right, and became smaller, when the primary source shifted to the left. When the off-axis shift of the primary source increased to 0·8 m, the quiet zone shifted further to the right, and the size of the zone decreased further.

The computation simulation of the quiet zones created by the same control system with the same configuration was conducted. The results of the simulation are presented in Figure 14 for comparison. It is obvious that they match very well with the experimental results.

6. DISCUSSION AND CONCLUSIONS

A pre-arranged optimal MIMO control system can still create a large area of quiet zone even if the primary source moves within a limited range in front of the control system. For the system in which the control sources and the error microphones are arranged in two parallel lines (System I), the wavefront matching between the primary and control fields decreases with the primary source shifting off-axis along the control source array (x direction). It decreases even faster when the primary-source shift is in the direction perpendicular to the control source array (z direction). The critical primary-source shift described by equation (6) indicates that the maximum primary-source shift, in the x direction for System I and in both the x and z directions for System II, is mainly

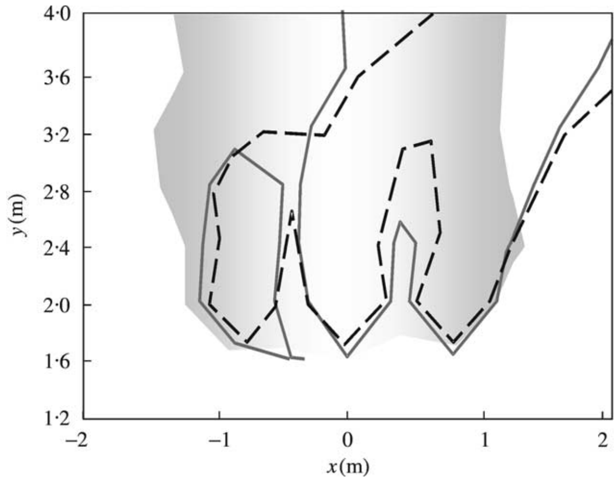


Figure 13. Measured quiet zones created by the control system when the primary shifts are $\Delta x = 0$, 0·4, and 0·8 m, respectively: , $\Delta x = 0$; ——, $\Delta x = 0{\cdot}4$; — —, $\Delta x = 0{\cdot}8$.

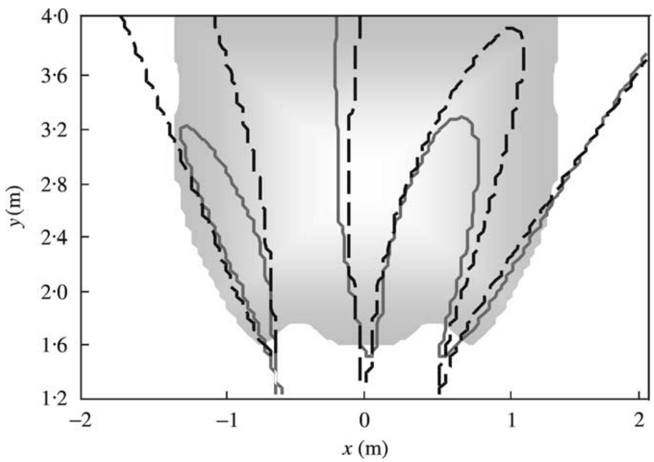


Figure 14. Calculated quiet zones created by the control system when the primary shifts are $\Delta x = 0$, 0.4, and 0.8 m, respectively: , $\Delta x = 0$; ——, $\Delta x = 0{\cdot}4$; — —, $\Delta x = 0{\cdot}8$.

determined by the length (or size) of the control-source array. Thus, the effective control range for the moving noise source can be extended either by increasing the number of control channels, or by maximizing the length (or width) of the control-source array. The further the primary source moves away from the central axis of the control system, the narrower the low power-output-increase range becomes, and the further the quiet zone shifts in the opposite direction of the primary noise-source movement (if there still is a quiet zone), the narrower the effective frequency band becomes.

The investigations in this paper demonstrate that a pre-arranged, optimal, MIMO control system has acoustical limitations in controlling the noise radiated from a moving source. The control system remains effective in creating quiet zones only when the primary source moves in a critical range in front of the control system. If the primary source moves outside this critical range, the control system is no longer able to attenuate the primary-noise field over a large area, no matter how fast the controller is at tracking the change of the primary source. This acoustical limitation of the MIMO control system restricts its efficiency in the case of moving noise sources.

In practical application, the effective range of the control system for a moving noise source can be extended by using more control channels. The acoustical limitation of the control system with a moving noise source can also be minimized by moving the control system along with the primary source, or by rotating the control system in accordance with the moving primary source.

ACKNOWLEDGMENTS

The first author would like to acknowledge the support from the Natural Sciences and Engineering Research Council of Canada (NSERC) and from the Department of Commerce and Trade of Government of Western Australia.

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