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A light-weight wireless omni-directional sound source for room acoustic measurements

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Abstract

One of the biggest challenges in room acoustic measurements, according to the ISO 3382 standard (parts 1-3), is to use sources that maintain omnidirectional directivity (with small deviations) across the frequency range, from the 125 Hz to 4 kHz octave bands. Conventional omnidirectional sources can achieve adequately omni-directional directivity with the use of more than one loudspeaker unit (e.g. twelve units in a dodecahedron). However, these sources tend to have poor performance at low frequencies, because of the restricted volume shared by the units, as well as non-uniform directivity at high frequencies. In addition, their size makes them far from ideal point sources and discourages acousticians from performing measurements more often, due to their reduced portability. In this paper, a novel sound source is presented, which solves the aforementioned problems. The source consists of a single loudspeaker unit, which keeps the size small and close to an ideal point source. The loudspeaker unit is backed by a cavity with sufficient volume for efficient low-frequency performance. In front of the loudspeaker unit is an acoustic lens with a doughnut-like shape, designed in such a way that the high-frequency radiation is close to omni-directional. This acoustic lens contains all electronics required to make the sound source fully portable and wireless. Free-field measurements of the sound source show that the frequency response is fairly flat over a wide frequency range and that the directivity pattern is well within the limits of ISO 3382, also for frequencies outside the default range (63 Hz and 8 kHz octave bands). An application example is presented, showing that the source is well-suited for room acoustic measurements in small to medium-sized rooms. In addition, the source can be used for measuring the room frequency response, e.g. from 20 Hz to 200 Hz, when positioned in a corner.

Keywords: room acoustics, measurements, loudspeakers, omnidirectional, calibration.

1 Introduction

In general, room acoustic measurements refer to the process of measuring a series of objective parameters that characterize the acoustics of a variety of spaces, such as offices, classrooms, auditoria, concert halls etc. ISO 3382 provides the guidelines for room acoustic measurements in performance spaces, ordinary rooms and in open-plan offices [1]. Such guidelines include the definitions of room acoustic parameters (for example the variations of reverberation times T_{15}, T_{20}, T_{30}; clarity, C_{80}, gravity time, T_s) the positioning of sound sources and microphones in space, as well as the requirements for the source. Specifically for the source, the following requirements must be fulfilled:

1. The source must be able to produce at least 45 dB above the background noise level at the microphone position, to ensure a sufficient impulse response decay range. If T_{20} is to be measured, it is sufficient to use 35 dB above the background noise level.

2. The source must be as omnidirectional as possible. To evaluate omnidirectionality, the source is driven with pink noise in free-field conditions and the level is measured at a fixed radius every 5° for a full 360° circle. This is done on the plane with the greatest asymmetry. From these measurements a *reference level* is calculated as an energetic average. Then, a 30° arc moving average is calculated and subtracted from the reference level. Finally, the difference is compared with the maximum acceptable deviation from Table 1. ISO 3382 covers the range between the 125 Hz and 4 kHz bands. However, in several situations an extended range from 63 Hz to 8 kHz is more relevant, especially in musical applications or auralisations of measured impulse responses. For these extra bands, the values from 125 Hz and 4 kHz are used.

Table 1: Maximum deviation of source directivity in dB per octave band when pink noise is used for measurement in free field (anechoic chamber). The bands from 125 Hz to 4 kHz are provided by ISO 3382 [1], while the 63 Hz and 8 kHz bands are extrapolated.

Frequency (Hz)	63	**125**	**250**	**500**	**1000**	**2000**	**4000**	8000
Maximum deviation (dB)	± 1	± 1	± 1	± 1	± 3	± 5	± 6	± 6

ISO 3382 does not specify the size or the actual shape of the omnidirectional source. However, it is desired that the size is as small as possible and close to that of an ideal point source, which makes it consistent with the assumptions used in room acoustic theoretical models [2]. Therefore, using an omnidirectional source that is close to a point makes it easier to compare measurements with simulations. On top of that, a small, lightweight source encourages acousticians to make more measurements due to the convenience provided.

Traditional omnidirectional sources involve many loudspeaker units that point towards different angles in order to ensure sufficiently uniform sound radiation. A typical example is a *dodecahedron* source, which consists of 12 faces with one loudspeaker unit mounted on each of them, as the models manufactured by NorSonic [3] and Brüel Kjær [4]. Although these type of sources fulfil the directivity requirements of Table 1, they tend to be large in size (usually requiring external amplifiers) which makes them far from ideal point sources and harder to transport. There are other types of sources, that use fewer units and have a much smaller volume. The model *Qoms2* by Qsources [5] uses two loudspeaker units in a vertical configuration, facing each other. However, the need of external amplification and cabling make these sources less portable. Recently, a low-cost alternative method has been suggested, by averaging the response from three common directional loudspeakers [6]. This can be useful when it is possible to make use of existing loudspeakers in a room, instead of bringing a separate measuring source.

In this paper, a light-weight wireless omnidirectional source is presented. The source is called *OdeonOmni* and has been designed and developed by Odeon A/S, specifically for room acoustic measurements with the sine-sweep method [7]. It consists of a single loudspeaker unit (driver), which keeps the size small and close to an ideal point source. The device was developed primarily for portability and ease of handling, to encourage acousticians to perform more room acoustic measurements. Therefore the device is wireless and includes a built-in amplifier. The project was initiated in 2015 and was also part of Danish Tech Challenge 2016.[1]

2 Description of *OdeonOmni* source

Figure 1 shows a drawing of the *OdeonOmni* source. It has an overall height of 35 cm, diameter of 14 cm and a total weight of 1.5 kg. The device consists of two main elements:

[1] https://dtusciencepark.dk/futurebox/danish-tech-challenge/

1. A loudspeaker cabinet with sufficiently large and damped volume for low-frequency performance. On top of the cabinet, a single full-range loudspeaker driver is mounted.
2. An acoustic doughnut-like shaped lens, mounted at approximately 1.5cm above the loudspeaker driver (measured from the lowest part of the lens to the centre of the driver). Its shape has been optimized for omnidirectional high-frequency radiation, according to Table 1. This acoustic lens contains all electronic components required to make the sound source fully portable and wireless. Mainly, a *digital amplifier*, a *Bluetooth module* and *rechargeable batteries*.

The source is mounted on a tripod at vertical position. Henceforth, we will consider the top side as 0° and the bottom side as 180°. Audio signal is transferred to the source by wireless Bluetooth connection or by a 3.5 mm jack audio cable. The source can be used with any measuring software, such as the module included in ODEON [8].

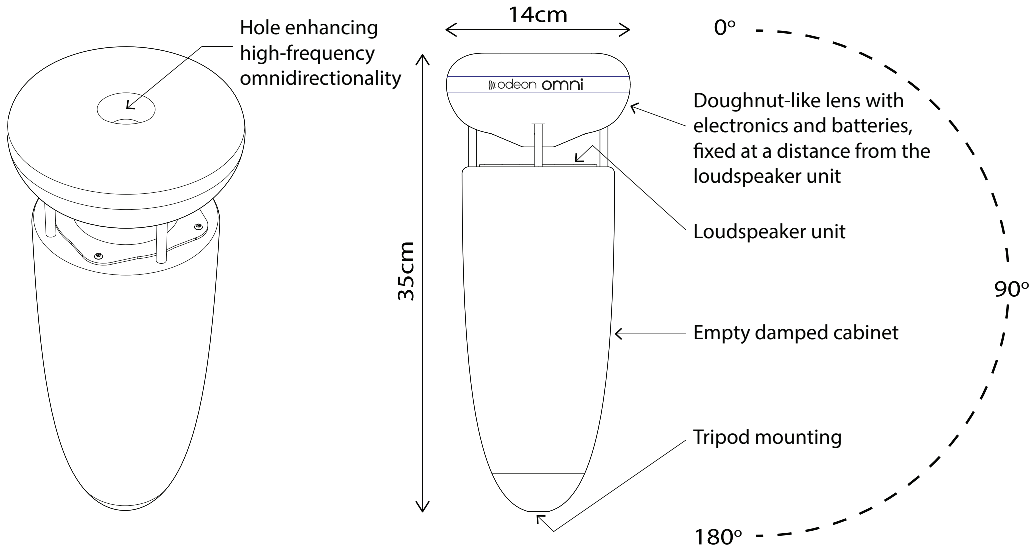


Figure 1: Sketch of the *OdeonOmni* source. The main elements include the cabinet, as well as an acoustic lens that encompasses all electronics and batteries for the operation of the device, and helps radiating sound evenly.

3 Specifications and design of *OdeonOmni* source

The design of *OdeonOmni* source has been determined following three main goals: 1) Sufficient omnidirectionality, according to the directivity limits provided in Table 1. 2) As flat as possible frequency response. 3) High portability. The final design has been a result of many iterations both in terms of calculations and in terms of building and measuring a series of prototypes. The first prototypes were 3D-printed in plastic material and used external amplification via cable connection. The two separate parts of the device, the *cabinet* and the *acoustic lens*, made it possible to accelerate the prototype evaluation process, by testing combinations of them (eg. cabinet v.1 combined with lens v.2 and so on). In the initial stage, simple analytic formulas were used to determine basic loudspeaker parameters, such as the volume of the cabinet and the resonance frequency of the system [9]. The resonance frequency was required to be low, while the overall frequency response was required to be as flat as possible. Therefore, it was decided that *OdeonOmni* should be a closed system, as opposing to vented (open) systems that can have lower resonance frequency but very steep roll-off below that. Vented systems also require larger cabinet volume, which was not desired in terms of omnidirectionality and portability.

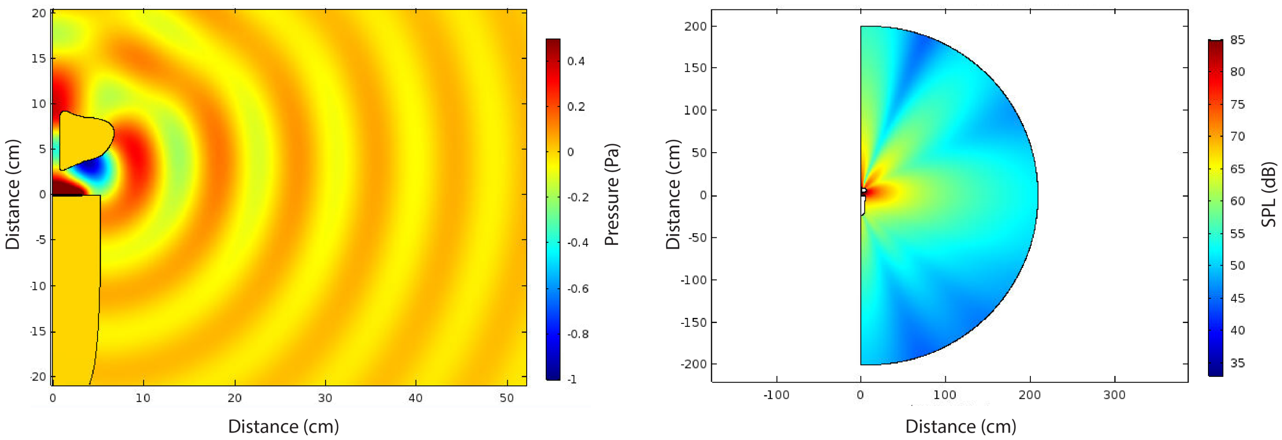
To keep the source portable and lightweight enough, the cabinet volume had to remain below 2 L. At the same time a low system resonance frequency was desired, so that the device could be efficient at the lower octave bands. For these reasons, a loudspeaker driver of compliance equivalent volume $V_{as} = 1.4$ L and resonance frequency $f_s = 74$ Hz was chosen. The driver has a high excursion capability X_{max} of 4.6 mm and a total quality factor Q_{TS} of 0.41. Choosing a system total quality factor Q_{TC} of 0.547, resulted to an active cabinet volume of approximately 1.8 L and a system resonance frequency $f_c \approx 99$ Hz. Using damping material inside the cabinet helps increasing the active volume by approximately 15%. Therefore only a physical volume of $1.8/(1 + 15\%) = 1.56$ L was necessary in the end.

3.1. Omnidirectionality

After fixing the cabinet volume, different geometries were tested to comply with the directivity limits of Table 1. Any plain loudspeaker system - with a cabinet and a driver on one of the sides - is highly directive as frequency increases. Therefore, to achieve sufficient omnidirectionality for *OdeonOmni* the main concept was to use an acoustic lens in front of the driver, that could reduce some radiation at high frequencies and reflect some sound towards the back of the cabinet. In this way a more uniform radiation was obtained.

Initially, a commercial Finite Element Method (FEM) software was used by B.Eng candidate A. K. Nørgaard [10] to simulate the directivity patterns obtained using different designs of the cabinet and lens, as well as the distance between them. The overall shape of the device was decided to be cylindrical at a very early stage. This made the directivity problem axially symmetric, therefore only the vertical plane had to be studied.

From numerous different designs, a long conical shape was chosen for the cabinet and a doughnut-like shape for the lens. These shapes provided the most uniform radiation on the vertical plane, while specifically **a central hole** in the lens offered better radiation at the high frequencies (4 and 8 kHz). Without the hole, the directivity shifted to the other side of the loudspeaker driver, as most of the sound was reflected towards the bottom. The hole helped mitigating that problem by letting some sound being radiating naturally in front of the driver. Figure 2 shows a screenshot of 2D FEM simulations. Radiation is uniform enough at 4 kHz, while the sound wavefront approaches that of an ideal point source at 0.5 m distance.



(a) Acoustic pressure up to 50 cm from source.

(b) Sound pressure level up to 2m from source.

Figure 2: A 2D FEM simulation with the cabinet and lens at 4 kHz, on the vertical plane, where directivity problems are more critical.

The FEM simulations provided only a basic indication of the actual cabinet and lens shape. After that, a *trial and error* iteration process took place using real prototypes and directivity measurements, according to Sec. 1, at the Technical University of Denmark. In these prototypes, several manufacturing issues (e.g. thickness of material, placement of electronics) were taken into account as well. At least 10 prototypes were 3D-printed, measured and improved, each of them with several distance variations between cabinet and lens. In Figure 3 the directivity plots of the final shape (Figure 1) are shown. Due to axial symmetry of the source (when placed in normal vertical position) only the part from 0° to 180° is displayed.

The majority of the directivity plots show that the directivity curve is well within the ISO limits. The most critical band in the directivity plots is at 500 Hz, where the directivity curve approaches - but does not exceed - the ISO limits at 90°. This is partly due to the fact that the limits have been set tight for 500 Hz (± 1 dB), while they become much broader at 1 kHz (± 3 dB). It is interesting to observe that with the current ISO 3382 limits, the *OdeonOmni* source performs very well at the highest bands (4 and 8 kHz). This is generally very difficult to achieve with a traditional dodecahedron and most of this behaviour comes from the actual design of the acoustic lens that evens out the highly directive components.

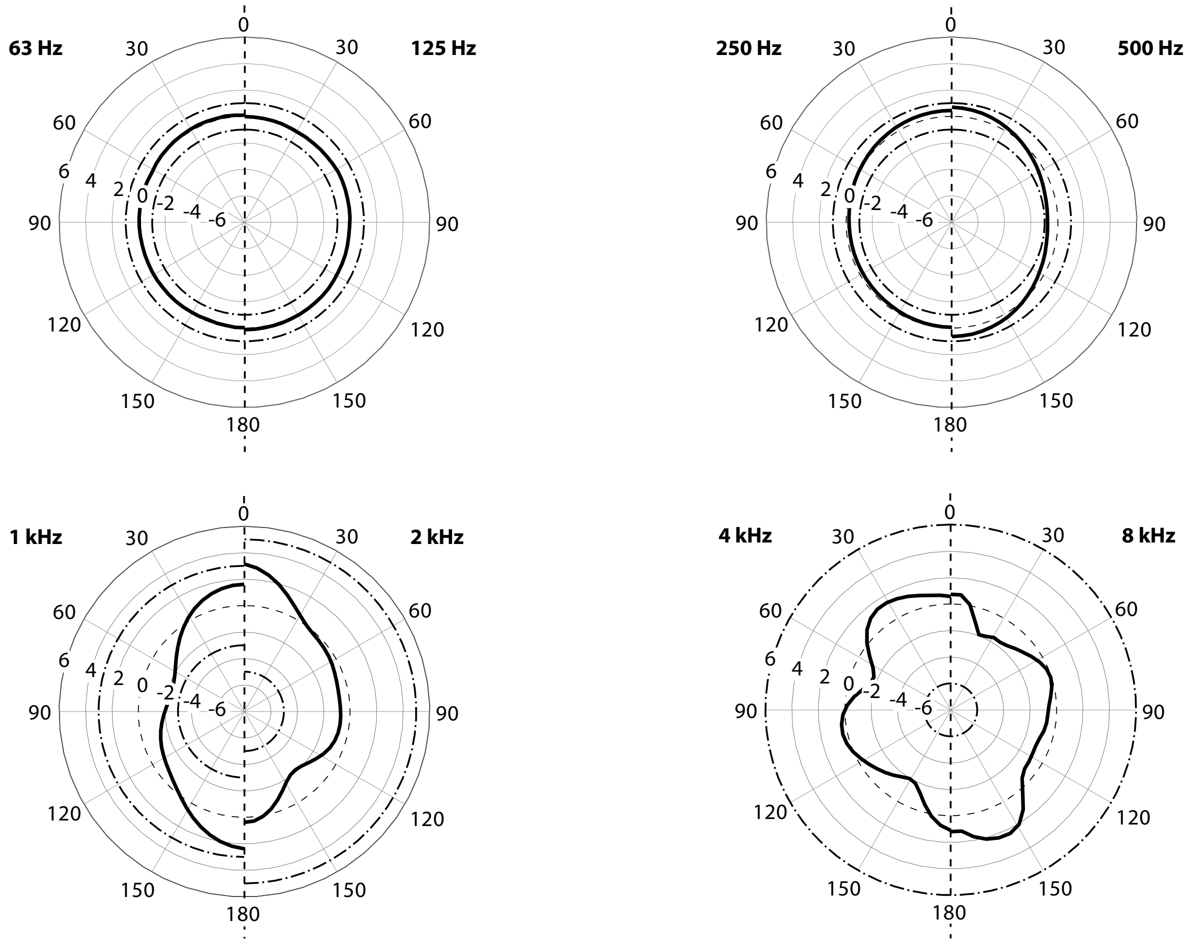


Figure 3: Directivity plots of *OdeonOmni* across the vertical plane for each octave band between 63 Hz and 8 kHz. Since the geometry is axisymmetric, only the part from 0° to 180° is displayed. ISO limits (-·-·). Directivity curve (—). 0 dB reference (- - -).

Using the minimum and maximum values from Figure 3, the largest deviations, together with the ISO 3382 limits can be plotted as a function of frequency (octave band), as shown in the simplified directivity plot of Figure 4. An interesting observation is that the current ISO limits between 2 and 4 kHz are very wide in comparison to the capability of *OdeonOmni*. This shows that these limits could be reduced in the future to encourage the manufacturing of better sound sources in terms of omnidirectionality.

3.2. Flat frequency response and sound power output

Although there is no specific requirement by the ISO 3382 standard, *OdeonOmni* was designed to provide as flat as possible frequency response between 125 Hz and 4 kHz. The main reason is that a flat frequency response provides an even weighting of all modal reverberation times within an octave band. Besides that, having enough

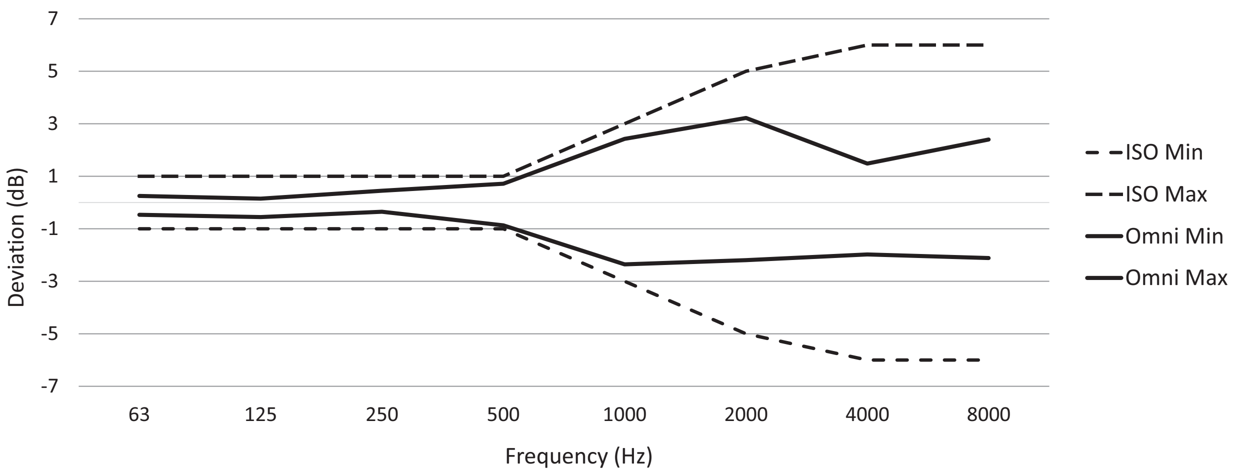


Figure 4: Simplified directivity plot showing the largest deviation from the reference level (0 dB) in each octave band. The plot uses the min and max values from each polar plot in Figure3.

power at 63 Hz and 8 kHz was considered an advantage for auralisations using measured impulse responses. For these reasons it was preferred to use only one high-quality full range loudspeaker driver that could work with the entire volume of the cabinet and provide good performance at low frequencies for its size. In contrast, dodecahedron sources use 12 drivers which share a common cabinet volume, resulting to a steeper decline of the frequency response at low frequencies. They also introduce narrow lobes at higher frequencies, which makes the response less uniform around the source. This results to certain directions having poor performance at the highest octave bands.

The drawback of using a single driver is that the overall sound power output is lower than when using multiple drivers. The maximum power level of the *OdeonOmni* source was measured inside a reverberation chamber at DTU, according to ISO 3741 [11]. The source was connected wirelessly to a laptop, via the available Aptx Bluetooth connection, meaning that the internal sound card and amplifier of the source were used. In such a case the output level of the source can be controlled digitally by the laptop's volume slider, which was set to max. Finally, the source was driven with pink noise of max amplitude 0.9 to ensure that distortion remained at low levels. The results are shown in Figure 5 and offer a good picture of the frequency response as well. The power levels vary approximately between 79 dB and 87 dB, from 80 Hz to 4 kHz, with a small roll-off at the lowest bands. This corresponds to a 8 dB dynamic range and it is a way to quantify the flatness of the response. Typical ranges for dodecahedron sources in the market are about 15 dB, which is much larger than the range of *OdeonOmni*. The last column shows that the total power level from all octave bands is 95 dB, which can be considered a limitation of the source for measuring large rooms, compared to certain dodecahedron sources that can output a total power level of 120 dB. However, due to its relative flat frequency response, the overall power of *OdeonOmni* is evenly distributed at all frequencies, especially at lower ones, where it is typically more difficult to achieve sufficient signal-to-noise ratio. Therefore, a higher overall power output might not be as crucial for *OdeonOmni*, as it is for other sources with less flat frequency response. On top of that, the source is designed for measurements with sweep signals. This offers the advantage of increasing the signal-to-noise ratio by increasing the length of the sweep.

3.3. Portability

The final design consideration of *OdeonOmni* was the high level of portability, with low weight and small size. Several lightweight materials were taken into account at the initial stages of the design process. These included: 1) Aluminum for the entire cabinet and lens, which would require an extensive turning machining process and significant waste of material. 2) Injection molded plastic for the cabinet and lens, which was also rejected

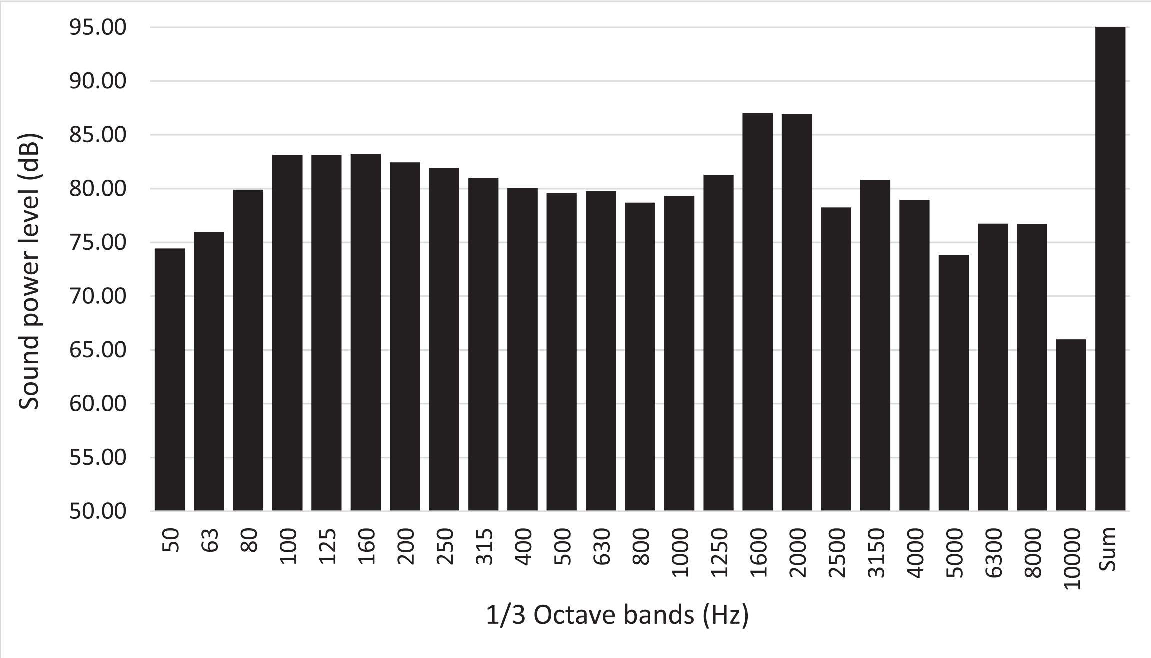


Figure 5: Max sound power of *OdeonOmni* per 1/3 octave. Last column: broadband sum.

because of high cost for the limited number of pieces that were planned in the beginning. 3) Carbon-fiber or glass-fiber composite, which allows a structurally strong, lightweight construction that is cost-effective for a limited number of pieces. The final choice was a coated version of glass-fiber composite.

All functional components were finally placed inside the so-far unused volume in the acoustic lens, in order to leave the loudspeaker cabinet as empty as possible for optimum performance. To enhance portability, the source is connected wirelessly using Bluetooth 5^{th} generation, with *AptX* technology, that ensures low distortion and high resolution compared to standard Bluetooth. An antenna inside the device can maintain a robust connection up to **30m** without obstacles, and up to **10m** with obstacles.

4 Real-case measurements in a cafeteria

The *OdeonOmni* source was tested inside the cafeteria at DTU Science Park (Lyngby, Denmark) together with a traditional Dodecahedron source, built at the Acoustic Technology Group at DTU. This source operated with an external amplifier. The cafeteria has several coupled spaces, a dining area and a large hallway. The overall acoustics is quite challenging because of non-uniform absorption and unstable background noise from ventilation, refrigerators and other machines. For the test measurements, a Zoom H3-VR ambisonic microphone has been used, together with a laptop using ODEON's measuring system [8].

Figure 6 shows a comparison of the cafeteria frequency responses, measured with *OdeonOmni* and the dodecahedron source at the same microphone-source position. The distance is 3 m between them (position S1 in Figure 7), which is considered close enough to reduce the influence from the room. Although the measured responses include both the response from each source plus the response from the room, they can still be used for comparison of the two sources since all other factors remain fixed (room, microphone-source positions). The responses in Figure 6 have been normalized to the peak value of each source. It can be seen that *OdeonOmni* has better performance both at low and high frequencies, as well as flatter overall response.

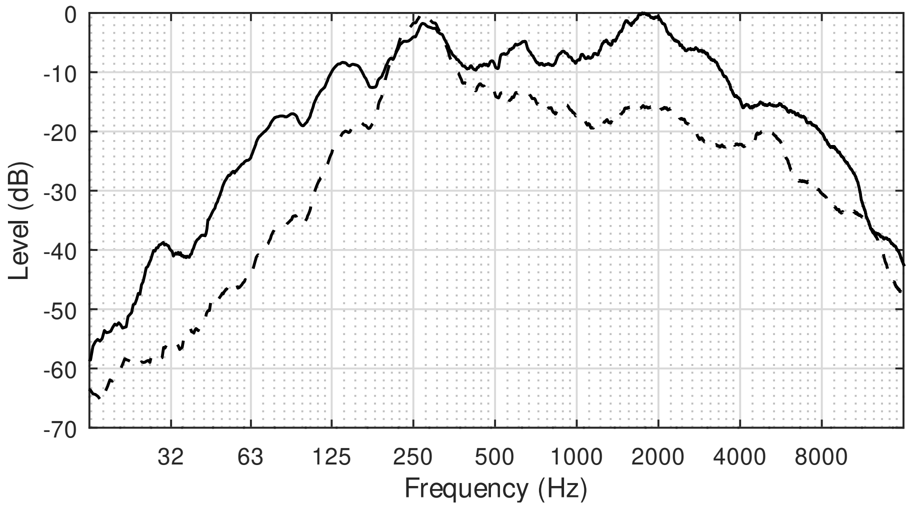


Figure 6: Measured frequency response of the same room with *OdeonOmni* (—) and the Dodecahedron source (- - -), normalized to peak value. The source is at 3m from the receiver.

4.1. Comparison of Room Acoustic Parameters

A line of impulse response measurements was used inside the lunch area of the cafeteria, as shown in Figure 7. It was decided to fix the microphone position at one end and move the source away from the microphone at 5 discrete positions with a total distance of 19 m. From the measurements the ISO 3382 room acoustic parameters [1] were derived in 8 octave bands, from 63 Hz to 8 kHz.

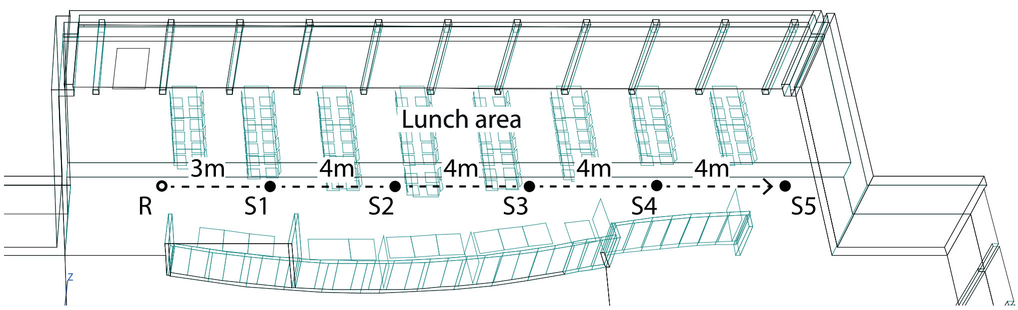


Figure 7: A sketch of the cafeteria at DTU science park used for comparing the performance of *OdeonOmni* with a Dodecahedron source. The receiver (R) position was fixed, while the sources were moved at five locations, with a total distance of 19 m.

To ensure that the output levels from both sources were comparable, a 1 kHz tone was recorded for 15 s, with the sources at the closest position, S1. The level of *OdeonOmni* was set to -4.5 dB digitally from within ODEON. The external amplifier level of the dodecahedron source was then adjusted to match that of *OdeonOmni*. Since the initial level was set below maximum, it allowed for some increase during the measurements, as the sources were placed further from the receiver. This ensured better Signal to Noise Ratio (SNR) and sufficient decay range for the derivation of room acoustic parameters. The advantage with adjusting the level digitally in ODEON is that any change is compensated automatically and does not modify the calibration of the initial level.

Figure 8 shows the measurements of T_{20} and C_{80}, at S3 and S4. The sources derive similar results for both parameters at position 3, while there are some significant differences for C_{80} at S4. Such differences could be attributed both to varying background noise conditions, as well as the properties of the sources. *OdeonOmni* has a flatter frequency response (Figure 6) which means that modes are excited more uniformly within each octave band. Therefore it is expected that measurements are of better quality. The C_{80} curve from the Dodecahedron seems more unstable with noticeable fluctuations, while the one from *OdeonOmni* looks smoother, following a stable and more reliable trend which is comparable to the C_{80} curve at S3.

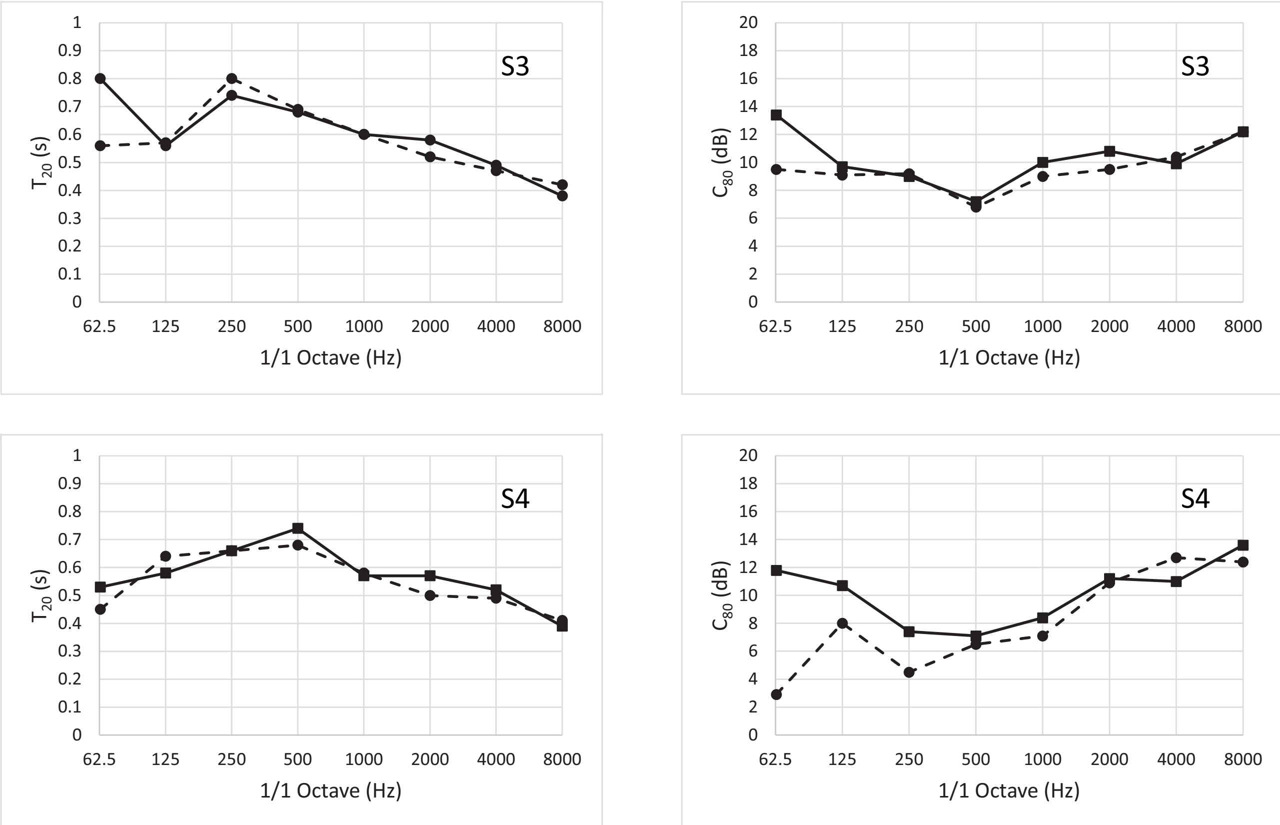


Figure 8: Room acoustic parameters T_{20} and C_{80} as a function of frequency (octave bands), measured at source positions 3 and 4 with *OdeonOmni* (—) and the Dodecahedron source (- - -).

OdeonOmni was also tested at the maximum distance of 30 m in another part of the cafeteria. Between 125 Hz and 8 kHz it was possible to derive all room acoustic parameters, while at 63 Hz, some of them were missing, mainly because of high background noise levels at lower frequencies. It is worth mentioning that a similar experiment with a conventional Dodecahedron would require very long cables, which makes it less practical.

5 Discussion

The design of *OdeonOmni* has been based on single loudspeaker driver which keeps the source small and lightweight. The biggest drawback of this design is a maximum power that is limited to 95 dB. However, with a relatively flat frequency response and use of sweep signals, the source seems to be capable for room acoustic measurements in rooms up to 30 m with moderate background noise levels. Two more advantages result from the specific design. First, the use of one loudspeaker driver makes it easier to know the exact shift in level between several *OdeonOmni* items, in contrast to a dodecahedron source were more drivers are involved and differences in levels cannot be tracked. This facilitates sound strength measurements using the *two-step calibration method* [12]. Using this method, only a prototype *OdeonOmni* needs to be calibrated in the laboratory. Any other items can go through an *in-situ* correction process, which compensates for any shifts in level, due to the different driver. In addition, because of its small overall size and good performance at low frequencies (below 63 Hz), *OdeonOmni* can be placed close to corners in a room for accurate measurement of modes [13].

6 Conclusions

In this paper, a new design of an omnidirectional source for room acoustic measurements has been presented. The source has been developed and manufactured by Odeon A/S as a light-weight, wireless and overall portable solution to encourage acousticians to perform more measurements in the future. The directivity pattern of the *OdeonOmni* has been measured in an anechoic chamber and it has been shown that it fulfills the requirements given in ISO 3382. Evaluation measurements in a large cafeteria space have shown that the impulse responses as well as common room acoustic parameters are similar to those obtained with a conventional dodecahedron source. In such a space, the *OdeonOmni* source has been able to make measurements up to 30 m with Bluetooth connection, with a power level sufficient to provide room acoustic parameters from at least 125 Hz and higher. Finally a direct comparison between the frequency response of *OdeonOmni* and the frequency response of a dodecahedron source, shows that *OdeonOmni* has much better performance at low frequencies and much flatter response throughout the range between 63 Hz and 8 kHz, providing more uniform excitation of the space under measurement and better auralisation when the measured impulse response is convolved with an anechoic signal.

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