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A New Method to Arrange an Additional Sound Source used in Active Noise Control

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Summary

This paper describes a new method for arranging an additional sound source close to a primary noise source in order to realize an effective active noise control system. A successful application of the method to duct noise control has already been reported [5]. The synthesized sound radiated by an additional source is identical to that of the primary source, except in polarity. In theory, the distance between the primary source and additional source should be much less than the shortest wavelength in the required frequency range in order to realize an ideal dipole source. However, in practice, this distance cannot be set small enough and the attenuation of noise power is limited, as pointed out in a separate paper [6]. In this paper we propose a new method to arrange an additional sound source close to the primary noise source. The noise attenuation obtained by this arrangement is much greater than that obtained by the ordinary dipole system even in the higher frequency range. Thus, the proposed arrangement realizes an effective noise control system even in practical cases. This paper describes the effects and performance limits of the proposed arrangement by means of computer simulation analysis.

Eine neue Methode zur Anordnung einer zusätzlichen Schallquelle bei der aktiven Lärmbekämpfung

Zusammenfassung

In dieser Arbeit wird eine neue Methode zur Anordnung einer zusätzlichen Schallquelle nahe an einer primären Lärmquelle mit dem Ziel beschrieben, ein wirksames System der aktiven Schallbekämpfung zu realisieren. Eine erfolgreiche Anwendung dieser Methode zur Lärmbekämpfung in Kanälen ist bereits beschrieben worden [5]. Abgesehen von der Polarität, ist das von der zusätzlichen Schallquelle erzeugte Schallsignal identisch mit dem der Primärschallquelle. Theoretisch sollte der Abstand zwischen der primären und zusätzlichen Schallquelle viel kleiner sein als die kürzeste Wellenlänge in dem erforderlichen Frequenzband, um eine ideale Dipolquelle zu realisieren. Praktisch kann dieser Abstand jedoch nicht hinreichend klein gehalten werden, weshalb die Lärmunterdrückung begrenzt ist, wie in einer getrennten Arbeit [6] gezeigt wird. In dieser Arbeit wird eine neue Methode zur Anordnung der Zusatzschallquelle in der Nähe der primären Lärmquelle vorgeschlagen. Sogar bei höheren Frequenzen ist die mit dieser Anordnung erreichte Lärmminderung viel größer als die bei einem gewöhnlichen Dipolsystem. Die vorgeschlagene Anordnung stellt somit ein wirksames Lärmbekämpfungssystem auch für praktische Anwendungen dar. In dieser Arbeit wird die Wirkung und die Grenzen der vorgeschlagenen Anordnung mit Hilfe einer Computersimulation beschrieben.

Une méthode nouvelle pour installer une source sonore additionnelle en vue d'une atténuation active du bruit

Sommaire

On décrit une nouvelle approche consistant à installer une source sonore additionnelle le plus près possible de la source primaire de bruit, afin de réaliser ainsi un système actif et efficace de réduction active du bruit. Une application réussie de ce procédé a déjà été présentée ailleurs dans le cas de bruit dans un conduit. Le son que doit rayonner la source additionnelle doit être la copie à l'identique du bruit émis par la source primaire, excepté pour sa polarité, qui doit être inversée. En théorie la distance qui doit séparer la source additionnelle de la source primaire devrait rester nettement inférieure à la plus petite longueur d'onde contenue dans le bruit à traiter de manière que l'ensemble formé par la source primaire et par la source additionnelle constitue un dipôle idéal. Cependant, dans la pratique, cette distance ne sera jamais assez petite, de sorte que l'atténation obtenue sera limitée à des fréquences relativement basses, comme on l'avait déjà remarqué dans un autre article. Ici on propose un procédé nouveau qui permet de disposer la source additionnelle plus près de la source primaire. L'atténuation ainsi obtenue est bien plus grande que celle que fournit le système dipolaire ordinaire, surtout dans le domaine des plus hautes fréquences. Ainsi l'arrangement proposé devient un système efficace de réduction du bruit, y compris dans les cas pratiques. Pour l'instant, les effets et les limites de ce nouveau procédé sont décrits au moyen d'une simulation par ordinateur.

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1. Introduction

There have been many methods proposed for active noise control and they are roughly classified into the following two categories: reduction of noise level in a specified region or in a direction [1], or reduction of total radiation power [2–3]. Most previous studies have dealt with the former because it is easier to realize. However, noise control for a one-dimensional system, such as a duct, aims to reduce the total noise power radiated from the duct end. Most previous methods of this kind employ a loudspeaker and a microphone of special directivity, or a pair of microphones and loudspeakers to prevent acoustic feedback from the additional loudspeaker to the microphone. By means of the output of the microphones, the control signal is synthesized [4]. These methods assume that the side length of the cross section of the duct is relatively small compared to the wavelength. However, this assumption of one dimensional space is satisfied only in the very low frequency range.

A more stable method was proposed by Kido [5] as shown in Fig. 1 a. In this system, an additional sound source S_2 is set close to the noise source S_1 at the duct end, and the additional source radiates sound of inverse polarity and the same wave form as the noise source. The loudspeaker S_2 is driven by the signal $y(t)$ which is synthesized using the wave form $x(t)$ picked up by the microphone M_1 set close to the noise source in the duct. The convolution between the signal $x(t)$ and an impulse response $-h(t)$ estimated by a special technique is calculated by using a FIR digital filter. Through the resultant sound, the above dipole system is realized and the total attenuation of sound radiated from the dipole has been shown to be much greater than that of a single sound source through experimentation [5].

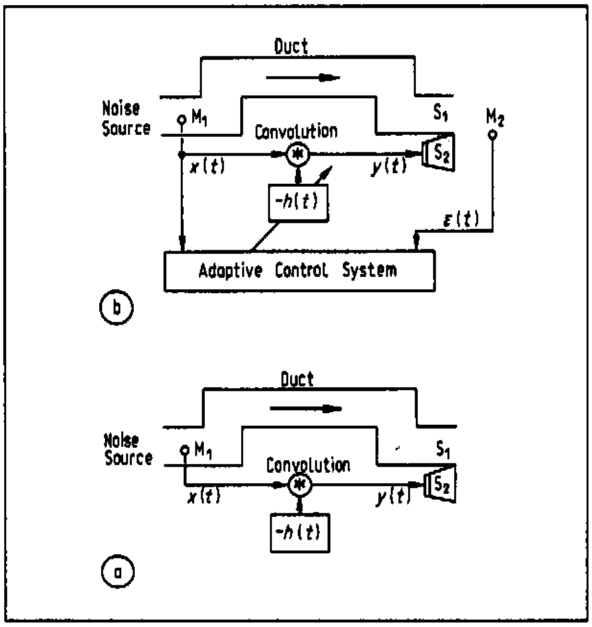

Fig. 1. Block diagram of the automatic noise control system for a duct proposed previously in separate papers. a) The ordinary active noise control system using a dipole. b) The adaptive control system is used to trace changes in the transfer function of the duct.

On the other hand, in order to trace the change in the transfer function $h(t)$ from the noise source to the duct end which occurs due to the changes in the temperature and in the velocity of flow in the duct, an adaptive control system has been introduced in a separate paper [6] as shown in Fig. 1 b. In this system, the coefficients of $h(t)$ are modified so as to minimize the sound pressure level (SPL) of the sound $\varepsilon(t)$ received by a monitor microphone M_2. From these experiments, carried out over a period of 24 hours, the proposed adaptive system traces changes in temperature and we find that total noise suppression is always more than 10 dB, regardless of temperature change [6]. In practical cases, however, the distance between primary and additional sound sources cannot be set small enough, and the attenuation of noise power is limited, as pointed out in a separate paper [6].

Therefore, in this paper we propose a new method for arranging an additional sound source close to the primary noise source. The noise attenuation obtained by this arrangement is much greater than that obtained by the ordinary dipole system, even in the higher frequency range. Thus, the proposed arrangement realizes an effective active noise control system even in practical cases. This paper describes the effects and performance limits of the proposed arrangement by means of computer simulation analysis.

2. The principle of attenuation in radiated power

In practical cases, the effects of the dimensions of the sound source are significant. Thus, both the primary and additional sound sources S_1 and S_2 are considered to be circular plates, with radii a_1 and a_2, respectively, as shown in Fig. 2. Each plate S_i $(i = 1, 2)$ vibrates uniformly in an infinite solid wall (infinite rigid baffle) in the x-y plane, and has a volume velocity G_i per unit area. Consider the vibration of the small area $dS_i = \gamma\, d\gamma_i\, d\theta_i$ on the circle S_i. The velocity potential $G_i\, d\phi_i(r, \alpha, \beta)$ due to dS_i at point $M(r, \alpha, \beta)$ is described as follows:

$$G_i\, d\phi_i(r, \alpha, \beta) = \frac{G_i\, dS_i}{2\pi R_i} \exp(j(\omega t - k R_i)), \quad (i = 1, 2) \quad (1)$$

where k is the wave number, ω is the angular frequency, and R_i denotes the distance between the small area

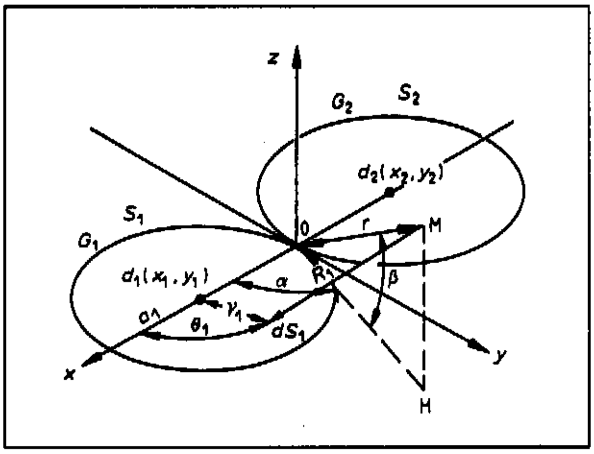

Fig. 2. The ordinary dipole system consists of the primary circular sound source S_1 and the additional sound source S_2. The additional sound source has the same strength and the inverse polarity of the primary source sound.

$\mathrm{d}S_l$ and the point $M(r,\alpha,\beta)$ on a half sphere with radius r as:

$$R_l^2 = (\gamma_l \cos\theta_l + x_l - r\cos\beta\cos\alpha)^2 + (\gamma_l \sin\theta_l + y_l - r\cos\beta\sin\alpha)^2 + (r\sin\beta)^2$$

where the coordinate of point $M(r,\alpha,\beta)$ is denoted by $(r\cos\beta\cos\alpha,\ r\cos\beta\sin\alpha,\ r\sin\beta)$. The effective value $G_l\,\mathrm{d}\Phi_l(r,\alpha,\beta)$ of the above velocity potential $G_l\,\mathrm{d}\phi_l(r,\alpha,\beta)$ is as follows:

$$G_l\,\mathrm{d}\Phi_l(r,\alpha,\beta) = \frac{G_l\,\mathrm{d}S_l}{2\pi R_l}\exp(-\mathrm{j}\,k\,R_l) \quad (l=1,2) \tag{2}$$

Thus, the effective value $G_l\,\mathrm{d}P_l(r,\alpha,\beta)$ of sound pressure at point M due to the vibration of the small area $\mathrm{d}S_l$ is denoted as follows:

$$\begin{aligned} G_l\,\mathrm{d}P_l(r,\alpha,\beta) &= \mathrm{j}\,\omega\,\varrho\,G_l\,\mathrm{d}\Phi_l(r,\alpha,\beta) \\ &= \mathrm{j}\,\omega\,\varrho\frac{G_l \exp(-\mathrm{j}\,k\,R_l)\gamma_l}{2\pi R_l}\mathrm{d}\gamma_l\,\mathrm{d}\theta_l \quad (l=1,2) \end{aligned} \tag{3}$$

where ϱ denotes the density of air. Thus, the sound pressure $G_l P_l(r,\alpha,\beta)$ at point $M(r,\alpha,\beta)$ due to the vibration of the plate S_l is obtained by integrating the above $G_l\,\mathrm{d}P_l(r,\alpha,\beta)$ as follows:

$$\begin{aligned} G_l P_l(r,\alpha,\beta) &= \int_{S_l} G_l\,\mathrm{d}P_l(r,\alpha,\beta)\,\mathrm{d}S_l \\ &= \frac{\mathrm{j}\,\omega\,\varrho\,G_l}{2\pi}\int_0^{2\pi}\mathrm{d}\theta_l\int_0^{a_l}\frac{\gamma_l\exp(-\mathrm{j}\,k\,R_l)}{R_l}\mathrm{d}\gamma_l \end{aligned} \tag{4}$$

The particle velocity $G_l\,\mathrm{d}V_l(r,\alpha,\beta)$ at point $M(r,\alpha,\beta)$ due to $\mathrm{d}S_l$ is denoted as follows:

$$\begin{aligned} G_l\,\mathrm{d}V_l(r,\alpha,\beta) &= -G_l\frac{\mathrm{d}\Phi_l(r,\alpha,\beta)}{\mathrm{d}r} \\ &= -G_l\frac{\partial\Phi_l(r,\alpha,\beta)}{\partial R_l}\frac{\mathrm{d}R_l}{\mathrm{d}r} \\ &= \frac{G_l}{2\pi R_l^2}(1+\mathrm{j}\,k\,R_l)\exp(-\mathrm{j}\,k\,R_l)\frac{\mathrm{d}R_l}{\mathrm{d}r}\mathrm{d}S_l \end{aligned} \tag{5}$$

where

$$\mathrm{d}R_l/\mathrm{d}r = [r - \cos\beta\,\{x_l\cos\alpha + y_l\sin\alpha + \gamma_l\cos(\alpha-\theta_l)\}]/R_l.$$

Thus, the particle velocity $G_l V_l(r,\alpha,\beta)$ at point $M(r,\alpha,\beta)$ due to the vibration of the plate S_l is obtained by integrating the above $G_l\,\mathrm{d}V_l(r,\alpha,\beta)$ as follows:

$$\begin{aligned} G_l V_l(r,\alpha,\beta) &= \int_{S_l} G_l\,\mathrm{d}V_l(r,\alpha,\beta)\,\mathrm{d}S_l \\ &= \frac{G_l}{2\pi}\int_0^{2\pi}\mathrm{d}\theta_l\int_0^{a_l}\frac{1+\mathrm{j}\,k\,R_l}{R_l^2}\frac{\mathrm{d}R_l}{\mathrm{d}r}\gamma_l\exp(-\mathrm{j}\,k\,R_l)\,\mathrm{d}\gamma_l \end{aligned} \tag{6}$$

The acoustic power $\mathrm{d}W(r,\alpha,\beta)$ at point $M(r,\alpha,\beta)$ is described from eqs. (4) and (6) as follows:

$$\mathrm{d}W(r,\alpha,\beta) = \mathrm{Re}\,[(G_1 P_1 + G_2 P_2)(G_1 V_1 + G_2 V_2)^*] \tag{7}$$

where * denotes the complex conjugate. By integrating $\mathrm{d}W(r,\alpha,\beta)$ over the upper half hemisphere, the total radiation power $W(r)$ s obtained as follows:

$$\begin{aligned} W(r) &= r^2\int_0^{2\pi}\mathrm{d}\alpha\int_0^{\pi/2}\mathrm{d}W(r,\alpha,\xi)\cos\beta\,\mathrm{d}\beta \\ &= C_{11}G_1^2 + 2\,C_{12}G_1G_2 + C_{22}G_2^2 \end{aligned} \tag{8}$$

where the real constants C_{11}, C_{12}, and C_{22} denote the powers $P_1V_1^*$, $(P_1V_2^* + P_2V_1^*)/2$ and $P_2V_2^*$, respectively, as follows:

$$C_{ll} = r^2\int_0^{2\pi}\mathrm{d}\alpha\int_0^{\pi/2}\mathrm{Re}\,[P_l V_l^*]\cos\beta\,\mathrm{d}\beta, \quad (l=1,2)$$

and

$$C_{12} = r^2\int_0^{2\pi}\mathrm{d}\alpha\int_0^{\pi/2}\mathrm{Re}\left[\frac{P_1V_2^* + P_2V_1^*}{2}\right]\cos\beta\,\mathrm{d}\beta \tag{9}$$

When G_2 is equal to $-(C_{12}/C_{22})\,G_1$, the minimum value $W_{\min}(r)$ of the total radiation power is achieved as follows:

$$W_{\min}(r) = \frac{(C_{11}C_{22} - C_{12}^2)}{C_{22}}G_1^2, \quad (\text{when } G_2 = -(C_{12}/C_{22})\,G_1) \tag{10}$$

The optimally attenuated power $\lambda_{\min}(r)$ due to the additional sound sources is calculated by the ratio of the minimum value $W_{\min}(r)$ to the total radiation power $W_0(r) = C_{11}\,G_1^2$ without active noise control as follows:

$$\lambda_{\min}(r) = W_{\min}(r)/W_0(r) = 1 - C_{12}^2/(C_{11}\,C_{22}) \qquad (11)$$

Since the constants C_{11} and C_{22} of eq. (9) are always non-negative values and $W_{\min}(r)$ and $W_0(r)$ are always non-negative values as well, the inequality $0 \leq \lambda_{\min}(r) \leq 1$ holds. Thus, by using the additional sound source S_2 with the volume velocity $G_2 = -(C_{12}/C_{22})\,G_1$, the total radiation power decreases even when the dimensions of the sound sources are not negligible. The optimally attenuated power $\lambda_{\min}(r)$ of eq. (11) indicates that the optimum attenuation of noise power depends only on the constants C_{11}, C_{12} and C_{22}, but not on the volume velocities G_1 and G_2 of the plates. The constants are determined by the geometrical relation between the primary and additional sound sources. From eq. (10), the minimum radiation power $W_{\min}(r)$ becomes zero when $C_{11}\,C_{22} = C_{12}^2$, that is, when the cross term C_{12} is equal to the geometrical average of the auto-terms C_{11} and C_{22} due to the primary and additional sources, respectively. When there is a strong correlation between the sounds radiated from the primary and additional sources, the value of the constant C_{12} becomes large. Thus, the closer the distance between the primary and additional sounds, the greater the noise attenuation. Therefore, in order to realize an effective noise control system, it is imperative that we find an optimal arrangement of sound sources.

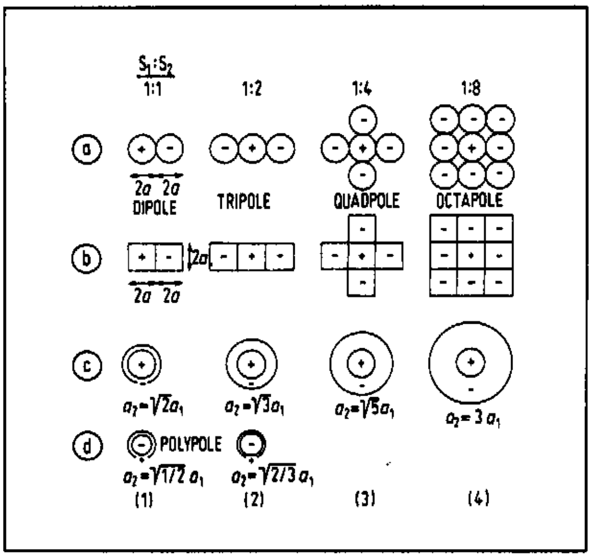

Fig. 3. Geometry of the primary sound source S_1 and the additional sound source S_2 on an infinite baffle board. They are indicated by the marks "+" and "−", respectively. a) Using circular sound sources. b) Using rectangular sound sources. c) The additional sound source is arranged around the primary sound source with a radius $a_1 = a$. d) The additional sound source is arranged inside the primary sound source with a radius $a_1 = a$.

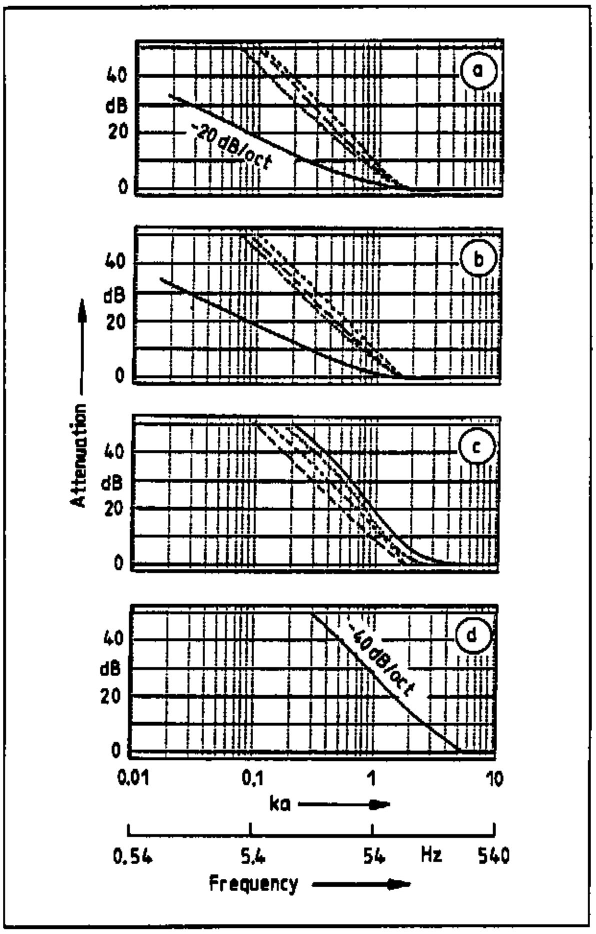

Fig. 4. The characteristics of attenuation for various arrangements shown in Figs. 3(a-1) to 3(d-2) as a function of the product $k\,a$ of the wave number k and the radius a of the primary sound source. (——) 1:1; (····) 1:2; (–·–) 1:4; (– –) 1:8.

3. Effects of arrangements of sound sources

Optimum attenuation depends on the arrangement between primary and additional sounds. Therefore, for each of the various arrangements of sound sources (shown in Fig. 3), the optimally attenuated power $\lambda_{\min}$ [dB] is calculated as a function of the product of the wave number (k) and the diameter (a) of the primary sound source. (See also Fig. 4.) The dipole having circular plates with radii (a) in Fig. 2 is also illustrated in Fig. 3(a-1). The distance between the centres of the circles is equal to twice their diameters. In each arrangement of Figs. 3(a-2), 3(a-3) and 3(a-4), the ratio of the area of the primary sound source S_1 to that of the additional sound source S_2 is 1:2, 1:4, and 1:8, respectively. In the arrangements of Fig. 3 b, each sound source has a square plate with the side length $2a$. To make the distance between these sound sources close, the additional sound source is arranged around the primary sound source as shown in Fig. 3 c. Conversely, in Fig. 3 d the additional sound source is arranged inside the primary sound source. The proposed arrangement of the polypole of Fig. 3 (d-1) is also shown in Fig. 5. Though it is quite difficult to arrange the sound sources shown in Fig. 3 c, it is easy to realize the arrangement shown in Fig. 3 d or Fig. 5. Fig. 4 shows optimum attenuation, which is equal to the negative of the optimal attenuation power $\lambda_{\min}$ [dB] of eq. (11), in the various arrangements of Fig. 3. There is no evident difference between the attenuation calculated for the arrangements shown in Figs. 3 a and 3 b. By arranging additional sound sources around primary sound sources, as shown in Fig. 3 (a-2), 3 (a-3), 3 (a-4), 3 (b-2), 3 (b-3), 3 (b-4) and 3 c, great attenuation can be achieved. As shown in Fig. 4 d, when the additional sound source is arranged inside the primary sound (as shown in Fig. 3 d or Fig. 5), the most effective attenuation can be achieved and the highest cut off frequency can be obtained.

Fig. 6 shows the relation between the values C_{12}/C_{11} and C_{12}/C_{22} of eq. (11) for each arrangement of Fig. 3 when the product ka is equal to 0.1 and 1.0. When the correlation between the sounds is optimum, the value $C_{12}^2/(C_{11}C_{22})$ is equal to 1. In the case of $ka = 0.1$, all the points of each arrangement are on the line: $C_{12}^2 = C_{11}C_{22}$. However, in the case of $ka = 1.0$, only the four points corresponding to the arrangements of Figs. 3 (c-1), 3 (c-2), 3 (d-1) and 3 (d-2) are on the line. Therefore, the arrangement of Fig. 3 d, which is easy to realize in a practical system, has strong correlation between primary and additional sounds and the greatest attenuation is achieved.

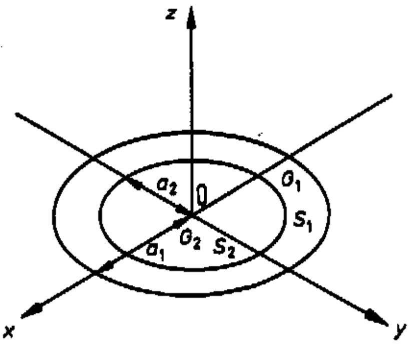

Fig. 5. The proposed polypole system consists of the primary sound source S_1 and the additional sound source S_2 inside S_1.

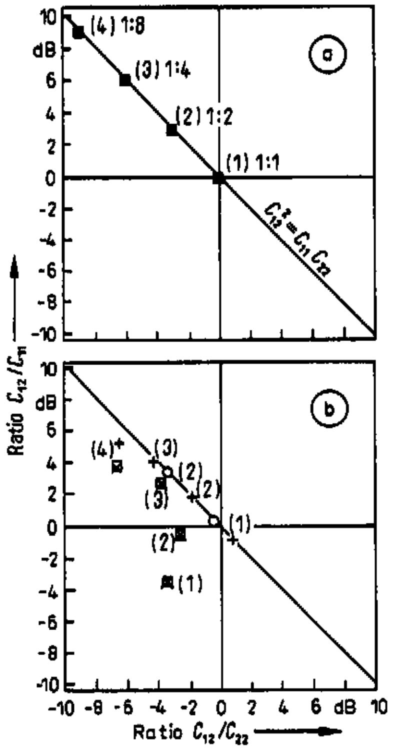

Fig. 6. The relation between the ratio C_{12}/C_{11} and C_{12}/C_{22} of eq. (11) for various arrangements shown in Fig. 3 (a-1) to 3 (d-2). When the point $(C_{12}/C_{11}, C_{12}/C_{22})$ is on or near the line: $C_{12}^2 = C_{22}C_{11}$, large attenuation is obtained even in the case of $ka = 1$. a) $ka = 0.1$; b) $ka = 1.0$. (× × ×) Fig. 3 a; (□□□) Fig. 3 b; (+ + +) Fig. 3 c; (○○○) Fig. 3 d.

4. Relative sound pressure level on *x*-*z* plane

Fig. 7 shows the relative sound pressure level (SPL) [dB] on the *x*-*z* plane when the additional sound source is arranged as shown in Figs. 3 (a-1) and 3 (d-1) for both cases $ka = 0.1$ and $ka = 1.0$. In each case, the volume velocity G_2 of the additional sound is equal to the optimum value $-(C_{12}/C_{22})G_1$ of eq. (10). The relative SPL is calculated from the ratio of SPL with additional sound to SPL without additional sound. In Fig. 7 (a-1), the points on the *z*-axis have the minimum SPL of the neighbouring space. In contrast, in Fig. 7 (b-1), the points on the *z*-axis have the maximum SPL of the neighbouring space. As shown in Figs. 7 (a-2) and 7 (b-2), great attenuation is achieved throughout the space when the proposed arrangement of Fig. 5 is used.

5. Relation between SPL received by sensor microphone and total radiation power

In a practical adaptive noise control system such as that shown in Fig. 1 b, a sensor microphone M_2 is

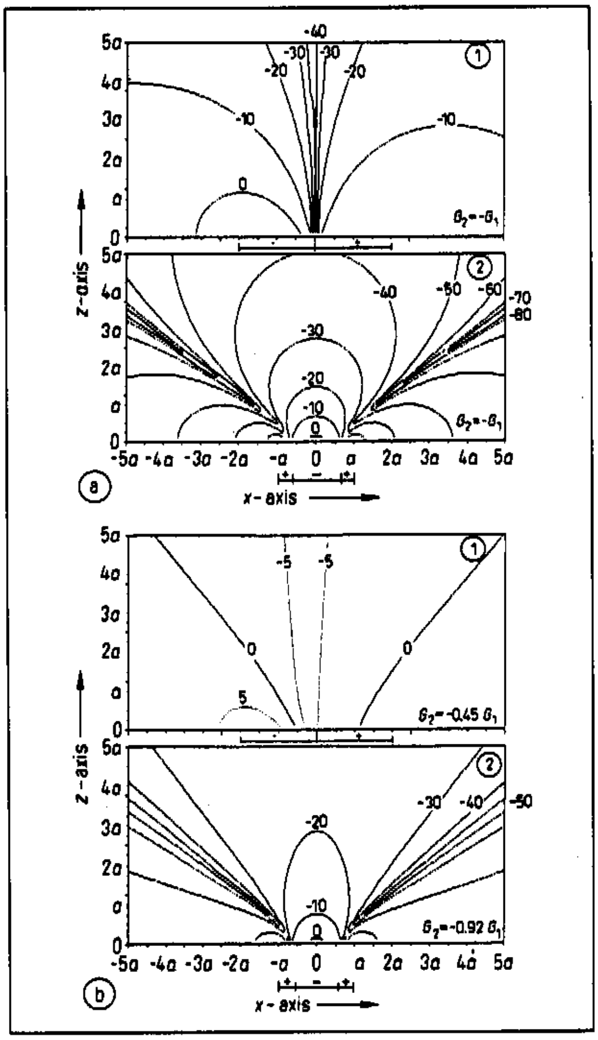

Fig. 7. The relative sound pressure level [dB] on the x-z plane. The value on each contour indicates the ratio of the SPL due to primary and additional sound sources to the SPL due to the only primary sound source. The optimum values of the volume velocity G_2 of the additional sound source are obtained from eq. (10) for each figure. 1) For the ordinary dipole system. Both diameters of the primary and additional sound sources are equal to a. 2) For the proposed polypole system. The diameters of the primary and the additional sound source are a and $a/2$, respectively, and they have the same area $\pi a^2/2$. a) $ka = 0.1$; b) $ka = 1.0$.

used to measure the SPL radiated from the duct end in order to determine the optimum value G_2 of the volume velocity of the additional sound source. However, it is not guaranteed that the resultant SPL measured by the microphone corresponds directly to the total attenuated power radiated from the half hemisphere used in the analysis in eqs. (8) to (11). Thus, we must show the relation between SPL measured by the sensor microphone and the total acoustic power radiated from the half hemisphere for the various positions of the sensor microphone.

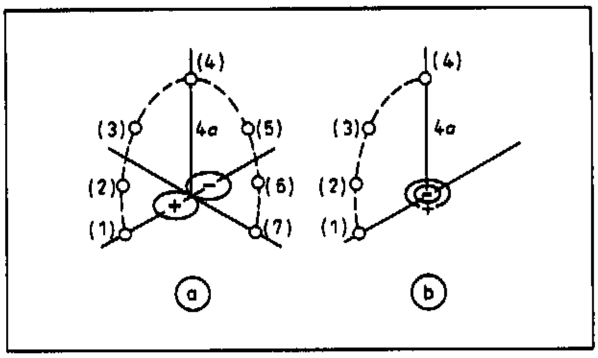

Fig. 8. Geometry of the sensor microphone M_2 used in the adaptive control system in Fig. 1. They are on the circle with radius $4a$ on the x-z plane or y-z plane. a) For the ordinary dipole system. b) For the proposed polypole system.

Fig. 8 shows each position of the sensor microphones used. The arrangements shown in Figs. 8a and 8b correspond to the ordinary dipole system (Fig. 2 or Fig. 3(a-1)) and the proposed polypole system (Fig. 3(d-1) or Fig. 5), respectively. The uppermost graphs shown in Fig. 9α show the optimum attenuation of the total radiation power for various values of (G_2/G_1) when the product ka is equal to 0.1. The optimum attenuation is calculated from eq. (11). When the value (G_2/G_1) is equal to -1, that is, when the synthesized sound radiated by the additional source is identical to that of the primary sound, except in polarity, optimum attenuation is achieved for both cases of Figs. 9(α-a) and 9(α-b). The middle graphs shown in Fig. 9α show the relative SPL of the sound received at each point of Fig. 8 for various value of (G_2/G_1). The lowest graphs shown in Fig. 9α show the relations between the relative SPL received by each sensor and the attenuation of the total radiation power. These relations are obtained from the results of the uppermost and the middle graphs. As shown in Fig. 9(α-a), optimum attenuation depends much on the position of the sensor microphone in the ordinary dipole system. However, as shown in Fig. 9(α-b) in the proposed polypole system, optimum attenuation is always achieved by minimizing the SPL of the sensor microphone even when the sensor microphone is not on the z-axis for the important range of total attenuation level in practical application. From Fig. 9(β), in the case of $ka = 1$, great attenuation, about -27 dB, is obtained by using the proposed arrangement, and the attenuation of the total radiation power corresponds closely to the SPL received by the sensor microphone.

6. Conclusions

The attenuation of an active noise control system is usually investigated theoretically by using an ideal

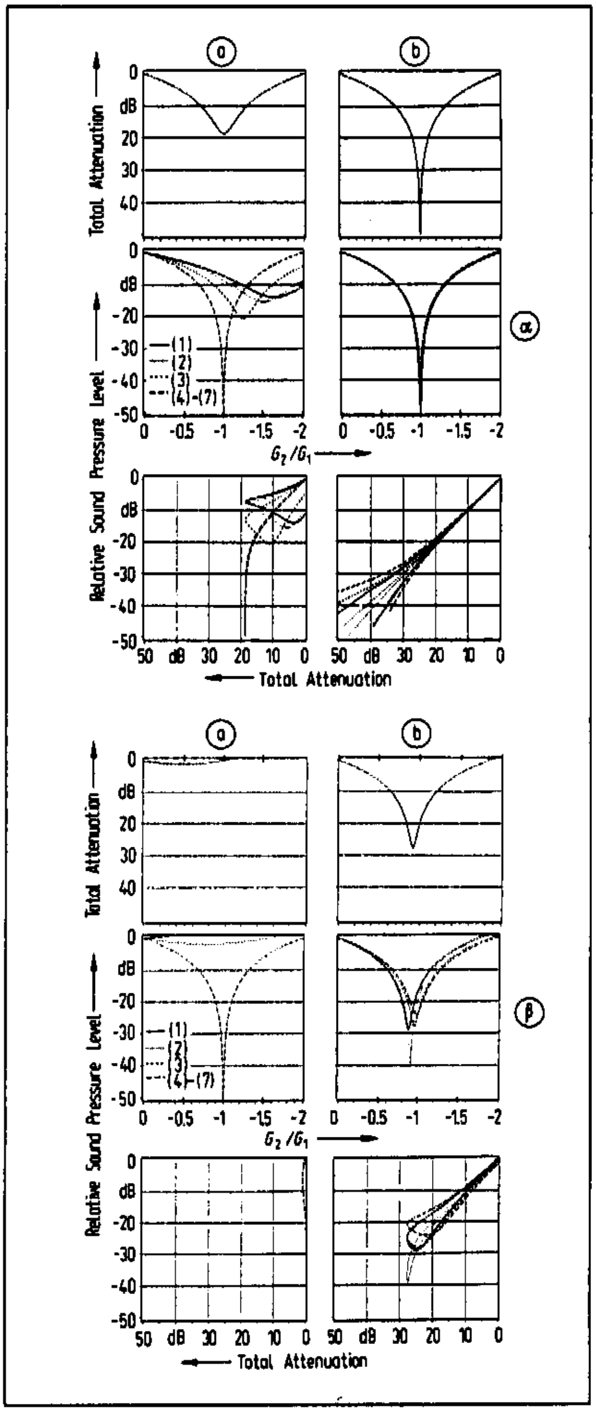

Fig. 9. The relation between the sound pressure level received by each of the sensor microphones (1) to (7) shown in Fig. 8 and the attenuation of the total radiation power from the upper half hemisphere. The uppermost graphs show the optimum attenuation of the total radiation power for various values of (G_2/G_1). The middle graphs show the relative SPL of the sound received at each point in Fig. 8 for various values of (G_2/G_1). SPL on at each sensor and the attenuation of the total radiation power. a) For the ordinary dipole system in Fig. 2. b) For the proposed polypole system in Fig. 5. α) $ka = 0.1$; β) $ka = 1.0$.

dipole with two-point sound sources. However, in practical cases, the dimensions of the sound sources cannot be negligible. Thus, in this paper, by using a dipole with two plates, the characteristics of attenuation have been considered. From the generalized consideration of the attenuation of eq. (11), the optimum attenuation is shown to depend on the arrangement of the primary and additional sound sources. Moreover, the characteristics of attenuation in various arrangements of additional and primary sound sources have been investigated by means of computer simulation analysis. From the results, the arrangement in the proposed system of Fig. 5, which is easily realized, is shown to have the optimum characteristics of attenuation. Here, the attenuation of total radiation power is greater than that obtained by the ordinary dipole system, and the cut-off frequency of the polypole system is also higher than that of the ordinary dipole system. In the polypole system, moreover, the sound pressure level of the sensor point on the arbitrary space in the upper hemisphere directly corresponds to the total radiation power from the half hemisphere. Thus, in a practical noise control system such as an adaptive control system, the optimum attenuation of the total radiation power may be achieved by minimizing the sound pressure level of the sound received by the sensor microphone. An experimental system using the proposed polypole system is under production in our laboratory.

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