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# Comparison of Different Omnidirectional Sound Sources with the Validation of Coupled Speakers as a Measurement Source for Room Acoustics

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**Featured Application: The presented research describes the method of so-called coupled speakers used in the room acoustic measurements. It is a practical and cheap alternative to commonly used dodecahedral loudspeakers, which may be essential for multiple professionals and laboratories working in room acoustic. The solution offers proper results compared to dodecahedral sound sources for room acoustic parameters measurements, such as EDT, T30, D50, and C80, in the range of 250–2000 Hz.**

**Abstract:** Omnidirectional sources used in room acoustics usually take the form of multi-speaker sources. Few alternatives for the most commonly used dodecahedral sound source have been derived recently. The project aimed to measure room acoustic parameters using three different sound sources: a dodecahedron, a cube, and a new source of two coupled loudspeakers. The measurements were made by rotating the sources every 15 degrees. The differences in the EDT, T30, D50, and C80 parameters in the function of the rotation angle of the sources were analyzed. Statistical analysis was carried out to examine the sensitivity of the measured parameters' JND (just a noticeable difference) on the source's rotation angle. This presentation will show the results and analysis of measurements showing the influence of the used source on obtained parameters and the validation of coupled speakers' use. A comprehensive discussion of the results obtained with different sources (coupled, dodecahedral, cubic) will be provided. The results confirmed using the coupled speakers as an alternative for omnidirectional sound source in the range of 250–2000 Hz.

**Keywords:** omnidirectional sound source; acoustic measurement uncertainty; sound directivity

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## 1. Introduction

Room acoustic measurements perform a significant function in the architectural acoustic design process and qualify the room for the speech or music function. Therefore, performing those measurements with the highest possible accuracy is essential. However, it has been proven that in most acoustic measurements, significant uncertainty is present [1–3]. The direct connection between the source orientation and the source–receiver configuration's influence on the results of measurements was proven [2,4]. The dispersions in measured room acoustic parameters caused by the source-connected uncertainty propagate to the troubles in acoustic modeling and design process [1,5,6]. One of the reasons that is claimed to be a significant source of uncertainty in the room acoustic measurements is the non-ideal sound source directivity. Those features significantly interfere with the currently used strategies in the acoustic space design, which are based on numerical modeling with ray tracing or wave-model-based methods, and the later verification of the performed design with the acoustic field measurements, which is conducted using omnidirectional sound sources.

Omnidirectional directivity is a difficult-to-achieve characteristic of acoustic measurement sources. If the measurements are executed in a diffuse field, then the uncertainties caused by the source directivity can be minimized by averaging more measurements. However, nearly ideal omnidirectionality is significant when performing measurements in a free field, e.g., in an anechoic chamber [7]. The typical case in room acoustic is the mixed reverberant field, where the omnidirectionality is less crucial than in the free field but still can cause significant dispersion in the measurement results regarding the source used. The parameters such as C80 and EDT based on the early part of the decay curve can especially differ regarding the source directivity and their rotation. Omnidirectional sound sources are required in most standard room and building acoustic applications, as they are claimed to reduce the effect of the used source on the measurement results [8–10]. One of the best approximations of an acoustic point source is a dodecahedral loudspeaker array, which, in theory, is almost ideally omnidirectional in a frequency range depending on the source radius [11–13]. To be qualified for the field measurements, its directivity characteristic should meet the minimum requirements specified in ISO 3382 or ISO 140 standards [14,15]. Discovering a perfectly omnidirectional source causes the development of diverse dodecahedron alternatives, as some of the disadvantages of these solutions are already known. In the past, few papers were published providing comprehensive information on the influence of the non-ideal omnidirectional sound source directivity on the measured room acoustic parameters [2,4,16]. The research on dodecahedral source replacement focused on using impulse sources [17–19], but they do not offer complete control over the measurement signal. It was proved in previous research that impulse sources can replace electroacoustic sound sources, especially in places where the use of electric devices is limited, such as caves or catacombs [20–22]. The other alternatives studied [23,24] have significant limitations, such as the increased measurement length or the complication of measurement conduction. It eliminates the need for fast field measurement performance, which is crucial in experimental room acoustic. Some of the research provided the conclusion that the multiple-speaker arrays may cause significant changes in the measured acoustic parameters if one of the speakers is directly facing the microphone, so in that case, the limited number of loudspeakers in the omni-source simulation may provide better results and reproductivity.

To obey the known limitations of multi-speaker arrays, some novel sources were developed, such as the inverse horn approach source [25], elastomer balloon source [26], or laser induction-based sound source [27]. Those original solutions were efficient; however, they required developing complicated R&D processes, which are expensive in reproduction and may be challenging to recreate in a typical sound lab. Other researchers provided better methods for the external calibration of omni-sources to control their radiated sound field [28,29]. Those methods improved the radiated sound power level but did not offer significant gain in directivity, which is the main reason for troubles with the uncertainty of room acoustic measurements. At the same time, researchers also pursue alternatives that may be cheaper in construction as they may allow the undertaking of new types of measurements, such as those requiring multiple omnidirectional sources. Simple, cheap, and efficient omnidirectional sound source development is still needed.

The proposed research describes the experimental validation of the new concept of omnidirectional sound sources, called coupled speakers, where only two loudspeakers are used. The coupled speakers can be easily constructed with limited cost (the enclosure preparation and two loudspeakers)—the current project aimed to validate their use in room acoustic measurements. The proposed research was based on directly comparing three types of omnidirectional sound source representations to verify the possible dispersions between them and if the coupled speakers could be used as an alternative for dodecahedral or cubic sound sources. This paper is divided into the following sections: Section 2 describes the coupled speakers used in the room acoustic measurements and their advantages and disadvantages over other solutions in this field. In Section 2, the anechoic chamber measurements for the coupled speakers set are also presented. Section 3 describes the experiments conducted to prove the coupled speakers' validity for the measurement purpose and the descriptions of the derived parameters. Section 4 contains the analysis of the experimental results conducted in the example auditoria for educational purposes. Section 5 covers the conclusions and summary of the conducted experiments.

## 2. Coupled Speakers as an Omnidirectional Sound Source Representation

Coupled speakers are a novel solution for miniature omnidirectional sound source construction. Similarly to isobaric speakers, they are connected cone to cone but excited by signals in a coherent phase. A detailed explanation of the proposed concept and its preliminary verification was described in the referenced papers [30,31]. In the given research, the direct comparison between the coupled speakers and most common omnidirectional sound sources was conducted, employing also the cubic sound source and omn idirectional sound source from Bruel & Kjaer. The sound sources used in the current research are presented in Figure 1.

**Figure 1.** Omnidirectional sound sources used in the research—the coupled speakers (**left**), cubic omnidirectional sound source (**middle**), and dodecahedral omnidirectional sound source (**right**) [32].

The current version of the coupled speakers source was prepared using Visaton AL 140 loudspeakers, which shared the closed enclosure volume at a distance of 2 cm. The proposed concept of coupled speakers was formally tested in an anechoic chamber with the ISO 3382 requirements for omnidirectional sources. The sound directivity measurements were performed at 2 m from the source, and the angular resolution of 2 degrees was obtained using a rotating table. Figure 2 presents the directivity and frequency characteristics of implementing coupled loudspeakers conception. In the analyzed variant, coupled loudspeakers exhibit excellent omnidirectional quality in the range of 250–2000 Hz and a lesser quality for the last octave assessed following ISO 3382 standard. The frequency response was measured with an on-axis position to indicate the actual SPL output the coupled speaker system provided. It is essential to consider the coupled speakers' source characteristics regarding frequency response shown in Figure 3. Because of the coupled speakers' implementation (cone-to-cone placement inside the minimal volume), the source frequency response and sensitivity are significantly limited. However, the source should be helpful across the desired range of 250–2000 Hz. The present project aimed to experimentally validate coupled loudspeakers as a measurement source in room acoustics and compare them to different constructions of omnidirectional sources—dodecahedral and cubic.

In addition to the directivity assessment and on-axis frequency response, some directivity polar plots are presented in Figure 4. A direct comparison between the coupled speakers and the dodecahedral sound source was performed. It is clear that in lower octaves, both sources can be called omnidirectional, but in higher frequencies, the output SPL is strongly angle dependent. For the coupled speakers, we observe the conversion from the monopole to the dipole-like directivity characteristics for the frequencies near 4000 Hz and above. This limitation should be investigated in future works to improve this kind of design.

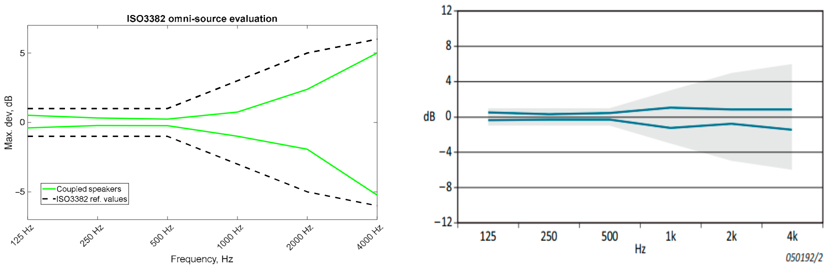


**Figure 2.** Measurement results of sound source directivity used in the research—coupled speakers (**left**) and B&K Type 4292 (**right**) [32].

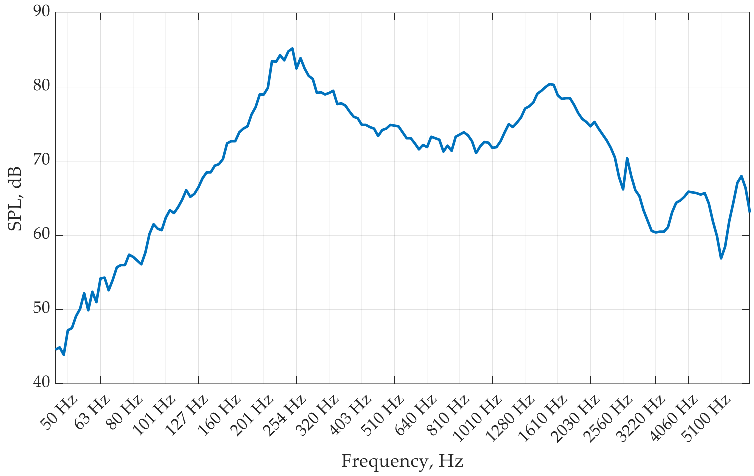


**Figure 3.** On-axis frequency response of coupled speakers used in the research.

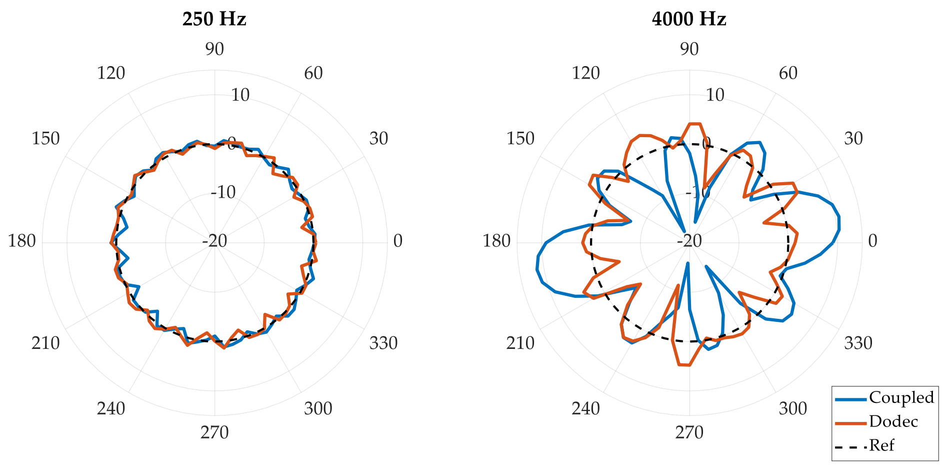


**Figure 4.** The comparison of coupled speakers and dodecahedral sound source directivity on polar plots for 250 Hz and 4000 Hz octave band.

The preliminary options for the coupled speakers' performance improvement were investigated. To improve the low-frequency range, speakers bigger than the 14 cm diameter Visaton 140 AL should be used, and for better high-frequency performance, a closer distance between the speakers should be used. However, adjusting the speaker's technical properties to the desired measurement function may be essential. The given research was designed to verify the possibility of this construction being used in room acoustics, but future works should also employ improvements in the directly coupled speakers' construction performance. In the next iteration of this project, the two-way type of coupled speaker construction should be investigated with different types of loudspeakers in two cone-to-cone distances for separated frequency ranges.

## 3. Method for Evaluating the Omnidirectional Performance of Source through On-Site Measurements of Acoustic Parameters

To verify the utility of coupled loudspeakers as an omnidirectional source and compare it with two other sources, on-site measurements of the acoustic parameters were conducted within a selected interior. Based on the previous research, a method using step rotation of the source was conducted with a resolution of 15 degrees. This type of measurement was established for the in situ omni-source verification via acoustic measurements [33]. The measurements were carried out in building D1 of the AGH University of Krakow in one of the lecture halls. The measurement situation is shown in Figure 5.

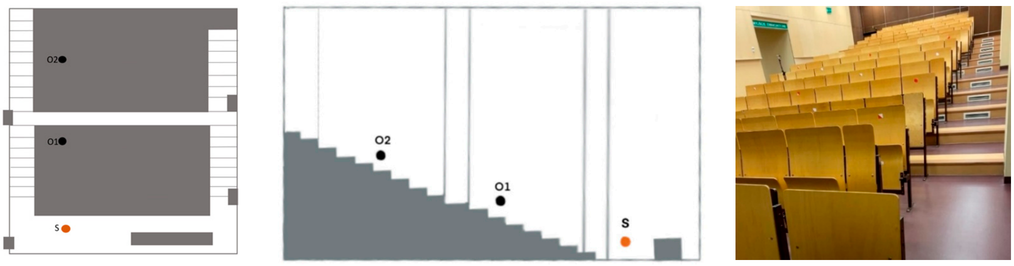


**Figure 5.** Measurement situation in the examined room. O1, O2—receiver positions, S—source position.

In theory, the ideal omnidirectional sound source should provide the same result of the acoustic parameters measured with a microphone at a given point, regardless of the angular position of the source. Previous research provided that this is difficult to achieve, and a better omnidirectional source is used—a smaller dispersion of the measured parameters is observed regarding the changes in source rotation. For each source, 24 measurements were performed by rotating them every 15 degrees using a protractor, allowing for precise rotation. The room impulse responses were determined using the swept-sine measurement method. The measurements were conducted using GRAS 46AE free-field microphones. A cubic source manufactured in the Laboratory of Technical Acoustics at AGH and a dodecahedron sound source Bruel & Kjaer type 4295 were used as alternative sound sources. Based on the acquired signals, the acoustic parameters of the room, such as reverberation time and energy coefficients (D50, C80), were determined in the B&K Dirac 5.0 program.

When the directivity deviations are near the limits stated in the norm, the recommendation is to rotate the source three times and average the results to decrease the possible dispersion in measurements. A minor standard deviation determined from the conducted measurements indicates better omnidirectional source quality and qualifies it for performing measurements in room acoustics. Based on this assumption, the two stages of analysis were performed:

1. The acoustic parameter deviation in the function of source rotation—this method will allow us to study directly how the given parameter changes regarding the source's angular position, which was recognized in the reference papers [2,4]. This analysis was performed for two points marked in Figure 4.
2. Single-value parameters analysis in the function of frequency for all measured sources, which was the comparison of standard deviation (SD) calculated from all rotation angles in measurement points (24 measurements) divided by the JND values defined in the standard ISO 3382 [14]. The analysis of this parameter was previously described [1,34], as it describes the possible audibility of the changes in room acoustic parameter estimation based on the given measurements. If the value of SD/JND is greater than 1, the changes could be audible, and the source should not be used for the measurements. This analysis was provided as an average from two measured points in the room.

The most common room acoustic parameters, such as EDT, T30, D50, and C80, were used for the analysis [35,36]. The EDT (early decay time) is one of the reverberation time parameters used in acoustics. It is calculated considering the time in which the sound pressure level decays by 10 dB from its original value, and then, it is extrapolated to −60 dB decay time as RT60 [36]. Based on its definition, EDT is strongly connected with the subjective perception of reverberation. The EDT was considered the parameter most affected by the source rotation [34,37] as the rotation performance may affect mainly the distribution of early reflections, which may lead to EDT value change. The T30 was selected for analysis as it is the most common parameter for the room acoustic measurements, for example, for the calibration of geometrical models [38,39].

Similarly to EDT, it is an extrapolated value of RT60 decay time but calculated considering the decay from −5 dB to −35 dB of the decay curve [36]. As the decay curve's first part is not included in this calculation, the T30 should be less affected by the strong first reflections and should keep better consistency in the proposed research. In addition to reverberation time parameters, the energetic parameters were considered. The C80 is marked as a "clarity" parameter for music and is defined following Equation (1) [40]:

$$C_{80} = 10\log\frac{\int_0^{80\ ms} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}, \tag{1}$$

where $p(t)$ is the room's impulse response at the given point, the resulting parameter $C_{80}$ (clarity) is expressed in decibel measure. $D_{50}$ has a similar formula in Equation (2) [40]; however, the result is typically presented in the percentage value:

$$D_{50} = \frac{\int_0^{50\ ms} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}. \tag{2}$$

Parameters defined by Equations (1) and (2) consider the early part of the decay curve up to 50 or 80 ms, where the impulse response is integrated. Based on their equations, the D50 and C80 energetic parameters should be less affected thanks to the averaging method used in their calculation [29,41], and the shift in reflection distribution should not affect those features.

## 4. Results

### *4.1. Analysis of Acoustic Parameters in the Function of Source Rotation*

To describe the differences in measurements, an analysis was conducted on the variations in these parameters as a function of the source rotation, which is one of the methods for analyzing the influence of source directivity on acoustic measurement results. The graphs illustrating these dependencies for the investigated sources are shown in Figures 6–9. In this chapter, the most crucial data were analyzed to illustrate the essential differences across the sources, while Section 4.2 will comprehensively compare the sources with single number parameters. Point 1 was analyzed in two representative frequency bands, while 1000 Hz emphasizes the proper results received with omnidirectional sound sources and 4000 Hz octave band—the significant dispersion in the received results.

For the frequency of 1000 Hz (Figures 6 and 7), changes in the value of the C80 parameter are similar regardless of the tested source, and they remain within the border of 1.5 dB, which is the JND for this parameter. The most minor changes in C80 can be observed for the coupled and dodecahedral loudspeakers. For the cubic source, the differences were the most significant. Besides the rotational changes, the obtained C80 values differ significantly in absolute value regarding the sources used. Despite all tested sources being qualified for measurements in this frequency range and exhibiting good omnidirectional quality, the range of results exceeded 4 dB, which requires further analysis and verification as two of the used sources were commercially available, professional sound sources. This is an important finding indicating that the currently used standards for omnidirectional sources qualification may not be accurate as even the professional sound sources (cubic and dodecahedron) provide the dispersion in measured values (such as 2 dB in C80 in 1000 Hz, 0.2 s in EDT in 4000 Hz). However, with the detected dispersion in the dodecahedral and cubic source results, the coupled speakers received proper compliance with professional sources. The shape of the curves observed in the T30 analysis may indicate the variability across the measurements. However, it is essential to note that the absolute difference in the T30 values was within 0.08 s across all sources, and the maximum dispersion between the coupled speakers and dodecahedral source was 0.05 s, which is below the JND in this case and qualifies all sources for proper T30 estimation in this frequency range. As T30 is the most important reverberation parameter used for the calibration of geometrical models, proper compliance between the used sources is essential. Regardless of the step rotation, all sources provided the dispersion below the JND.

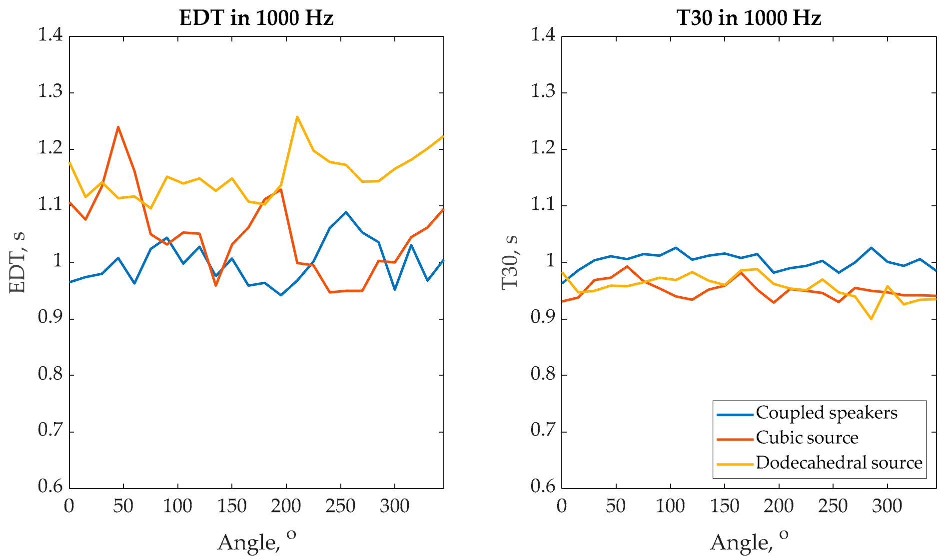


**Figure 6.** The results of the measurement of EDT and T30 parameters in the 1000 Hz octave band performed with the 3 versions of omnidirectional sound sources in the function of source rotation.

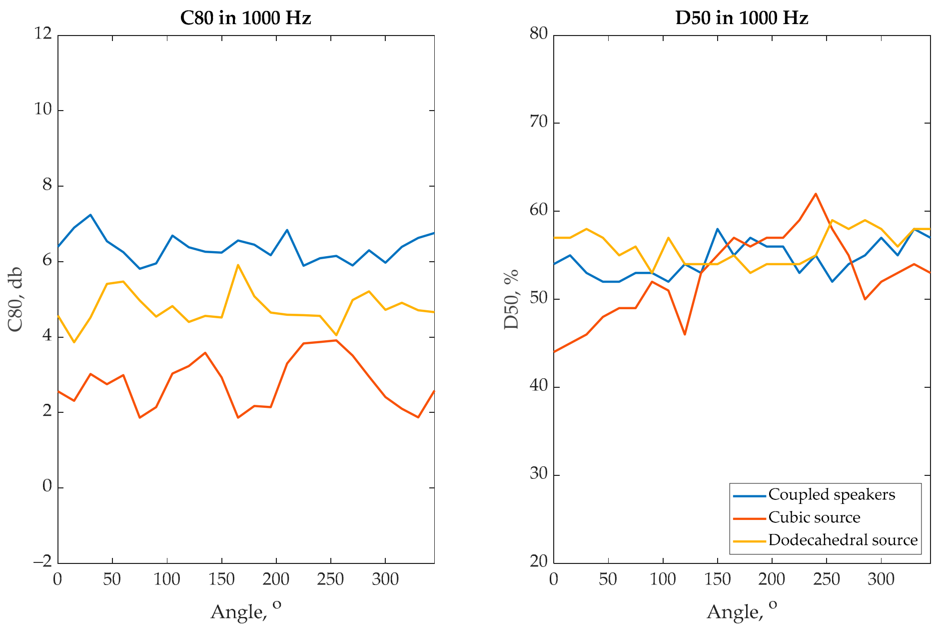


**Figure 7.** The results of the measurement of D50 and C80 parameters in the 1000 Hz octave band performed with the 3 versions of omnidirectional sound sources in the function of source rotation.

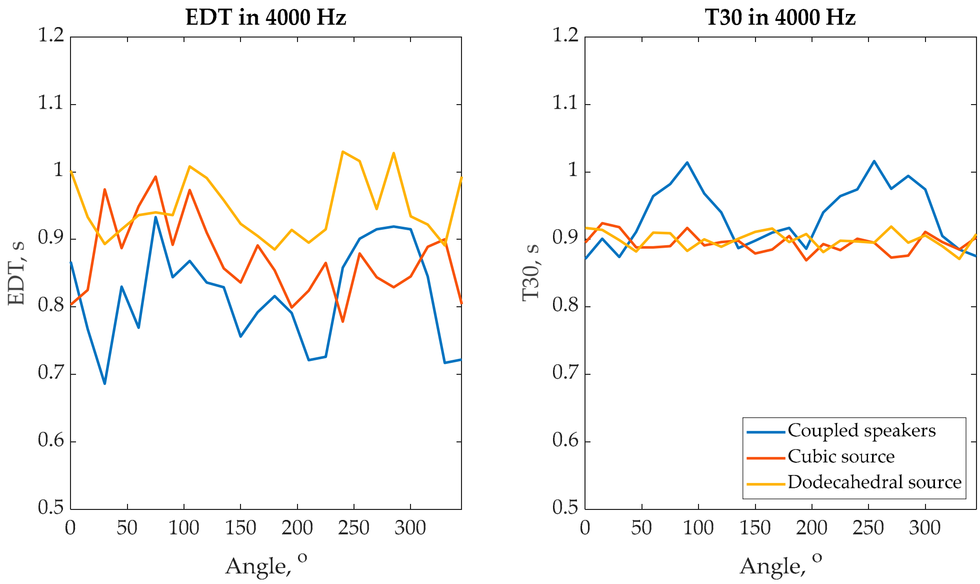


**Figure 8.** The results of the measurement of EDT and T30 parameters in the 4000 Hz octave band performed with the 3 versions of omnidirectional sound sources in the function of source rotation.

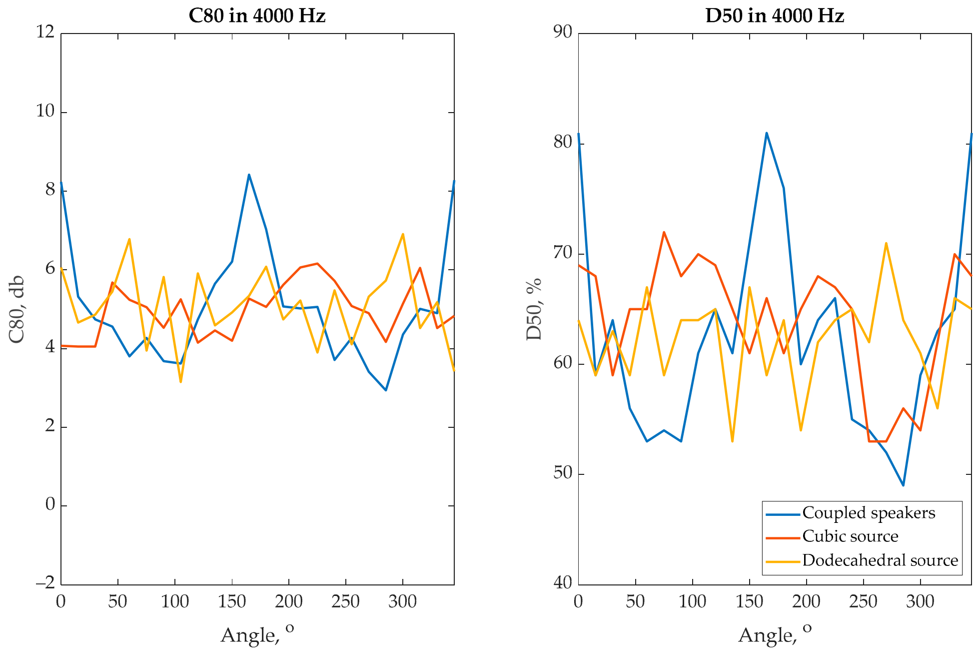


**Figure 9.** The results of the measurement of D50 and C80 parameters in the 4000 Hz octave band performed with the 3 versions of omnidirectional sound sources in the function of source rotation.

Analyzing the frequency of 4000 Hz (Figures 8 and 9), significantly worse results can be observed for the coupled loudspeakers, which also corresponds to a significant deterioration in the omnidirectional quality of this source type at high frequencies. In this case, the discrepancies between the sources directly stem from differences in their directivity. It is observed in which case the loudspeakers were facing the microphone or the walls of the room, and the conclusion is that in this frequency range, even if the requirements set by ISO 3382 standards regarding the source directivity were met, the coupled speaker source should not be used in measurements. This is also an essential finding that even when the standard conditions are met and higher averaging is performed, the differences between the omnidirectional sources used for measurements could be significant. It is important to note that regardless of the significantly worse coupled speakers' performance in the 4000 Hz octave band, the professional sources also provided noticeable dispersion in the high-frequency range. By averaging the step rotation for all sources, the average value should be similar for all selected sources. However, it is essential to indicate that it is possible that with the three-step rotation point (as suggested in ISO 3382), the high-dispersion rotation angles may be selected, and the dispersion in measurements will increase. For this reason, using a higher number of rotation angles for the sound source is suggested if the possible lack of omnidirectionality occurs. For this reason, the improvement of coupled speakers design may be necessary if their advantages will also be brought to higher frequencies, and some detected disadvantages of professional sound sources may be obeyed.

Additional data regarding this section and all measurements performed are shown in Appendix A. Due to the high amount of data used, only the most essential data are presented in the current chapter; however, it is crucial to note that the high dispersion between the used sources is often. For further discussion, see Appendix A.

### *4.2. Analysis of the Source Rotation on the Change of the Measured Acoustic Parameters in the Room*

After analyzing the parameter variations as a function of rotation for each source, a comprehensive analysis of all parameters determined at each measurement point was also conducted. The SD/JND analysis was applied following the methodology in [1]. Standard deviations divided by the Just Noticeable Difference (JND) were also calculated to compare parameters expressed in different units (Figures 10–12). JND represents a minor perceptible difference in values of individual acoustic parameters as perceived by humans, and its values were defined in ISO 3382-1 standard. The value SD/JND over 1 indicates the high audibility of the changes in source rotation and should be avoided.

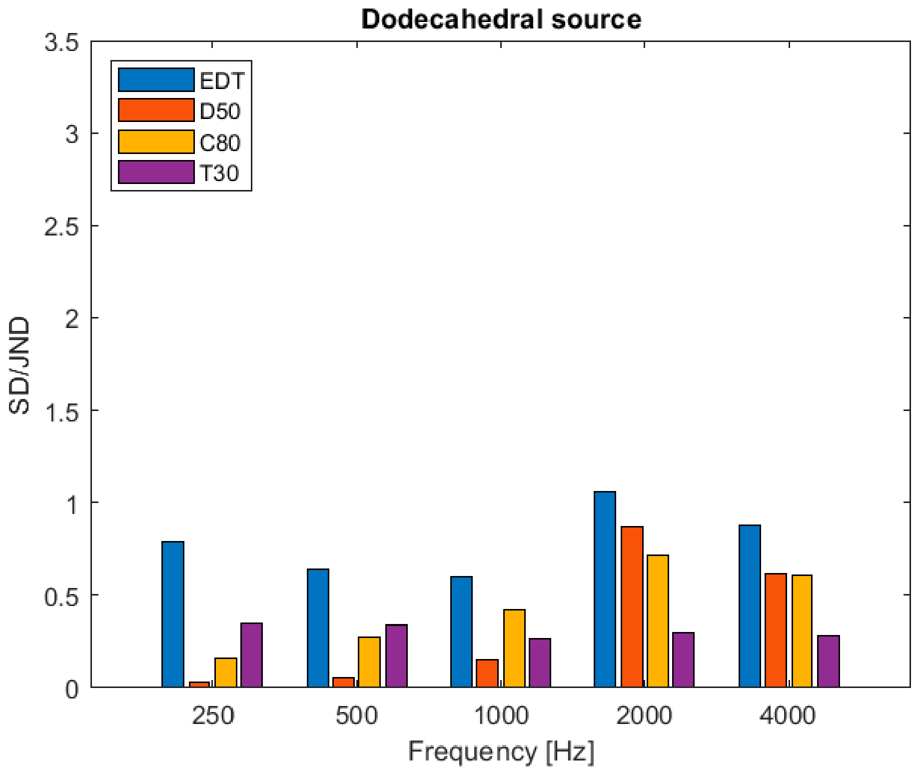


**Figure 10.** SD/JND values for dodecahedral source.

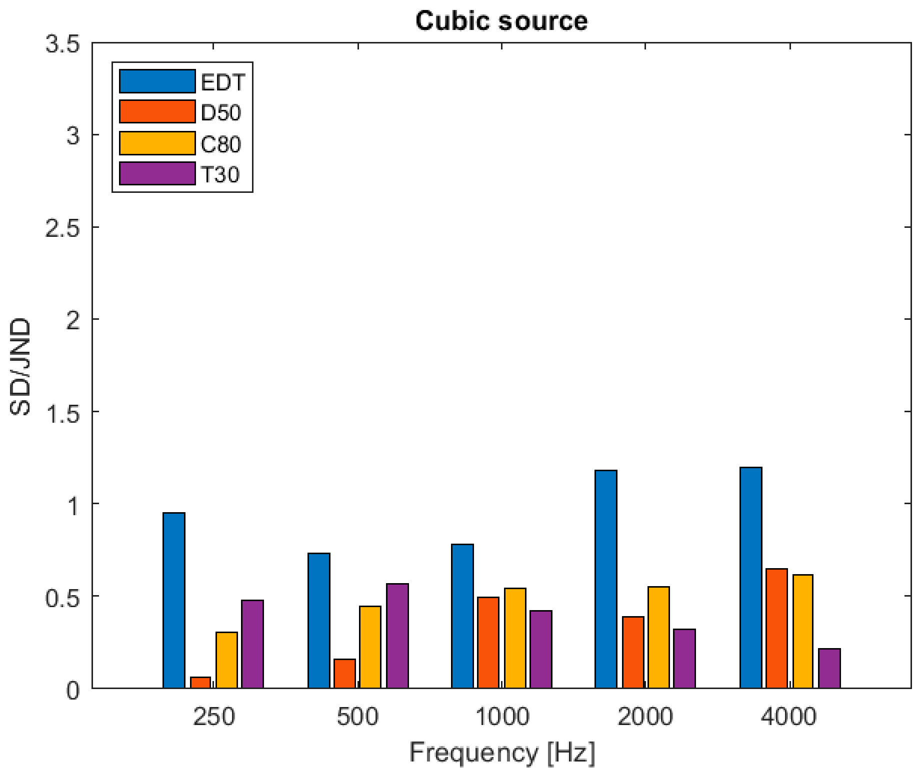


**Figure 11.** SD/JND values for cubic source.

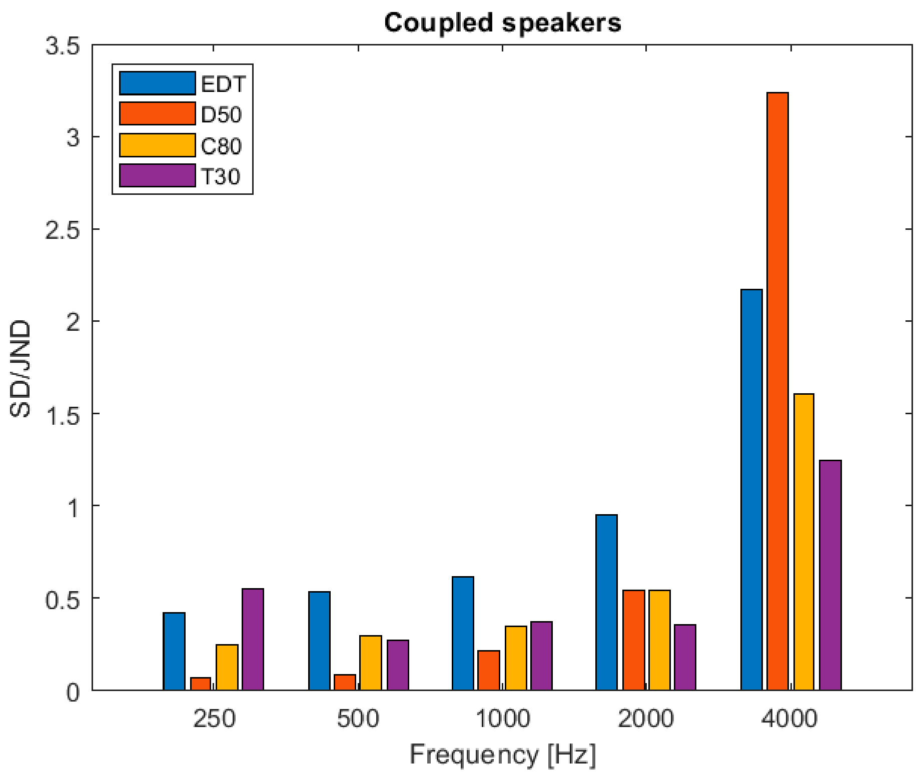


**Figure 12.** SD/JND values for coupled speakers.

Comparing the graphs, it was observed that the coupled loudspeakers achieve the lowest values of the SD/JND parameter in the frequency range of 500–2000 Hz. However, its performance differs for the parameters selected for the comparison. Above this range, the deviation values significantly increase along with the deteriorating directivity characteristics. Based on this, it can be concluded that within this frequency range, the coupled loudspeaker source meets the requirements for indoor acoustic testing devices and achieves better results than analogous commercial systems. For easier comparative analysis, the SD/JND values are also presented in Table 1, where the lowest (green) and highest (red) values are compared for each parameter and each frequency band analyzed.

**Table 1.** Tabular representation of SD/JND values for all measured sound sources (coupled speakers, dodecahedral sound source, cubic sound source).

| | **SD/JND** | **250 Hz** | **500 Hz** | **1000 Hz** | **2000 Hz** | **4000 Hz** |
|---|---|---|---|---|---|---|
| EDT | Coupled | 0.42 | 0.63 | 0.60 | 0.88 | 2.66 |
| | Cubic | 0.95 | 0.74 | 0.78 | 1.18 | 1.20 |
| | Dodecahedral | 0.79 | 0.64 | 0.60 | 1.06 | 0.88 |
| D50 | Coupled | 0.07 | 0.08 | 0.22 | 0.55 | 3.24 |
| | Cubic | 0.06 | 0.16 | 0.49 | 0.39 | 0.65 |
| | Dodecahedral | 0.02 | 0.05 | 0.15 | 0.87 | 0.61 |
| C80 | Coupled | 0.24 | 0.30 | 0.35 | 0.54 | 1.61 |
| | Cubic | 0.3 | 0.44 | 0.54 | 0.55 | 0.61 |
| | Dodecahedral | 0.15 | 0.27 | 0.42 | 0.71 | 0.61 |
| T30 | Coupled | 0.55 | 0.28 | 0.38 | 0.35 | 1.25 |
| | Cubic | 0.47 | 0.57 | 0.42 | 0.32 | 0.22 |
| | Dodecahedral | 0.34 | 0.34 | 0.26 | 0.30 | 0.28 |

Detailed analysis of Table 1 leads to the following conclusions:

- The coupled speaker solution is unsuitable for measurements in the 4000 Hz octave band as the received values of SD/JND were very high.
- In the overall comparison, the cubic source occurred as the worst across the measured parameters, while in the frequency range of 250–2000 Hz, the coupled speakers performed better or no worse than the dodecahedral sound source.
- EDT—The coupled speakers were selected the best in the range of 250–2000 Hz, proving the superiority over both dodecahedral and cubic sources, while only in the 1000 Hz band did the dodecahedral sources provide the same results as coupled speakers.
- D50—In the frequency range of 500–2000 Hz, all sources performed correctly in those measurements but received decent results as the SD/JND values were significant except for the 250 Hz band.
- C80—The results in measurements with coupled speakers and dodecahedral sound sources were very similar in this parameter except for the octave band 4000 Hz, while the overall values of SD/JND were also relatively small. The worst results were received for a cubic type of source.
- T30—The SD/JND values across all sources and frequency ranges used in the comparison were similar, where no source superiority was proved. This indicates the conclusion that if the analysis will be limited only to reverberation time, the sources perform similarly.

It is essential to state that the conclusions provided above are based only on the step-rotation source of dispersions (SD/JND analysis), while the differences in the general absolute value between the sources were significant. However, in the current state of research and the state of the art, it is impossible to compare the direct results and state which value of the analyzed parameter was the ground truth.

## 5. Conclusions

Acoustic parameter measurements were performed using three omnidirectional sources: coupled loudspeakers, dodecahedron, and cubic source. The step rotation of 15 degrees was performed to determine if the measurement results of the possible source position would differ. The standard deviations of the obtained results were analyzed to compare the performance of the coupled loudspeaker source with the commonly used omnidirectional sources. Based on the calculated parameters EDT, T30, C80, and D50, as well as the analysis of the standard deviation divided by JND, it was found that coupled loudspeakers are highly useful in measurements within the 250–2000 Hz range. It was also demonstrated that for commonly used cubic/dodecahedron sources, significant differences occur depending on the source rotation, and using three different source positions may not be sufficient. It is important to note that in T30 measurements, all sources performed similarly, so if the analysis should be limited only to reverberation time, the influence of different sources used may be neglected. The final statement is that the coupled speakers could be a cheap and effective replacement for commercial dodecahedral sound sources in room acoustic measurements. The negative features of this solution are a limited frequency range (currently 250–2000 Hz) and relatively low overall output SPL. Reaching the desired SNR with coupled speakers may be difficult in noisy environments or large venues. Further research should explore methods to improve the omnidirectional quality of coupled loudspeakers, particularly in the 4000 Hz octave, to achieve full utility in architectural acoustics measurements. Also, possibilities for higher output SPL (higher sensitivity) should be investigated.

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## Appendix A. Complete Results of the Performed Measurements

The complete measurement results are presented to support scientific transparency and further cross-verifications. The following chapter contains the measurements for both points in all significant octave bands, presented separately for all sources (Figures A1–A8). It is essential to notice that for several cases, even the commercial sources (cubic, dodecahedral) could provide significant dispersion in measurement results:

- Figure A2—dodecahedral source in 250 Hz provided 10% higher value of D50 than the average;
- Figure A2—cubic source in 500 Hz provided a 15% lower value of D50 than the average;
- Figure A3—cubic source in 250 Hz provided a 4 dB lower value of C80 than the average;
- Figure A4—cubic source in 500 Hz provided a 4 dB lower value of C80 than the average;
- Figure A7—cubic source in 250 Hz provided 0.2 s lower value of EDT than the average;
- Figure A8—dodecahedral source in 250 Hz provided 0.3 s higher value of EDT than the average.

The surprising results stated above may lead to concerns about using a cubic source in room acoustic measurements as this source has the highest number of outliers. Comprehensive research projects using currently used omnidirectional sound sources should still be conducted.

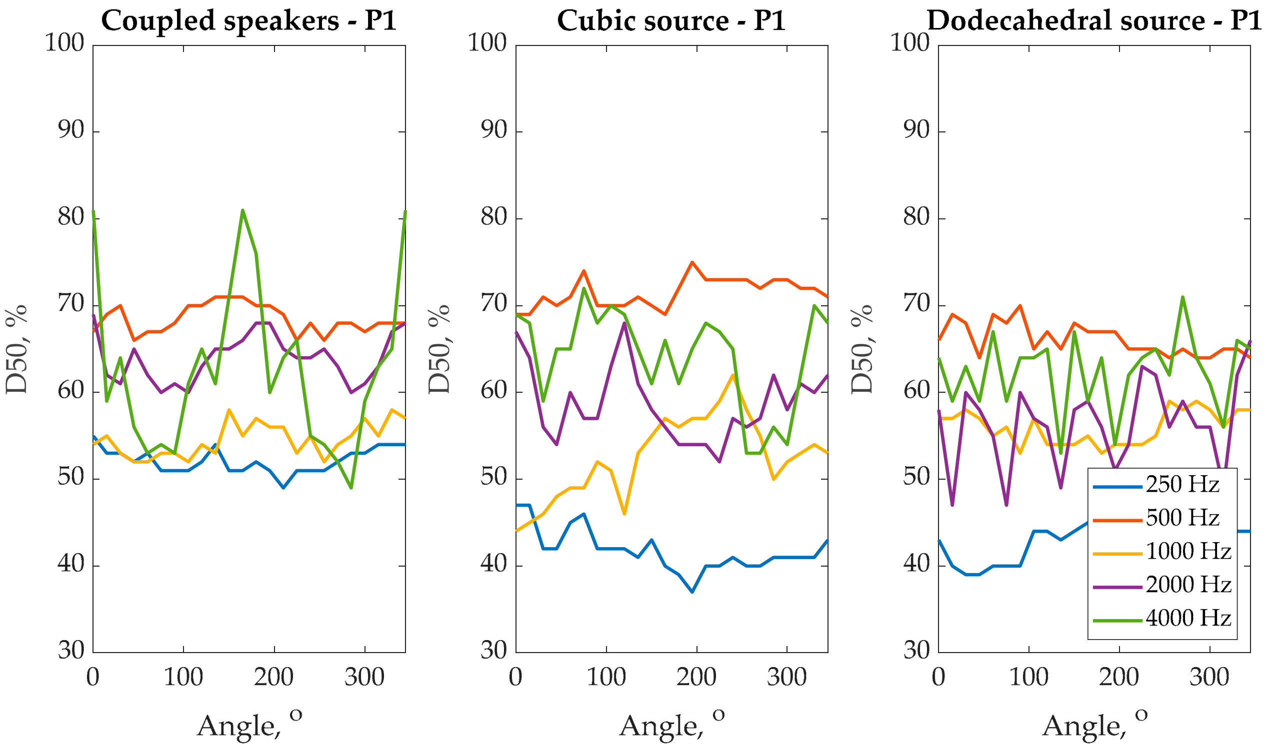


**Figure A1.** The results of D50 measurements in P1 position.

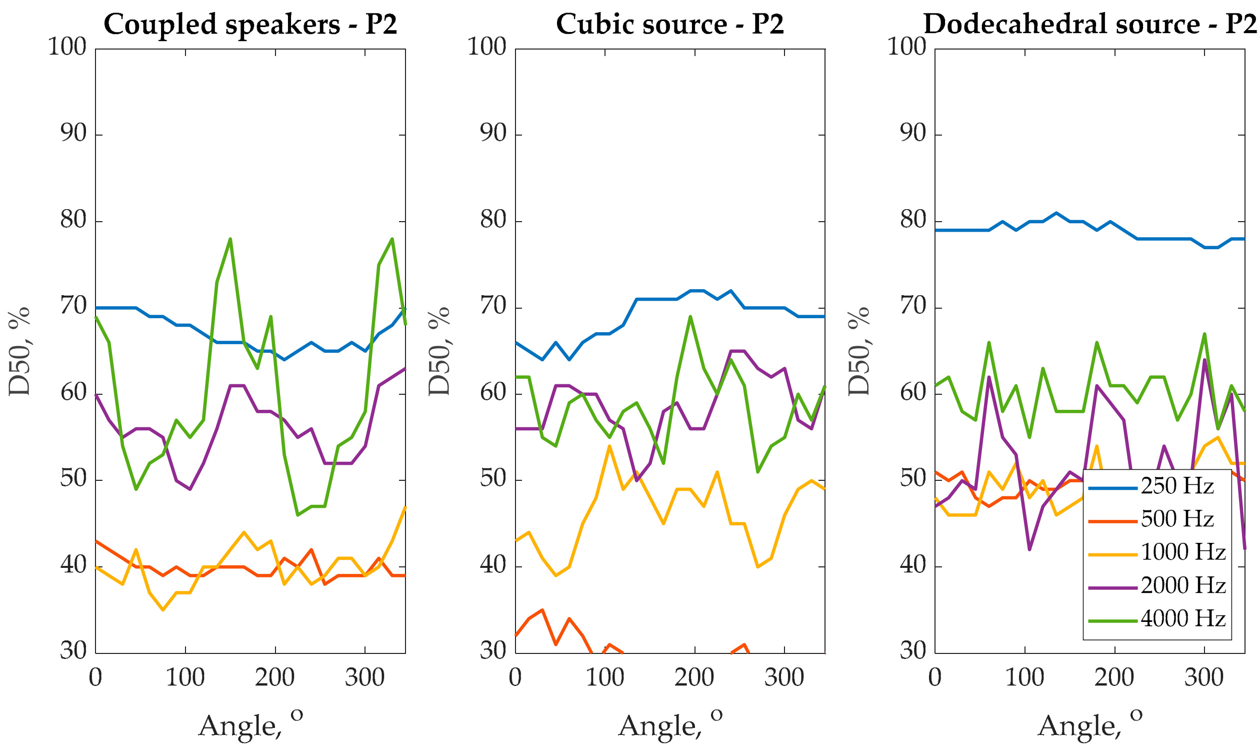


**Figure A2.** The results of D50 measurements in P2 position.

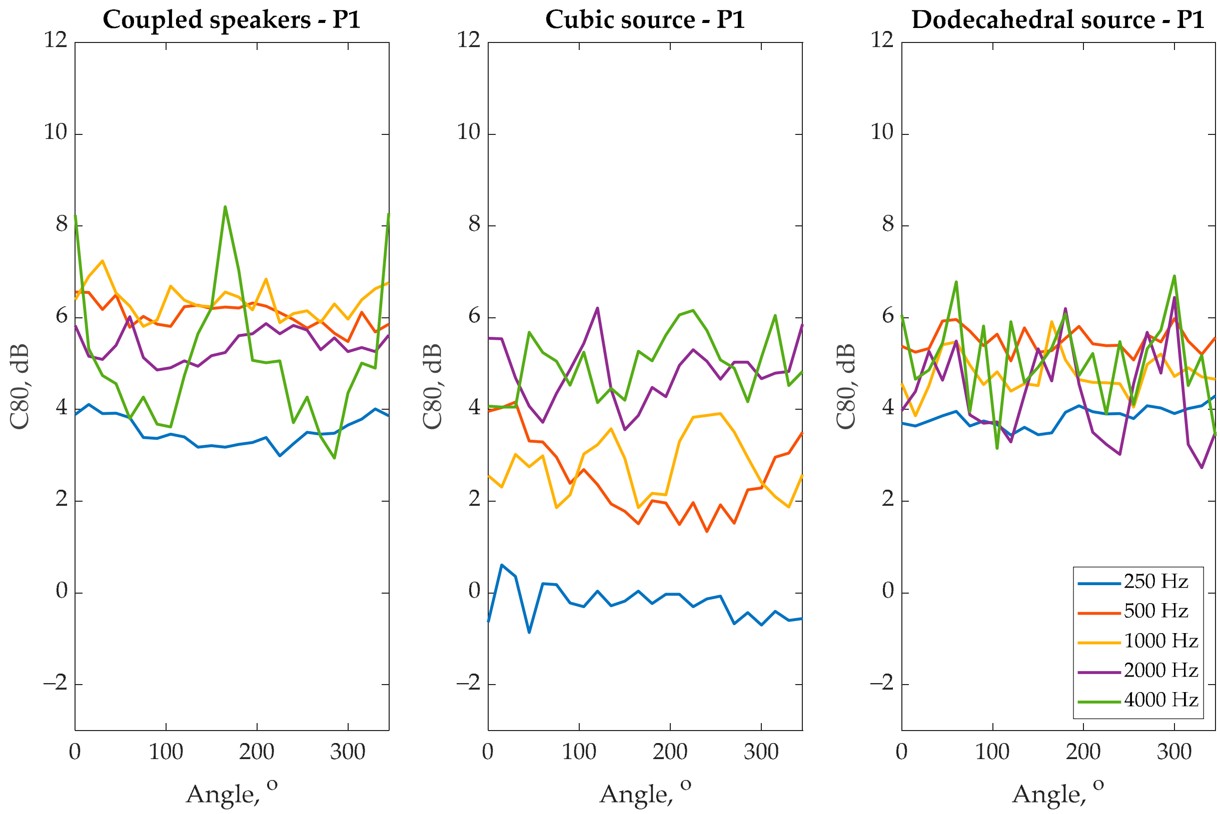


**Figure A3.** The results of C80 measurements in P1 position.

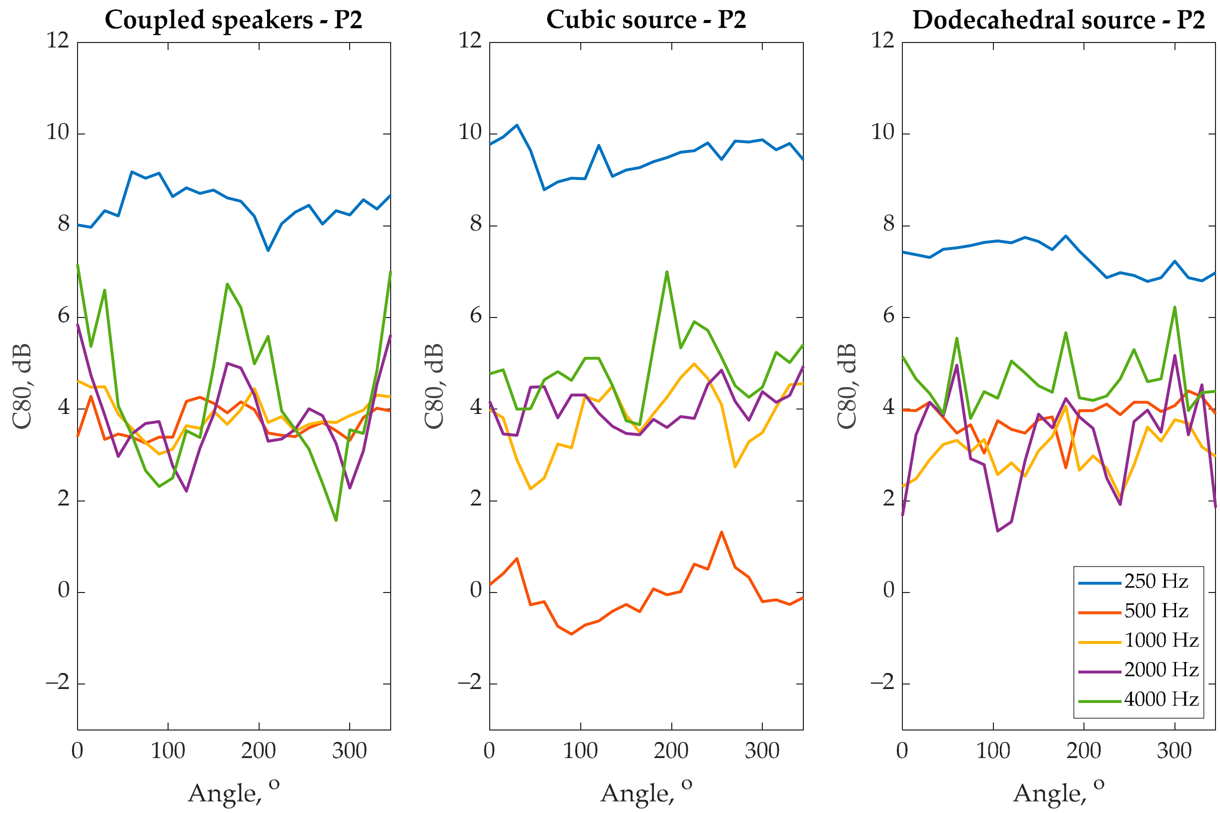


**Figure A4.** The results of C80 measurements in P2 position.

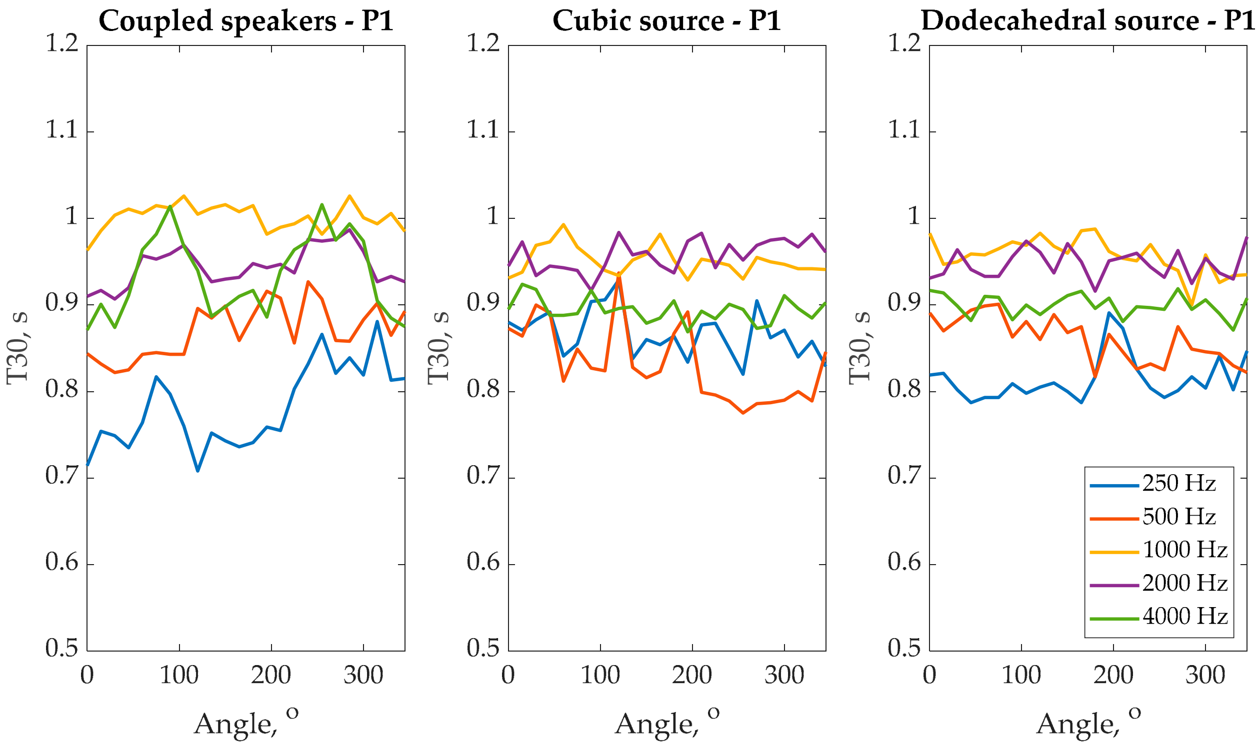


**Figure A5.** The results of T30 measurements in P1 position.

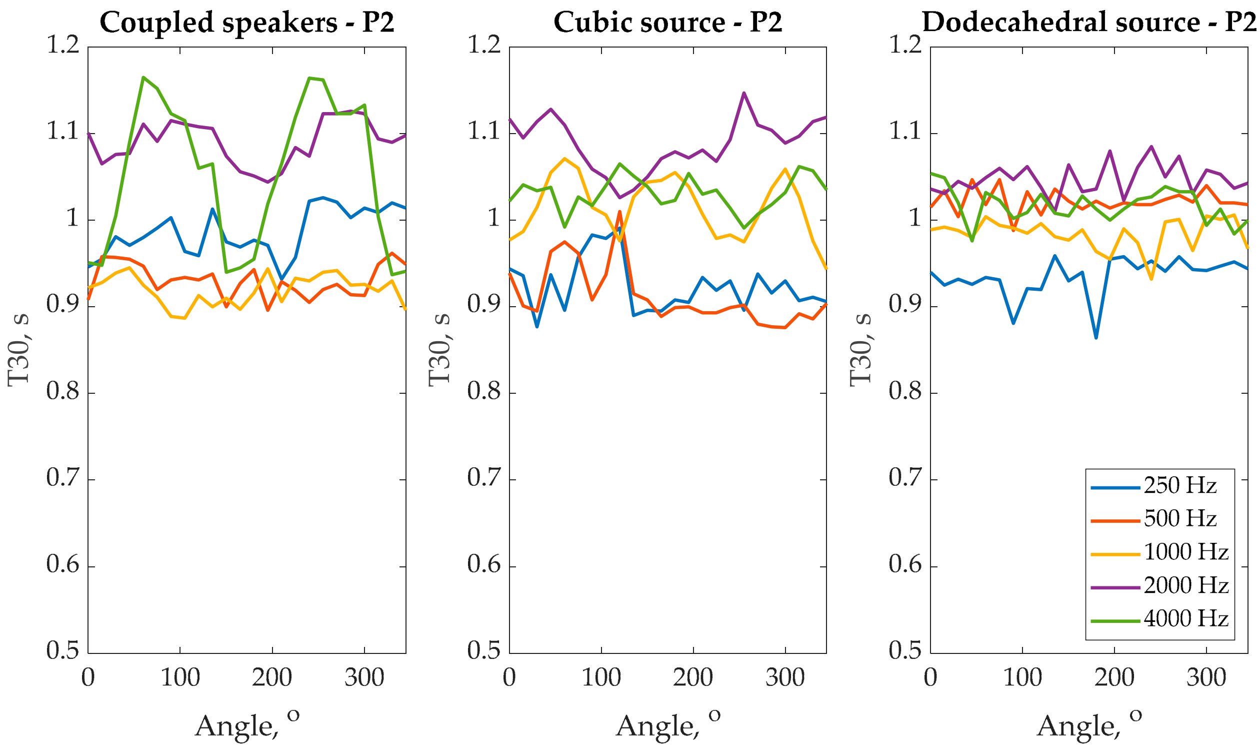


**Figure A6.** The results of T30 measurements in P2 position.

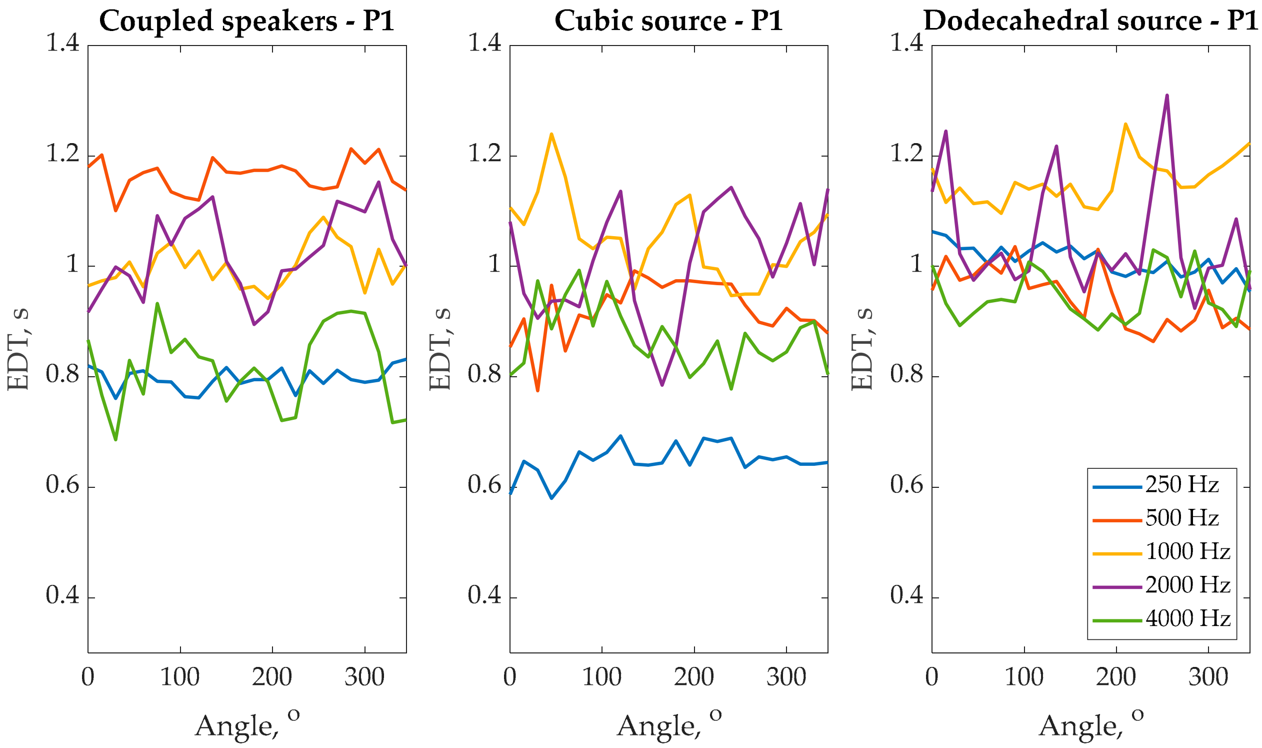


**Figure A7.** The results of EDT measurements in P1 position.

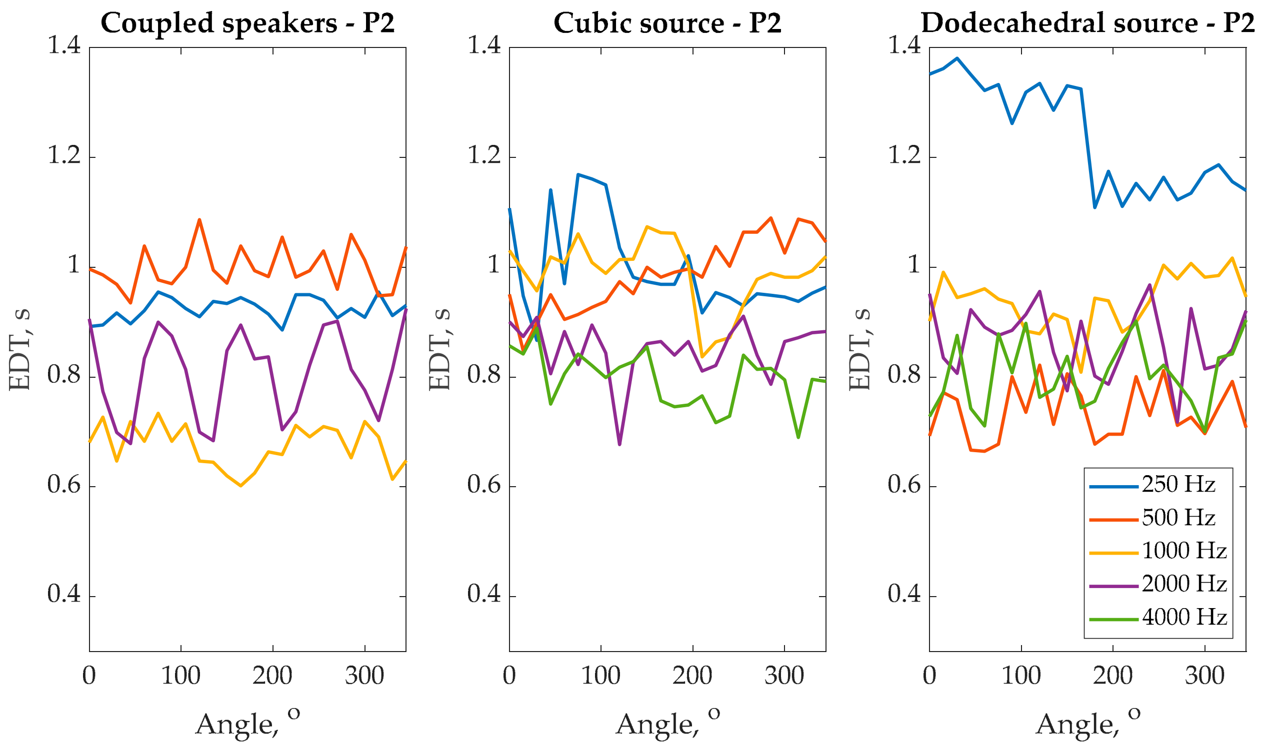


**Figure A8.** The results of EDT measurements in P2 position.

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