VPS VIBRATIONS IN PHYSICAL SYSTEMS

DOI: 10.21008/j.0860-6897.2022.1.01
Vibrations in Physical Systems, 2022, 33(1), 2022101

Numerical Directivity Simulations Of Speaker Arrays For Omnidirectional Sound Source Quality Assessment

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Abstract Omnidirectional sound sources are standard devices used in numerous acoustic measurements, such as the ones described in ISO3382, ISO140, or ISO354 standards. They are used when information on the sound diffraction at an object is required. State of the art findings describe several engineering designs of omnidirectional sound sources; some commercial applications can be also found. However, there is no universal design method for this kind of sound sources, neither in terms of the size and number of the transducers nor any general electroacoustic principles. This paper describes the use of Finite Elements Method (FEM) to derive the directivity patterns of different speaker arrays, such as spherical speaker arrays and the most popular polyhedrons. The number of transducers studied in the paper varies from 4 to 36. The influence of transducer size and the enclosure size was also preliminarily investigated. The simulation results were assessed with new strict omnidirectionality quality measures, and the influence of the transducers' number or size on a final omnidirectional sound source performance was verified.

Keywords: directivity assessment, speaker design, ISO354, ISO3382.

1. Introduction

An omnidirectional sound source in a 3D loudspeaker array format is one of the most recognized measurement devices in acoustics. They are used for standardized procedures, such as reverberation time measurements ISO3382 [1], sound absorption coefficient measurements in a reverberation room [2], sound insulation measurements described in ISO140 [3], and others. They are also commonly used in scientific and non-usual applications when sound source directivity must be neglected [4–6]. State of the art contains the engineering reports with the designs of traditional multi-transducer sound sources in arrays [7–9] and novel designs such as balloon dielectric elastomer sound sources [10], spark sources [11], or mimicked dodecahedrons [12]. While the new sound sources are being developed, the classic conventional speaker arrays are not sufficiently described in the literature and require deep revision and essential design principles development. Directionality of a sound source increases the uncertainty in many acoustic measurements [13–15]. This paper provides a critical review of a few implementations of the omnidirectional sound sources simulated in the Finite Element Method (FEM) environment. The goal of this paper is to answer the question of whether FEM modelling is a sufficient tool for initial sound source design phase and if it allows the determination of the required numbers and sizes of the transducers for the omnidirectional sound source.

2. Omnidirectional sound source assessment methods

The most commonly used method for evaluating sound source directivity is described in ISO 354 standard [2]; however, it is usually used for diffuse field measurements. The standard-based methods can be easily applied for the commercial sound sources intended for in-situ measurements and contain numerous "averages" and "smoothing" techniques, which improve the value of the final performance indicator. As a result, objectively worse and sometimes insufficiently omnidirectional sound sources, pass the tests required by the standards. There are few methods for assessing the omnidirectionality of a source based on essential statistical functions. The so-called **s**tandard **d**eviation of **a**rea-**w**eighted **l**evels (STD AWL – σ_{AWL}) is adopted in the presented work, following the criteria described in [8] and Equation (1):

$$\sigma_{AWL}(f) = \sqrt{\frac{\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} S_{m,n}\left[L_{m,n}(f) - \langle L_{m,n}(f)\rangle_S\right]^2}{\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} S_{m,n}}}, \tag{1}$$

where M, N are the total numbers of measurement points on the partitioned sphere. $L_{m,n}(f)$ is sound pressure level (SPL) measured at m,n points, $\langle L_{m,n}(f)\rangle_S$ is the average SPL – measured or calculated on the sphere of a given radius, and $S_{m,n}$ is the area of the sphere part corresponding to the point number m,n. As such, σ_{AWL} is a frequency-dependent objective metric that indicates the uniformity of the sound source strength over all directions. A large value of σ_{AWL} indicates that the sound source is not omnidirectional for a given frequency band. Leishman et al. [8] suggested using $\sigma_{AWL}(f)$ value of 1 dB as the threshold of a sound source omnidirectionality. The frequency at which this threshold is exceeded is described as the cut-off frequency f_0 of the sound source for the remainder of this paper. Together with the frequency-dependent parameter $\sigma_{AWL}(f)$, the average value of σ_{AWL} parameter was also used, calculated from all N_f frequency bands used in each case, in order to provide a single value rating for each configuration, following the Equation (2):

$$\mu_{STD} = \frac{\sum_{i=1}^{N_f} \sigma_{AWL}(f)}{N_f}. \tag{2}$$

3. FEM model for sound source directivity modelling

The literature review did not bring an explicit answer to the question of how the transducers should be placed on the sphere surface. In the case of polyhedron sound sources, the transducers are normally placed in the middle of each face. What arises curiosity, is the popularity of polyhedron sound sources over spherical ones. Nowadays, the only answer could be the complexity of manufacturing spherical enclosures. When spherical enclosure shape is considered, several sphere division algorithms can be used to divide a sphere into equal areas. In this paper, the Equal Partitions Algorithm derived by Paul Leopardi was applied with the use of dedicated MATLAB toolboxes [16]. The demonstration of algorithm effects and sphere partitions used in this research are shown in Fig. 1.

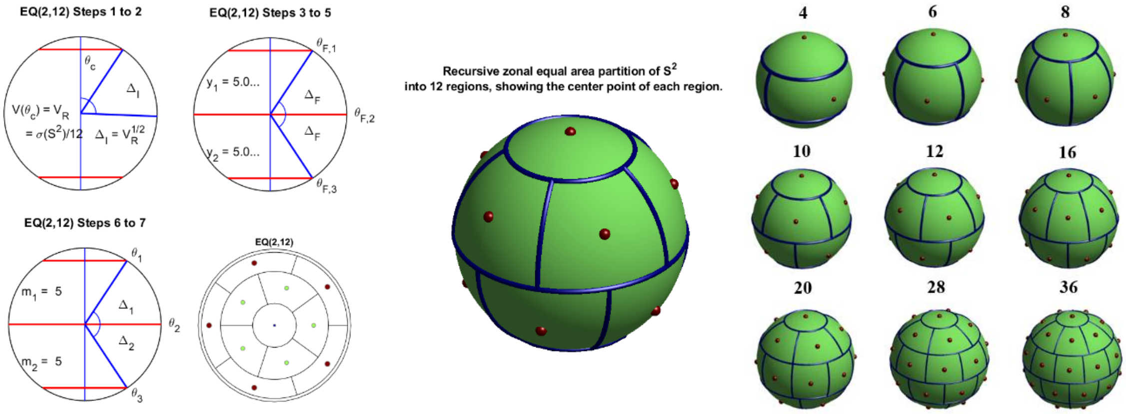

Figure 1. A scheme of equal sphere partition algorithm with resulting sphere divisions and the transducers distribution used in FEM directivity modelling.

To assess the omnidirectionality of the sound sources, a perfect rigid sphere (50 mm radius) with several cylinders (12 mm radius) mimicking electroacoustic transducers placed all over the surface was chosen to begin with in the FEM model. In this research, four strategies were investigated to derive the most effective modification trend to be pursued during the sound source performance optimization:

1. A number of transducers placed on a spherical sound source enclosure with Equal Sphere Partition Algorithm marked as EQ model, from EQ6 (6 transducers) to EQ36 (36 transducers). All transducers were 12 mm in radius.
2. Polyhedron-based sound source enclosures with the transducers in the middle of each face, transducers radius 12 mm, used geometries marked as a cube (6 transducers), octahedron (8 transducers), dodecahedron (12 transducers), and icosahedron (20 transducers). The tetrahedron is omitted in this research.
3. **R_T -** transducers size modification effect – considering the regular size of the spherical enclosure (50 mm radius) and EQ12 transducers placement, the modification of the transducers size was investigated, radii varying between 12-18-24 mm.
4. **R -** Enclosure size modification effect – similarly to point 3; keeping the transducers' size and number constant (EQ12 and 12 mm of transducers radius), the radius of the enclosure was investigated, varying between 50, 40, and 30 mm.

All described designs and strategies were designed as 3D models in FEM modelling software COMSOL Multiphysics. The enclosure surface was considered perfectly rigid, and the transducers were modelled as cylindric disks placed on the surface of the enclosures with acoustic velocity conditions applied to the surface. The models were placed inside the air sphere of a 1000 mm radius with PML conditions applied on the borders. The SPL was calculated on the sphere around the 1000 mm distance with 2° resolution for both azimuth and elevation angles. The model definitions for selected EQ partition models and all polyhedron geometries are presented in Fig. 2, together with an example of 3D directional patterns from the EQ12 geometry model.

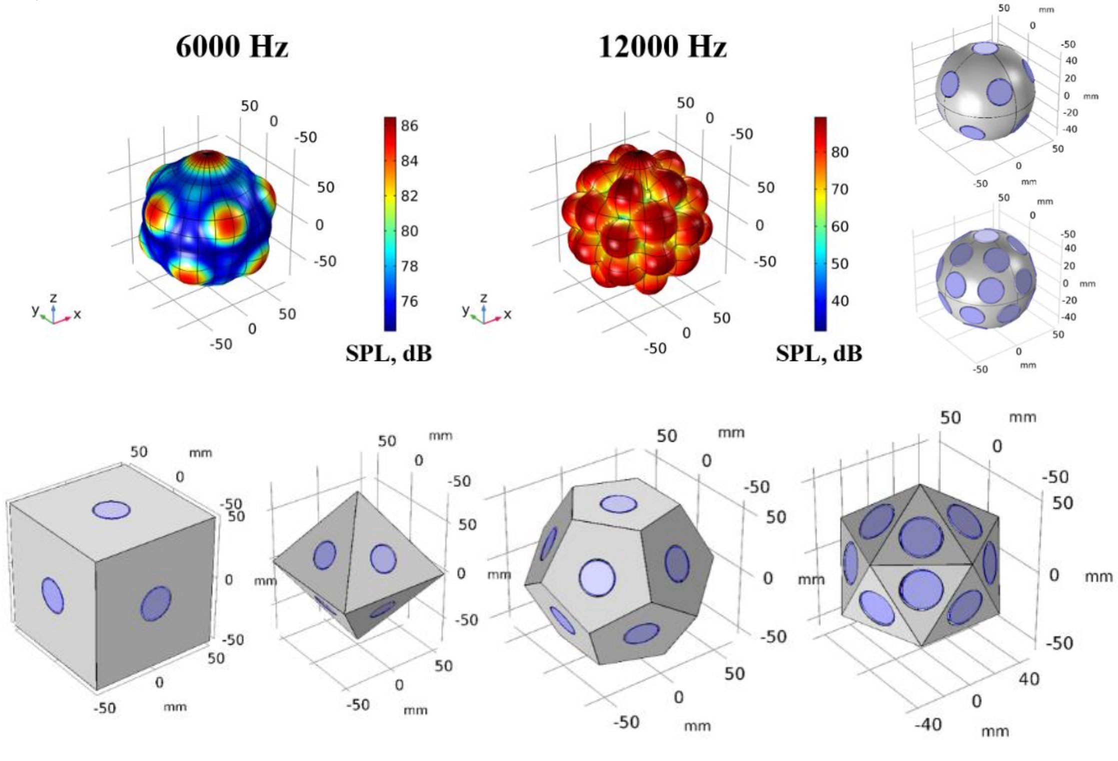

Figure 2. Example directivity patterns determined for EQ12 source variant together with several examples of geometry models used in the research.

4. Omnidirectional performance of the selected designs

This section discusses the results of the σ_{AWL} calculation for all the selected designs with the distinction between categories described in Section 3. Figures 3-6 present the σ_{AWL} as a function of frequency calculated for discrete frequency bands between 1000 and 16000 Hz with 100 Hz resolution.

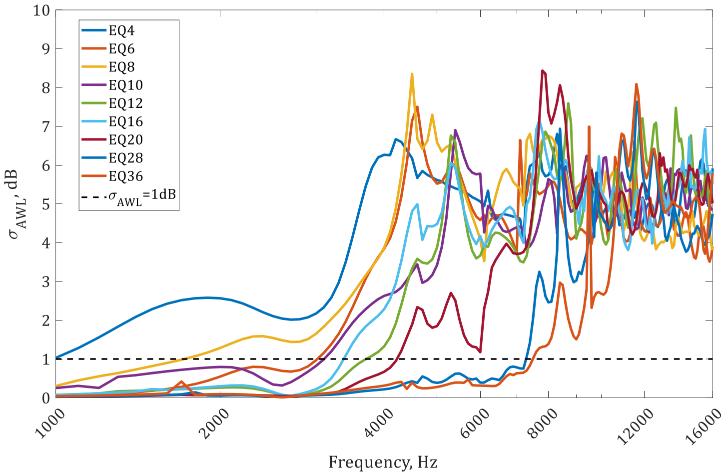

Figure 3. The influence of the number of transducers used for 50 mm radius omnidirectional sound source with 12 mm radius transducers on the value of σ_{AWL}.

The number of transducers used in a spherical loudspeaker array implies numerous construction problems with loudspeaker matching and increases the cost and weight of the sound source. In Fig. 3, a constant improvement of omnidirectionality with the increasing number of transducers is observed. However, the results seem to be partially grouped. We can observe similar results for models EQ6, EQ10, EQ12, and EQ16. A significant increase of σ_{AWL} and f_0 shift to around 7.5 kHz is observed for EQ28 and EQ36 models. Regardless of the average results or cut-off frequency parameter, for a small number of transducers such as EQ6, we observe good omnidirectional performance in the frequency range up to 3 kHz, which may be sufficient for some applications (such as ground impedance measurements [17]). A bigger number of transducers is desired when omnidirectionality is required in the high-frequency range as well. EQ8 configuration seems to be an exception from this pattern. It breaks the rule of better omnidirectional performance with the increasing number of transducers, leading to the preliminary conclusion that for some reason eight transducers may be the worst choice for an omnidirectional sound source.

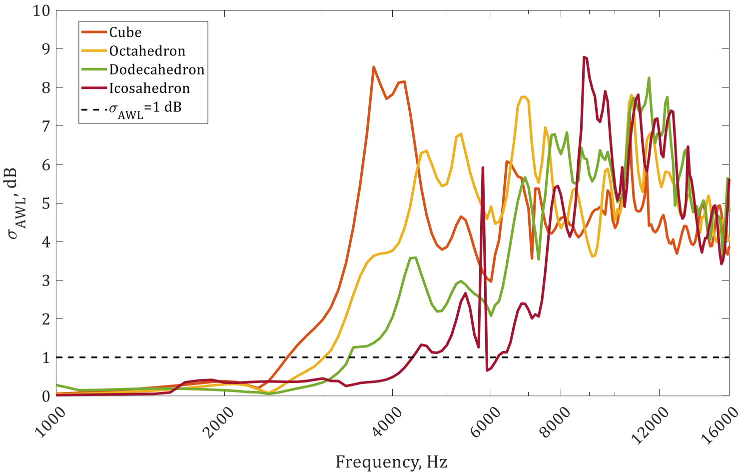

Figure 4. Directivity assessment of different polyhedrons modelled as omnidirectional sound sources with 12 mm radius transducers.

It is interesting to compare EQ6, EQ8, etc. designs with their polyhedron equivalents: cube, octahedron, and dodecahedron, presented in Fig. 4. In the polyhedron source type, we observe the same trend of better omnidirectional performance with the increasing number of transducers, the octahedron matching the general trend. Apart from the octahedron, other geometries seem to correspond with their EQ counterparts.

In this case, we can conclude that if the considered number of transducers has its polyhedron equivalent, there is no significant difference between spherical and polyhedral shape of the enclosure.

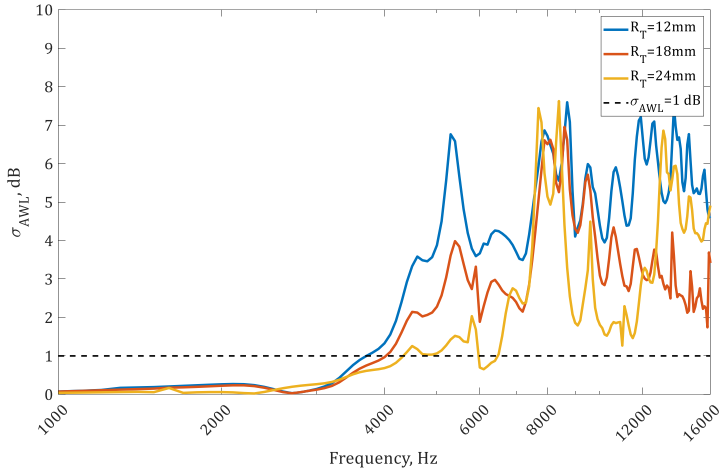

Figure 5. The influence of the size of the transducers within the range range of 12-24 mm in radius used for 50 mm omnidirectional sound source construction on the value of σ_{AWL}.

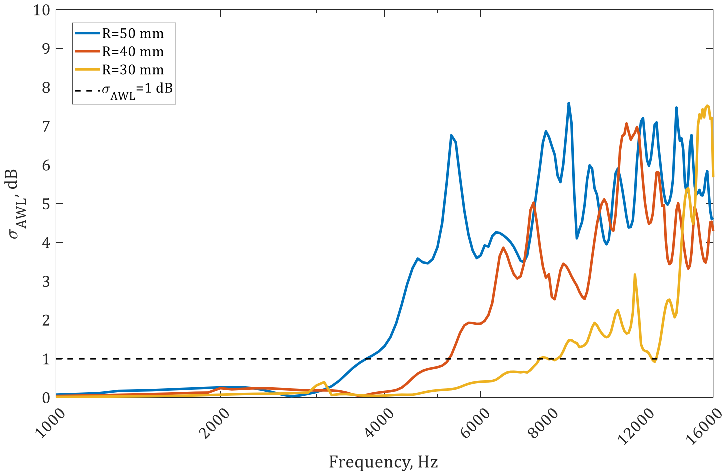

Figure 6. The influence of the size of the enclosure within the range of 50-30 mm in radius used with 12 mm radius transducers for omnidirectional sound source construction on the value of σ_{AWL}.

The last considered configurations are based on the EQ12 spherical matrix, which is the most common solution for omnidirectional sound sources. It is based on the dodecahedron shape and it is described in the literature as covering the highest percentage of the sphere with transducers [18,19]. While the use of the dodecahedron seems to be well-grounded in mathematical considerations, the practical aspects of the construction are critical and finally the loudspeakers do not cover the whole face surface. In this research, two approaches to increase the percentage coverage of the sphere surface were used: increasing the size of the transducers and decreasing the size of the enclosure. Both options improved the omnidirectionality of the modelled sound source. The size of the sound source is usually determined by the required sound source parameters, such as the desired frequency range and sound power level. On one hand, the smaller the sound source, the better its directional performance. On the other hand, the lower frequency or the higher power is required, the bigger transducers and enclosure must be used [6,20]. Nevertheless, we should try to keep the enclosure possibly small to receive the best omnidirectional directivity pattern.

5. Discussion

Several aspects need to be considered simultaneously while designing an omnidirectional sound source, and the final strategy should be a compromise between the frequency response and the desired sound power level. However, the directional pattern should be optimized each time. In this research, the number and the distribution of the transducers is studied in order to propose optimal design strategies for researchers and engineers in each particular case. The choice of the enclosure shape should be made after determining the desired SPL and frequency range of the sound source. However, the construction and electroacoustic aspects very often affect the initial assumptions for the sound source design. The enclosure scales up to fit the bigger transducers or their back parts like magnets and cones, so the number of the transducers must be known earlier to design an enclosure that will fit them. This section describes the results of the single-number parameters for an easy assessment of the described sound source models. Fig. 7 shows the cut-off frequencies and σ_{AWL} parameters averaged across the frequency range. The numeric values of the results are also pointed in Table 1.

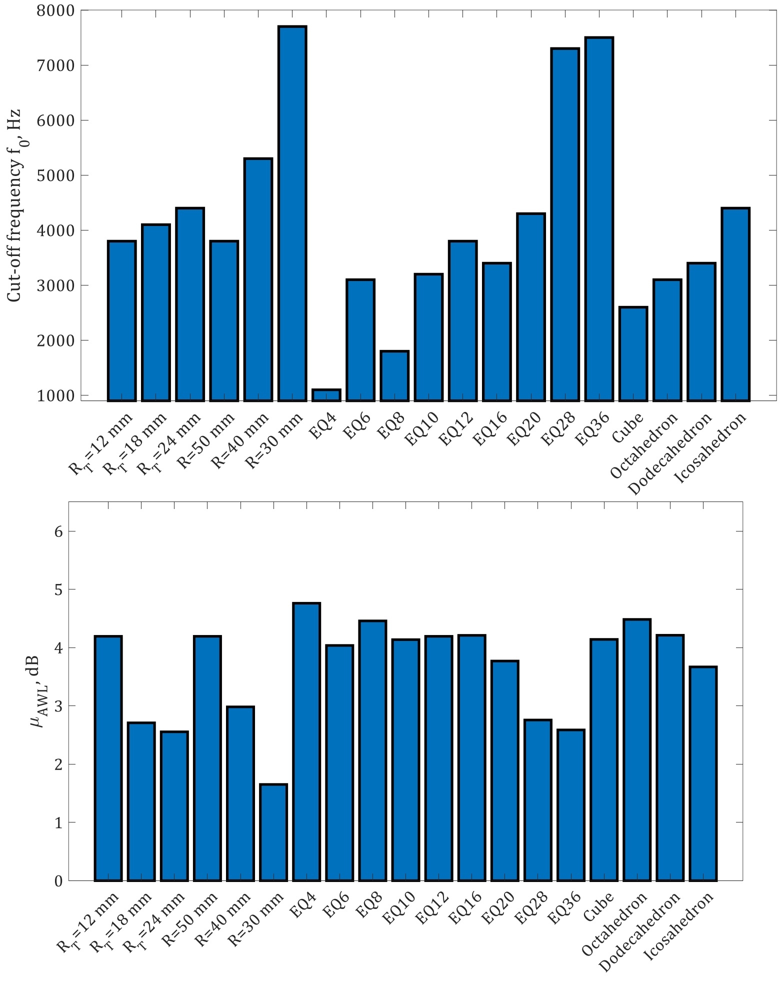

Figure 7. Cut-off frequencies f_0 (top) and σ_{AWL} (bottom) values averaged over the frequency range for all the tested omnidirectional sound source designs.

The analysis of the cut-off frequencies proves the advantage of the combination of the smallest enclosure and the biggest transducers used in the research – EQ12 configurations. However, the differences observed in the μ_{AWL} values are less dispersed than f_0. It is challenging to decide which of these two parameters is more important for the assessment of the omnidirectionality. f_0 can be used as a sort of a threshold where the source loses its omnidirectional character. However, the overall σ_{AWL} can also be used above the omnidirectionality limit, where we agree that the source is not perfectly omnidirectional, but we also want to perform the assessment. Practically, the difference between EQ patterns and corresponding polyhedrons is not observed (apart from the octahedron discussed in Section 4). What is important, is that the differences between EQ6-16 designs are relatively small in terms of μ_{AWL} and f_0 (except from EQ8). Following these results, we should consider that sometimes increasing the number of transducers from 6 to 12 or 16 can only causes a small improvement of omnidirectional performance. Maintaining the number of transducers and increasing their size or decreasing the size of enclosure may significantly improve source omnidirectionality. The practical aspects of a large number of transducers should be considered as well, such as the parameters matching and tolerance [21,22].

Table 1. Cut-off frequencies f_0 and σ_{AWL} values averaged over the frequency range for all tested omnidirectional sound source designs.

	RT12	RT28	RT24	R50	R40	R30	EQ4	EQ6	EQ8	EQ10
f_0	3800	4100	4400	3800	5300	7700	1100	3100	1800	3200
	EQ12	EQ16	EQ20	EQ28	EQ36	Cube	Octa.	Dodec.	Ico.	
f_0	3800	3400	4300	7300	7500	2600	3100	3400	4400	

	RT12	RT28	RT24	R50	R40	R30	EQ4	EQ6	EQ8	EQ10
μ_{AWL}	4.2	2.7	2.6	4.2	3.0	1.7	4.8	4.0	4.5	4.1
	EQ12	EQ16	EQ20	EQ28	EQ36	Cube	Octa.	Dodec.	Ico.	
μ_{AWL}	4.2	4.2	3.8	2.8	2.6	4.1	4.5	4.2	3.7	

6. Conclusions and summary

The paper discusses the choice of the number, size, and distribution of transducers in multitransducers speaker arrays. It was shown that in some cases, increasing the number of transducers in a spherical loudspeaker array does not provide a significant improvement of its performance. Equal Partition Algorithm transducers' distribution method was compared with classical polyhedron solids. It was shown that both methods provide similar performance in all the cases apart from the octahedron. Polyhedrons may be considered for technical reasons as they are usually easier to be manufactured. The performed experiments proved the advantage of keeping the transducers as large as possible on the surface of the source face and the enclosure possibly small to reach the best omnidirectional sound source performance. The proposed methods and findings may lead to a better understanding of omnidirectional sound source design methods and offer better products to the market. The final choice of the speaker placement strategy should be made in correspondence with practical sound source construction aspects, such as the size and the geometrical parameters of the speakers available on the market.

Acknowledgments

Research financed by a research grant for Ph.D. students from Dean of the Department of Mechanics and Robotics, AGH University of Science and Technology in Cracow.

Additional information

The author declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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