INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2024, VOL. 70, NO. 2, PP. 443-448
Manuscript received February 5, 2024; revised June, 2024. doi: 10.24425/ijet.2024.149564

Measurement of nonlinear and Doppler distortion in Distributed Mode Loudspeakers

Karol Czesak, and Piotr Kleczkowski

Abstract—**Distributed Mode Loudspeakers (DMLs), as other electroacoustic transducers with electrodynamic excitation, are susceptible to the occurrence of nonlinear distortion. The literature on nonlinear distortion in DMLs is scarce. The vibrations of the DML panel are very small in amplitude, thus the coil excursion of the exciter is low, which is a favorable condition for low nonlinear distortion. The scope of this paper covers investigation of harmonic and intermodulation distortion, occurring in the DML. The harmonic distortion was examined with two methods and the intermodulation distortion – with three, including one author's proposed method. The result indicate, that nonlinear distortion in DMLs may be a bigger problem than those in diaphragm loudspeakers.**

Keywords—**DML; loudspeaker characteristics; loudspeaker measurements; nonlinear distortion; Doppler effect**

I. INTRODUCTION

DISTRIBUTED MODE LOUDSPEAKERS (DML), like other electrodynamic transducers, are characterized by susceptibility to distortion. The origin of these distortions can be attributed to the fact that a loudspeaker is a system that generates mechanical vibrations. This system is characterized by specific operating conditions, such as the mass, thickness, and stiffness of the vibrating element, the coil's displacement from its equilibrium position, the number of coil windings, and the depth of coil placement within the magnet at equilibrium. In the case of DML, the mass and mounting method of the exciter, and the method of attaching the vibrating element to the device's housing (support, fixation, and the application of damping) also contribute to distortions.

The substantial thickness of the vibrating plate in the DML leads to nonlinearity when executing flexural vibrations by the plate, while structural imperfections, if present in a given plate, cause the vibrations to lose their symmetrical character. Notably, the most significant displacements from the equilibrium position occur at points where electrodynamic exciters are attached to the plate.

Based on the literature review, at low frequencies, due to significantly smaller displacements of points on the surface of the DML compared to classical electrodynamic loudspeaker diaphragms, we can expect a reduced contribution of occurring harmonic distortions. In frequency ranges where the diaphragm displacements of electrodynamic loudspeakers do not reach such high values, the advantage of the DML is diminished. [1]

II. TYPES OF INVESTIGATED NONLINEAR DISTORTIONS AND METHOD OF THEIR DETERMINATION

For the purposes of this study, harmonic and intermodulation distortions occurring in the DML were examined.

Harmonic distortion was investigated in two ways: the classic THD+N method and by determining the content of the harmonic distortions themselves in the signal using the built-in FFT detectors function in the measurement analyzer. These values were plotted as a function of excitation power for a frequency of 1 kHz and as a function of frequency for an excitation power of 3.25W. They were also presented as single-number measures for excitations with powers of 0.03 W, 0.013 W, 0.55 W, 0.98 W, 2 W, and 3.25 W.

Distortions occurring in DMLs were examined in a small anechoic chamber in the Department of Mechanics and Vibroacoustics, AGH University of Science and Technology in Krakow. Measurements were conducted at two points: on the axis of the transducer and at an arbitrarily selected point with an azimuth of 90 degrees, and an elevation of 30 degrees away from the transducer's axis, which was due to the angle of usage of DMLs for stereophonic listening. The distance between the loudspeaker and the measurement microphone in both cases was 1 m. The placement of the tested device in the anechoic chamber is shown in Fig. 1

Fig. 1. Placement of the investigated DML in the anechoic chamber.

We subjected two units from the Amina Edge 5i series to examination. Measurements were conducted using the G.R.A.S. 40 AF free-field microphone, connected to the Norsonic 1201 preamplifier. The system was powered by the G.R.A.S. 12 AA conditioner. The voltage signal obtained in this manner was

This work was supported by research subsidy of The Faculty of Mechanical Engineering and Robotics, AGH University, no. 16.16.130.942.

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

directed to the Prism dScope Series III measurement analyser, which also served as the excitation source. The excitation was delivered to the loudspeaker using the Anthem PVA-7 power amplifier. A voltmeter was connected in parallel with the tested electroacoustic transducer at the amplifier's output. The measurement setup diagram is presented in Fig. 2.

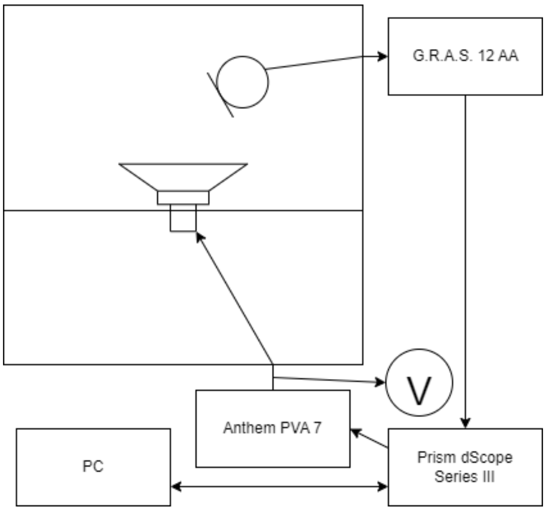

Fig. 2. Diagram of the measurement setup used in the investigation of distortions occurring in the DML.

In the single-number measurements of Total Harmonic Distortion (THD) and Total Harmonic distortion + Noise (THD+N) values, the excitation signals were sinusoids with a frequency of 1 kHz and amplitudes as listed in Tabs I and II. For intermodulation distortion measurements, excitation consisted of combinations of sinusoids. One of them was derived from the method described in DIN 45403, where the test device is provided with tones at frequencies of 250 Hz and 8 kHz at a 4:1 amplitude ratio (DIN IMD). The second combination of sinusoids, known as the CCIF method (described in IEC 268.3, IHF A202 documents), involves applying two tones of equal amplitude to the input of the tested system, spaced 1 kHz apart [2]. In the present case, the CCIF method variant was applied, which specified excitation with tones at frequencies of 13 kHz and 14 kHz (CCIF IMD).

Attempts to examine the Doppler effect occurring in Distributed Mode Loudspeakers were made using the method indicated in SMPTE TH22.51, modified by the authors. The modification involved generating a 120 Hz sinusoid instead of a 60 Hz sinusoid. The amplitude ratio of these sinusoids remained unchanged (Doppler IMD).

Regarding single-number values associated with intermodulation distortions (DIN IMD, CCIF IMD, Doppler IMD), the quantities contained in columns Lu, U, and P in Tabs I and II represent respectively: voltage level at the output of dScope, voltage at the output of power amplifier and power delivered to DMLs.

TABLE I

SINGLE-NUMBER QUANTITIES DESCRIBING HARMONIC AND INTERMODULATION DISTORTIONS, MEASURED ON THE TRANSDUCER AXIS

L_u [dBV]	U [V]	P [W]	THD+N @ 1kHz [%]	THD @ 1kHz [%]	DIN IMD [%]	CCIF IMD [%]	Doppler IMD [%]
-40	0,5	0,03	0,335	0,354	0,021	0,142	0,016
-35	1	0,13	0,675	0,720	0,017	0,250	0,017
-30	2,1	0,55	1,286	1,363	0,036	0,084	0,024
-28	2,8	0,98	0,272	0,282	0,025	0,132	0,022
-25	4	2,00	0,377	0,398	0,019	0,158	0,016
-23	5,1	3,25	0,473	0,503	0,017	0,232	0,015

TABLE II

SINGLE-NUMBER QUANTITIES DESCRIBING HARMONIC AND INTERMODULATION DISTORTIONS, MEASURED 30° FROM THE TRANSDUCER AXIS.

L_u [dBV]	U [V]	P [W]	THD+N @ 1kHz [%]	THD @ 1kHz [%]	DIN IMD [%]	CCIF IMD [%]	Doppler IMD [%]
-40	0,5	0,03	0,585	0,624	0,032	0,022	0,056
-35	1	0,13	1,178	1,264	0,030	0,052	0,083
-30	2,1	0,55	2,350	2,513	0,033	0,025	0,035
-28	2,8	0,98	0,396	0,420	0,031	0,017	0,041
-25	4	2,00	0,594	0,636	0,028	0,023	0,054
-23	5,1	3,25	0,775	0,833	0,030	0,036	0,063

It can be noticed in Tables I and II that single-number parameters attain lower values when measured on the transducer axis compared to measurements taken at a point 30° away from its axis. A similar effect is observed for parameters indicating the content of distortions in the signal, determined through the measurement of intermodulation distortions using the DIN 45403 method and its modification aimed at investigating the presence of the Doppler effect in Distributed Mode Loudspeakers. A different trend is noticeable when examining intermodulation distortions using the CCIF method. Here, single-number values pertaining to the content of distortions in the signal achieve lower values for measurements conducted at a point 30° away from the loudspeaker's axis. This observed phenomenon can be attributed to the fact that the first mode of plate vibrations remains unexcited when subjected to CCIF excitation. When the first mode of the DML vibrations remains unexcited, the omnidirectional component in the directivity pattern of DML is absent, and the directivity of DML becomes strongly connected with side-lobs [3].

III. HARMONIC DISTORTIONS ANALYZED WITH TRADITIONAL METHOD (THD+N)

The traditional method for analyzing harmonic distortions [4] involves applying a sinusoidal excitation to the tested device and filtering the signal obtained at the device's output to remove the frequency of this excitation using a high-Q notch filter. Subsequently, the root mean square (RMS) value of the amplitude of the prepared signal is compared to the RMS value of the filtered component at the frequency equal to the frequency of the excitation signal and expressed in percentages (as presented in Tabs I and II). This process yields the parameter value of THD+N (Total Harmonic Distortion + Noise). In the resulting signal, in addition to harmonic distortions, there are also components originating from potential interference, crosstalk, and noise [5]. Based on the above, the equation for calculating THD+N can be written as:

$$THD + N = \frac{X - X(\omega_0)}{X(\omega_0)} * 100\% \qquad (1)$$

where:

$X(\omega_0)$ – RMS value of the filtered component at the frequency equal to the frequency of the excitation signal,

X – RMS value of the signal appearing on the input of the analyser.

Conventionally, the THD+N parameter is reported for an excitation at a frequency of 1 kHz, although this is not a strict rule. In the course of this study, single-number THD+N values were measured for both measurement points at a frequency of 1 kHz and various amplitudes (see Tabs I and II). Additionally, for an excitation amplitude of 5.1 V, a spectral plot of the signal recorded at the input of the measurement analyser was plotted (Fig. 3). Furthermore, THD+N parameter measurements were conducted for excitation with variable frequencies ranging from 80 Hz to 20 kHz, with a step size of 19.45 Hz, resulting in 1025 measurements (Fig. 4). The amplitude of the excitation was 5.1 V. The charts from Figs 3 and 4 were prepared for two sets of data collected at the two measurement points considered in this chapter.

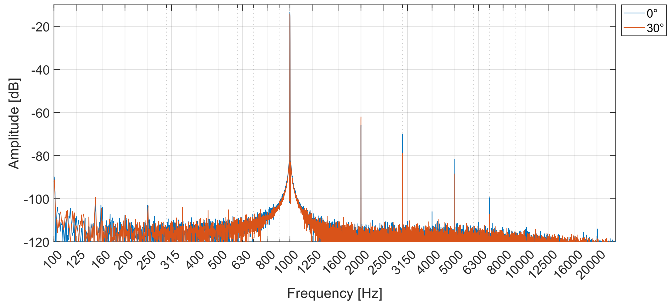

Fig. 3. The spectrum of the response of the DML to a sinusoidal excitation at a frequency of 1 kHz and an amplitude of 5.1 V

As seen in Tabs I and II, a lower level of harmonic distortions and noise occurs when measured on the loudspeaker axis for excitation at a frequency of 1 kHz. Initially, this can be misleading, as apparent in Fig. 3; however, it's crucial to note that when measuring at a 30° angle from the transducer axis, the second harmonic plays a more significant role, and as observed in the graph, subharmonic distortions appear. In the frequency range of 5 kHz to 20 kHz, higher levels of distortions in the output signal of DMLs are observed when measured on the transducer axis. This is related to the irregular radiation pattern of the DML at high frequencies, as well as irregularities in the amplitude-frequency characteristic. For excitation frequencies where the DML exhibits reduced efficiency, the THD+N parameter values are exceptionally high, primarily due to the high ratio of the background noise recorded by the measurement system to the component at the excitation frequency, which is then reproduced with small amplitude. The data in Fig. 4. demonstrate that the THD+N method is inappropriate for the measurement of THD in DMLs.

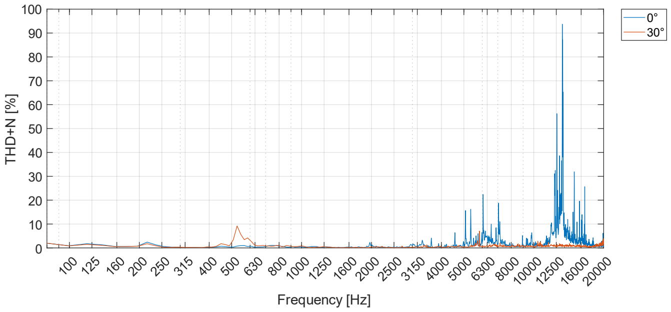

Fig. 4. The variation of the THD+N parameter for sinusoidal excitation with an amplitude of 5.1 V and variable frequency

IV. HARMONIC DISTORTIONS ANALYZED USING FFT DETECTOR METHOD (THD)

The method described in Chapter 2 for analyzing harmonic distortions provides information that depends not only on such distortions themselves but also on noise and electromagnetic interference originating from the device's power supply. One advantage of the THD+N parameter, from the perspective of operating the tested device, is its ability to offer a more comprehensive indication of the presence of undesirable components in the signal transmitted by the device.

Given the above-mentioned situation, the THD parameter, which is the root of the sum of squares of individual harmonics' amplitudes, is gaining increasing popularity. This can be expressed by formula [6]:

$$THD = \frac{\sqrt{(A_2)^2 + (A_3)^2 + \cdots + (A_n)^2}}{A_1} * 100\% \qquad (2)$$

where:

A_1 – the amplitude of the component at the frequency of the excitation,

$A_2, \ \ldots, A_n$ – amplitudes of harmonics.

Data on the amplitudes of these components are obtained using a bank of precisely tuned high-Q filters (which typically limits the analysis range to a few lowest-order components) [4], or through Fourier analysis (as is the case with the Prism dScope III analyser used in this study), where amplitudes of local maxima in the spectrum of the signal recorded at the input of the analyser are sought.

Similarly to THD+N parameter, single-number THD values were measured for both measurement points at a frequency of 1 kHz and various amplitudes (see Tables I and II). For an excitation with the amplitude of 5.1 V, a spectral plot of the signal recorded at the input of the measurement analyser was presented in Fig. 3. Additionally, the THD parameter measurements were conducted for excitations with variable frequencies ranging from 500 Hz to 20 kHz, with a step size of 19.45 Hz (Fig. 5). The amplitude of the excitation was 5.1 V.

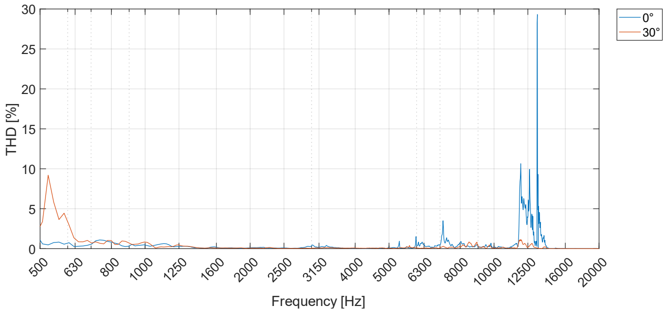

Fig. 5. The variation of the THD parameter for sinusoidal excitation with an amplitude of 5.1 V and variable frequency

The results of the analysis of harmonic distortion introduced by the DML obtained using the FFT detector method, do not significantly differ from the results obtained by the traditional method of measuring THD+N. The results obtained from measurements on the transducer axis are lower than those collected in measurements at a point 30° away from its axis, similar to the examination using the traditional method.

When examining results obtained with the FFT detector method on the transducer axis, an increased content of distortion in the output signal of the DML is also observed for the frequency range of 5 kHz to 20 kHz.

V. INTERMODULATION DISTORTION ANALYZED USING DIN 45403 METHOD (DIN IMD)

The method for analyzing intermodulation distortion, as described in the DIN 45403 standard, involves applying a signal consisting of two sinusoids to the input of the tested system. One of them should have a frequency of 250 Hz, while the other should be at 8 kHz. The amplitudes of these sinusoids should be in a 4:1 ratio (the second sinusoid should exhibit an amplitude level 12.04 dB lower than the first). In this case, the spectrum of intermodulation distortion takes the form of sidebands around the component at 8 kHz, similar to amplitude modulation, where the spectrum of the modulating signal takes the form of sidebands around the carrier [2].

The single-parameter characterizing intermodulation distortion in the DIN 45403 method is the percentage modulation depth assuming that the 8 kHz component is treated as the carrier. This is also described by the formula [7]:

$$DIN\ IMD = \frac{\sqrt{(A_{8kHz-250Hz})^2+(A_{8kHz+250\ Hz})^2+(A_{8kKz-500Hz})^2+(A_{8kHz+500\ Hz})^2}}{A_{8khz}} * 100\% \tag{3}$$

where:

A_{8kHz} – the amplitude of the 8 kHz component,

$A_{8kHz-250Hz}$, $A_{8kHz+250Hz}$, $A_{8kHz-500Hz}$, $A_{8kHz+500Hz}$ – amplitudes of intermodulation products.

Parameters describing intermodulation distortion, measured by the specified method, in the case of the DML take values several orders of magnitude lower than the parameters describing harmonic distortion in such electroacoustic transducers, while maintaining identical excitation amplitudes. Discrepancies in recorded values of the IMD parameter depending on the chosen measurement point are significant. For a point 30° away from the transducer axis, the values of the IMD parameter are approximately 50% higher than those recorded for measurements on the device axis (see Tabs I and II).

The values of the parameter describing the content of intermodulation distortion in the acoustic signal obtained using the DML for various excitation amplitudes, as presented in Tabs I and II, are complemented by a chart showing the spectrum of the signal recorded at the input of the measurement analyzer for excitation at 5.1 V, delivered to the DML (Fig. 6).

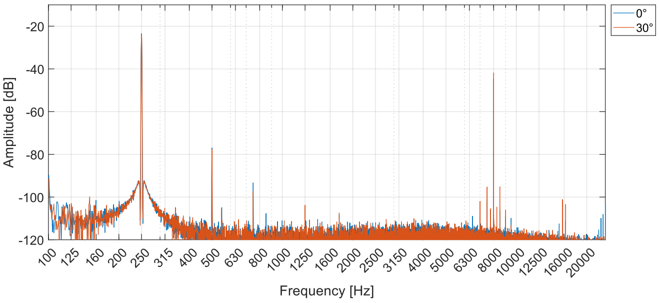

Fig. 6. The spectrum of the response of the DML to the excitation described in the DIN 45403 standard and the amplitude of 5.1 V

It is worth noting that in the response obtained using the DML for the excitation specified in the DIN 45403 standard, in addition to the components provided at the transducer input and those resulting from intermodulation distortions, the harmonics of 250 Hz and non-harmonic components around this frequency also appear. Furthermore, in the spectra of signals recorded at both measurement points, components at frequencies of 15750 Hz and 16250 Hz appear. In the spectrum of the signal recorded on the transducer axis, there are additional components at 15.25 kHz, 22.5 kHz, 23 kHz, 23.5 kHz, and 24 kHz. The 16 kHz component is absent in the signal, which indicates that when measuring intermodulation distortion in DMLs, sidebands resulting from the modulation of the harmonic frequency of 8 kHz - treated as the carrier - with a frequency of 250 Hz are also generated, even if these harmonics themselves are not present in the signal.

VI. INTERMODULATION DISTORTION ANALYZED USING CCIF METHOD (CCIF IMD)

The measurement of intermodulation distortion using the CCIF method (described in the documents IEC 268.3 and IHF A202) involves applying excitation to the tested device, consisting of two sinusoids with equal amplitudes and slightly different frequencies, located in the upper part of the acoustic spectrum. Typical pairs of sinusoids used have frequencies of 13 kHz and 14 kHz or 19 kHz and 20 kHz [2]. The analysis focuses on the amplitudes of the second and third-order components located around the excitation components, as well as the amplitude of the second-order component, which represents the difference tone. The arithmetic sum of the amplitudes of the second and third-order components, expressed as a percentage of the sum of the amplitudes of the excitation tones, serves as a measure of CCIF intermodulation distortions in the signal [2]. A simplified analysis is also possible, considering only the amplitude of the difference tone [2], [8], expressed by the formula [7]:

$$CCIF\ IMD = \frac{A_{14kHz-13kHz}}{\sqrt{(A_{13kHz})^2+(A_{14kHz})^2}} * 100\% \tag{4}$$

where:

$A_{14kHz-13kHz}$ – Product of IMD amplitude.

A_{13kHz}, A_{14kHz} – components of frequencies equal to excitation frequencies) amplitudes.

In this work, an analysis of intermodulation distortion using the CCIF method was conducted, taking into account only the amplitude of the difference tone, which in this case had a frequency of 1 kHz.

The values of obtained parameters describing intermodulation distortion, measured using the CCIF method, are presented in Tables I and II, depending on amplitude of the excitation . The spectrum of the response of the DML to excitation, as described in documents IEC 268.3 and IHF A202, with an amplitude of 5.1V, is presented in the graph shown in Fig 7.

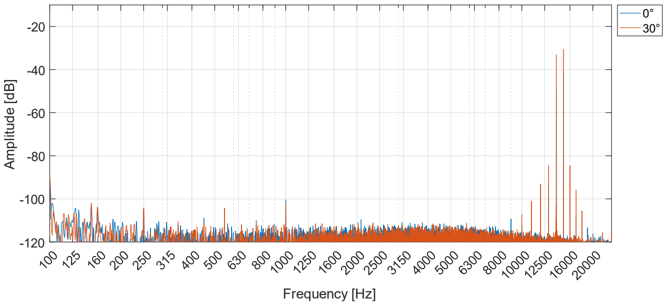

Fig. 7. The spectrum of the response of the DML to the excitation described in IEC 268.3 and IHF A202 standards with an amplitude of 5.1 V

Here, an opposite trend can be observed compared to the analysis of the previously discussed distortions. Specifically, the CCIF IMD parameter reaches lower values for measurements taken at a point located 30° away from the transducer's axis than for measurements conducted at a point along its axis. Such a situation is undoubtedly related to the fact that when applying the excitation to the DML consisting of sinusoids at 13 kHz and 14 kHz, the first mode of vibration of the plate is not stimulated. This results in uneven beam directivity characteristics for the DML. The difference in the amplitudes of sinusoids at 13 kHz and 14 kHz indicates irregularities in the amplitude-frequency characteristics and directivity characteristics of the DML.

VII. INVESTIGATION OF DOPPLER EFFECT IN DML

When reproducing acoustic signals that contains spectral components differing in frequency by two orders of magnitude over the loudspeaker, there is a chance of the Doppler effect occurring. Due to the construction and operation principles, this chance appears to be the highest in the case of diaphragm loudspeakers. However, it has been demonstrated that the distortion content resulting from the Doppler effect in signals reproduced over diaphragm loudspeakers is negligible, furthermore, these distortions are masked by the presence of spectral components at low frequencies in the signal, causing the Doppler effect [9].

In this work, the aim was to investigate whether the Doppler effect occurs in a signal reproduced using the DML. For this purpose, it was decided to modify the method for measuring intermodulation distortion described in SMPTE TH22.51. Originally, this method is very similar to the method specified by DIN 45403; however, in this case, the excitation consists of two sinusoids with frequencies of 60 Hz and 7 kHz, with amplitudes in a 4:1 ratio [2]. For the analysis of phenomena occurring in DML loudspeakers, a modification of this method was used, in which a sinusoid with a frequency of 120 Hz was generated instead of the 60 Hz sinusoid. This is related to the characteristics of the DMLs investigated, which when excited with frequencies below 70 Hz - according to the manufacturer's declaration - are prone to damage. The calculation of the percentage content of intermodulation distortion in the recorded signal took place in a manner analogous to the method described in DIN 45403, but with the inclusion of the entire energy contained in the sidebands of the 7 kHz component. The calculated numerical values are presented in the last columns of Tabs I and II. They were calculated from modified formula (3) [5]:

$$DOPPLER = \frac{\sqrt{\left(A_{7kHz-720Hz\,;\,7kHz+720Hz}\right)^2 - \left(A_{7kHz}\right)^2}}{A_{7khz}} * 100\% \tag{5}$$

where:

$A_{7\,kHz}$ – the amplitude of the 7 kHz component,

$A_{7kHz-720Hz\,;\,7kHz+720Hz}$ – amplitudes of intermodulation products.

The obtained values are smaller for the series of measurements conducted in the axis of the transducer. Furthermore, it is worth noting that for measurements carried out in the axis of the transducer, the percentage content of IMD measured by this method is below the percentage content of IMD measured by the DIN 45403 method (at the same excitation amplitude). A completely different regularity can be observed for the series of measurements taken at a point located on the parallel circle, 30° away from the transducer's axis. Here, the percentage content of IMD measured by the method described above exceeds the percentage content of IMD measured by the DIN 45403 method (while maintaining the excitation amplitude) and is several times higher than the values observed for measurements in the loudspeaker's axis.

However, the occurrence of the Doppler effect itself was associated by Allison and Villchur with the presence of sidebands around the higher-frequency excitation component [10], which does not have a harmonic character.

In this work, the intention was to investigate the occurrence of the Doppler effect based on a comparison of the spectra of an acoustic signal generated by the DML when excited with two sinusoids - with frequencies of 120 Hz and 7 kHz (Fig. 8) and when excited with a single sinusoid with a frequency of 7 kHz and an amplitude identical to the previous case (Fig. 9). The total amplitude of the excitation in the first of the discussed cases was 5.1 V.

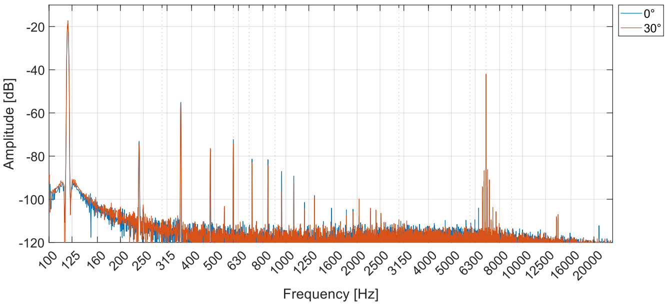

Fig. 8. The spectrum of the response of the DML to an excitation containing sinusoids at frequencies of 120 Hz and 7 kHz, with amplitudes in a 4:1 ratio

As can be observed in Figure 8, in the recorded signal, in addition to the driving components, there are also harmonics of the lower of the driving components. This results from the simultaneous presence of harmonic and intermodulation distortions. Additionally, components at frequencies of 13880 Hz and 14120 Hz appear, resulting from the modulation of the amplitude of the higher of the driving components, as well as its second harmonic (absent in the recorded signal), and the third harmonic of the higher of the driving components (21 kHz) – observed only when measured along the transducer axis. This demonstrates the complexity of the Doppler effect determination in the DML, as the spectral components of the signal resulting from frequency modulation due to the Doppler effect overlap with components resulting from amplitude modulation.

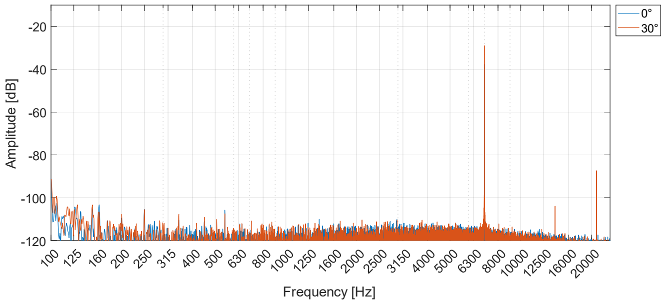

Fig. 9. The spectrum of the response of the DML to a sinusoidal excitation at the frequency of 7 kHz.

When sinusoidally driven at a frequency of 7 kHz, in the signal recorded at the input of the measurement analyzer, apart from the driving component, its harmonics are present. However, the amplitudes of the harmonic components at 7 kHz are higher than those occurring for the excitation consisting of two pure tones (120 Hz and 7 kHz). The driving component itself is recorded with a higher amplitude than in the previous case, despite being applied to the loudspeaker with identical amplification. However, it should be noted that by exciting the DML with a 7 kHz sinusoid, we do not activate its first mode of vibration.

CONCLUSION

Distributed Mode Loudspeakers (DML) turn out to be more susceptible to harmonic distortions than conventional piston-type speakers. This finding is rather different from those in other works [11]. This is particularly noticeable when, at a specific excitation frequency and in a certain direction, there is a sharp drop in the efficiency of the DML. In such cases, with minimal recorded amplitude of the driving component, the calculated percentage of distortion tends to reach high values.

Intermodulation distortion measurements yield satisfactory results. In their case, the recorded percentage contents are at least an order of magnitude lower than in the case of harmonic distortions. The recorded values are strongly related to the chosen measurement point, indicating the uneven spatial characteristics of DML radiation.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the employees of the Department of Mechanics and Vibroacoustics, AGH University of Science and Technology, especially to prof. Maciej Kłaczyński for providing access to the reverberation chamber and equipment, as well as for training in the use of the measurement system. The research was partially funded by the research grant from the Faculty of Mechanical Engineering and Robotics, AGH University, grant number: 16.16.130.942/Czesak, and the Integrated Development Program II of AGH University, project number: POWR.03.05.00-00-Z309/18-00..

REFERENCES

[1] M. Colloms, V. Gontcharov, J. Panzer, and V. Taylor: „ Distortion Mechanisms of Distributed-Mode Loudspeakers (Compared with Direct Pistonic Radiators; Modeling, Analysis, and Measurement)" , presented at: 104th AES Convention, 1998 May 16-19 Amsterdam, Netherlands, AES, USA, 1998. http://www.aes.org/e-lib/browse.cfm?elib=8423

[2] R. Metzler: „Test and Calibration Applications of Multitone Signals" , presented at: 11th International Conference: Test & Measurement (May 1992), AES, USA, 1992. http://www.aes.org/e-lib/browse.cfm?elib=6291

[3] G. Bank, N. Harris: „The Distributed Mode Loudspeaker-Theory and Practice" , presented at: 13th UK Conference: Microphones & Loudspeakers (March 1998), AES, USA, 1998. http://www.aes.org/e-lib/browse.cfm?elib=7985

[4] B. Metzler, "Audio Measurement Handbook", Audio Precision, Beaverton, pp. 29-32, 1993.

[5] R. C. Cabot: „ Design Factors in a Programmable Distortion Measurement System" , in: JAES Volume 32 Issue 12 pp. 964-983; December 1984, AES, USA, 1984. http://www.aes.org/e-lib/browse.cfm?elib=4466

[6] C. M. Bates: „ Total Harmonic Distortion Measurements in Magnetic Tape Equipment" , presented at: 70th AES Convention, 1981 October 30 – November 2, New York, NY, USA AES, USA, 1981. http://www.aes.org/e-lib/browse.cfm?elib=10249

[7] Wang, Hongwei. (2020). Measurements of Various Intermodulation Distortions (IMD, TD+N, DIM) using Multi-Instrument. https://doi.org/10.13140/RG.2.2.24792.72968

[8] I. Dennis and G. Boswell, "dScope Series III M1 Operation Manual", Spectral Measurements Prism Media Products Ltd, Cambridgeshire, UK, 2020

[9] R. Allison and E. Villchur: „ On the Magnitude and Audibility of FM Distortion in Loudspeakers" , in: JAES Volume 30 Issue 10 pp. 694-700; October 1, 1982, AES, USA, 1982. http://www.aes.org/e-lib/browse.cfm?elib=3816

[10] R. Allison and E. Villchur: „ The Audibility of Doppler Distortion in Loudspeakers" , presented at: 69th AES Convention, 1981 May 12 - 15, Los Angeles, California, USA, AES, USA, 1981. http://www.aes.org/e-lib/browse.cfm?elib=11984

[11] C. Minsung, E. Prokofieva, J. Munoz and M. Barker: „ Improvement of Sound Quality by Means of Ultra-Soft Elastomer for the Gel Type Inertia Driven DML Type Transducer" , presented at: 128th AES Convention, 2010 May 22 - 25, London, UK, AES, USA, 2010. http://www.aes.org/e-lib/browse.cfm?elib=15304