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Low-Frequency Noise Attenuation in a Closed Space Using Adaptive Directivity Control Sources of a Quadrupole Type

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A novel method of active noise control using adaptive radiation sound sources is investigated. A finite element model of a modal enclosed sound field is excited harmonically, representing a noise field in the low-frequency range. The control sources are comprised of elementary dipole sources for which the driving signals are adjusted by an optimization method. Two set-up cases of the proposed compound sources are investigated. The coupling of the control sources with the modal sound field is discussed. The simulated performance of the proposed method is compared with that of a system with distributed simple sources and the results show the effectiveness of the sources with adaptive radiation for active noise control in small enclosures.

Keywords: modal field; noise control; adaptive radiation sources.

1. Introduction

Low-frequency noise (LFN) is an important component of residential and occupational noise. Steady-state LFN in a workplace is emitted from a multitude of sources such as ventilation, air conditioning systems, rotating machines or power stations. It is a cause of severe annoyance to people, whether in a living or a working environment. LFN propagates efficiently for long distances and is highly pervasive to buildings. Indoors, it can be amplified by the modal behaviour of a closed room, strengthening it in comparison to the noise of higher frequencies. Additionally, it is selectively not attenuated due to the insufficient low-frequency insulation and absorption of the room walls. Hearing protection devices are inefficient against LFN, which is often the cause of workers' complaints.

The harmful effects on the community and the risks to workers' health and safety due to the exposure to LFN are already indicated in the literature (Concha-Barrientos *et al.*, 2004; Pawlaczyk *et al.* 2004). Hearing impairment resulting from exposure to excessive noise is a significant health concern. Other commonly reported symptoms include headaches or a feeling of pressure in the head or on the eardrum and vibrations in the body. Mental tiredness and lack of concentration are of concern that can lead to a reduced productivity and work satisfaction. Further consequences are social isolation and decreased self-esteem. Contrary to mid- and high-frequency sounds, LFN does not usually pose an immediate distraction. A common reaction, and especially to steady-state noise, is a feeling of relief when the noise ceases, even when the exposed persons have not been aware of the noise presence (Persson, 2011). For these reasons, methods have been studied for assessing the noise-induced risk of the human hearing system during noise exposure (Czyżewski *et al.*, 2007; Kotus, Kostek, 2008) and the occupational LFN to prevent its effects on workers' performance (Młyński *et al.*, 2014; Shehap *et al.*, 2016).

Across the last few decades of research LFN control methods have been developed. Active noise control (ANC) is a widely-used method of suppressing an annoying sound. The underlying concept of ANC, which is the destructive interference of acoustic waves among primary and secondary sources, was proposed by Lueg (1936) as a sound damping process between waves having opposite phase. In the free field, cancellation of a primary monopole's sound field by the use of secondary multipole sources has been studied (Bolton *et al.*, 1995). A numerical study on the types of secondary sources for sound radiation control concluded that arrays of monopoles are suitable for controlling a primary source, which is either large or time-variant and not fully defined (Qiu, Hansen, 2000). An ANC system with multiple compound secondary sources, consisting of two closely monopoles near to the primary source, was proposed by Weisong *et al.* (2010).

In enclosed spaces, numerous works have indicated that applied low-frequency ANC is effective. Nelson *et al.* (1987) attempted to calculate the optimal positions of secondary sources and proved that for frequencies higher than Schroeder's cut-off frequency (f_s) the distance between the primary and secondary source must be less than half a wavelength. Bullmore *et al.* (1987) succeeded in minimizing the total time-averaged acoustic potential energy in a lightly damped, rectangular, shallow enclosure. By calculating the secondary sources' complex strengths to minimize the squared pressures at selected control points, it was shown that when they are placed at an antinode or at a pressure maximum of the primary field, substantial reduction of the acoustic potential energy is achievable for frequencies higher than f_s. Numerical methods and active control techniques combined with measurements have been used to predict ANC performances in enclosures like vehicles (Mingsian, Sernshen, 1996; Stanef *et al.*, 2004; Kozień, Wiciak, 2008; Žiaran, Chlebo, 2016) or more flexible structures (Prezelj, Čudina, 2007; Wrona, Pawelczyk, 2016).

The previous research shows that the level of noise reduction is critically dependent on the sources' locations. A major concern of the sources positioning in an enclosure is that radiation is highly dependent on the modal field. The control units should preferably be positioned at pressure antinodes to achieve the best possible attenuation. The controllability of a primary field is more effective when the number of control sources is increased. While these solutions have a significant contribution to noise reduction, some of them require the distribution of secondary sources across the closed space to effectively control the low-frequency sound field. In the free field, the control of a noise source is achieved by placing closely a single or multiple control sources.

In the present work, a new method that aims to achieve the control of a LFN in a small closed space using one compound source is proposed. Simulations are made in a sound field with low modal density. The general design method for the secondary sources is addressed along with their radiation pattern, as they are being coupled with the acoustic modes. A finite element model is developed using the "ANSYS Mechanical APDL" software. Optimization-based simulation results present the control of a steady-state primary field using an adaptive secondary source across the low-frequency range. The contribution of the latter to the noise reduction is compared to a method that uses distributed secondary sources. The obtained results demonstrate a significant reduction of the noise level. A comparison of the noise control effectiveness between two different set-ups of compound sources completes the study. The proposed method shows the possibility of the adaptive directivity sources application to active low-frequency noise control for realistic cases.

2. Compound sound sources in ANC

A monopole is the simplest elementary sound source. At low frequencies, it can be approximated by a driver in a sealed box with dimensions much smaller than the radiated wavelength, so that $ka \ll 1$, where k is the wavenumber and a is the primary dimension of the source moving surface. A dipole source is consisted of two monopoles at a small distance d, radiating out of phase. The radiation conditions for the far-field are $d \ll \lambda$, $d \ll r$, $r^2 \ll \lambda^2/36$ and $d \leq \lambda/2$, where λ is the wavelength and r the observation distance (Beranek, 1996). Considering the dipole as an elementary source, compound sound sources can be composed in many topologies.

Low-frequency directivity is controlled using the principles presented by Olson (1973) concerning the gradient loudspeakers, which exploit two or more simple sources to achieve the desired radiation pattern. In a compound sound source, it is the result of the radiated wave superposition of each source. It is dependent on the set-up and the driving parameters of the elementary sources. The control of the directivity pattern positively affects noise control by the superposition of a sound with the same waveform and inverse phase to the noise (Kido, 1991). It has been shown that compound sources can be used to substitute the monopole sources to reduce the number of control channels of an ANC system (Weisong *et al.*, 2010). An equalization model (Hill, Hawksford, 2010) consisting of multiple low-frequency components driven each by a dedicated signal adjustable to amplitude and phase, can adapt itself to its surroundings to give equal low-frequency coverage within a defined listening area.

The radiation pattern of a compound source is adapted by changing the driving parameters of the comprising sources, resulting in narrower radiating lobes comparing to monopole sources. The change of acoustic pattern towards different directions was confirmed in the free field, with the investigation of various compound source topologies (Sevastiadis *et al.*, 2014). In the same work, it was verified that the adaptive radiation of a compound source can control a modal field and highly directive sources can provide more efficient sound field control, as it was tested for an axial mode excitation in a room model. A longitudinal quadrupole source consists of two dipoles with opposite phase separated by a small distance, while their axes lie on the same line as shown in Fig. 1a (Russell *et al.*, 1999). This source topology turned out to be very adjustable, regarding changes in the radiation pattern while varying its driving parameters. In a typical sized room model of another work, simulations were made in a single axial resonant frequency with a longitudinal quadrupole type source (Giouvanakis *et al.*, 2016). It was shown that by adjusting the complex excitation of each dipole, attenuation of a primary field in an area of interest can be achieved.

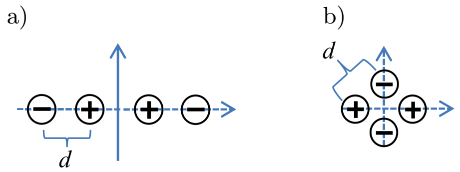

Fig. 1. Longitudinal (a) and lateral (b) quadrupole compound source.

As the order of the source increases, the radiation pattern becomes increasingly narrower and the source efficiency decreases for radiation of low frequencies (Norton, Karczub, 2003). A compound source radiates in a different way regarding a free, semi-free and closed space. A review of the effect of a reflective surface on an active noise control system, which is subject to the characteristics and configurations of the sources, has been made concluding that a reflective plane has a positive effect on the noise control (Boodoo *et al.*, 2015)

3. Analysis method of a harmonic noise field minimization with a compound sound source

3.1. Enclosed sound field modelling method

To examine the proposed method with a compound secondary source, noise control FEM analyses were made in a model of a small, rectangular, horizontal enclosure using ANSYS. The internal acoustic volume was modelled by tetrahedral elements with a constant 1% attenuation coefficient in the boundaries. The sound speed c_0 in the air is 343 m/s and the air density ρ_0 is 1.21 kg/m^3. Both primary and secondary sources were modelled as simple sources inside the model cavity, as a simplification for obtaining general noise cases. Regarding the sources excitation, as mass flow rate is $\dot{m} = \rho_0 Q$ with monopole strength Q as volume velocity in m^3/s, they introduce pressure waves in kg/s (Istvan, Beranek, 2006). A combination of monopole sources is included as a forcing term in the acoustical wave equation, which results in the inhomogeneous Helmholtz equation for the steady-state sound pressure response,

$$\nabla^2 \widehat{p} + \left(\frac{\omega}{c_0}\right)^2 \widehat{p} = -\frac{i\omega\rho_0}{V}\widehat{Q} = -\frac{i\omega}{V}\widehat{\dot{m}}, \quad \text{N/m}^4, \qquad (1)$$

operating at the forcing frequency $f = \omega/2\pi$ in Hz.

Total time-averaged acoustic potential energy E_p is a measure of the amplitude of the pressure fluctuations in a closed sound field and can be used for evaluating the performance of a noise control system. This is given by

$$E_p = \left(\frac{1}{4}\rho_0 c_0^2\right) \int\limits_V |p(\mathbf{x},\omega)|^2 \, \mathrm{d}V, \qquad (2)$$

where $p(\mathbf{x},\omega)$ is the complex pressure amplitude in Pa at a point and V the volume of the enclosure in m^3 (Nelson *et al.*, 1987).

In this study, the control strategy is to follow an alternative approach of E_p calculation, which monitors the amplitude of the pressure fluctuations at a discrete number of locations in the enclosure (Bullmore *et al.*, 1987). Summing the squared pressure amplitudes at these locations enables an approximation to the E_p and can be defined as

$$J_p = \left(\frac{V}{4}\rho_0 c_0^2 L\right) \sum_{l=1}^{L} |p(\mathbf{x}_l,\omega)|^2, \qquad (3)$$

where $p(\mathbf{x}_l,\omega)$ is the complex pressure amplitude at the l-th location and the summation is performed over L locations. As the number of evenly distributed locations tends to infinity, the value of J_p tends to the value of E_p as specified by Eq. (2).

3.2. Driving parameters optimization method

The objective of the optimization procedure is the minimization of the acoustic potential energy in a small enclosure due to the excitation of a steady-state noise source ($J_{p,n}$). Acoustic potential energy after the ANC ($J_{p,c}$) depends on the driving parameters of the compound secondary source, as it results from the sum of the squared pressures at discrete points. The noise minimization in the modal field is achieved by finding the optimal set of driving parameters of the control source. If the source consists of n dipoles, then the adjustable driving parameters are the excitation of the monopoles in each dipole $\{\dot{m}_1, \ldots, \dot{m}_n\}$ and their phases $\{\varphi_1, \ldots, \varphi_n\}$.

A brute force approach is used with a stepped sweep of the driving parameters of the elementary dipoles to find a possible set of optimal values. Afterwards, the iterative procedure of Multidimensional Gradient Steepest Descent (MGSD) method is applied to this set to find the optimal set of parameters values (Adby, Dempster, 1982).

The excitation of each monopole of the dipoles of the compound source is calculated in dB relative to the monopole noise source's mass flow rate ($\dot{m}_0 = 1$ kg/s). The difference between the dipoles' excitations of the compound source should not exceed an upper limit, e.g. 10 dB. With a steady polarity of the primary source at 0 rad, the algorithm also seeks the optimal polarity between the dipoles. Every iteration updates the parameters that minimize the J_p and the algorithm terminates when there is no longer a significant improvement.

The investigated frequency range is divided into individual regions. These are split into successive zones of resonances and valleys of the $J_{p,n}$ curve and the optimization algorithm runs for the frequencies in which local maxima (resonances) or minima (valleys) appear. The optimal values are calculated and set as driving parameters of the secondary source for the respective region.

4. Conducted analyses of ANC with compound sound sources

The acoustic response of a source is determined substantially by its position and coupling with the acoustic modes of a closed space, which is dominated by the low-frequency modal field with distinct and intense resonances. Below the f_s, an important portion of LFN is included. When a noise source is located at an anti-node of a room mode, it can be amplified significantly due to the maximized coupling. Since room modes tend to have anti-nodes at room corners, they will be maximally excited with corner source-placement.

The radiation of a compound source depends on the location in the modal sound field. A longitudinal quadrupole, which consists of two consecutive dipoles along the same line, has a similar radiation pattern to a dipole with higher directivity. If it is placed in front of one reflecting surface at low frequencies, maximal reinforcement of the pressure output can be achieved by turning the orientation of the dipole-axis parallel to a wall, as it mostly acts as a gradient source. The defined directivity causes excitation of modes which travel in the direction of the dipole-axis (Ferekidis, Kempe, 1996). Thus, the position of the compound secondary source is an important issue for noise control. A summary about the influence on the sources efficiency due to the proximity to room boundaries, the coupling to room modes and the source directivity on room response is given in (Borwick, 2001).

Taking these into consideration, two topologies of quadrupole type; the longitudinal and the lateral, are investigated as control sources under the same conditions to facilitate comparison. Therefore, there are three parameters to be optimized; the excitation of the two dipoles ($\dot{m}_1$, $\dot{m}_2$) and their relative polarity (φ).

The aim of this study is to place a compound source in a fixed position to control all the modes of a small enclosure and minimize a primary field in the low-frequency range. The distance between the comprising monopoles is 15 cm, which satisfies the radiation conditions presented in Sec. 2 for the investigated frequencies. While multiple modes need to be controlled in the enclosed cavity and the method uses a secondary source with a combination of multiple poles, several set ups and positions of the secondary source were examined. An optimal position was found to be in a corner, with the source axes oriented as seen in Fig. 2 for both topologies.

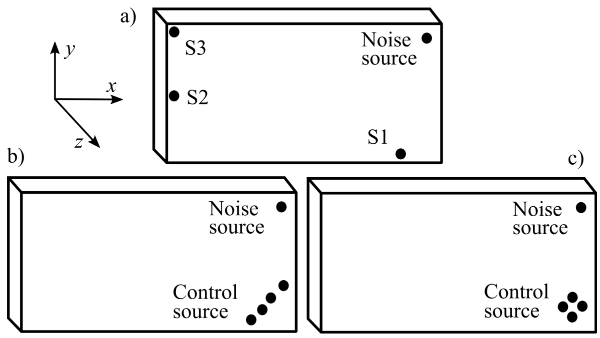

Fig. 2. Schematic diagram of the enclosure modelled for noise minimization, using as control sources: a) three distributed simple sources, b) a longitudinal quadrupole and c) a lateral quadrupole control source.

Bullmore *et al.* (1987) studied a small enclosure that was excited by a primary source, as depicted in Fig. 2a. By computing the necessary complex strengths of three secondary sources (S1–S3) in the range 50–300 Hz with 1 Hz step, a successful attenuation of the acoustic potential energy, E_p, was achieved. In the present work, the same enclosure with dimensions $(x,\ y,\ z) = (2.264\ \text{m},\ 1.132\ \text{m},\ 0.186\ \text{m})$ is modelled. The simulations are carried out at the first six natural frequencies inside the enclosure, which are: a) 75.5 Hz $(1,0,0)$, b) 150.6 Hz $((0,1,0),\ (2,0,0))$, c) 169.4 Hz $(1,1,0)$, d) 214.3 Hz $(2,1,0)$, e) 227.3 Hz $(3,0,0)$, and f) 273.1 Hz $(3,1,0)$.

Two hundred equally-distanced points upon a surface perpendicular to the third dimension (z = 0.186 m) are used for computing the J_p. The distance between two consecutive points across the x and y directions is 10.78 cm and 10.29 cm respectively. Under the same conditions with the method of the three distributed secondary sources, such as the boundaries' attenuation coefficient and the noise source set in the same position $((x,\ y,\ z) = (2.087\ \text{m},\ 0.993\ \text{m},\ 0.186\ \text{m}))$, investigations are conducted into optimizing the driving parameters of the compound source to control all the dominant modes in the frequency range 50–300 Hz. After extracting the $J_{p,n}$ curve, the boundaries of every individual region are set in the frequencies where the value of J_p falls 6 dB below each resonance peak. The frequency regions are shown in Tables 1 and 2. Finally, the $J_{p,c}$ curve is extracted with 1 Hz step, which shows the sound field attenuation after the control.

Table 1. Optimized driving parameters for a longitudinal quadrupole type secondary source in each frequency region. Dipoles' excitations are relative to the noise source ($L_{0,1}$, $L_{0,2}$). Modes attenuation by two methods is shown.

Frequency region [Hz]	Modes	$L_{0,1}$ [dB]	$L_{0,2}$ [dB]	Polarity φ $\{0, \pi\}$	Acoustic potential energy reduction [dB]		
					Proposed method	S1–S3 method	Improvement
50–78	(1, 0, 0)	11.8	19.5	0	25.4	34	−8.6
79–147		8.6	15.1	0			
148–156	(0, 1, 0) & (2, 0, 0)	6.1	14.2	0	26.5	22	+4.5
157–164		5.8	13.6	0			
165–176	(1, 1, 0)	5.8	13.0	0	25.8	21	+4.8
177–208		6.1	11.1	0			
209–219	(2, 1, 0)	6.0	7.3	0	21.3	18	+3.3
220–231	(3, 0, 0)	5.8	7.3	0	17.7	15	+2.7
232–269		5.5	2.2	0			
270–300	(3, 1, 0)	5.5	0	0	17.2	13	+4.2

Table 2. Optimized driving parameters for a lateral quadrupole type secondary source in each frequency region. Dipoles' excitations are relative to the noise source ($L_{0,1}$, $L_{0,2}$). Modes attenuation is shown.

Frequency region [Hz]	Modes	$L_{0,1}$ [dB]	$L_{0,2}$ [dB]	Polarity φ $\{0, \pi\}$	Acoustic potential energy reduction [dB]
50–78	(1, 0, 0)	14.6	13.9	π	29.7
79–147		12.8	7.6	π	
148–156	(0, 1, 0) & (2, 0, 0)	9.8	1.1	π	5.2
157–164		9.3	1.2	π	
165–176	(1, 1, 0)	20.7	12.6	π	−2.6
177–208		17.9	13.7	π	
209–219	(2, 1, 0)	17.3	13.0	0	15.2
220–231	(3, 0, 0)	16.4	14.8	0	13.7
232–269		11.1	7.1	0	
270–300	(3, 1, 0)	8.4	1.5	0	20.5

4.1. ANC with a longitudinal quadrupole type source

Table 1 presents the optimized driving parameters values of the longitudinal quadrupole type source for all the examined frequency regions. The results of noise reduction with the proposed method are presented for the frequency regions which include the acoustic modes. Also, the respective results are given from the method with the S1–S3 secondary sources, as they were obtained approximately from Fig. 11 in (Bullmore *et al.*, 1987).

Driving the longitudinal source with the optimized parameters, noise attenuation in the whole investigated frequency range is achieved as it is shown in Fig. 3, by simultaneously suppressing all the dominant modes. Regarding the resonant frequencies, noise reduction can reach up to 26.5 dB, according to Table 1. As the resonant frequencies decrease, more power is needed for successful control. The polarity between the dipoles in every region does not need to be changed.

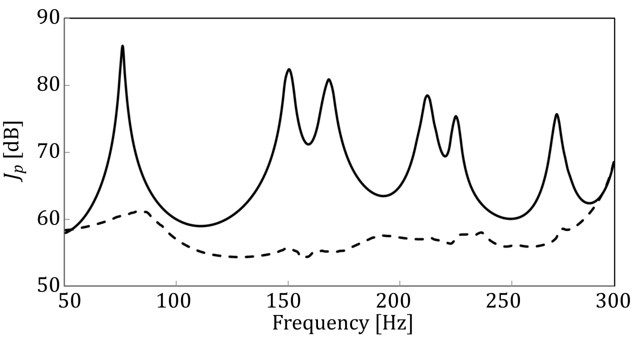

Fig. 3. $J_{p,n}$ due to the noise source (—) in the enclosure. $J_{p,c}$ using a longitudinal quadrupole type (– – –) as secondary source.

The ANC system with the compound source in a fixed position can offer higher noise attenuation of at least 2.7 dB compared to the method with three distributed sources, as can be seen in Table 1. The exception stands for the low-frequency region up to

90 Hz, where the proposed method offers less reduction for the axial mode $(1,0,0)$. The maximum attenuation happens for the resonant frequencies 150.6 Hz and 169.4 Hz.

The performance of the method in noise level attenuation is depicted in Fig. 4, before and after the control. The spatial distribution of sound pressure level (SPL) is represented graphically for all the resonant frequencies up to 300 Hz in the enclosure, upon a surface perpendicular to the third dimension (z = 0.186 m). The SPL with ANC in this area was obtained by superposition of the calculated primary and secondary source fields. For each case, the noise SPL reduction is obvious. While the sound field produced by the primary source is highly non-uniform, after the control of the compound source all the major contributing modes of the enclosure are attenuated and the sound energy is distributed more equally.

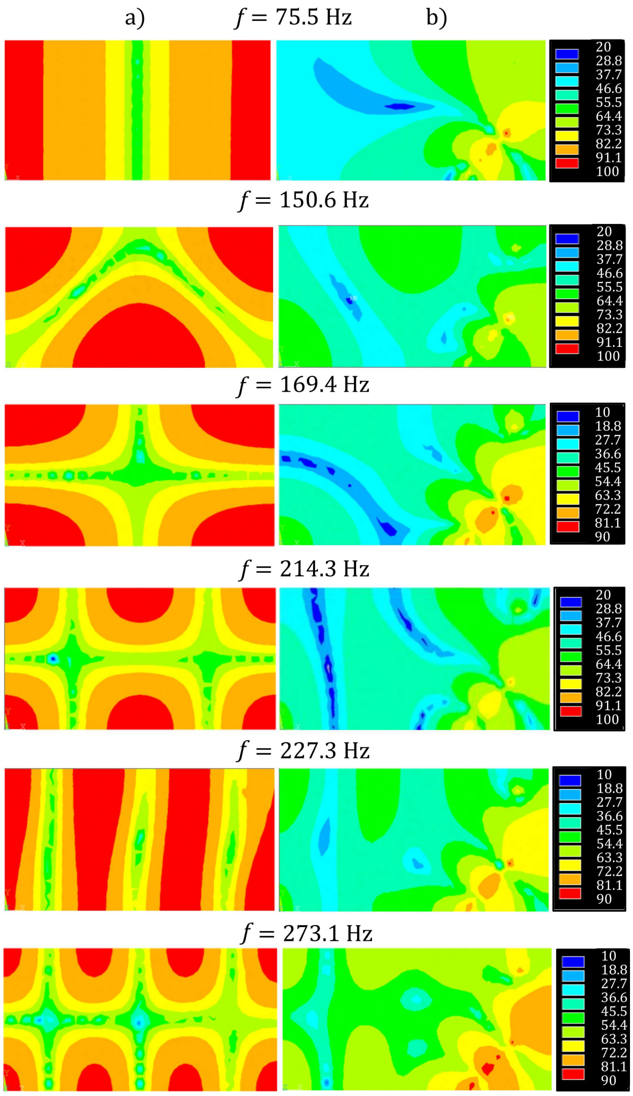

Fig. 4. Modal sound field SPL distribution in dB for six resonant frequencies of the enclosure: a) sound field of a primary source placed in the upper right corner of the enclosure and b) sound field after control with a longitudinal quadrupole type source.

4.2. ANC with a lateral quadrupole type source

The lateral quadrupole source consists of two dipoles with opposite phase, as their axes lie in parallel (Fig. 1b). The ANC optimized results are presented in Table 2. In Fig. 5 the comparison in ANC contribution between the two compound sources is depicted.

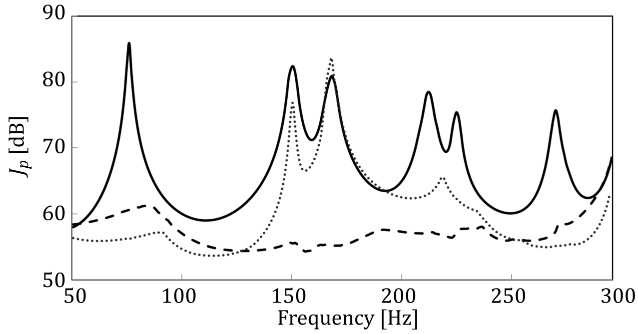

Fig. 5. Comparison between the longitudinal (– – –) and the lateral quadrupole type (···) as control sources for a primary (—) field reduction.

It is observed that with the use of the lateral quadrupole type source, the primary field cannot be minimized over the entire frequency range. Comparing to the longitudinal set up, this control source offers higher noise attenuation in some frequency regions. However, not all modes can be controlled. The reason is that the topology of a lateral quadrupole allows only one dipole to contribute to a specific direction and the sound field of one dipole can interfere destructively with the other.

More specifically, the resonances at 150.6 Hz and 169.4 Hz are not suppressed. The degenerate resonance at 150.6 Hz, consisting of the $(2,0,0)$ and $(0,1,0)$ axial modes, has a faint reduction. The respective modes travel in transverse directions, in which the dipoles of the control source partially contribute to the primary field attenuation and, at the same time, they destructively interfere. The same applies to the resonant frequency of 169.4 Hz for the $(1,1,0)$ tangential mode more obviously. As there is one nodal pressure plane in each of the x, y dimensions, with this secondary source topology the primary field cannot be controlled at all. On the contrary, an increase of 2.6 dB is observed for this mode when applying the optimized parameter values, which are the highest among the examined frequency regions according to Table 2.

It is also acquired that the sources of the lateral quadrupole type case require higher excitation levels to suppress the modes. It is worth mentioning that for the first six frequency regions, the polarity between the two dipoles should be inverted for the possible attenuation of the primary field.

From the two curves in Fig. 5 showing the ANC performance of the control sources that were investigated and the reduction results of Table 2, a difference of up to 4.5 dB of noise attenuation in favour to the lateral quadrupole type source is observed in frequencies out of the range 130–250 Hz. However, this occurs at the expense of demanding higher control source excitation levels.

Hence, the longitudinal quadrupole type source can offer a more satisfying noise control in the low-frequency range. Given the higher and adjustable directivity, it is suitable for such noise control systems as it is unaffected by the direction of the traveling modes in relation to its axis direction, unlike the way one lateral quadrupole type source is dependent on.

5. Conclusions

This study presents a low-frequency ANC approach for small enclosures. A primary source field amplified by a dominant mode can be successfully controlled by a source with adaptive directivity. The secondary source's radiation pattern, which is adapted by adjusting the driving parameters, can be super-positioned over the noise and partially cancel it. The investigations of this method have shown that a further attenuation of harmonic noise can reach about 5 dB around two consecutive resonance peaks of the system, compared with a method using distributed secondary sources. Topologies with elementary sources on the same line seem to offer better controllability over the low-frequency range. The polarity between the dipoles may need to be changed for suppressing some modes.

The proposed method offers the flexibility that there is no need to relocate the control source for noise suppression of different low-frequency bands. Therefore, this ANC system provides an alternative to the common monopolar systems, especially in small rooms with big restriction in positioning.

Although in most cases the control focuses on a narrowband noise, attenuation over the broad low-frequency range is also attainable by placing a compound source in a single location. Nonetheless, further investigations including secondary sources in different topologies of more-than-four poles and acquiring more degrees of freedom should be investigated for implementation in ordinary rooms or more complicated enclosures. In cases of working in an industry, the area of interest is commonly small. Given the potential of compound sources for ANC applications, the subject of ongoing work is the investigation of local noise control in constrained and different areas of a closed space, while having a secondary source in a fixed position. Finally, since the directivity is a leading parameter in control systems with multiple sources, practical arrangement of loudspeakers is challenging and the design of such an adaptive secondary source will be an advantage.

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