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SECONDARY ACOUSTIC SOURCE TYPES FOR ACTIVE NOISE CONTROL IN FREE FIELD: MONOPOLES OR MULTIPOLES?

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1. INTRODUCTION

In the field of active noise control, the attenuation achievable is not only highly dependent on the secondary source number and locations, but also on the types of secondary source. A huge amount of work has been directed towards the use of arrays of monopole-like secondary sources and also a certain amount of work has been directed towards the use of higher order secondary sources. Most of the work can be found listed in the very complete literature review on the concepts and application of active noise control in free field in reference [1] and the following two studies are related closely to the topic of this letter.

First, Bolton *et al.* discussed global free-field cancellation in the region exterior to a single compact primary source by the use of a single, multipole secondary source [1]. It was found that improved attenuation could be achieved by choosing the secondary multipole component source strengths to minimize the total sound power radiated by the combination of primary and secondary sources rather than using a direct multipole expansion of the primary sound field. Although the primary conclusion of their work was that global cancellation could be obtained by using a multipole secondary source placed at a relatively large fraction of a wavelength from the primary source, it was also shown that it was more efficient in some instances to use a single secondary multipole rather than an array of secondary monopoles for global cancellation. For example, a multipole truncated at octopole order along the x-axis (four control output channels needed) gives a performance comparable with or better than, an eight monopole spherical array of secondary sources (eight control output channels needed), and there are circumstances in which it would be more convenient to cancel a sound field by using a multipole secondary source at a single location rather than a distributed array of monopole sources.

Second, Martin and Roure proposed a procedure to optimize the locations of the control sources and error sensors in an active noise control system using a spherical harmonic expansion of the primary field [2, 3]. The primary field was decomposed on a spherical harmonics basis (the components are identified as the radiation of multipole-type sources) with one or several centres shifted from the geometrical centre of the primary source, and this allowed the estimation of the number and realistic arrangement of secondary sources likely to minimize the primary field. After locating the secondary sources, a least-squares method was used to compute their strengths. The simulations and experiments carried out on the primary sound fields of a monopole, a dipole and a 1·8 m high electrical transformer, respectively, showed a global reduction in the whole space at low frequency even when long distance separated the real acoustical centre of the primary source and those of the secondary sources. It was also shown in the work that for all the primary sources studied

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(a monopole type, a dipole type and a general type), case (c) gave the best results while case (a) gave the worst results. Case (a) consisted of a multipole secondary source truncated at order 2, and it took one optimized control source location, nine controller output channels and 19 monopoles to construct it. Case (b) consisted of two multipole secondary sources truncated at order 1, and it took two optimized control source locations, 12 controller output channels and 14 monopoles to construct them. Case (c) consisted of nine monopoles, and it took nine optimized control source locations, nine controller output channels and only nine monopoles.

The differences between the two results, which are sometimes confusing to the readers, are that for a monopole primary sound source. Bolton *et al.* found that a multipole truncated at octopole order gives a performance comparable with or better than, an eight monopole spherical array of secondary sources, whereas Martin *et al.* found that an array of nine monopoles can produce more global reduction than a multipole of two orders. Because some terms of the spherical harmonic series do not correspond to a standard multipole source and the two cases discussed are for different orders of a multiple and a different number of monopoles, it is hard to compare the two results directly; however, the conclusion of Bolton *et al.* is that for the same number of control output channels, a multipole can give better attenuation, contrary to the conclusion of Martin *et al.* This is probably caused by the different distances from the control source to the primary source in the two cases. Bolton *et al.* draw their conclusion based on small distances from the control sources to the primary source, for instance, $kd < 1$ (k is the wavenumber, d is the distance) while Martin *et al.* draw their conclusion based on medium distances from the control sources to the primary source, for instance, $1{\cdot}6 < kd < 3{\cdot}14$. When the distance from the control sources to the primary source is large, for instance, $kd > 6{\cdot}28$, it is difficult for either method to provide large global attenuation.

In this letter, a simple numerical study is performed on a baffled rectangular plate to show the use of the two types of secondary acoustic source for sound radiation control. The first type is an array of monopoles, and the second is a multipole secondary source. The question is that for a complicated primary noise source such as a large electrical transformer, which type of secondary acoustic source can give better attenuation for a specified number of control output channels?

2. CONTROL OF A LARGE PANEL

A large simply supported baffled panel of dimensions $\lambda \times \lambda$ and vibrating in the simplest (1, 1) mode is considered here. Although active control of low-frequency harmonic sound radiated by a small finite panel ($kd \ll 1$) has been studied extensively by others [4], the purpose here is to show the influence of the large dimension of the primary source. The formulae and equations used in the calculation can be found in section 8.7.2 of reference [5]. In the calculations there, near-field formulae and numerical integration were used. Figure 1 shows the global acoustic power attenuation as a function of the secondary source location. The secondary source is a monopole located on the panel along a diagonal line originating from a corner (0 on the x-axis) of the panel and ending at the centre of the panel (0·707 on the x-axis).

It can be seen from Figure 1 that, even for the panel vibrating in the (1, 1) mode, a secondary monopole placed in the corner of the panel cannot globally attenuate acoustic power effectively because it cannot match the primary sound field, whose dimensions are comparable with the acoustic wavelength. In this situation, a multipole cannot be expected to obtain better performance than a monopole because the primary source cannot be

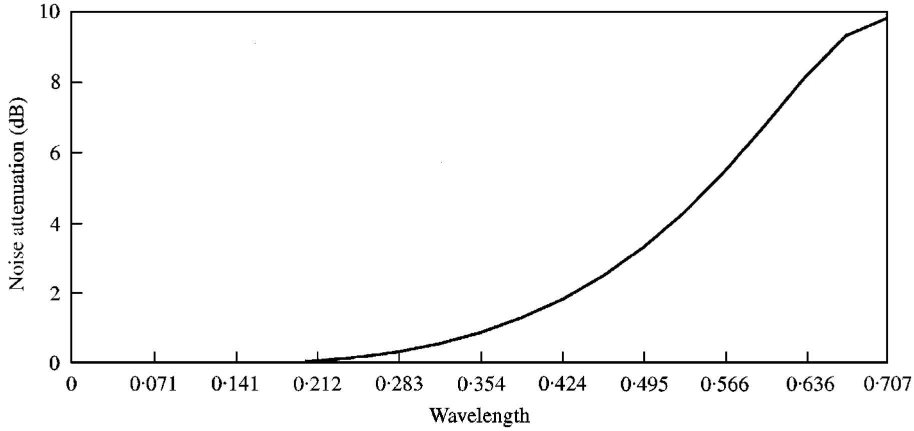

Figure 1. Acoustic power attenuation produced by a monopole secondary source as a function of its location on the panel.

expanded easily with just one acoustic centre. For example, if a multipole of 1 order (1 monopole plus a dipole) is used, when it is located in the centre of the panel, the attenuation is 9·8 dB, and when it is at the corner of the panel, the attenuation is 0·10 dB, which is the same order of attenuation as that of a monopole.

The results of this simple example show the importance of the number of secondary sources in a practical system, especially for higher frequencies, and this was also noticed by Cunefare and Koopmann in their study on three-dimensional structures [6]. It seems that at least the same number of secondary sources, whether they are monopoles or multipoles, should be used as the number of acoustic centres. In these situations, it does not seem possible to save control output channels by using multipoles, although it is clear that not all primary sources are most efficiently represented as a superposition of monopoles and in some circumstances it may be more efficient to use secondary sources of order higher than that of a monopole.

The results can also be used in a sense to explain what usually happens in an active transformer noise control system. For example, for their 1·8 m electrical transformer, Martin *et al.* obtained 11 dB reduction for the 100 Hz component and only 5 dB for the 200 Hz component with four acoustic centres [3]. This also happens in commercial active noise control systems such as Quiet Power's active transformer quieting system although both acoustic and vibration secondary sources are used [7]. For a 5 m high large electrical transformer which radiates significant noise at 100, 200 and 300 Hz, etc., it is obviously unreasonable to use just one secondary source (monopole or multipole) because the primary sound field generated has more than one acoustical centre (at least five for four sides and a top) and the distances between the acoustical centres are so large that $kd > 6{\cdot}28$, even for the 100 Hz component. So the challenge is how to find the minimum number and locations of acoustic centres for a practical system which can be used to match the primary sound field?

3. CONTROL OF A SMALL PANEL

The sound cancellation of a primary monopole by the use of secondary multipoles has been studied extensively [1], and the sound radiation by a small, baffled, simply supported

Table 1

The global acoustic power attenuation (dB) for the various types of secondary source

Primary source	(a)	(b)	(c)	(d)	(e)
Odd–odd mode	79·6	83·8	80·7	91·1	91·7
Even–odd mode	37·0	43·1	85·4	85·2	85·3
Even–even mode	0	0	76·4	0	0

panel is investigated in this letter to show the difference between using an array of monopoles and a multipole. The size of the panel is $L_a \times L_a$ (L_a equals $\lambda/100$), and the origin of the co-ordinate system is located at the left lower corner. Table 1 shows the global sound attenuation for three types of panel modes in the following cases: (a) three monopoles located at $(0, 0)$, $(L_a, 0)$ and $(L_a/2, L_a)$; (b) three monopoles located at $(1/4L_a, 3/4L_a)$, $(3/4L_a, 1/4L_a)$ and $(3/4L_a, 3/4L_a)$; (c) four monopoles located at $(1/4L_a, 1/4L_a)$, $(1/4L_a, 3/4L_a)$, $(3/4L_a, 1/4L_a)$ and $(3/4L_a, 3/4L_a)$; (d) a multipole centred at $(L_a/2, L_a/2)$, consisting of one monopole and two dipoles, with one the dipoles pointed from $(L_a/2, L_a/2 - \delta)$ to $(L_a/2, L_a/2 + \delta)$, and the other from $(L_a/2 - \delta, L_a/2)$ to $(L_a/2 + \delta, L_a/2)$, where $\delta = L_a/10$; (e) a multipole centred at $(L_a/2, L_a/2)$, consisting of one monopole and two dipoles, with one of the dipoles pointed from $(L_a/2 - \delta, L_a/2 - \delta)$ to $(L_a/2 + \delta, L_a/2 + \delta)$, and the other from $(L_a/2 - \delta, L_a/2 + \delta)$ to $(L_a/2 + \delta, L_a/2 - \delta)$.

For the even–even modes, if a lateral quadrupole is added into the multipole in the centre, the acoustic power attenuation can be changed from 64·8 to 0 dB within 45° angles of the quadrupole rotation. For example, a quadrupole located at points $(L_a/2 \pm \delta, L_a/2 \pm \delta)$ gives the best attenuation of 64·8 dB while a quadrupole located at points $(L_a/2, L_a/2 \pm \delta)$, $(L_a/2 \pm \delta, L_a/2)$ cannot reduce global sound power at all.

The results shown here are not surprising as the importance of the matching of the secondary source distribution to the type of panel mode has been fully understood [4]; however, the results in the letter show that, if the radiation pattern of a primary sound field is known and stable, then a special multipole secondary source with a certain number of orders and directions can be designed to provide much better attenuation with the same number of or fewer control output channels than an array of monopoles. For example, a quadrupole (one control output channel) oriented in a certain direction in the centre of the panel can provide larger attenuation than that provided by three or four monopoles (three or four control output channels). But if a primary sound field cannot be fully known or changes with time, an array of monopoles seems to be a better and more robust solution. In this situation, if a multipole is used in an attempt to provide the same attenuation, the high order multipoles must have a certain number of directions and more control output channels may be needed in the system than for an array of monopoles. This is very different from the results obtained for a monopole primary source [1]. In summary, in most general situations, even when the size of a primary source is much smaller than the acoustic wavelength, it is difficult to use multipole secondary sources to save control output channels.

4. CONCLUSIONS

From the two examples considered above, it is clearly seen that the selection of the most appropriate secondary acoustic source types such as monopoles or multipoles depends on the characteristics of the primary sound field. If the size of a primary source is much smaller than the wavelength of the acoustic wave and the primary source is stable and the radiated sound field is well defined, using a multipole very near the primary source is better than using an array of monopoles with respect to the number of the control output channels and the sensitivities of secondary source locations. If the small primary source is time variant and cannot be fully defined, an array of monopoles seems to be better and more robust. If the size of primary source is comparable with the acoustic wavelength of noise, or the primary source is a little more complicated so that it cannot be expressed with just one acoustic centre, then arrays of monopoles usually give better attenuation than just a multipole because in these situations, a multipole secondary source cannot match and cancel the primary sound field better than a group of monopoles. Although in some situations, for each part of a complex primary source or for each acoustic centre, a multipole may still be used to improve the attenuation by substituting for the monopole, it seems that arrays of monopole secondary sources are best suited to active noise control of a large practical primary source such as a large electrical transformer, due to their robustness and generality.

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