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Research Paper

Measurement of Compound Sound Sources with Adaptive Spatial Radiation for Low-Frequency Active Noise Control Applications

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The proposed compound sound sources for low-frequency noise control applications are composed of dipole sources. Their spatial radiation, which is critical in the modal field of small, closed spaces, is intended to be controlled with independent driving signals of each dipole. The need for small and efficient low-frequency elementary monopole sources led to the proposed vented sub-woofer loudspeaker design with low force factor (low-*Bl*) drivers. The investigated sources are set up in quadrupole configurations and measured in terms of polar near field response patterns to verify the theoretical predictions. The measurement results consist of the validation of the proposed compound sound sources on the implementation of active noise control problems in the low-frequency range. Also, their small size and modular construction make them interesting for use in other applications.

Keywords: Low-*Bl* loudspeakers; compound sound sources; adaptive spatial radiation; active low-frequency noise control.

1. Introduction

Low-frequency noise is defined as a broadband one whose sound energy is dominant in the range 20–250 Hz. It is a primary constituent of the environmental noise, caused to a great extent by industrial equipment. Steady-state low-frequency noise in residential buildings and workplaces emits from many sources such as ventilation systems and rotating machines. As a significant component of these sources, it can cause severe annoyance to people. The exposure to low-frequency noise can cause harmful effects on the community and risks to workers' health, such as irritation, headaches, hearing impairment, and mental tiredness (Barrientos *et al.*; Pawlaczyk *et al.*, 2004). The lack of concentration is of concern that can lead to deterioration of task performance and work satisfaction. The exposed persons are not usually distracted immediately, but rather a common reaction is a feeling of relief when the low-frequency noise ceases, even when they are not aware of its presence (Persson, 2011). So far, studies have been published regarding the assessment of the induced harmful effects of the human hearing system during noise exposure (Czyżewski *et al.*, 2007; Kotus, Kostek, 2008). The occupational low-frequency noise and its prevention in workplaces have been studied (Młyński *et al.*, 2014; Shehap *et al.*, 2016). Furthermore, a recent assessment has been done on the impact of low-frequency noise on the education learning process (Zagubień, Wolniewicz, 2020).

Regarding the active noise control (ANC) techniques, the secondary source's radiation pattern can be superimposed over the noise field and attenuate or even cancel it. In the free field, secondary multipole sources (Bolton *et al.*, 1995) and arrays of monopoles for controlling a large or time-variant primary sound field (Qiu, Hansen, 2000) have been studied. Also, compound sound sources have been utilized in noise control systems. As the energy radiation pattern of the compound source may be similar to that of the noise field, the secondary monopole sources can be substituted with the result of reducing the number of channels in a control system (Chen *et al.*, 2010). ANC is implemented widely in enclosures or structures (Wrona, Pawelczyk, 2016). Contrary to mid- and high-frequency sounds, low-frequency noise is highly pervasive to buildings and can be intensified by the modal field of the enclosed space. Symmetrically distributed secondary sources have been proposed to achieve attenuation of sound radiation from inside to the outside of a cavity (Wang *et al.*, 2017).

As far as the control of low frequencies in modal fields is concerned, a common issue is the physical size of the usually big-volume secondary sources, which is considered as a limitation that can reduce the efficiency of the system. Moreover, the control of a primary field is more effective as the number of secondary sources increases, and the noise reduction level is dependent on their position that, in turn, is dependent on the modal field. In workplaces, secondary sources and error microphones are not preferred to place near the workers, so the problem of the available space for the control implementation is bigger. The directivity in low frequencies, as its principles were presented by Olson (1973) concerning the gradient loudspeakers, is exploited to partially solve these limitations. In multipole topologies, it results from the radiated wave superposition of the elementary sources and is dependent on their set-up and driving parameters. The control of the directivity pattern can have an advantageous effect on noise attenuation (Kido, 1991). A system consisting of multiple low-frequency components can adapt to a defined listening area for equal coverage in the lower range (Hill, Hawksford, 2010). Numerical simulations and experiments have demonstrated the feasibility of active directivity control of radiated sound from the near to the far field (Wang *et al.*, 2018).

This work extends our previous studies on low-frequency noise control with adaptive radiation sources comprised of dipoles, for which the driving signals are adjusted by an optimization method to minimize the acoustic potential energy in finite element (FE) models of small enclosures (Giouvanakis *et al.*, 2018; 2019). Attenuation of a primary source field amplified by a dominant mode over the broad low-frequency range can be achieved by using a compound source in a single location. In a further study, a type of small low-frequency source was designed and assessed utilizing a low-Bl loudspeaker driver in a ported box, with the aim to be combined in compound topologies and applied for noise attenuation in ordinary rooms. The implementation of such control sources has been achieved by utilizing low-Bl drivers with high suspension compliance, after an optimum design for high efficiency at a narrow low-frequency range of about 20 Hz (Giouvanakis *et al.*, 2019). In the present work, four identical loudspeakers are constructed as monopoles. Two quadrupole topologies are arranged and measured in terms of polar near field response patterns in a fully anechoic chamber. To verify the obtained patterns, both analytical and numerical calculation results are presented for the theoretical prediction of the quadrupoles operation in the examined low-frequency range. The measured results demonstrate a significant similarity with the predicted polar patterns. The operation of the proposed low-frequency sources is verified. The under-research ANC method, which utilizes the presented sources considering their radiation coupled with the acoustic modes of a closed space, presents great prospects to be effective.

2. Small compound sources of adaptive radiation for noise control in modal fields

In low frequencies, a monopole source can be approximated by a loudspeaker driver mounted in a sealed box with dimensions much shorter than the radiated wavelength, so that $ka \ll 1$, where k is the wavenumber and a the primary dimension of the source moving surface. A dipole source consists of two monopoles radiating out of phase at a small distance d, with radiation conditions for the far field $d \ll \lambda$, $d \ll r$, $r^2 \ll \lambda^2/36$, and $d \leq \lambda/2$, where λ is the wavelength and r the observation distance (Beranek, 1996). Numerous compound sources can be composed in many configurations utilizing dipoles as elementary sources.

Regarding the sound transducers, although the electrodynamic ones are employed for many decades, they still have potential in research due to implementation in noise control. As the movement of the loudspeaker cone is dominated by the electromagnetic forces, the study and exploitation of the driver's constitutive parameters properties can have a beneficial effect on a noise reduction system (Chan *et al.*, 2013).

Low-frequency sources must be mounted in large cabinets to be efficient in the frequency range up to 100 Hz. However, both small volume and high efficiency can be offered using a driver with low force-factor, Bl (Aarts, 2005). Being the product of the flux density B in the air gap and the effective length l of the voice coil wire, this factor determines the loudspeaker's efficiency, response, and weight. Low-Bl values indicate low damping of the loudspeaker's mechanical parts, while offering higher voltage sensitivity and power efficiency than common bass drivers in a limited range tuned at its low resonance frequency, f_{S}. Such loudspeakers behave as narrow bandwidth filters, and their total volume may be reduced as the magnet can be smaller and even of moving type. While in ordinary rooms, the first discrete axial mode frequencies extend up to about 100 Hz, the combination of these loudspeakers in multipole set-ups can be employed to control the modal field excited by a low-frequency source. This is achieved by exploiting their adaptive spatial radiation, i.e., the compound source's radiation coupled with room resonances can be adapted to the specific modal noise field and attenuate it through the comprising sources' driving signals. The requirement for flat frequency response with the resonance frequencies alignment is relaxed, and the efficient pass-band range of the driver decreases considerably, but this is not an issue in a noise control system, as the performance in this region is of no concern.

In the preceded work (Giouvanakis *et al.*, 2019) two low-frequency loudspeakers with low-Bl drivers were designed, with dimensions $20 \times 18.5 \times 18.5$ cm and an approximate internal net volume of 3.5 L (Fig. 1a). The box walls' thickness is 15 mm. Enclosing the loudspeaker into a cabinet, it increases the resonant frequency of the system according to $a = \frac{V_{\text{AS}}}{V_{\text{AB}}} = \frac{C_{\text{AS}}}{C_{\text{AB}}}$, which determines the degree of loudspeaker's coupling with the box (Small, 1973). Due to the small volume of each designed loudspeaker, it is obtained that $\alpha > 3$, so it is an "air suspension" model in which the system's stiffness comes mainly from the enclosed air. Optimal bass-reflex box design with two ports was implemented to extend the tuning frequency of the box-port, f_{B}, lower, and hence, the efficient operating range. In this case, an addition of mass upon the diaphragm could be an option, but it was rejected, as the suspension may not withstand the extra weight, or the diaphragm motion-axis may be displaced. Such modification should also be applied very precisely so as not to change the weight distribution on the diaphragm resulting in non-linear motion of the cone. Moreover, the "weak" magnet of a low-Bl driver makes it prone to these failures. On the other hand, the advantage of a vented box is the low cone excursion comparing to a sealed enclosure, but only above the f_{B}, as in the lower frequencies, the diaphragm excursion is increased rapidly (Dickason, 2006). The utilized commercial 4″ drivers Visaton KT-100V, meet the design criteria with a low resonance frequency (f_{S} = 37 Hz), low force factor (Bl = 3.43 T m), and specifications as seen in Table 1. Two cylindrical tubes of length L_{V} = 19 cm and diameter d_{V} = 1.8 cm result in a port tuning frequency f_{B} = 41 Hz (Dickason, 2006; Small, 1973). With this design, it is, therefore, possible to shift the f_{B} in different frequencies, by changing only the vents dimensions while keeping the cabinet volume constant. The constructed loudspeakers were measured individually in terms of their sensitivity and polar radiation, resulting in essentially omnidirectional sources at low frequencies, with a small deviation of 1 to 2 dB. Dipole configurations of these sources were measured to obtain their polar response change during various tests with diaphragms and ports orientations.

Table 1. Loudspeaker Visaton KT-100V technical data.

Nominal impedance Z	4 Ω
Resonance frequency f_{S}	37 Hz
Frequency response	32–9500 Hz
Moving mass M_{MS}	7.5 g
DC resistance R_{E}	3.6 Ω
Force factor Bl	3.43 T m
Effective piston area S	54.1 cm^2
Equivalent volume V_{AS}	9.8 l
Mechanical Q factor Q_{MS}	2.22
Electrical Q factor Q_{ES}	0.54
Total Q factor Q_{TS}	0.43

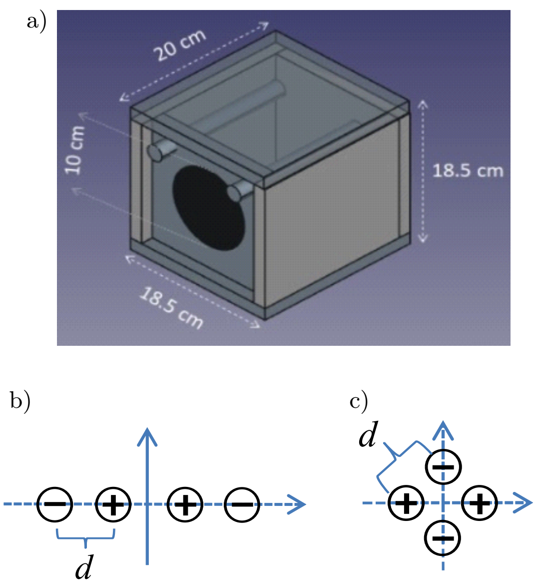

Fig. 1. Model of the designed bass-reflex system for a 4″ low-Bl driver (a). Schematic diagrams of longitudinal (b) and lateral (c) quadrupole compound sources.

The main concept regarding the developed lightweight sources is to arrange them in various compound set-ups for low-frequency noise control. With the proposed optimal design and tuning, low-frequency monopole sources were constructed in such sizes that they could be combined to form complex compound control sources. The study is expanded here on such compound sources as quadrupole configurations of the designed ones for obtaining their radiation pattern through theoretical and measurements results. Instead of employing multiple secondary sources, a compound one is constructed. The adaptive spatial radiation of such a source is the key element for the integration of a flexible control system for low-frequency ANC in small enclosures.

3. Theoretical predictions and measurements methodology

The investigated sources were the longitudinal and the lateral quadrupoles, for which the polar patterns were obtained. A longitudinal quadrupole source consists of two dipoles with their axes laying on the same line, while the lateral one consists of two dipoles with parallel axes, as seen in Fig. 1b and 1c (Russell *et al.*, 1999). The demand of $d \ll \lambda$ for the comprising dipole sources is met (d, distance; λ, wavelength). For the theoretical predictions, both analytical and numerical simulations were calculated. For the first, the

Matlab software was used to calculate and plot the total pressure of four spherical sources in quadrupole set-ups radiating in free space, as given by Eq. (4.1) in (Beranek, 1996). Regarding the numerical analyses, a FE model simulating a free field was developed with the "ANSYS Mechanical APDL" software. The monopoles were modeled as point sources with a mass flow rate excitation, $\dot{m} = \rho_0 Q$, with monopole strength or volume velocity, Q, in m^3/s, and density of air, ρ_0, in kg/m^3, introducing pressure waves in kg/s (Istvan, Beranek, 2006). Therefore, for the investigated quadrupoles, 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 operating at the forcing frequency, as stated by Eq. (6.9) in (Istvan, Beranek, 2006).

As far as the experimental procedure is concerned, the low-frequency loudspeakers assessment is a subject under the inherent measurement difficulty of the longer wavelengths in free field conditions. It is known that the directivity pattern of a loudspeaker system must be assessed in the far field (Beranek, 1996). Especially for the longitudinal quadrupole source, it must be observed in the deep far field for well-defined radiation (Russell *et al.*, 1999). However, it is hard to find an acoustic anechoic chamber for testing loudspeaker systems down to the lowest audible frequency (20 Hz). Moreover, it is not possible to find an outdoor free field testing site with the adequately low background noise level. Therefore, a kind of compromise is usually made through different proposed techniques to compensate for the absence of free field conditions for the low frequencies. A simple and inexpensive technique has been proposed for measuring the free field frequency response up to about 200 Hz through measurement of the acoustical pressure within the loudspeaker enclosure, without the need to establish free field radiation conditions (Small, 1972). Similarly, another method was proposed based on sound pressure measurements taken in the near field outside the system enclosure for the low-frequency assessment (Keele, 1974). Both can be applied in any environment with simple equipment. As the purpose of the present work was to assess the designed small loudspeakers combined in quadrupole configurations through measurements of the polar radiation patterns, the only feasible option was to conduct them in an available anechoic chamber. Among the various difficulties that were met in the set-up of the whole compound source, the chamber's cut-off frequency of 125 Hz was the biggest challenge faced.

The drivers were operated by an audio power amplifier driven by an NTI Audio MR-2 Minirator signal generator. The excitation signals were sine waves of the one-third octave band center frequencies, in the range 40–200 Hz, giving a range for ka values from 0.07 to 0.37, which satisfy the simple source approximation. The investigated quadrupoles were placed appropriately on a constructed base upon a B&K type 9640 turntable system, consisting of a type 5960 controllable turntable, a type 5997 turntable controller, and a WB 1254 remote control. For each dipole source, the distance between the acoustic centers of the two elements was about 20 cm. For the longitudinal source, the distance between the two dipole sources was 60 cm, while for the lateral one 50 cm, as seen in Fig. 2 (up). An NTI Audio XL2 Sound Level Meter & Acoustic Analyzer with an NTI Audio M4261 microphone was utilized to measure the sources' responses. The microphone was positioned 2 meters from the quadrupole's geometric center (Fig. 2 (up)). The sound pressure level was measured with a θ-step of 5° on the horizontal plane ($\varphi = 0°$). With a full peripheral rotation, 72 positions were obtained. This is consistent with the instructions given in the AES56-2008 standard, regarding the measurements of loudspeaker polar radiation (AES56-2008). The height of the horizontal plane was 1.5 m above the grid plane, at the center of the anechoic chamber. The reference axis of $\theta = 0°$, corresponds to the microphone pointing towards along the longitudinal source axis, while for the lateral case, towards the middle distance of the two dipole sources axes, as seen in Fig. 2 (down). The two quadrupole set-ups were assessed separately.

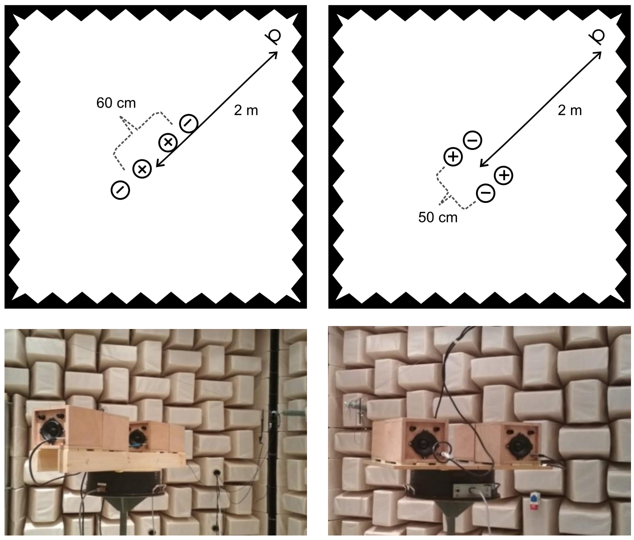

Fig. 2. Measurement of the quadrupole set-ups upon a turntable in a fully anechoic chamber. Left – longitudinal, right – lateral. Up – top view diagram, down – *in situ*.

4. Compound sources radiation results

In Fig. 3a, analytical directivity patterns for far field sound pressure levels are shown for the longitudinal quadrupole in one-third octave bands of 40–80 Hz. The minimum observation distance that fulfills the far field radiation condition for the maximum wavelength

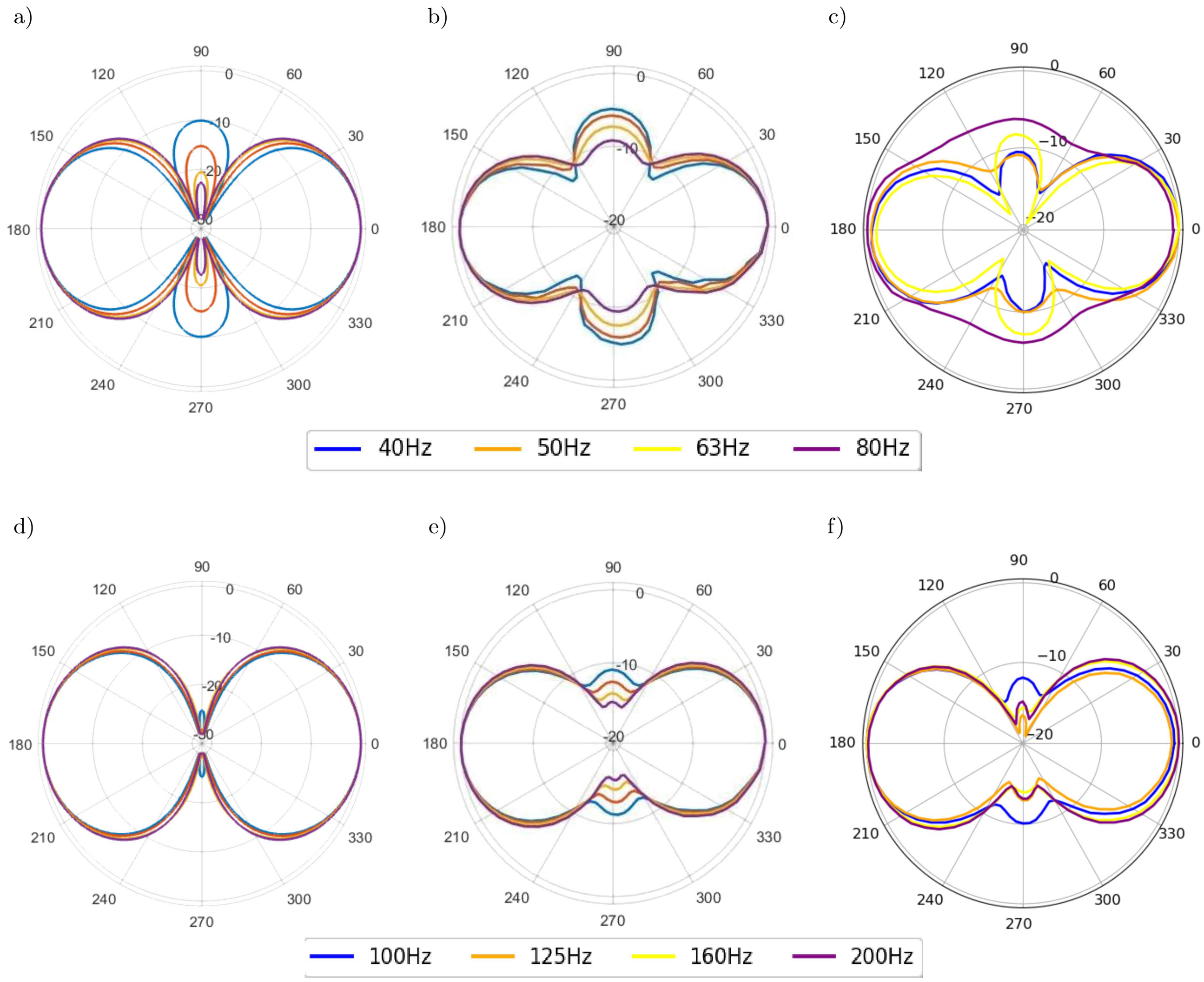

Fig. 3. Polar diagrams in degrees and dB. Longitudinal quadrupole analytical calculations for the far field at 14 m: a) 40–80 Hz and d) 100–200 Hz; numerical calculations for the near field at 2 m: b) 40–80 Hz and e) 100–200 Hz; and measurements in the near field at 2 m: c) 40–80 Hz and f) 100–200 Hz.

of 40 Hz, calculated at 14 m, was chosen for the analyses. For the same frequencies, numerical simulations results are presented for the near field at 2 m in Fig. 3b. Relative theoretical results are given in Figs 3d–e for the frequencies 100–200 Hz. In Figs 3c and 3f, the polar patterns for the longitudinal source obtained from measurements in the anechoic chamber are shown. The similarity between the calculated and experimentally measured patterns is observed. The main concern regards the obtained patterns at the frequencies of 63 and 80 Hz, as can be seen in Fig. 3c. In spite to the theoretical predictions, the side lobes are not developed as expected. Especially for the 80 Hz, the pattern approximates that of an omnidirectional source without presenting discrete radiation lobes.

Investigating further the above deviations between measurement and simulation results, more numerical simulations were calculated. In Fig. 4, polar responses are shown at the distances of 1.5, 2 and 2.5 m, for the frequencies of 40 and 80 Hz. It is observed that the case of 80 Hz is mainly affected, contrary to 40 Hz. Small steps of observation distance in the near field can lead to non-negligible differences in the polar responses. However, for the higher frequencies of 100–200 Hz, there is good agreement between the theoretical predictions and measurements.

Finally, in Figs 5 and 6, the theoretical predictions and measured radiation patterns respectively, are presented for the lateral quadrupole source for all the one-third octave band center frequencies of interest. In this case, radiation lobes in four directions are obtained, and the agreement between theory and measurements is quite good. No change is observed between the investigated frequencies in the theoretical radiation patterns, a deduction that is also verified by the measured results.

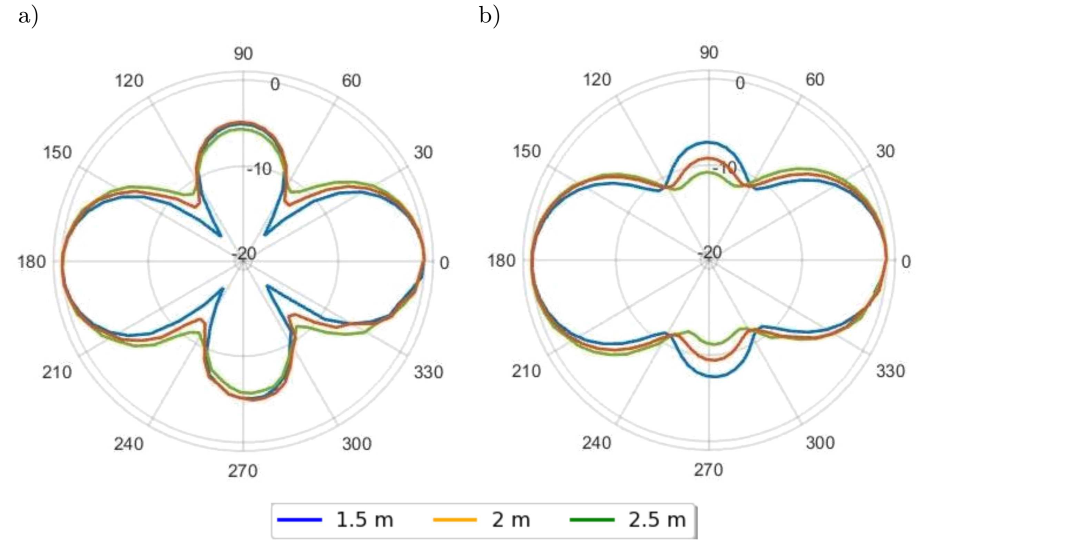

Fig. 4. Polar diagrams in degrees and dB. Longitudinal quadrupole numerical radiation at three near field distances for 40 Hz (a) and 80 Hz (b).

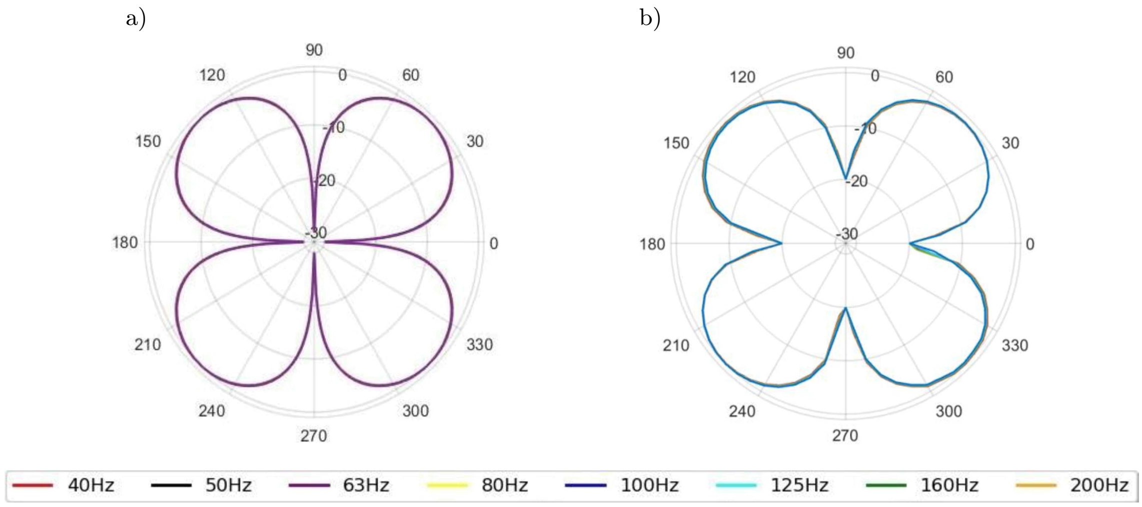

Fig. 5. Lateral quadrupole theoretical radiation: a) analytical, for the far field at 14 m, b) numerical, for the near field at 2 m. There is no distinction between the different frequencies.

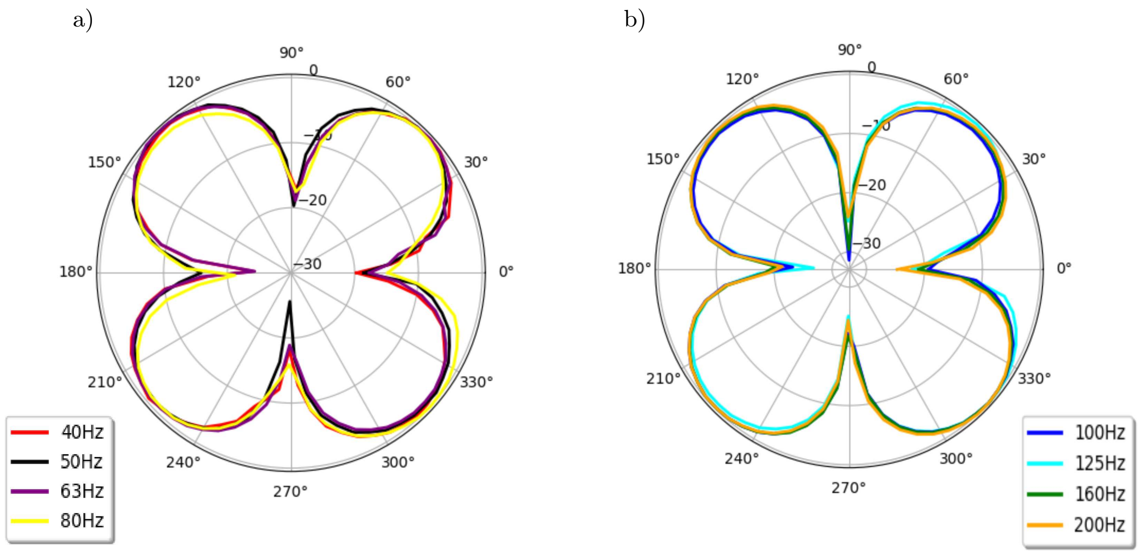

Fig. 6. Measured lateral quadrupole radiation in the near field at 2 m.

5. Discussion

The proposed sources were designed with the assumption that they radiate, at low frequencies and in free field conditions, like point sources. Additionally, the corresponding simulations were conducted with the combined stimulation of point sources. The specific simple source design choice was made for simplicity and clarity reasons, for which the fundamental design principle must be independent of the implemented sources. Another assumption was that the critical far field conditions for the quadrupole arrangements could not be achieved in the specific anechoic chamber for the frequency range under investigation. However, the full-perimeter response in modal conditions of the near field was considered as the proper assessment of the quadrupole set-ups, as it is intended to be applied for low-frequency control in small rooms, and consequently, they would radiate within modal sound fields with which they would be coupled.

It also was known that the ports of the vented loudspeakers operate as different acoustic centers in different frequencies, combined with the diaphragms. It was expected that in the lower frequencies, the topology of the acoustic centers is changing, resulting in different inter-dipole distances, depending on the configuration and orientation of the proposed sources. That was the price to pay to lower the frequency edge of the sources' response instead of applying additional mass on the cone diaphragms, which was considered as more problematic construction issue. However, the effect of the number, size, geometry, and position of the ports on the sound radiation should be further studied through more detailed simulations for optimization reasons.

Essentially, the only visible and significant difference between measurements and theoretical predictions occurs in a specific frequency, for which the influence of a chamber mode is very likely. In this case, the effect of the different acoustic centers, due to the venting ports, was rejected because the box-port resonance frequency is much lower. Moreover, it is assumed that the remaining deviations, such as the slight non-symmetry of the responses at the lower frequencies, are connected with the measurement conditions, which nevertheless are closer to the reality of the specific application conditions. Thus, the comparison results of the measurements with the simulations can be considered as a reasonable verification of the proposed sources' adequacy for their intended operation. After all, the proposed ANC method aims to adapt the directivity and coupling of the compound sources and not to generate a perfect quadrupole radiation pattern. Therefore, the likely differences between simulations and measurements are not of great concern as the principal concept is verified.

Owing to the potential adjustment of the effective operation range through the vents' geometry and the adaptive spatial radiation of the elementary monopoles' combination in various topologies, the proposed compound sources can be utilized for noise suppression at different frequency bands in a modal field. Furthermore, the control source can be in a fixed location, as has been investigated in our previous works. All the sound source advantages make the technique very feasible, especially in small enclosures where the available space for ANC implementation is often limited.

6. Conclusion

This work presents the assessment of compound sources radiation for low-frequency noise control through measurements in comparison with theoretical predictions. Quadrupole set-ups were measured to obtain the polar pattern in compromised free field conditions. The obtained measurements verify the analytical and numerical simulation results and validate the proposed ported low-Bl source design. The small-sized low-frequency sound sources offer the flexibility to configure numerous compound topologies.The design of the proposed sources is advantageous, and the next step is to develop an application, e.g. with an FxLMS-based algorithm, to adapt the compound sources' spatial radiation with a modal noise field. The presented results serve as a guideline to the integration of such an ANC system that will provide an effective alternative solution to the existing control systems in dealing with the abatement of the low-frequency noise, in cases of small enclosed sound fields.

Acknowledgement

The acoustic measurements took place in a fully anechoic chamber, built in accordance with the ISO 3745 standard, of the Hellenic Institute of Metrology, located in Sindos/Thessaloniki, Greece.

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