ACTIVE CONTROL OF AN OFF-AXIS NOISE SOURCE

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ABSTRACT

A multi-channel active-noise-control system can been used to create a large quiet zone in free-space when the noise source is on the symmetry axis of the control system. In this study, the efficiency of a multi-channel active-noise-control system is investigated numerically for the case of a noise source located at off-axis positions. It was found that both the location and the size of the quiet zone change significantly with the off-axis location of the noise source. The control system is still able to construct a large area of wavefront matching, and create a large quiet zone, when the off-axis shift of the noise source is within this range. There exists an off-axis range for which an optimally pre-arranged multiple-channel control system remains optimized. This range is expressed analytically in terms of the wavelength at the frequency of interest, and of the configuration of the control system.

SOMMAIRE

Un système multi-canaux de contrôle actif du bruit peut créer une grande zone de silence en champ libre quand la source sonore est située sur l'axe principal du système. Dans cette étude-ci, on étudie numériquement l'efficacité d'un système de contrôle actif dans le cas d'une source déplacée de l'axe principal. On a trouvé qu'et la position et la forme de la zone de silence changent nettement avec le déplacement de la source. Il existe une gamme de déplacement pour laquelle un système multi-canaux, optimisé au préalable, demeure optimal. Tant que le déplacement reste dans cette gamme, le système de contrôle est encore capable de créer une grande zone d'adaptation des fronts d'onde. Cette gamme peut être définie analytiquement en fonction de la longeur d'onde et de la configuration du système.

1. INTRODUCTION

Active control of noise in open environments has been studied extensively recently. It has been found that the control efficiency is strongly influenced by the config-uration of the control system.[1-3] However, in this previous research the optimal strategies and configurations of the control system were investigated for arrangements where 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 cannot be fixed at an on-axis position, or even at any specific location; examples are in the active control of moving noise sources and of multiple noise sources.

When the noise source moves, the noise field changes with the movement of the noise source. The efficiency of the control system is limited by both the controller and the configuration of the control system. There have been recent attempts to control moving primary sources by using a multi-input and multi-output (MIMO) active-noise-control system.[4-5] However, these previous studies were mostly focused on the controller, and examined if it was able to adapt to the changes resulting from the movement of the primary source. The limitation of the control-system configuration - i.e., whether a control system is still effective when the primary source moves to an off-axis location - has not been analyzed.

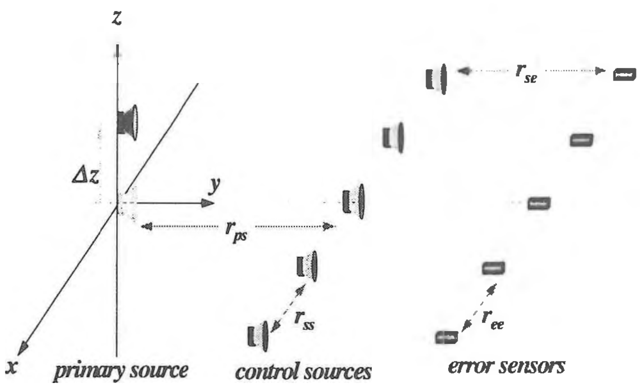

Fig. 1. MIMO local-control system arranged in two parallel lines.

For the analysis presented here, the efficiency limitation of a MIMO local-control system in the case of an off-axis noise source is studied by examining whether an optimally arranged control system is still effective at creating a large area of quiet zone. 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 efficiency of the control system is examined with respect to two measures: the total power-output increase and the size of the quiet zone.[2-3]

2. SYSTEM DESCRIPTION

In most studies of multi-channel active local control in free-space, the number of control sources is usually chosen to be the same as that of the error microphones[1-3]. With such a setup, the control sources are able to drive the sound pressures at the error microphones to zero, and a quiet zone can be created in the area around the error microphones. A multi-channel active local-control system in open space, in which the N control sources and N error microphones are equally distributed in two parallel lines, is shown in Fig. 1. The spacings of the control sources and error microphones are equal – i.e., $r_{ss} = r_{ee}$. The sound pressures at the error microphones can be minimized (theoretically, to zero) if the strengths of the N control sources are chosen as,

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

where q_p is the strength of the primary source, $\mathbf{q}_s$ is a column vector of source strengths for the N control sources, $\mathbf{Z}_{se}$ is an $N \times N$ matrix of acoustical transfer impedances from the N control sources to the N error microphones, and $\mathbf{Z}_{pe}$ is a column vector of acoustical transfer impedances from the primary source to the N error microphones. Then the total radiated acoustical power of the system, which is the summation of the power outputs of

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

where $Z_0 = \omega^2 \rho_0 / 4\pi c_0$, in which ω is the angular frequency, ρ_0 the air density and c_0 the sound speed. $\mathbf{Z}_{ss}$ is the $N \times N$ transfer-impedance matrix between the N control sources; $\mathbf{Z}_{ps}$ is the column vector of transfer impedances between the primary source and the N control sources. The principle of acoustical reciprocity applies in this discussion – i.e., $\mathbf{Z}_{sp} = \mathbf{Z}_{ps}^T$. 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, when the control system creates quiet zones in some desired areas, it increases the sound pressure in other areas. The total sound pressure at any position after control is the summation of the primary and control sound pressures at this position, given by,

$$P_T = P_p + P_s = q_p Z_{pr} + \mathbf{q}_s \mathbf{Z}_{sr}, \tag{3}$$

where Z_{pr} and $\mathbf{Z}_{sr}$ are the transfer impedances from the primary source and control sources to the observation position, respectively.

The optimal design of the local-control system involves arranging the control system to create the largest possible quiet zone which, at the same time, undergoes the least increase of total power output. The optimal design has been found to be very sensitive to, and also very important in defining, the control efficiency of the system.[2-3]

It has been found that when the primary source is on the central axis of the control system – i.e., at the origin in Fig. 1 – there always exists an optimal range of spacing between adjacent control sources and adjacent error microphones of the control system. The upper and lower limits of the optimal range are given analytically in Reference 2. The performance of the control system is very sensitive to the sensor/actuator configuration and, therefore, these configurations need to be strictly observed when designing a multiple-channel local-control system in free space.

However, it is not known if the MIMO control system is still effective when the primary noise source is placed at, or moves to, off-axis positions, as also shown in Fig. 1. In the following discussion, the performance of the control system is examined for cases when the primary source is at both an on-axis position, as well as at several off-axis positions. The objective is to extend the MIMO control system to cases when the primary source is at off-axis positions, or even to the case of moving noise sources.

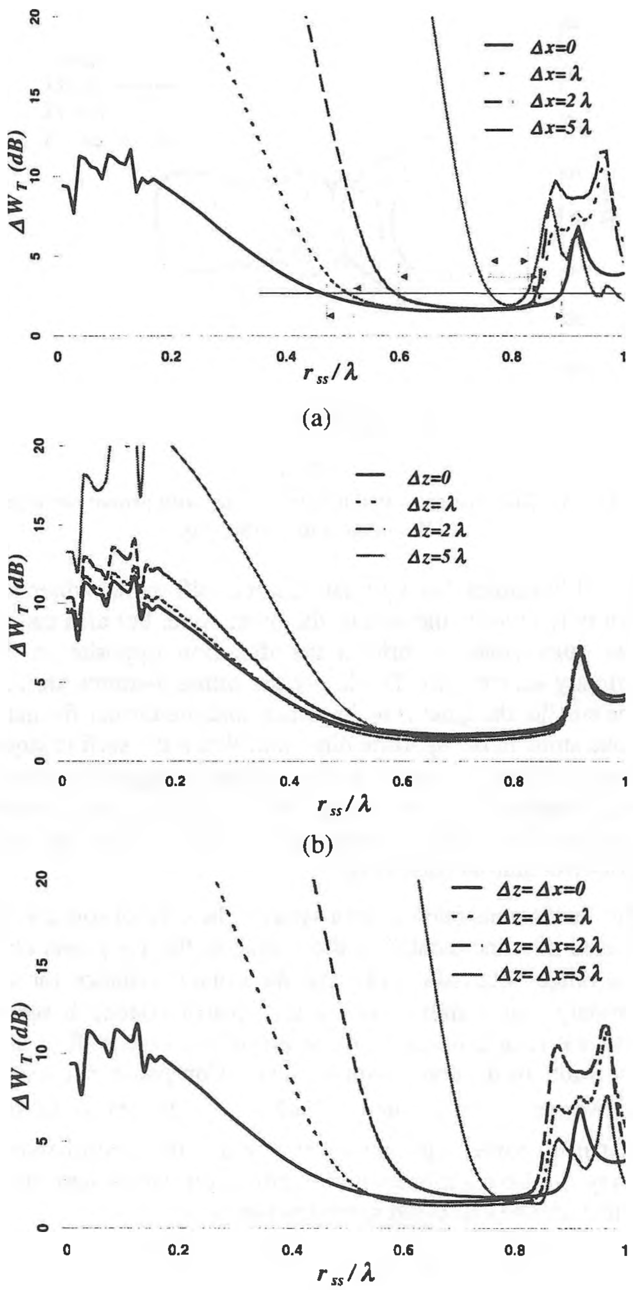

Fig. 2. Total power-output increase of the control system with primary-source shifts in: (a) x direction only; (b) z direction only; and (c) both x and z directions.

3. EFFECT ON TOTAL POWER OUTPUT

The total power output of the multiple-channel control system can be calculated using Eq. (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,

$$\Delta W_T = 10\log(W_T / W_0), \tag{4}$$

where $W_0 = |q_p|^2 Z_0 / 2$ is the sound-power output of the primary source alone when the control system is off.

Examination of the total power-output increase has been done for various system configurations and various primary-source off-axis positions. 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.

For the control system shown in Fig. 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, respectively. 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 $r_{ps}=2\lambda$, and the distance between the control-source array and the error-microphone array is $r_{se}=5\lambda$.

Fig. 2 shows the change in the increase of total sound-power output caused by the control system as a function of 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 0.45λ to 0.89λ according to Ref. 2, is also shown for comparison.

Fig. 2 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. Fig. 2(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 larger the primary-source shift is, the narrower the optimal range becomes. When the primary-source shift is $\Delta x=5\lambda$, the optimal range becomes very narrow – around $r_{ss}=0.8\lambda$. 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 Fig. 2(b). The range of low power-output increase decreases when the primary source shifts in both the x and z directions. Fig. 2(c) shows that the range reduction is very similar to that of the case illustrated in Fig. 2(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.

It is shown in the following section that the decrease of low power-output range due to the off-axis shift reduces the ability of the control system to create a large quiet zone significantly.

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, and so do the size and location of the quiet zone created by the control system. Analysis of the power-output increase indicates that a notable range of low power-output increase 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 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 range of low power-output increase. A 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.

The sound-pressure attenuation in the space due to the control system is defined as,

$$\Delta P = 20\log(|P_T|/|P_p|), \quad (5)$$

where P_T is the total sound pressure in the space after the control, and P_p is the sound pressure generated by the primary source only when the control system is off, as defined in Eq. (3). The effect of the primary-source shift on the quiet zone is discussed separately for the previous system.

The previous control system with 11 channels is again taken as an example, to demonstrate the effect of a primary-source shift on the quiet zone. The spacing of the control sources and of the error microphones is chosen as $r_{ss}=0.8\lambda$, which corresponds to the arrangement giving the lowest increase of total power output, as shown in Fig. 2(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 Primary-source shift in the x direction only

The quiet zones created in an x-z plane by the system with three different primary-source shifts – $\Delta x=2\lambda$, 4λ and 5λ – in the x direction only are presented in Fig. 3. The above-described 11-channel control system with $r_{se}=5\lambda$, $r_{ss}=0.8\lambda$ and $r_{ps}=2\lambda$ is taken for demonstration. The shaded area shown in Fig. 3 for comparison is the quiet zone created by the control system without primary-source shift.

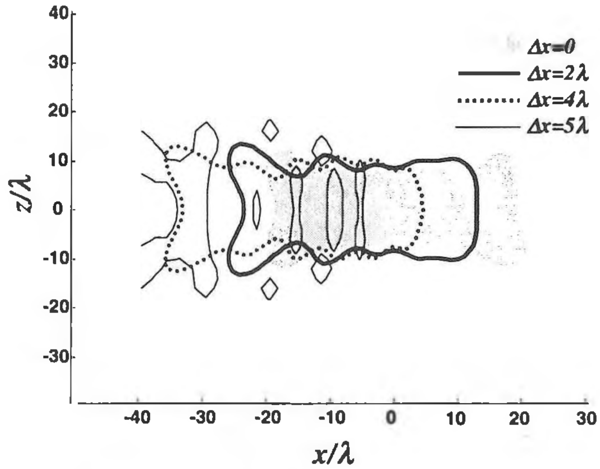

Fig. 3. Quiet zones created by the system, with primary-source shifts in the x direction only.

Fig. 3 illustrates that a 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 direction opposite to the primary-source shift. The larger the primary-source shift is, 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 still within the low power-output-increase range.

For the demonstrated control system, the control sources are placed in a line parallel to the x axis, in the x-y plane, over the range $-4\lambda\leq x\leq 4\lambda$. 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 results for various control systems (N=2, 3, $\cdots$, 21) show that the distance between the primary source and the control-source array r_{ps} also contributes to the critical primary-source shift, which can be expressed approximately as,

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

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., $-\Delta x_c \leq \Delta x \leq \Delta x_c$.

4.2 Primary-source shift in the z direction only

While the control system is still able to create a quiet zone with the primary-source shift along the x axis, the quiet zone disappears very quickly when the primary source shifts in the z direction. The contour plots of the quiet

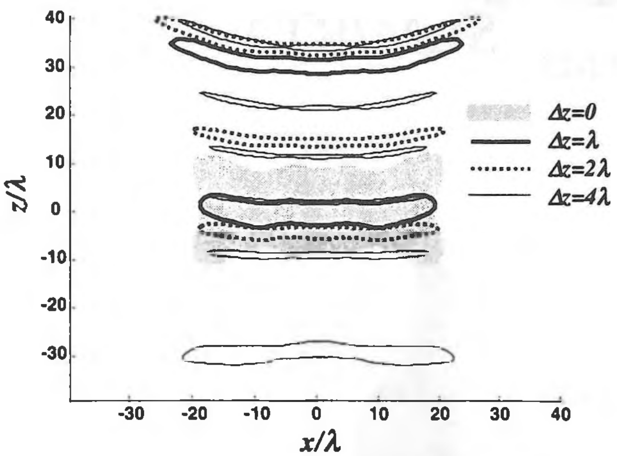

Fig. 4. Quiet zones created by the system, with primary-source shifts in the z direction only.

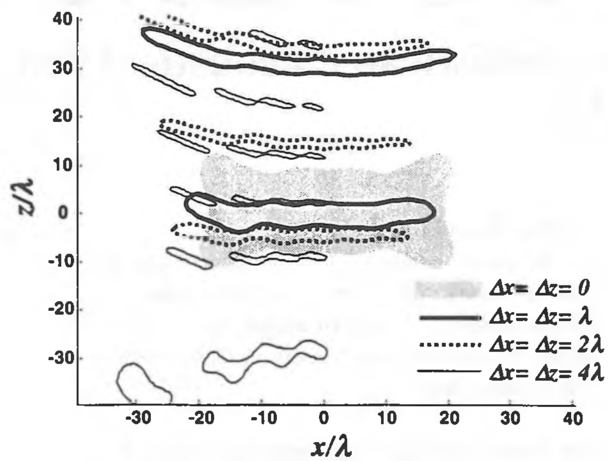

Fig. 5. Quiet zones created by the system, with primary-source shifts in both the x and z directions.

zones resulting from the primary-source shifts are shown in Fig. 4, in which the primary source shifts to $\Delta z=\lambda$, 2λ and 4λ. It can be seen that a large area of quiet zone in the space is replaced by several narrow quiet zones, and that these narrow quiet zones are separated in the z direction.

4.3 Primary-source shift in both x and z directions

The contour plots of the quiet zones created by the control system with primary-source shifts in both the $+x$ and $+z$ directions are shown in Fig. 5. 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 – for example, only one wavelength. Unlike the case of primary-source shifts in the z direction only, these narrow quiet zones also shift in the $-x$ direction.

5. SUMMARY

A pre-arranged optimal MIMO control system can still create a large area of quiet zone if the primary source moves within a limited range in front of the control system. The critical primary-source off-axis shift described by Eq. (6) indicates that the maximum primary-source shift is mainly determined by the length (or size) of the control- source array. This can be increased by either increasing the number of control channels or by maximizing the length (or width) of the control-source array. The further the primary source shifts away from the central axis of the control system, the narrower the range of low power-output increase becomes, the further the quiet zone shifts in the direction opposite to the primary noise-source movement (if there still is a quiet zone), and the narrower the effective frequency band becomes. These conclusions also pertain limitations of the MIMO control-system efficiency in the case of moving noise sources.

6. ACKNOWLEDGMENTS

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