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# Sound power level as a measure of efficiency of Distributed Mode Loudspeakers

Karol Czesak, and Piotr Kleczkowski

*Abstract*—**Distributed Mode Loudspeakers (DMLs) are characterized by properties, which make them significantly different from conventional electrodynamic loudspeakers. Such differences occur due to the design assumptions of the DML. In this work, a series of SPL measurements of DML in a reverberation chamber has been carried out, which were compared with those for an electrodynamic loudspeaker. Sound power level was determined from the results of conducted measurements for both types of transducers. It was calculated in 1/3 octave bands, for the pink noise excitation. The sound power level obtained with these two different types of loudspeakers is not significantly differing between each other.**

*Keywords*—**DML, sound power level, loudspeaker characteristics, loudspeaker measurements, reverberation chamber**

## I. Introduction

THE characteristic feature of DMLs, which distinguishes them from conventional electrodynamic transducers, is the lack of the phenomenon of narrowing the width of the radiated sound beam with increasing excitation frequency [1]. Also, the sound pressure level, measured on the axis perpendicular to the surface of the speaker panel, does not reach the highest values among all measurement points located on the hemisphere [2, 3, 4]. It is also worth noting that the frequency characteristics obtained at two adjacent measurement points (for the same elevation, but with a different azimuth, or possibly with the same azimuth and a changed elevation angle) very often significantly differ from each other, which makes it difficult to plot directivity characteristics for a DML using an approach similar to that of a conventional electroacoustic transducer [5]. Typically, these speakers are rectangular in shape with different dimensions on both sides [6], which can result in different directional characteristics in the horizontal and vertical planes. From the above-mentioned features [7], it follows that the measurement of the frequency response of a DML cannot be carried out only in the axis of the loudspeaker, nor in the horizontal plane. Averaged from the measurements on the surface of the hemisphere, with appropriate weights, frequency characteristics of distributed mode loudspeakers can be treated - while maintaining a certain level of generality - as a spectrum of the sound power level generated by them. However, touching on this subject, it is justified to measure the sound power level obtained with the use of distributed mode loudspeakers in the strict sense of the term, i.e. defined by the PN-EN ISO 3741:2010 standard [8]. The sound power level measurement, conducted in a reverberation chamber, in compliance with [8] takes much less time, than conducting a set of anechoic measurements in a dense grid of measurement points. Based on the above, a sound power level of DML measured in a reverberation chamber can be considered as a quick and simple way of obtaining coarse information about overall DML's performance, that can be expected after applying such a transducer in situ. The paper is organized as follows: section II describes measurement conditions, section III treats about preliminary measurements cycle, section IV describes in detail a whole procedure of sound power level measurement, as well as series of calculations leading from a set of sound pressure level data to sound power level. It also includes description of correction coefficients computation. Section V compares results obtained for DML with results obtained for pistonic loudspeaker under the same conditions. Section VI presents comparison of sound power level obtained with DML, according to [8] with frequency characteristics of DML, averaged from anechoic measurements taken in 325 points of hemisphere [3] and smoothed in 1/3 oct. bands. Section VII discusses obtained results with results of Gontcharov's research [5].

The measurements were made in the reverberation chamber located at the Technical Acoustics Laboratory at the Department of Mechanics and Vibroacoustics, at the Faculty of Mechanical Engineering and Robotics of the AGH University of Science and Technology in Krakow.

## II. Measurement conditions

This reverberation chamber has a volume of 180.4 $m^3$ and a total surface area of 193.6 $m^2$. It does not have parallel walls, and there is no parallelism of the ceiling surface in relation to the floor surface.

The chamber is equipped with two dodecahedral, omnidirectional sound sources - used in the reverberation time measurements of the chamber with a sample installed, and six G.R.A.S. scattered field microphones: 46 AQ. The omnidirectional sources are powered by Crest CPX2600 power amplifier, and data acquisition (as well as the generation of excitation during reverberation time measurements) is carried out using the National Instruments PXI system, which consists of the NI PXIe-1082 housing, the NI PXIe-8108 controller equipped with the modules: NI PXIe-4496, NI PXI-4461, NI

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First Author and Second Author are with AGH University of Science and Technology, al. Mickiewicza 30,. 30-059 Kraków; czesak@agh.edu.pl, kleczkow@agh.edu.pl

PXI-4462 and NIPXI-7354. For the tested electroacoustic transducers, noise excitation was provided using the Anthem PVA-7 power amplifier. Information about the atmospheric conditions in the chamber is provided by the LB-701H thermo-hygrometer with the LB-705 display panel. All elements of the chamber's equipment are arranged in appriioprate relation to each other and in relation to the planes limiting the space of the chamber, in accordance with the PN-EN ISO 3741:2010 standard. Also – all of measurement devices used during research descried in this paper, meet the requirements of the standard. The diagram of measurement setup is presented in Fig. 1.

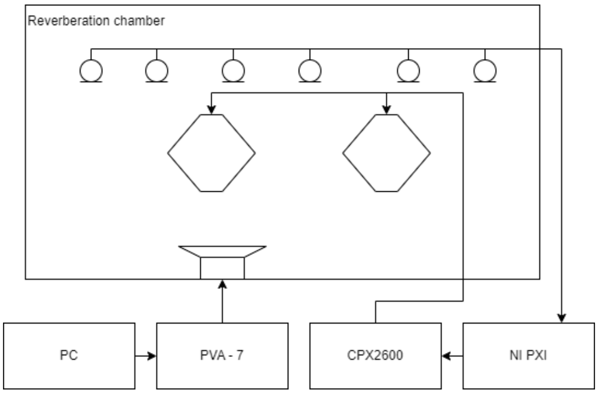


Fig. 1. Diagram of measurement setup used in the investigation of Sound Power Level obtained with DML

## III. PRELIMINARY MEASUREMENTS

The standard PN-EN ISO 3741:2010 specifies the calculation of the sound power level generated by the tested sound source based on averaged measurements of the Sound Pressure Level (SPL) during its operation in a reverberation chamber. Averaging should be performed for measurements taken at multiple positions of the measuring microphone (with a minimum of 6 positions) and, if necessary, for multiple positions of the tested sound source. The conversion from the averaged sound pressure level to the sound power level is done with the knowledge of the reverberation time in the chamber (with the tested sound source installed) and atmospheric conditions such as temperature, atmospheric pressure, and relative humidity. It is also important to determine SPL of the background noise in the reverberation chamber.

Based on the standard deviations of the measured quantities in preliminary measurements, the minimum number of positions for the tested sound source and the minimum number of positions for the measuring microphone during the actual measurements are determined. The standard deviations of the SPL measured by six measuring microphones for a single position of the tested sound source are calculated using the following formula:

$$S_M = \sqrt{\sum_{i=1}^{N_{M(pre)}} \frac{\left[L'_{pi(pre)} - L'_{pm(pre)}\right]^2}{N_{M(pre)}-1}} \quad (1)$$

where:

$L'_{pi(pre)}$ – time-averaged SPL in the 1/3-octave band, measured at the $i$-th initial position of the microphone during the operation of the investigated sound source, in decibels;

$L'_{pm(pre)}$ – arithmetic mean value of time-averaged SPL pressure in the 1/3-octave band, measured at six initial positions of the microphone during the operation of the investigated sound source, in decibels;

$N_{M(pre)} = 6$ – initial number of microphone positions.

By processing with (1) the obtained values of SPL from preliminary measurements generated by a DML excited by pink noise with an RMS voltage of 0.5 V , high-pass filtered with a cutoff frequency of 90 Hz and a slope of 9 dB/oct., the value $S_M$ was determined. A resistive character of DMLs [3] lets us assume, that the same power would be supplied to the devices by applying the same voltage. High-pass filtering was necessary to protect the DML, which has low efficiency below 100 Hz. The maximum value of $S_M$, calculated for a 1/3 octave band with a middle frequency of 100 Hz was equal to 3.25, which determined the value of $K_S$ for this frequency as equal to 5. For the rest of 1/3 octave bands, the values of $S_M$, are not greater than 1.27., what determined $K_S = 0$. The calculated values were compared with the analogous values presented in Tables 4 and 5 of the PN-EN ISO 3741:2010 standard. A minimum number of microphone positions, $N_M$=6, and a value of $K_S$=5 were obtained for the 1/3-octave band with a middle frequency of 100 Hz. For the rest of the bands (according to tables 4 and 5 of [8]), the following values were obtained: $N_M$=6, and $K_S$=5. Based on this, the minimum number of sound source positions in the test room was calculated using the formula:

$$N_S \geq K_S \left[ \left(\frac{T_{60}}{V}\right)^2 \left(\frac{1000}{f}\right)^2 + \frac{1}{N_M} \right] \quad (2)$$

where:

$T_{60}$ - numerical value of a reverberation time, for individual 1/3-octave bands, in seconds;

$V$ = 180.4 - numerical value of the volume of the reverberation chamber, in cubic meters;

$f$ - numerical value of a centre frequency of the 1/3-octave band, in Hertz.

The calculated minimum number of positions for the investigated sound source in the reverberation chamber was $N_S$=4. The measured numerical values of the reverberation time in the test room turned out to be identical for the case of placing both the DML and the conventional electrodynamic loudspeaker mounted in a bass-reflex enclosure. These values ranged from 0.4 s to 14 s. The variation of the reverberation time in the reverberation chamber, as a function of centre frequencies of 1/3-octave bands, is presented in Fig. 2.

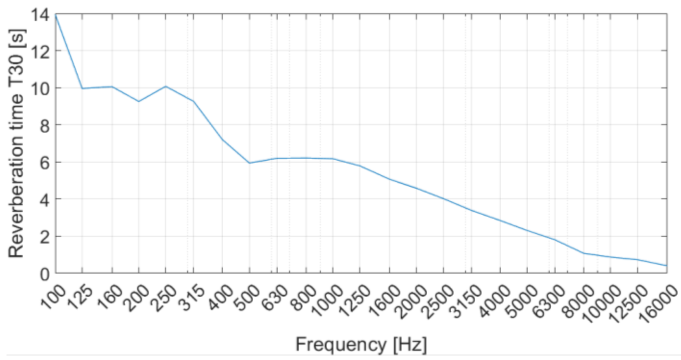


Fig. 2. The reverberation time of the reverberation chamber as a function of the frequency, in 1/3 octave bands

During the measurements, the temperature in the chamber was 22.7 °C, relative humidity 34.3% and atmospheric pressure 1018 hPa.

## IV. DML's SOUND POWER LEVEL MEASUREMENT IN REVERBERATION CHAMBER

The sound power level of a sound source in a reverberation chamber is calculated based on the average of time-averaged measurements of SPL conducted for all source and microphone positions, along with relevant corrections introduced due to the reverberation time of the test room, the surface area of its boundaries, its volume, prevailing atmospheric conditions, and the background noise level.

In the case of using more than one sound source position, the first step is to average the SPL recorded at each microphone position for each source position, using the following formula:

$$L'_{pi(ST)} = 10log\left\{\frac{1}{N_S}\sum_{j=1}^{N_S} 10^{0,1[L'_{pi(ST)}]_j}\right\} \text{ dB} \quad (3)$$

where:

$[L'_{pi(ST)}]_j$ – time-averaged SPL in the 1/3-octave bands of the investigated noise source during operation, measured at the $i$-th microphone position and for the $j$-th source position, in decibels. Averaging time was specified as 30 s, according to the requirements of PN-EN ISO 3741:2010 standard;

$N_S = 4$ – number of source positions.

Next, from the calculated average SPL in the 1/3-octave bands, for each measurement microphone position, the background noise level present in the reverberation chamber, in the corresponding 1/3-octave bands recorded at the respective microphone positions are subtracted, as described by the formula:

$$\Delta L_{pi} = L'_{pi(ST)} - L'_{pi(B)} \quad (4)$$

where:

$L'_{pi(ST)}$ – time-averaged SPL in the 1/3-octave band, measured at the $i$-th position of the microphone during the operation of the investigated sound source, in decibels;

$L'_{pi(B)}$ – time-averaged background noise SPL in the 1/3-octave band, measured at the $i$-th position of the microphone, in decibels;

If $\Delta L_{pi}$ > 15 dB, which occurred during the investigations described in this chapter, no correction considering the background noise is applied. In this case, the average value of the time-averaged SPL in the 1/3-octave band of the investigated sound source during operation in the test room is calculated using the formulae:

$$\overline{L_{p(ST)}} = \overline{L'_{p(ST)}} = 10log\left[\frac{1}{N_M}\sum_{i=1}^{N_M} 10^{0,1L'_{pi(ST)}}\right] \text{ dB} \quad (5)$$

where:

$L'_{pi(ST)}$ – time-averaged SPL in the 1/3-octave band, measured at the $i$-th position of the microphone during the operation of the investigated sound source, in decibels;

$N_M = 6$ – number of microphone positions.

Similarly, the average value of the time-averaged sound pressure level of the background noise was calculated from the formula:

$$\overline{L_{p(B)}} = 10log\left[\frac{1}{N_M}\sum_{i=1}^{N_M} 10^{0,1L'_{pi(B)}}\right] \text{ dB} \quad (6)$$

where:

$L_{pi'(B)}$ – time-averaged background noise SPL in the 1/3-octave band, measured at the $i$-th position of the microphone, in decibels;

$N_M = 6$ – number of microphone positions.

The average values of measured time-averaged SPL in 1/3-octave bands, obtained using two units of the Amina Edge 5 distributed mode loudspeaker and one unit of the SB Acoustics SB17NRXC35-4 6.5" electrodynamic loudspeaker, placed in a bass-reflex enclosure, powered by pink noise with an RMS voltage of 0.5 V, high-pass filtered with a cutoff frequency of 90 Hz and a slope of 9 dB/oct., as well as the averaged SPL of the background noise in the reverberation chamber and the absolute maximum SPL of the background noise in the reverberation chamber, described in the PN-EN ISO 3741:2010 standard, are presented in Fig. 3:

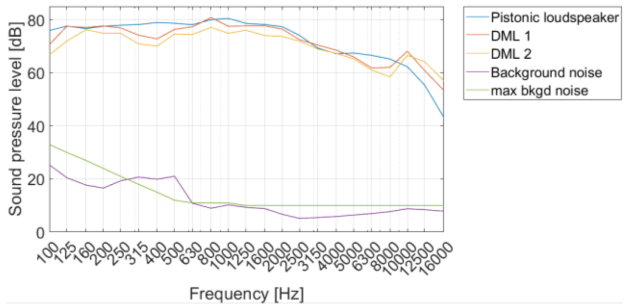


Fig. 3. Comparison of averaged SPL obtained in the reverberation chamber using three tested sound sources, along with the recorded background noise SPL and the profile of the maximum background noise SPL specified in the PN-EN ISO 3741:2010 standard

Although the recorded background noise SPL in the reverberation chamber slightly exceeded the maximum background noise SPL specified in the PN-EN ISO 3741:2010 standard, it was decided not to apply a correction to the measured sound pressure level values obtained using the tested loudspeakers due to a significant difference between the recorded sound pressure levels during their operation and the background noise SPL, far exceeding the specified threshold of 15 dB.

The sound sources were tested in four positions within the reverberation chamber. Each of these positions had a distance from the room's walls of no less than 2 meters, and the mutual distance between the points where the tested electroacoustic transducers were placed was not less than 1.5 meters in all cases. All loudspeaker devices were positioned directly on the floor of the reverberation chamber with their vibrating surface facing upward during the measurements. The placement of the DML in the reverberation chamber is shown in Fig. 4.

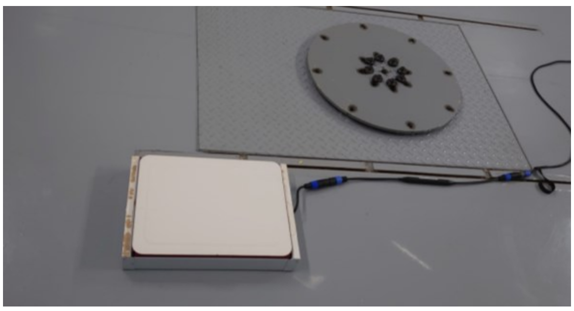

Fig. 4. The placement of the DML in the reverberation chamber

Based on the measured and time-averaged SPL as described above, the next step was to calculate the acoustic power levels generated by the tested electroacoustic transducers. This power was calculated using the formula:

$$L_W = \overline{L_{p(ST)}} + \left\{10log\frac{A}{A_0} + 4{,}34\frac{A}{S} + 10log\left(1+\frac{S*c}{8Vf}\right) + C_1 + C_2 - 6\right\} dB \quad (7)$$

where:

$\overline{L_{p(ST)}}$ – average value of time-averaged SPL in the 1/3-octave band of the tested electroacoustic transducer during operation in decibels;

*A* - equivalent absorbing area in square meters of the room, according to formula (8) below;

$A_0$ = 1 m$^2$;

*S* = 193.6 - numerical value of the total surface area in square meters of the reverberation chamber;

*V* = 180.4 - numerical value of the volume in cubic meters of the reverberation chamber;

*f* - numerical value of the centre frequency in Hertz of the 1/3-octave band;

*c* - speed of sound in air in meters per second at a temperature of $\theta$ = 22.7 °C in the reverberation chamber during the test (9);

*C1* - reference size correction in decibels, accounting for different reference sizes used for calculating SPL and sound power level in decibels and dependent on the specific air impedance under the meteorological conditions present during the measurements (10);

*C2* - radiation impedance correction in decibels, to convert the actual sound power level corresponding to the prevailing meteorological conditions during the measurement to the reference meteorological conditions (11).

$$A = \frac{55{,}26}{c}\left(\frac{V}{T_{60}}\right) \quad (8)$$

where:

$T_{60}$ - numerical value of reverberation time, for individual 1/3-octave bands, in seconds,

$$c = 20{,}05\sqrt{273+\theta} \quad (9)$$

where:

$\theta$ = 22.7 °C - numerical value of the Celsius temperature in the test room,

$$C_1 = -10log\frac{p_s}{p_{s,0}}\text{dB} + 5log\left[\frac{(273{,}15+\theta)}{\theta_0}\right]\text{ dB} \quad (10)$$

where:

$p_s$ = 101,8 - static pressure, in kilopascals, in the reverberation chamber, at the time of measurement;

$p_{s,0}$ = 101,325 - reference static pressure, in kilopascals;

$\theta_0$ = 314 K;

$$C_2 = -10log\frac{p_s}{p_{s,0}}\text{dB} + 15log\left[\frac{(273{,}15+\theta)}{\theta_1}\right]\text{ dB} \quad (11)$$

where:

$\theta_1$ = 296 K;

The profile of the calculated sound power level, obtained using the DMLs with pink noise excitation with an RMS voltage of 0.5 V, is presented in Fig. 5 for the 1/3-octave bands.

Observing the profiles of the calculated sound power level, obtained using two units of DML with pink noise excitation with an RMS voltage of 0.5 V, it can be stated that these devices exhibit very similar, almost identical amplitude-frequency characteristics in reproducing acoustic signals, with slight variations in efficiency. This can be seen as the fundamental parts of the profiles being vertically shifted relative to each other. The observed decreases in efficiency of the DML in specific frequency ranges, noticeable in free-field [2] measurements, are also evident when examining the sound power level of such transducers in the reverberation chamber.

The standard PN-EN ISO 3741:2010 assumes that measurements and calculations are done in 100 Hz – 10 kHz frequency range, but for a purpose of obtaining complete information about sound power level generated using DML – we decided to extend it to 100 Hz – 16 kHz.

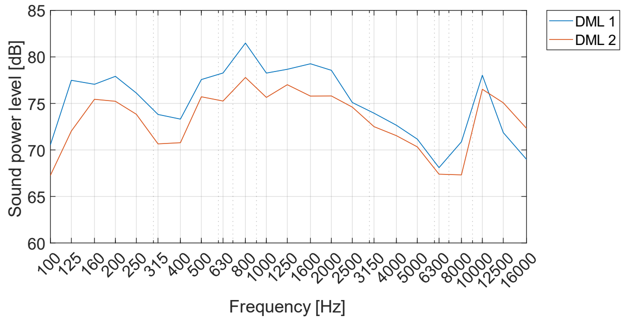


Fig. 5. The profile of the calculated sound power level, obtained using DMLs with pink noise excitation with an RMS voltage of 0.5 V, in 1/3-octave bands

Based on the measurement of sound power levels in 23 1/3-octave bands, the uncorrected sound power level for the entire frequency range can be calculated using the formula.

$$L_W = 10log\sum_{k=1}^{23} 10^{0{,}1L_{Wk}}\text{ dB} \quad (12)$$

where:

$L_{Wk}$ - sound power level in the *k*-th 1/3 octave band, in decibels;

The sound power levels obtained with both tested units of DML, with pink noise excitation with an RMS voltage of 0.5 V, were respectively 90.1 dB SPL and 87.8 dB SPL.

## V. COMPARISON OF THE SOUND POWER LEVEL OF DML TO THE SOUND POWER LEVEL OF A PISTONIC LOUDSPEAKER

The method used to calculate the sound power level obtained using DML was also applied to calculate the sound power level of a conventional electrodynamic loudspeaker, the SB Acoustics SB17NRXC35-4, installed in a bass-reflex enclosure. The same measurement setup, excitation signal, and source positions in the reverberation chamber were used as in measurements of DMLs described in section IV. Furthermore, the reverberation time measured in the reverberation chamber after placing the electrodynamic loudspeaker in the enclosure remained unchanged compared to the reverberation time measured in the same room in the presence of the distributed mode loudspeaker, as shown in Fig. 1. The electrodynamic loudspeaker, similarly to the DML, was positioned on the floor of the reverberation chamber with its vibrating surface (diaphragm) facing upward, as depicted in Fig. 6.

Fig. 6. The placement of the pistonic loudspeaker in the reverberation chamber. The high-frequency loudspeaker (tweeter) was inactive

The difference between the SPL obtained with the pistonic loudspeaker in 1/3-octave bands and the background noise SPL in the same frequency bands was estimated based on (4). In this case, the difference exceeded the specified value of 15 dB as outlined in the PN-EN ISO 3741:2010 standard. Hence, the further procedure could be conducted identically to the investigation of the sound power level obtained from the DML. The averaging of the SPL measurement results obtained at different source positions and with multiple microphones was performed using (3) and (5), respectively. The profile of the SPL obtained using the electrodynamic loudspeaker for pink noise excitation, is presented in Fig. 2.

Subsequently, under unchanged meteorological conditions in the reverberation chamber, the sound power level obtained using the electrodynamic loudspeaker with pink noise excitation was calculated in 1/3-octave bands. The profile of this parameter, with respect to the center frequencies of 1/3-octave bands, in relation to the previously calculated SPL obtained using DMLs, is shown in Fig. 7.

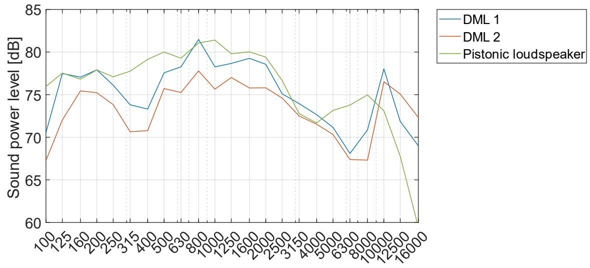


Fig. 7. The profile of the calculated sound power level, obtained using DMLs and the pistonic loudspeaker for pink noise excitation with an RMS voltage of 0.5 V, in 1/3-octave bands

The sound power level calculated using (12) for the conventional electrodynamic loudspeaker, with pink noise excitation with an RMS voltage of 0.5 V, was 91.2 dB.,

## VI. COMPARISON OF MEASURED SOUND POWER LEVEL OF DML WITH POWER SPECTRUM OBTAINED AS A WEIGHTED AVERAGE OF ANECHOIC MEASUREMENTS

A detailed investigation of frequency responses of DML across the hemisphere was conducted in an anechoic chamber located at the Technical Acoustics Laboratory at the Department of Mechanics and Vibroacoustics, at the Faculty of Mechanical Engineering and Robotics of the AGH University of Science and Technology in Krakow. The investigation was conducted in order to determine the variability of frequency characteristics of the DML as well as to obtain some detailed information about the directivity of such transducers.

Measurements were performed on a hemisphere, for three examples of the DML, keeping the angular resolution of 10°, what gave an amount of 325 measurements per transducer. The excitation signal was a sweep sine, with linearly increasing frequency, covering the frequency range from 70 Hz to 24 kHz, sampled at the frequency of 96 kHz, consisting of $2^{22}$ = 4 194 304 samples.

The averaging was performed, with regard to different fractions of the hemisphere, represented by points located on each orbit. That has resulted in the computation of appropriate weights for measurements taken at different points of the hemisphere. The detailed description of the measuring and averaging procedures can be found in [3]. The results obtained from such a set of measurements for one example of the DML were smoothed in 1/3 octave bands, scaled to become easily comparable with measurements performed according to [8] and presented in Fig. 8, along with the data collected in the reverberation chamber.

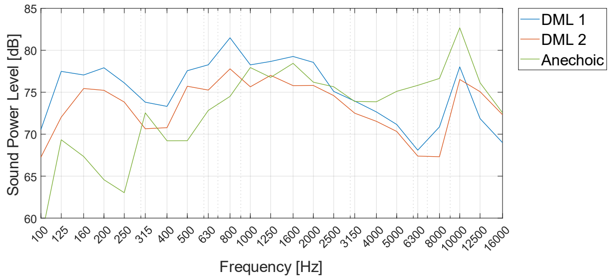


Fig. 7. The profiles of the calculated sound power level, obtained using DMLs, determined with different approaches

As can be seen in Fig. 7, the obtained sound power level profiles slightly differ, mainly in the lowest and two highest octaves. The differences may have been caused by significantly different measurement conditions, including measurement chamber characteristics, and excitation signal. A sweep sine with linearly increasing frequency is more suitable for fft measurements than for octave bands, what could affect the measured level for frequencies above 4 kHz. The influence of the reverberation time characteristics of the reverberation chamber (Fig. 2) could also be an important factor.

It is also worth noting, that the differences do not exceed 12 dB and some tendencies in the compared results are common, like e. g. a slope around 2 kHz or a peak about 10 kHz.

## VII. DISCUSSION

The results of measurements differ significantly from the results obtained by Gontcharov and presented in [5]. The causes of observed differences seem to be the following: the examination of different types of the DML, the usage of different excitation signals (MLSSA vs. linear sweep sine) and the measurement conditions. Gontcharov was performing measurements on a hemisphere in large, hard walled room, while measurements presented in sec. VI were conducted in an anechoic chamber. It's worth noticing, that the DMLAmina Edge 5 is characterized by highly variable and frequency-dependent directivity characteristics [4].

However, in Goncharov's work as well as in this work, the obtained results reveal similar tendencies. In both cases, the levels measured in reverberant chambers for the lowest octave are a few decibels higher than calculated from the hemisphere measurements. Similarly, in the highest registers (above 4 kHz), sound power levels obtained from hemispherical measurements tend to be yield higher values, than measured at the reverberant chambers. The differences between the results obtained in this study with both its approaches are slightly larger than in Goncharov's work.

## CONCLUSION

The total sound power level of the DMLs investigated was close to that of the example pistonic loudspeaker, on average it was lower by about 2 dB. This indicates similar efficiency of both types of loudspeakers, when related to the released sound power level. The impedances of both investigated types was 4 Ω, and it was resistive in the case of the DML.

When comparing the power spectra, the results obtained for the electrodynamic loudspeaker differ slightly from those obtained for the DMLs. In the frequency ranges where the DMLs exhibit a decrease in efficiency, this phenomenon does not occur for the electrodynamic loudspeaker. There is also a noticeable sharp roll-off in the sound power levels obtained using the conventional type of the transducer above the frequency of 8 kHz. This can be attributed to the investigated type of the electrodynamic loudspeaker, which is a woofer/midrange, but also to its inherent property of high-frequency beaming along the loudspeaker axis. Thus, the contribution of beamed high frequencies to the power spectrum is less than to the on-axis measured pressure in free-field conditions. Due to a high variability of frequency responses of the DML, (which highly depends on the choice of the measurement point) and irregularity of their directivity characteristics, the sound power level can be considered as a simple and convenient way of presenting a coarse information about their frequency characteristics. This can be useful in situations where concise information about product quality is needed (e. g. quality control, product leaflets) . Also – one of the biggest advantage of presented method is related with time. A set of measurements for a single transducer takes about half an hour.

An important application area where fast and simple measurements of frequency characteristics of the DMLs are very useful is electronic correction of these loudspeakers. As has been demonstrated in many works (e.g. [2,4,7]) and in this one, flatness of the frequency response is not an advantage of the DMLs, but methods of their correction are available and technologically accessible.

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