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Specific properties of phase characteristics of Distributed Mode Loudspeakers

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Abstract Distributed Mode Loudspeakers (DMLs) are characterized by a specific principle of operation, based on bending oscillations of a plate with a certain stiffness and dimensions. Because of this property DML produce a diffuse sound field in the proximity of the loudspeaker. In this work a series of phase characteristics measurements of a DML was carried out, which were compared with analogous ones, carried out for a conventional electrodynamic loudspeaker with a pistonic diaphragm. The elevations of measurement points were chosen in order to coincide with the most likely positions of a listener relative to the DML. A measurement on the axis of the transducer was also conducted. The results have demonstrated that the variability of phase value resulting as a function of frequency and localization of a measurement point is high. It may be concluded, that the DML is a non-minimum phase system, with some frequency regions of minimum phase behaviour. These regions are strongly dependent on the point of measurement.

Keywords: DML, loudspeaker phase, loudspeaker characteristics, loudspeaker measurements.

1. Introduction

Distributed Mode Loudspeakers (DMLs), also referred to as flat panel loudspeakers employ a different sound radiating element than the conventional cone-shaped diaphragm. In the DML the radiator is a flat and stiff panel, which has a rectangular shape. Its mass is considerably bigger than that of the diaphragm of electrodynamic loudspeakers. An electrodynamic or piezoelectric exciter attached to the panel induces uniformly distributed bending wave vibration. This is very different from the operation of the conventional electrodynamic cone loudspeaker which is designed to vibrate as a rigid piston.

There used to be a wave of interest in DML loudspeaker technology at the turn of this century. An introduction to the technology can be found in [1] and a review of its evolution with an extensive list of references was written by Heilemann et al. [2]. Big hopes were put in this technology, as it offered a unique possibility of mounting the loudspeakers in walls or behind paintings, owing to their small depth.

The technology has other advantages. The DML loudspeaker can reproduce sounds from about 100 Hz or below, up to well over the upper hearing frequency, so it does not require any crossover filters. It has a very wide radiation angle [3–5] and behaves as an incoherent sound source which turned out to bring perceptual advantages [1, 2]. Works of the team including the current authors (to be published) proved that subjective spatial properties of sound reproduction over DMLs substantially surpass those of electrodynamic loudspeakers. It seems that the new wave of interest in DMLs builds up together with a growing interest in spatial audio systems. These systems require seven, nine or more loudspeakers, hence the flexibility of installation of DMLs is likely to be even more valued than 25 years ago.

The DMLs have their downsides. Without doubt the main problem is the frequency response, which is considerably more uneven than responses of pistonic loudspeaker based systems in a similar price range. The appropriate method for measurement of frequency responses of DMLs is more complex than measurements of electrodynamic loudspeakers [3–5].

One of the ways of improvement of a loudspeakers' frequency response, or a combined response of a reproduction room and the loudspeaker is by applying electronic correction, usually with an inverse filter [6]. This is difficult. Loudspeaker units are usually minimum phase systems but loudspeaker systems are usually not, and loudspeaker and room systems are definitely not.

Thus in order to attempt any correction of DML frequency response it is indispensable to know its phase characteristics. To the best knowledge of these authors this is the first published study of DML phase characteristics. In this work we have used our experience from earlier studies of amplitude characteristics of the DMLs [3–5].

2. Vibrations in Distributed Mode Loudspeakers

Vibrations of DMLs can be considered as a superposition of panel's bending modes. To consider its modal behaviour, Anderson et al. [8] suggest to start with describing the unforced displacement of a point in a plane:

$$D\nabla^4 w(x,y,t) + ph\ddot{w}(x,y,t) = 0, \tag{1}$$

where dots represent time differentiation, ∇^4 is the biharmonic operator, and D is the bending stiffness of the panel. We can solve the equation (1), by separating the displacement of the plate w into a sum of "modes" and a time dependent modulating function $\Phi(r,t)$, where the mode index r is represented by a pair of indices $(r_m,\ r_n)$. Therefore we can define $w(x,y,t)$:

$$w(x,y,t) = \sum_{r=1}^{\infty} w_s(x,y,r)\Phi(r,t). \tag{2}$$

Considering the "simply supported" boundary condition, we can rewrite $w_s(x,y,r)$ as:

$$w_s(x,y,r) = \sin\left(\frac{r_m \pi x}{L_x}\right)\sin\left(\frac{r_n \pi y}{L_y}\right), \tag{3}$$

where L_x and L_y are panel dimensions. Combining Eqs. (1) – (3) yields:

$$D\sum_{r=1}^{\infty} \Psi_r^2 w_s(x,y,r)\Phi(r,t) + \rho h \sum_{r=1}^{\infty} w_s(x,y,r)\ddot{\Phi}(r,t) = 0, \tag{4}$$

where Ψ_r is a 'modal stiffness' equal to:

$$\nabla^2 w_s(x,y,s) = \left(\frac{\pi^2 r_m^2}{L_x^2} + \frac{\pi^2 r_n^2}{L_y^2}\right). \tag{5}$$

Assuming the amplitude of each mode is a complex exponential function, we can write a relationship:

$$\sum_{r=1}^{\infty} A_r w_s(x,y,r)[D\Psi_r^2 - \omega^2 \rho h] = 0. \tag{6}$$

This leads to a resonant frequency of each mode, expressed as:

$$\omega_r = \sqrt{\frac{D\Psi_r^2}{\rho h}}, \tag{7}$$

where h is the thickness of the panel, and ρ is a density of the material the panel is made of. D can be expressed [9] depending on the Young's modulus E and Poisson's ratio ν:

$$D = \frac{Eh^3}{12(1-\nu^2)}. \tag{8}$$

Furthermore, the bending wave speed in a panel is a function of the panel material, thickness, and frequency. The dispersive nature of panel's oscillations implies the existence of a coincidence frequency, which is the frequency at which the wave speed in the panel is equal to the wave speed in the air. Following [2] the coincidence frequency is given by:

$$\hat{f}_c = \frac{c^2}{2\pi}\sqrt{\frac{\rho h}{D}} = \frac{c^2}{2\pi}\sqrt{\frac{12\rho(1-\nu^2)}{Eh^2}}. \tag{9}$$

Below the coincidence frequency, the radiation response of the panel is determined by the radiation patterns connected with the panel bending modes. Above the coincidence frequency, a plane wave is radiated from the panel surface [2].

3. Measurement procedure

We chose a most widely available commercial line of the DMLs – from Amina Technologies and their model Edge 5 for comparison with a pistonic loudspeaker. The width and height of the panel are 450 × 345 mm. The unit has one exciter. The pistonic loudspeaker was SB Acoustics SB17NRXC35-4. This is a 6'' woofer-midrange unit with a usable upper frequency limit of about 5 kHz. We excluded the use of a two way system, to eliminate the effect of the crossover filter. The DML was factory mounted in a closed metal box of 70 mm depth, filled with an absorbing material. The pistonic loudspeaker was mounted in a ported loudspeaker enclosure with a volume of 19 L.

The measurement procedure was conducted using a free software, called Room EQ Wizard (REW) in 5.20.13 version. REW provided an excitation, acquisition of data and export to .csv format, which is easily readable by various computing environments. The excitation was a logarithmic sweep-sine signal, covering a frequency range from 100 Hz to 20 kHz. The lower limit of the frequency range was chosen because amplitude responses of DMLs roll-off at low frequencies so this range is not usable. For the measured type of the DML the usable range extends downwards to about 100 Hz. Some energy is still radiated below this limit, but it is recommended to restrain the electric power supplied to the DML at low frequencies for safety reasons. Every single sweep was 512 kSamples long and was repeated four times per every measurement point. The procedure was not designed to use a timing reference signal and the $t = 0$ point was established from the built in REW time delay estimate between the transmitted and received signal. Measurements were taken with 48 kHz kSamples frequency and 24 bit resolution. The measurement procedure is presented in Fig. 1.

The measurement environment was hosted and controlled by a personal computer, running Windows OS. The microphone used during the procedure was G.R.A.S. 46 AE free field ½'' microphone, connected to the G.R.A.S. 12AX Conditioner, sending signal via Klark – Teknik DI-20P di-box to the Focusrite Clarett 8 Pre USB audio interface. The excitation signal was delivered to the examined loudspeakers by the Anthem PVA-7 power amplifier, fed with the signal from the interface mentioned above. The output of the amplifier was checked with a voltmeter, in order to keep the voltage at ~2.5 V RMS, to have a confidence, that the transducer will not be damaged during the procedure. The measurement setup diagram is depicted in Fig. 2.

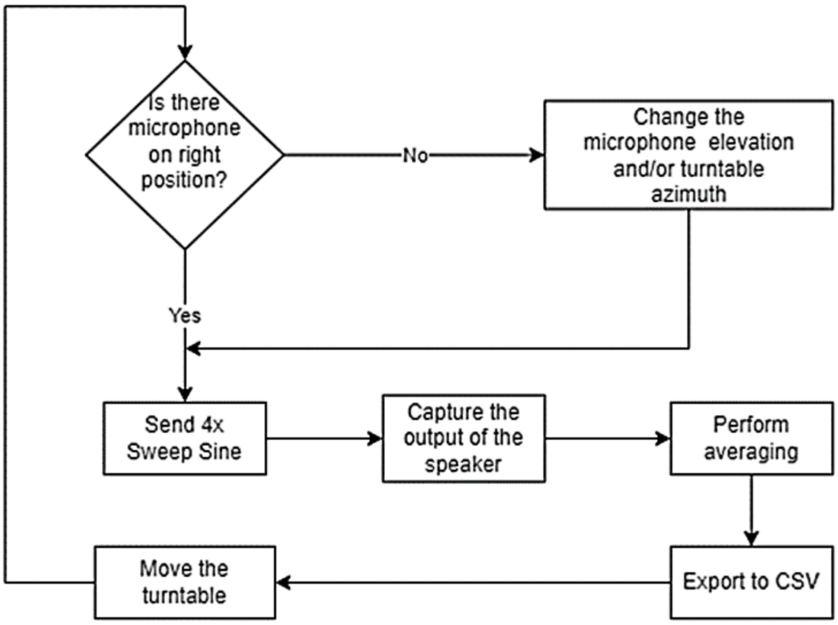

Figure 1. Schematic diagram of the measurement procedure.

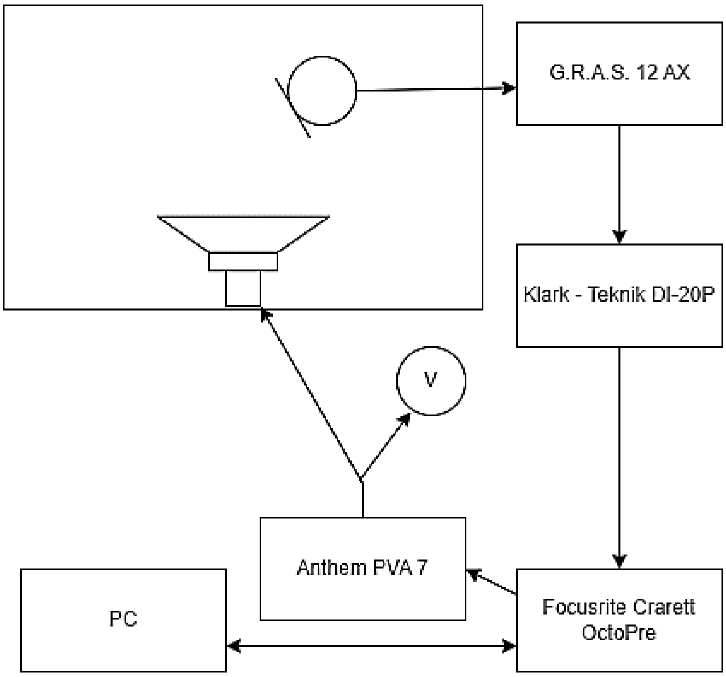

Figure 2. Measurement setup diagram. The widely used symbol of the loudspeaker is used in the diagram, but in the case of the DML it has no physical resemblance.

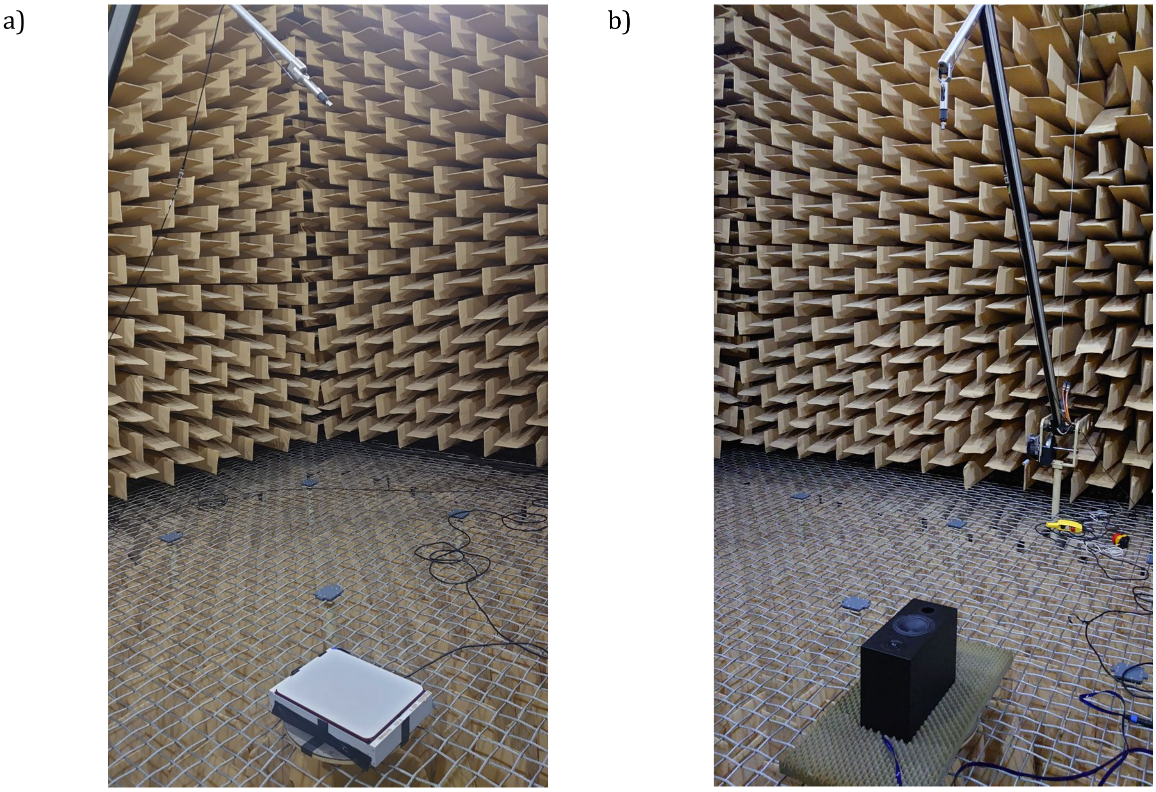

Figure 3. Loudspeaker placement in the anechoic chamber: a) DML loudspeaker, b) pistonic loudspeaker.

Phase characteristics of the measurement setup had not been measured, but because of their properties their effect on phase in the setup used within the frequency band investigated should be negligible. The measured loudspeakers, as well as the measurement microphone were placed in an anechoic chamber at the Department of Mechanics and Vibroacoustics of AGH UST. The volume of the chamber is 1000 m^3. The loudspeakers were attached coaxially to a turntable driven by a stepper motor and the microphone was mounted on a robotic arm. Both units were controlled by a custom made application software, developed in LabVIEW environment. Such a system made it easy and precise to adjust the measurement angles.

We decided to choose the measurement points on three orbits, coinciding with the most likely positions of a listener relative to the DML built in the wall. The elevations of the orbits were equal to 30, 45 and 60 degrees, relative to the DML surface. At each orbit, the characteristic was measured at six azimuths: 0°, 60°, 120°, 180°, 240° and 300°. For the sake of completeness a measurement on the axis of the transducer was also conducted. The measurement hemisphere had a radius of 1.5 m. Although the most common reference distance for loudspeaker measurement is 1 m, a longer distance was chosen as more representative, since the incoherent nature of sound radiation of the DMLs manifests itself in strong dependence of characteristics on the distance. The placement of loudspeakers in the anechoic chamber is shown in Fig. 3.

4. Samples of measurement results

For the purpose of this paper, the most representative and most revealing examples of measurement results were selected. The selection criterion involved three possible listening scenarios: stereo listening, according to equilateral triangle rule with speakers mounted in the surface of the wall (which is typical for DML loudspeakers), casual listening with quasi random placement of the listener relative to loudspeaker, and listening on the axis of the loudspeaker (which is the reference condition for the pistonic loudspeaker). According to such a criterion, measurements from three points for both types of loudspeakers are presented: 60° of elevation, 60° of azimuth (see Figs. 4, 5); 45° of elevation, 0° of azimuth (see Figs. 6, 7) and 90° of elevation (see Figs. 8, 9), which is equal to the axis of a loudspeaker.

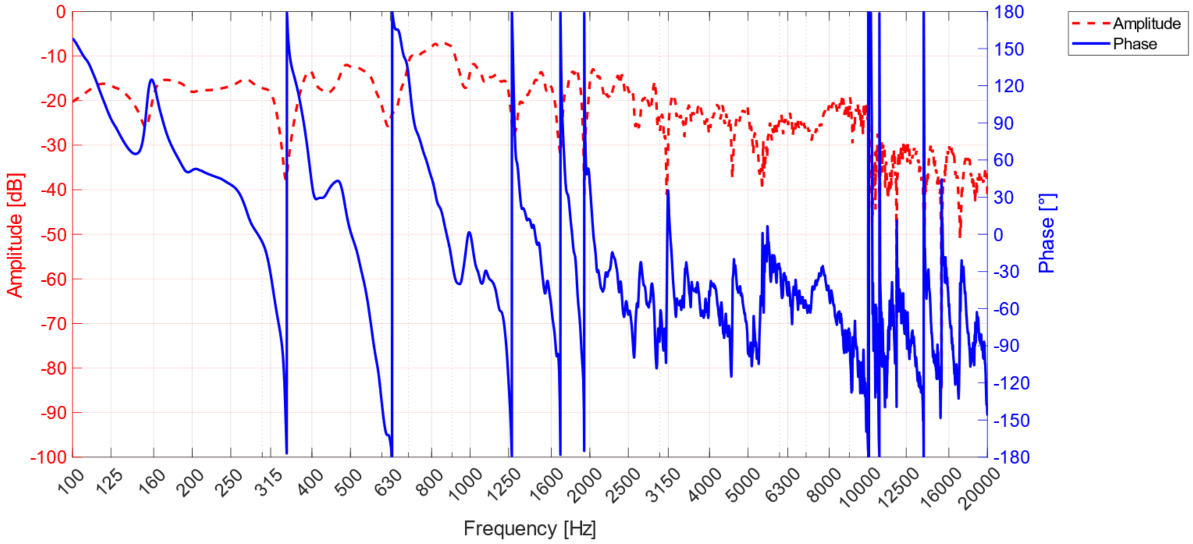

Figure 4. Frequency characteristics of a DML loudspeaker for 60° of elevation, 60° of azimuth.

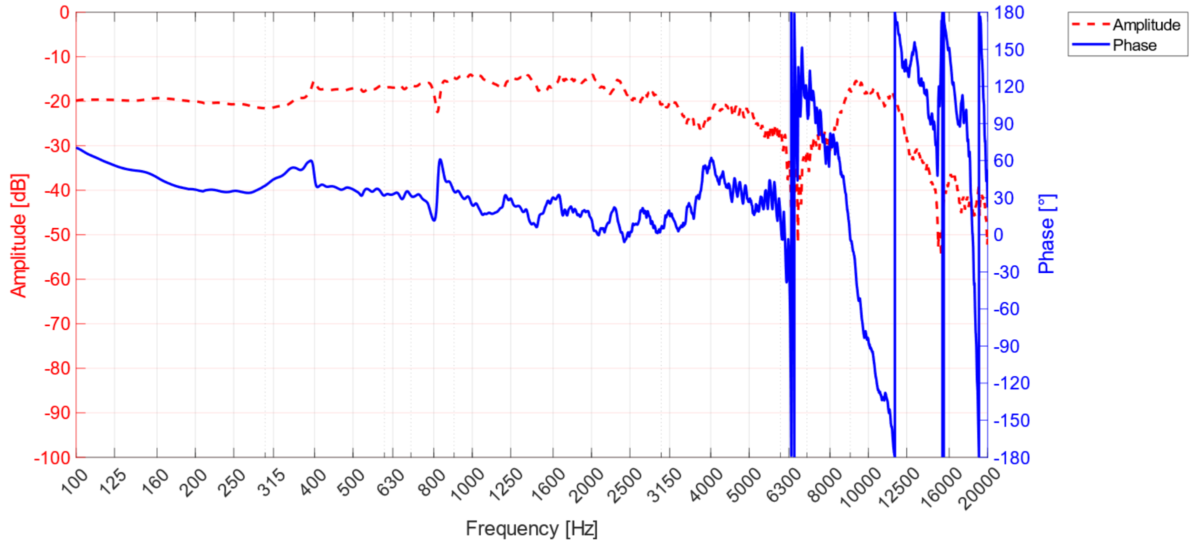

Figure 5. Frequency characteristics of a pistonic loudspeaker for 60° of elevation, 60° of azimuth.

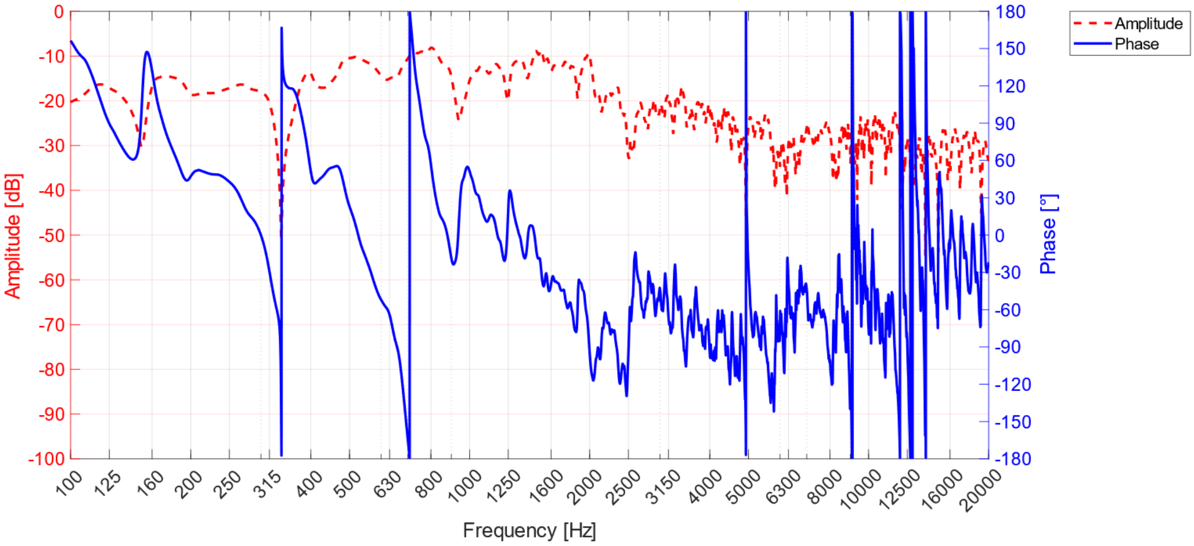

Figure 6. Frequency characteristics of a DML loudspeaker for 45° of elevation, 0° of azimuth.

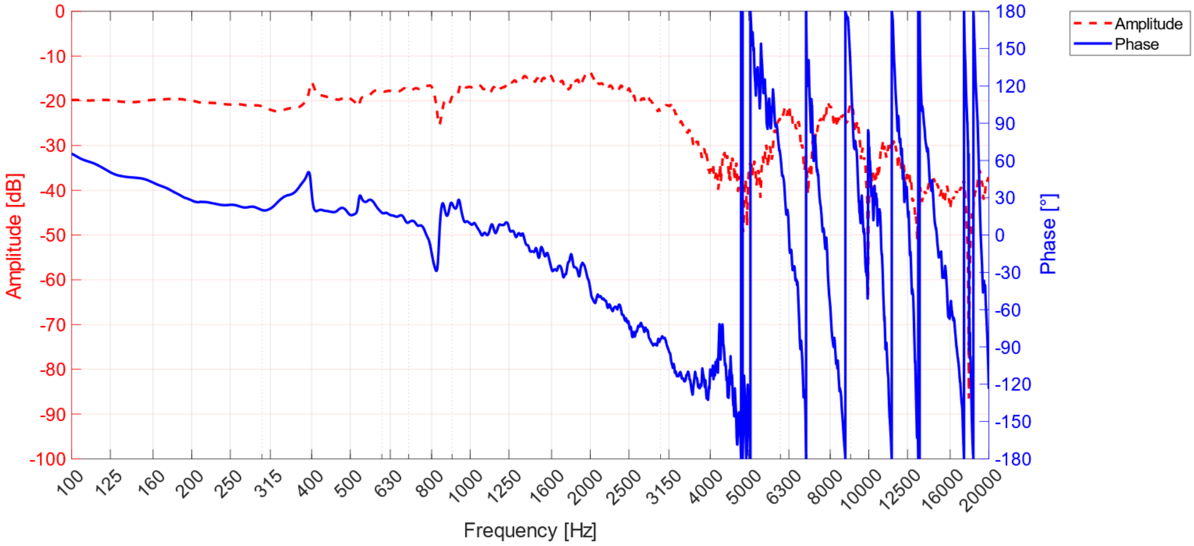

Figure 7. Frequency characteristics of a pistonic loudspeaker for 45° of elevation, 0° of azimuth.

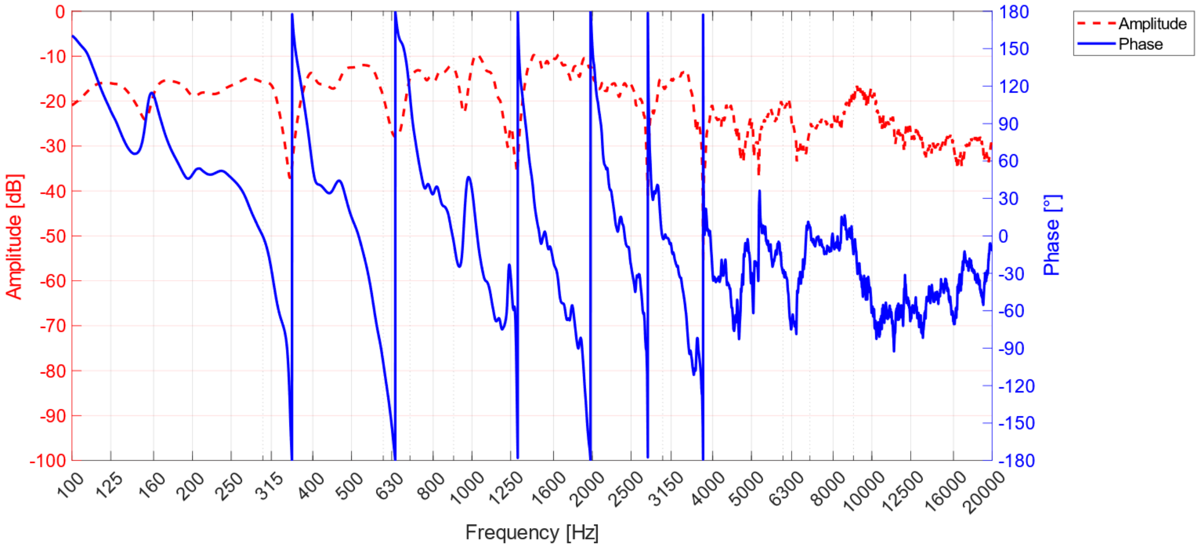

Figure 8. Frequency characteristics of a DML loudspeaker for the axis of the transducer.

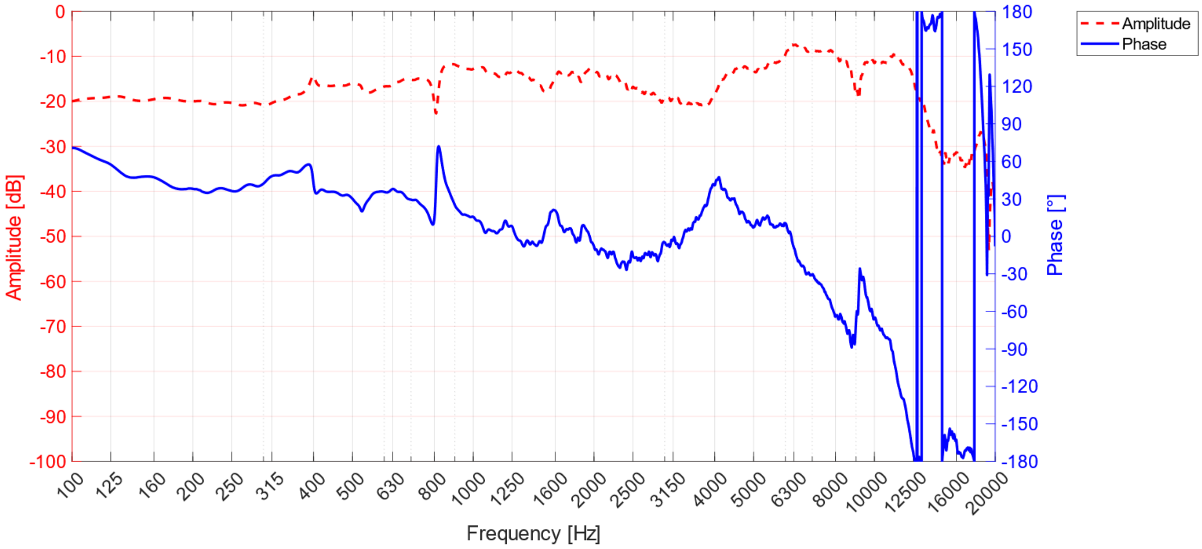

Figure 9. Frequency characteristics of a pistonic loudspeaker for the axis of the transducer.

One of the well-known [2, 6, 7] properties of the DML is high variability of their frequency characteristics, following changes of localization of the measurement microphone, relative to the loudspeaker. To exhibit that feature, we created aggregate plots of amplitude characteristics vs frequency for various points at 60° of elevation for the DML loudspeaker and pistonic loudspeaker (see Figs. 10, 11), as well as aggregate plots of phase characteristics vs frequency for various points at 60° of elevation for the DML loudspeaker and pistonic loudspeaker (see Figs. 12, 13). For the sake of completeness, analogous plots of amplitude characteristics vs frequency (Figs. 14, 15) and phase characteristics vs frequency (Figs. 16, 17) were created, but for 0° of azimuth and variable elevation.

To summarize the variability of the phase in the DML versus the measurement point, we combined the measured phases for the frequency of 1 kHz in every measurement point on the hemisphere within a single chart (Fig. 18). Such a chart was also prepared for a pistonic loudspeaker (Fig. 19) to show how the behaviour of the transducers differs between each other at that reference frequency. The letters 'E' in X-axis description stand for 'Elevation' and the letters 'A' – for 'Azimuth'.

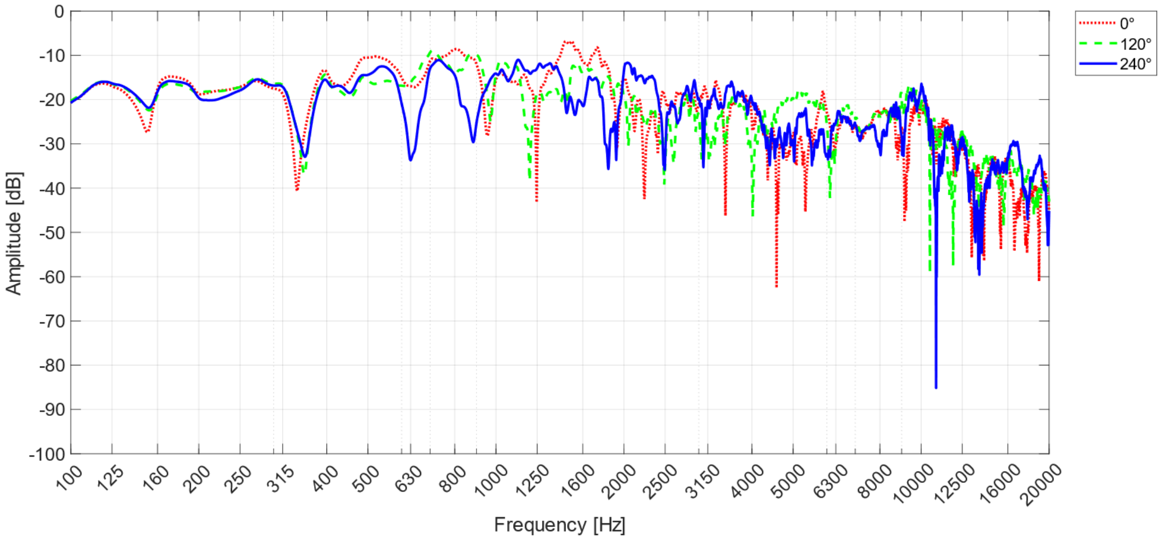

Figure 10. Amplitude characteristics of the DML loudspeaker for 60° of elevation and various azimuths.

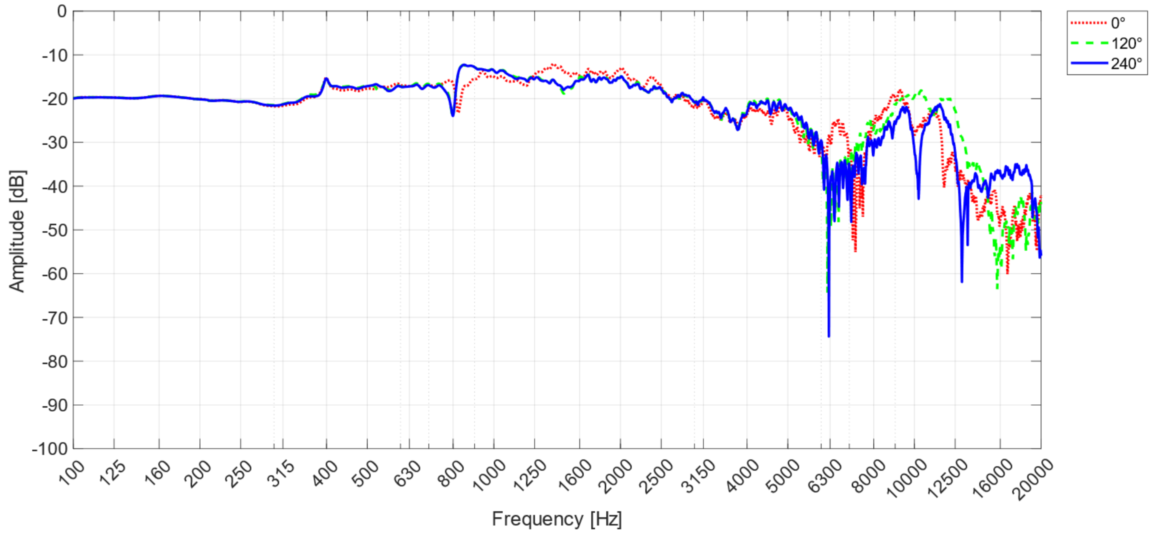

Figure 11. Amplitude characteristics of the pistonic loudspeaker for 60° of elevation and various azimuths.

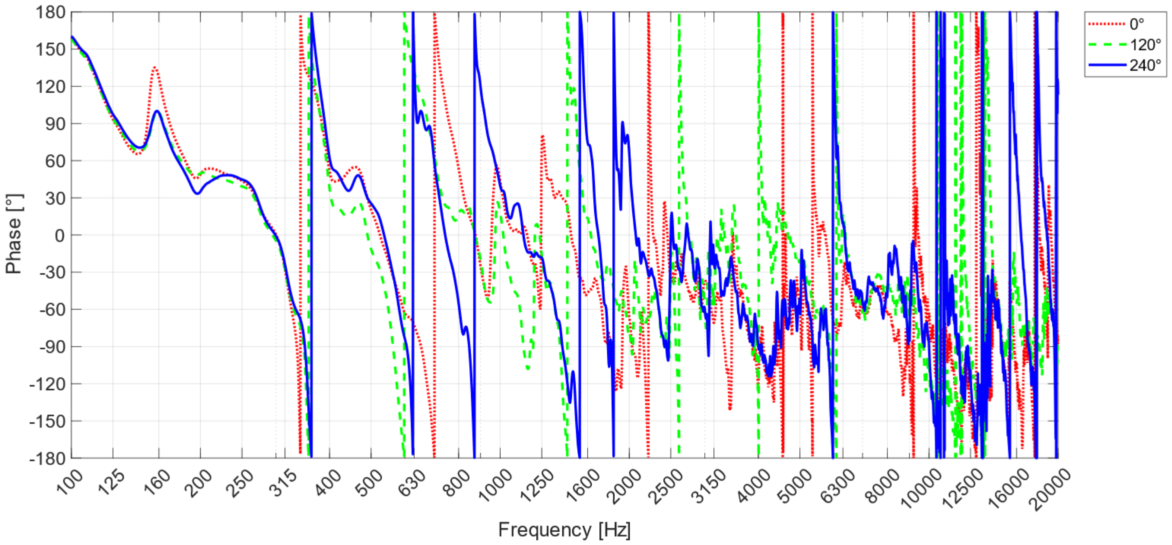

Figure 12. Phase characteristics of the DML loudspeaker for 60° of elevation and various azimuths.

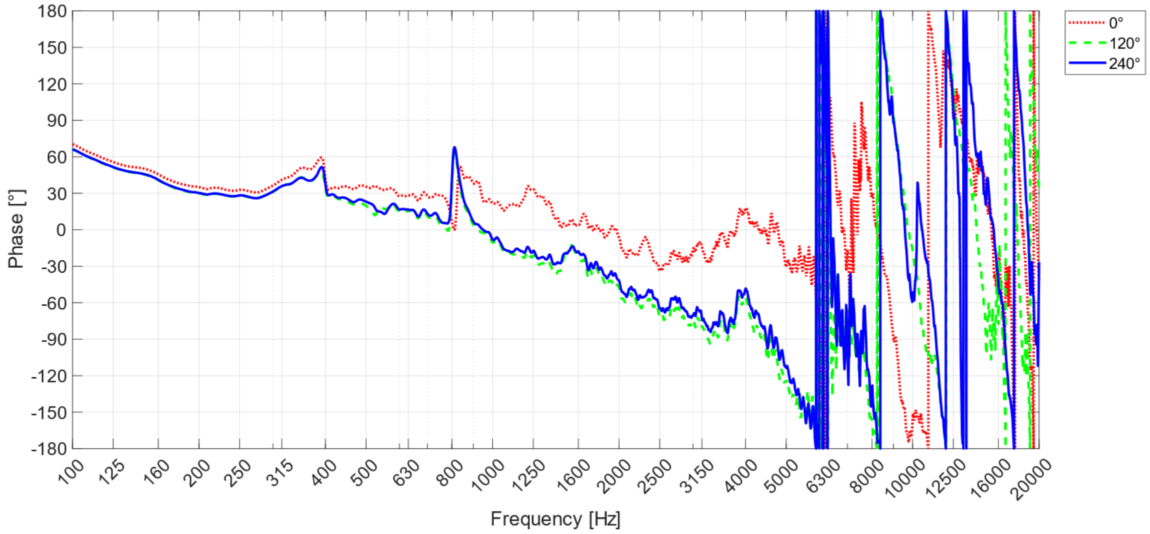

Figure 13. Phase characteristics of the pistonic loudspeaker for 60° of elevation and various azimuths.

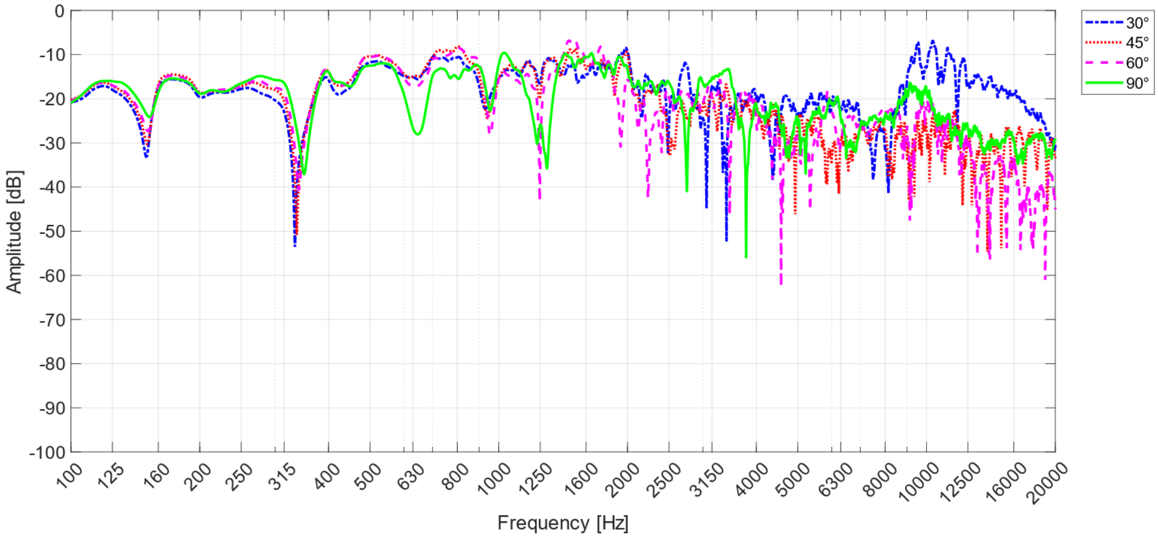

Figure 14. Amplitude characteristics of the DML loudspeaker for 0° of azimuth and various elevations.

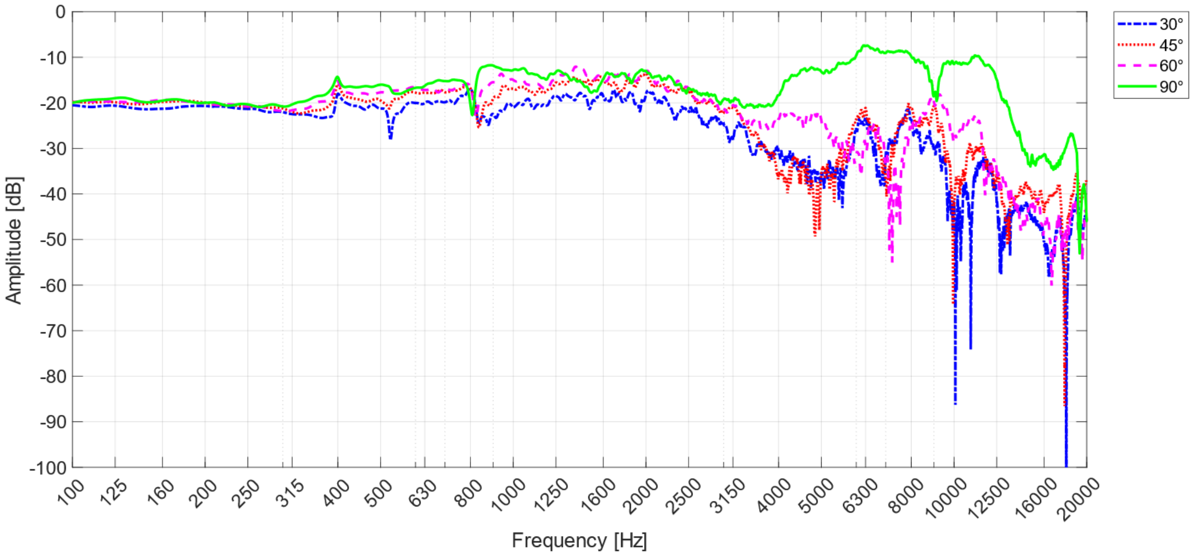

Figure 15. Amplitude characteristics of the pistonic loudspeaker for 0° of azimuth and various elevations.

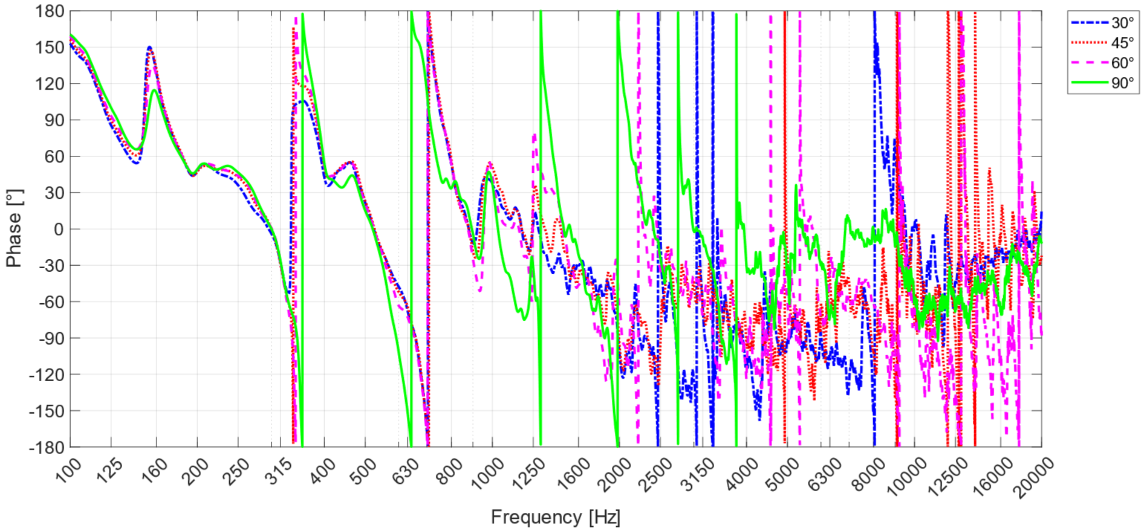

Figure 16. Phase characteristics of the DML loudspeaker for 0° of azimuth and various elevations.

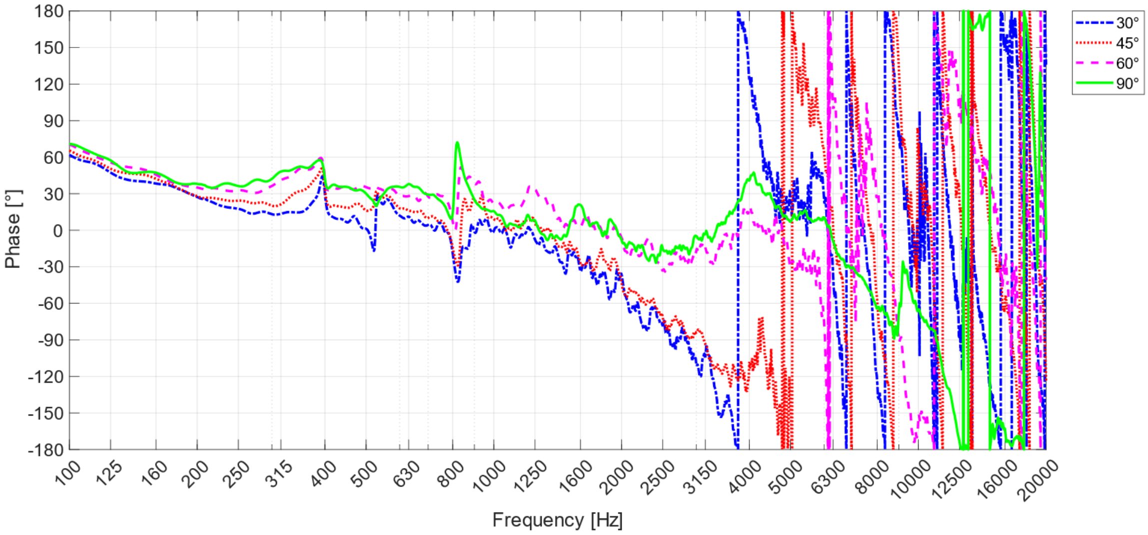

Figure 17. Phase characteristics of the pistonic loudspeaker for 0° of azimuth and various elevations.

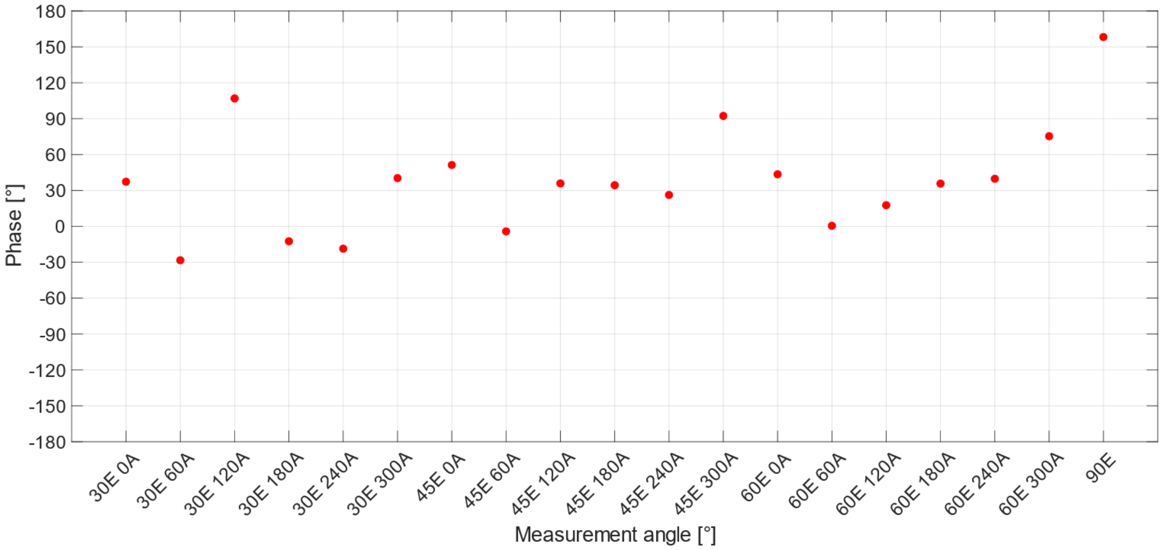

Figure 18. Measured phases of the DML loudspeaker at 1 kHz frequency for every measurement point.

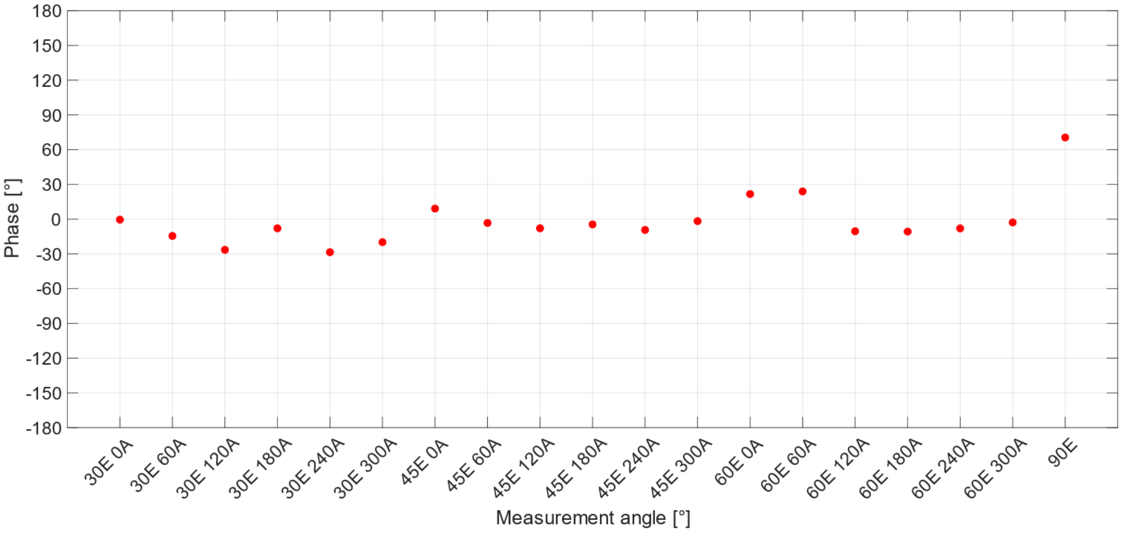

Figure 19. Measured phases of the pistonic loudspeaker at 1 kHz frequency for every measurement point.

4. Discussion

The first observation, after analysing Figs. 4, 6, 8 and Figs. 12, 14 and 16, is that the phase functions of the DML loudspeaker depend strongly on both the elevation and azimuth. The second observation is that in the pistonic loudspeaker there is a wide range of frequencies where phase characteristics are fairly smooth and constrained to +/-70° . This range extends from 100 Hz up to between 4 and 5 kHz, i.e. in that loudspeaker's usable frequency range. This refers to 90° and 60° elevation angle. At lower elevation angles (i.e. away from the loudspeaker axis) this range ends to about 2 kHz.

All phase plots of the DML measured present a number of phase wrapping points over the entire audio frequency range. In the case of the pistonic loudspeaker phase wrapping occurs only for frequencies above about 5 kHz, i.e. in the region where the efficiency of the loudspeaker rolls-off.

It is clear that after phase unwrapping the downwards slope of the phase vs frequency functions of the DML loudspeaker is much steeper than that of the pistonic loudspeaker. This indicates a high value of the group delay t_G in the DML:

$$t_G = -\frac{d\varphi(f)}{df}, \tag{10}$$

where φ is phase and f is frequency.

High value of group delay is an indication of a non-minimum phase system. An even stronger indication of a non-minimum phase system is brought by the relation between the amplitude and phase spectra in all measurements, seen directly in Figs. 4, 6 and 8, and when comparing plots in Fig. 14 with plots in Fig. 16. The rule linking local maxima and minima in the amplitude characteristic with the negative or positive slopes of the phase characteristics, which is a strong indication for the minimum phase system [7], is not met.

However, all amplitude and phase characteristics presented together in Figs. 4, 6 and 8 reveal a specific property of DML loudspeakers. A region of mild phase slope and relatively constrained values can be noticed in all these plots. At the elevation of 60° (Fig. 4) the region extends from 2 kHz through 10 kHz; at the elevation of 45° (Fig. 6) from 700 Hz through 9 kHz, with an anomaly at 5 kHz, and then again from 14 kHz upwards; at the elevation of 0° (Fig. 8) from 5 kHz up to 20 kHz. In all those ranges of constrained phase the rule indicating minimum phase system behavior is met. This demonstrates that depending on the elevation of measurement the range of reproduced frequencies in the DML is divided into separete regions of non-minimum and minimum phase behavior. A similar analysis performed for the pistonic loudspeaker indicate a regular rule: in the entire usable range of frequencies (up to about 5 kHz) the loudspeaker is the minimum phase system, and becomes non-minimum phase above that range. This may be expected for that type of the loudspeaker [7].

Another observation is that phase versus measurement position at fixed frequency of 1 kHz for the DML demonstrate large variance of phase values (Fig. 18), while analogous variance is substantially lower for the pistonic loudspeaker (Fig. 19). This confirms the incoherent character of the DML as a sound source.

5. Conclusions

Based on the presented results, the following conclusions can be formulated:

1) DMLs operate as both minimum and non-minimum phase systems, depending on the range of frequency. Both types of performance may be located in various ranges of frequencies. The ranges are wide, and their location depend to a great extent on the elevation and azimuth of the measurement point.
2) In the non-minimum phase mode of operation the value of group delay is large.
3) When phase is measured in different positions of the measuring microphone with the frequency fixed, the variability of phase of the DML is substantially larger than that of the pistonic loudspeaker, which confirms the incoherent sound radiation of DML loudspeakers.
4) Electronic correction of frequency response of DMLs is a difficult task, in view of their prevailing non-minimum phase character.

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Additional information

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

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