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Evaluation of non-linear distortion in compression chamber of a low frequency horn

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ABSTRACT

The subject of this study is to investigate non-linear behavior of air in a horn-loaded low frequency speaker device. Research and development of low frequency transducers continues to improve their linearity of excursion trough linearization of suspension compliance and BL factor as well as steadily increasing thermal power handling. The use of those latest transducers promises to achieve unprecedented efficiency and sound pressure levels, especially when combined with high compression horn-loading. This raises questions: what is the limiting factor of efficiency in those devices while retaining non-audible distortion? Should the transducers be improved or we have reached the limits of air non-linearity? This paper will hopefully give an insight on answers to those questions, trough analyzing a set of measurements and tests conducted with a prototype horn-loaded low-frequency loudspeaker device. High signal behavior of a technologically advanced, professional transducer was evaluated with and without horn-loading to study the effects of compression chamber in those extreme working conditions.

Keywords: nonlinear distortion, horn loudspeaker

1. INTRODUCTION

The low frequency horn loaded loudspeakers lost their popularity in 1990's due to reduction of amplification costs and introduction of digital sound processing. The industry switched to higher quantity of direct radiating loudspeaker devices, arraying them and controlling the directivity with DSP. The horns themselves were no longer developed – the technology was utilizing transducer capabilities of that time. Because of low efficiency of direct radiator devices, the low frequency drivers were vastly improved over the last 30 years with solutions for high excursion linearization, like split windings, mirrored suspension and demodulation rings to name a few. Heat management provided higher power handling and the introduction of neodymium magnets allowed weight reduction at first, then unparalleled magnetic flux in the gap. Those advancements in transducer construction impact direct radiator devices performance, but those devices are limited by efficiency and Helmholtz resonator compression. The current trend of constantly increasing power handling is questionable.

Technologically advanced transducers with robust diaphragms, high linear excursion and EBP factor (Efficiency Bandwidth Product, calculated by dividing the driver's resonance frequency by its electrical quality factor) allow horn loading with high compression ratio compared to historical horns, providing increased efficiency and wider bandwidth. Significant compression combined with high diaphragm excursion results in large pressure in the horn throat, which can potentially be a source of non-linear distortion.

2. LOUDSPEAKER DEVICE

2.1 Transducer

The loudspeaker for horn prototype is 300 mm (12 inch). It features aluminum demodulating ring, rubber surround, 100 mm diameter voice coil of 28.9 mm winding height and 12 mm magnetic gap depth resulting in 12.45 mm of rated Xmax value (maximum linear one-way excursion).

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2.2 Horn

The acoustical transformer was designed in "Hornresp" software, using driver's measured Thielle-Small parameters with "complex inductance model (2)". The resulting design is characterized by hybrid of exponential and hyperbolic expansion ratios with total horn length of 3.5 m; fundamental frequency of 39.5 Hz; 25 l rear chamber with acoustical lining; 130 cm^2 throat and 2500 cm^2 mouth.

2.3 Throat chamber

The actual, measured maximum displacement was higher than rated in the loudspeaker's datasheet, resulting in values presented in table 1. Significant changes in throat volume during loudspeaker operation at high excursions result in high particle velocity, which increases the probability of non-laminar airflow through the throat. The actual horn is rectangular in cross sections, a throat adaptor made with gradually expanding elliptical elements of constant surface area of 130 cm^2 was fabricated. To minimize turbulent behavior of air, a circular chamber adaptor was introduced. The resulting prototype is presented in Figure 1.

Table 1 – Throat chamber characteristics

Diaphragm surface area, cm^2	Horn throat surface area, cm^2	Compression ratio	Peak-to-peak diaphragm excursion, cm	Volume displaced by diaphragm, cm^3	Compression chamber volume, cm^3	Compression chamber volume change, %
476	130	3.66 : 1	2.3	1237.6	3086.0	40.1

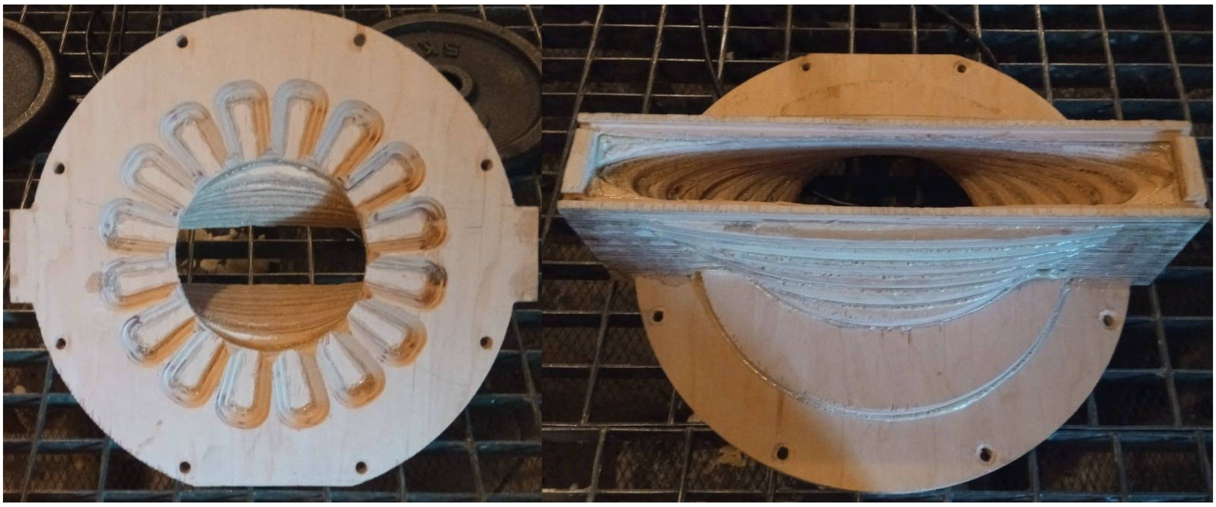

Figure 1 – Picture of a throat adaptor prototype

2.4 Rear chamber

The transducer is mounted in a sealed enclosure with net volume of 25 l, complimented with acoustical lining 3 cm thick and multiple access hatches. The shape, bracing and building materials are exactly the same as in actual horn loaded cabinet, for future measurement comparison.

3. MEASUREMENTS

3.1 Electrical impedance measurement

The loudspeaker impedance-frequency characteristics were measured in three cases: no rear chamber (transducer mounted in a baffle); sealed enclosure (direct radiator); sealed enclosure with compression chamber and throat adaptor (Figure 2). Resonance frequencies have been measured

(Table 2).

Table 2 – Resonance frequencies

Transducer mounted in a baffle, Hz	Transducer in sealed enclosure, Hz	Transducer in sealed enclosure with throat adaptor, Hz
46.80	66.15	59.80

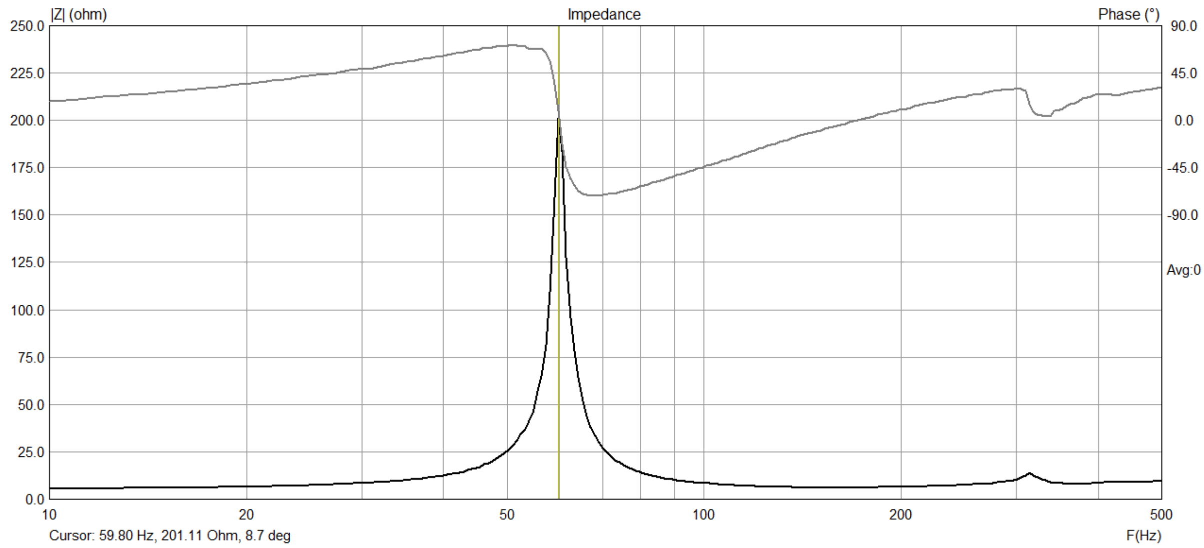

Figure 2 – Impedance measurement, transducer in sealed enclosure with throat adaptor

3.2 Diaphragm vibration measurement

The loudspeaker cone displacement measurement was made with scanning head and complementary data acquisition system. The laser was pointed at the center of loudspeaker dust cap, with a right angle. Signal source was the same as in acoustical measurements and consisted of: personal computer with 'REW' software; external soundcard; professional power amplifier in bridge mode, providing 80 V RMS at 0 dBFS soundcard setting. Test signal was defined as 10 s long chirp in range of 10 to 300 Hz at 0 dBFS.

Because this is a Doppler effect measurement, the results were acquired in form of diaphragm velocity as a function of time. Discrete data integration allowed to calculate the displacement. The spectrum analysis provided maximum peak-to-peak excursion of 26 mm which is close to the value provided by loudspeaker manufacturer (24.9 mm). The maximum value was recorded at frequency of 59 Hz which correlates with measured resonance frequency from impedance plot.

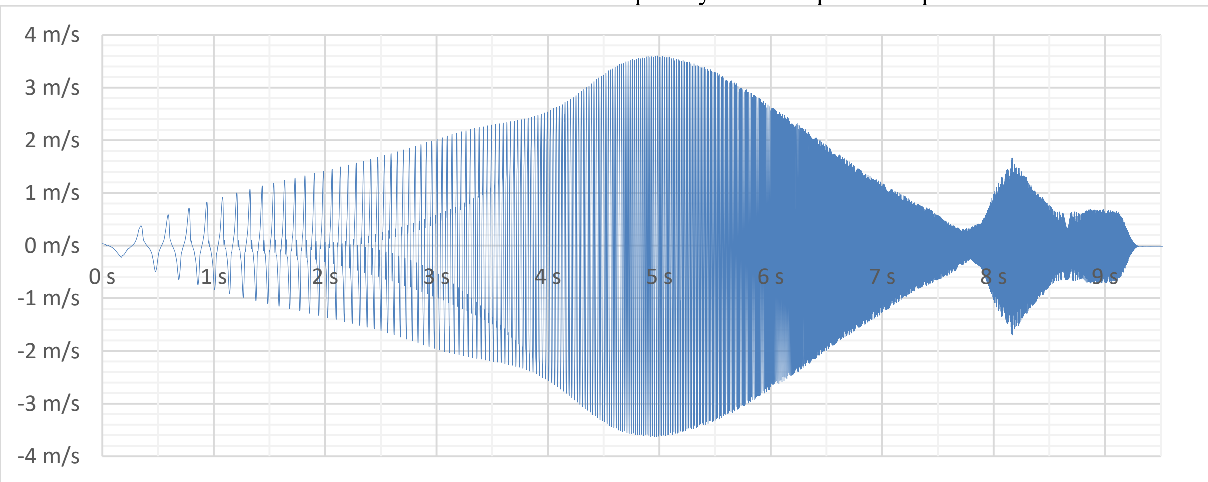

Figure 3 –Diaphragm velocity in function of time, with throat chamber, 0dBFS

3.3 Acoustical measurements

All acoustical recordings were made in an anechoic chamber, signal source and type were the same as described in laser vibrometry. Measurements were taken at different power levels set on the soundcard, from -20 to 0 dBFS.

At first, calibrated sound pressure meter was placed in volumetric center of the throat adaptor, 6 cm from the center of diaphragm. The measurements were taken with and without throat adaptor, with constant microphone position. At full power (0dBFS) without throat adaptor the microphone was clipping, recording over 140 dB above 70 Hz, introducing high levels of distortion. Addition of a throat chamber resulted in 20 dB of increased SPL in the whole measured frequency range. This indicates sound pressure level inside the throat adapter of over 160 dB, possibly 170+dB at full power input. High pressure 3.175 mm (1/8 inch) microphone will be used in future measurements.

Second, undistorted set of measurements was made with calibrated microphone placed at a constant distance of 2 m from loudspeaker diaphragm. Session resulted in 42 data sets of sound pressure and harmonic levels, 21 for the loudspeaker without throat chamber (Figure 4), 21 with (Figure 5).

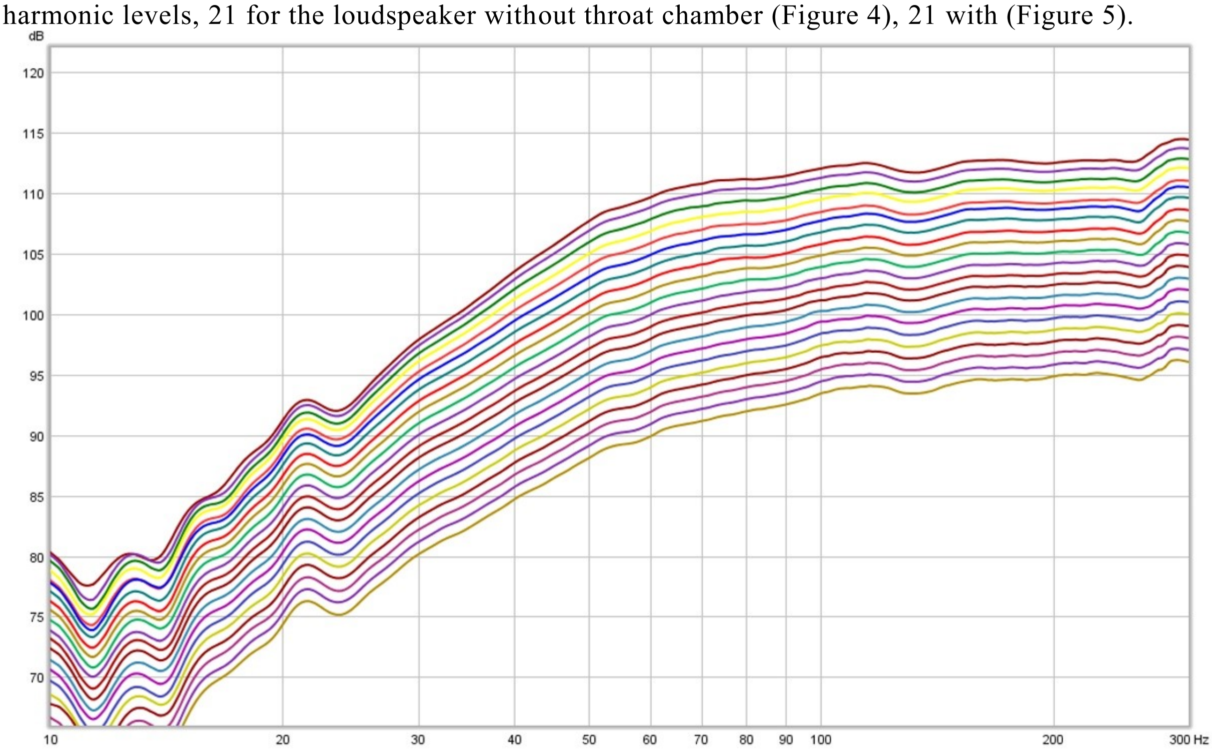

Figure 4 – Frequency response measurement dataset -20 to 0 dB in 1 dB increment, without throat adaptor

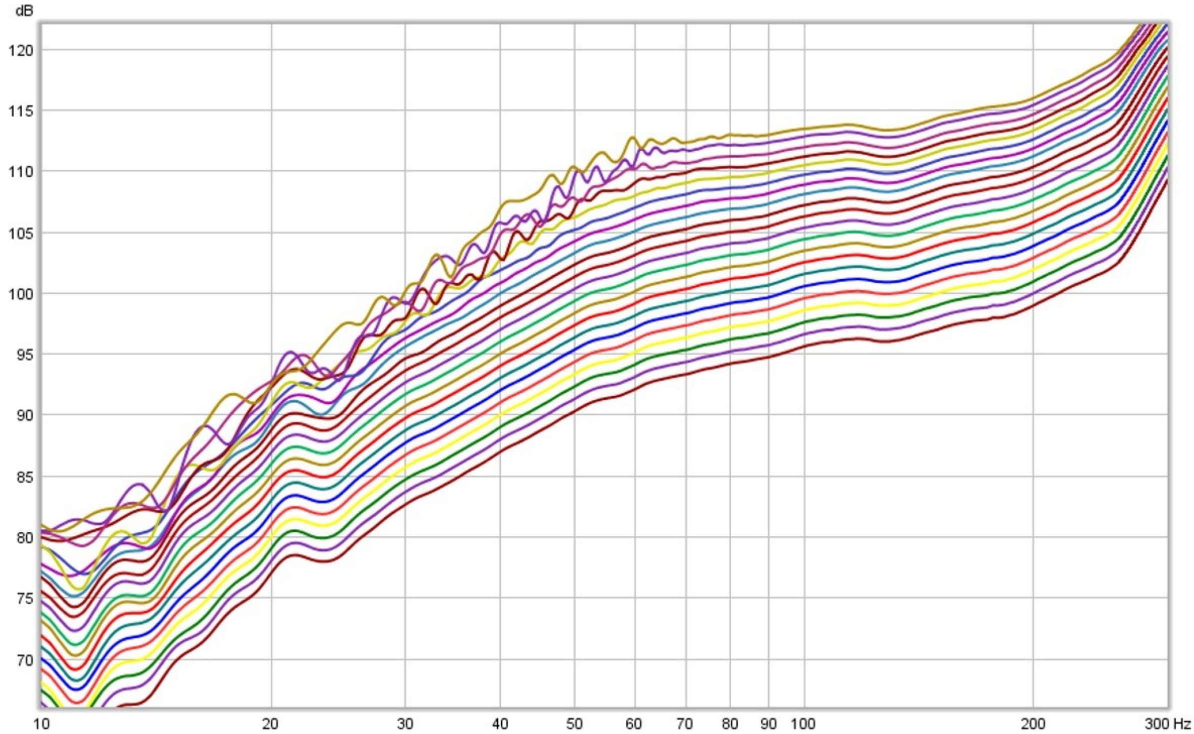

Figure 5 – Frequency response measurement dataset -20 to 0 dB in 1 dB increment, with throat adaptor

4. DATA PROCESSING

4.1 Harmonic levels

Every measurement file contained harmonic distortion data in function of frequency. The distortion analysis should be made for the highest registered loudspeaker cone displacement, at the resonance frequency of transducer in sealed chamber with throat adaptor, which is 59 Hz. Fundamental and first four harmonic levels at 59 Hz were exported from every measurement file for loudspeaker without throat adaptor (Table 3) same procedure was done for measurements with compression chamber (Table 4).

Table 3 – Harmonic levels without throat adaptor

Input level, dBFS	Freq, Hz	Fundamental level, dB	THD, dB	H2, dB	H3, dB	H4, dB	H5, dB	THD ratio, %
0	59	110.6	85.1	80.6	82.9	71.4	59.5	5.333%
-1	59	109.8	83.1	78.7	80.7	69.6	61.5	4.627%
-2	59	108.8	80.6	76.7	77.8	67.0	63.0	3.897%
-3	59	107.8	78.1	74.7	74.8	64.9	62.1	3.278%
-4	59	106.8	75.9	73.6	71.3	61.3	60.4	2.858%
-5	59	105.8	74.0	71.8	69.2	59.2	58.8	2.566%

Table 4 – Harmonic levels with throat adaptor

Input level, dBFS	Freq, Hz	Fundamental level, dB	THD, dB	H2, dB	H3, dB	H4, dB	H5, dB	THD ratio, %
0	59	113.1	91.7	88.1	85.8	85.0	81.0	8.516%
-1	59	111.9	89.7	85.8	84.7	80.9	81.6	7.837%
-2	59	111.2	89.4	88.3	80.2	79.0	71.2	8.107%
-3	59	109.7	82.7	80.8	74.1	70.8	74.8	4.480%
-4	59	108.9	78.7	74.3	74.5	65.4	71.9	3.087%
-5	59	107.9	77.6	74.8	71.7	62.8	70.1	3.039%

4.2 Throat chamber distortion

To calculate the throat chamber distortion product, the energy level of each harmonic in measurement without throat adaptor (Table 3) was subtracted from corresponding harmonic levels in measurements with throat adaptor (Table 4) using simple formula:

$$H_C = 10\log_{10}(10^{0.1H_B} - 10^{0.1H_A}), \qquad (1)$$

where:

H_C - resulting harmonic level (throat chamber contribution)

H_B - harmonic level of loudspeaker with throat adaptor

H_A - harmonic level of loudspeaker without throat adaptor

Calculated harmonic levels of throat chamber contribution have been juxtaposed with fundamental levels of measurements with throat adaptor (Table 5). The THD is energetic sum of those harmonics, THD ratio is percentage energy content relative to fundamental levels.

Table 5 – Harmonic levels as a throat chamber contribution

Input level, dBFS	Freq, Hz	Fundamental level, dB	THD, dB	H2, dB	H3, dB	H4, dB	H5, dB	THD ratio, %
0	59	113.1	90.6	87.2	82.7	84.8	81.0	7.516%
-1	59	111.9	88.7	84.9	82.5	80.6	81.6	6.946%
-2	59	111.2	88.8	88.0	76.5	78.7	70.5	7.559%
-3	59	109.7	81.9	79.6	74.1	69.5	74.6	4.052%
-4	59	108.9	75.5	66.0	71.7	63.3	71.6	2.129%
-5	59	107.9	75.1	71.8	68.1	60.3	69.8	2.277%

The THD ratio as a function of the input level from Table 3, 4 and 5 have been plotted in Figures 6, 7 and 8 respectively.

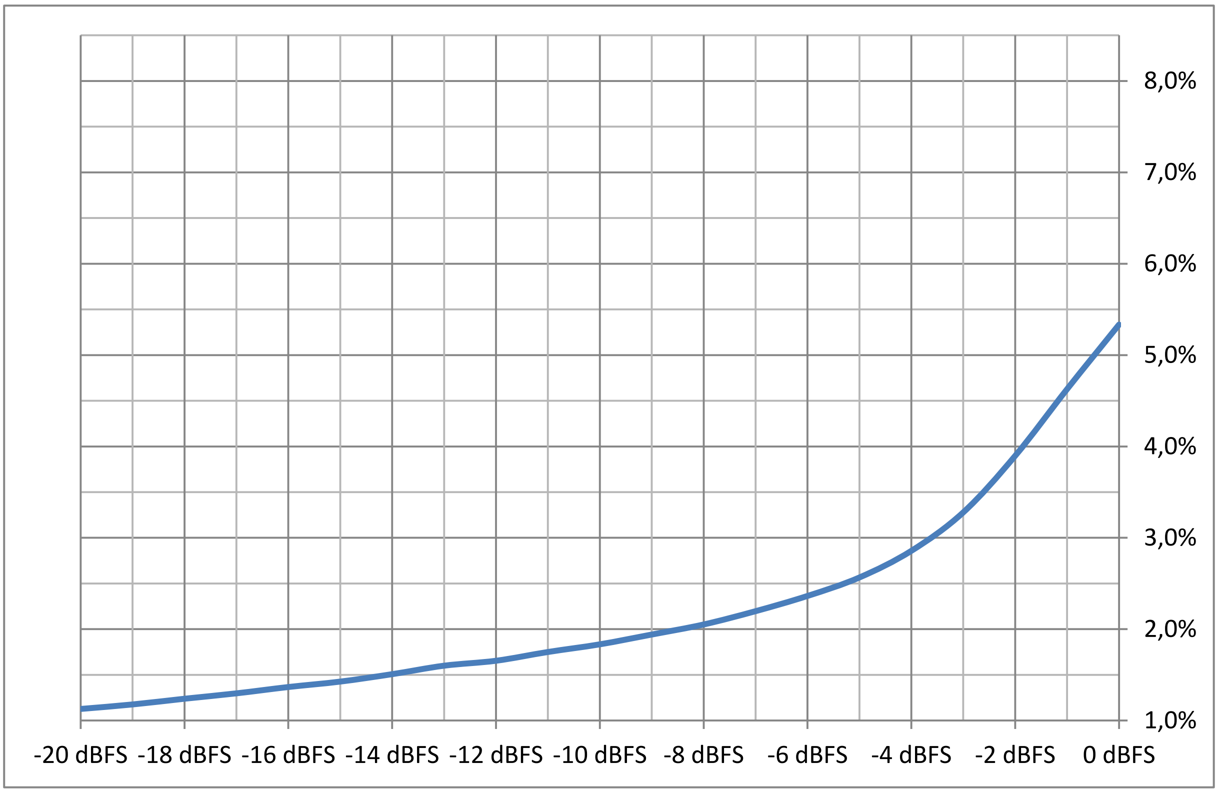

Figure 6 – THD ratio, measurement without throat adaptor

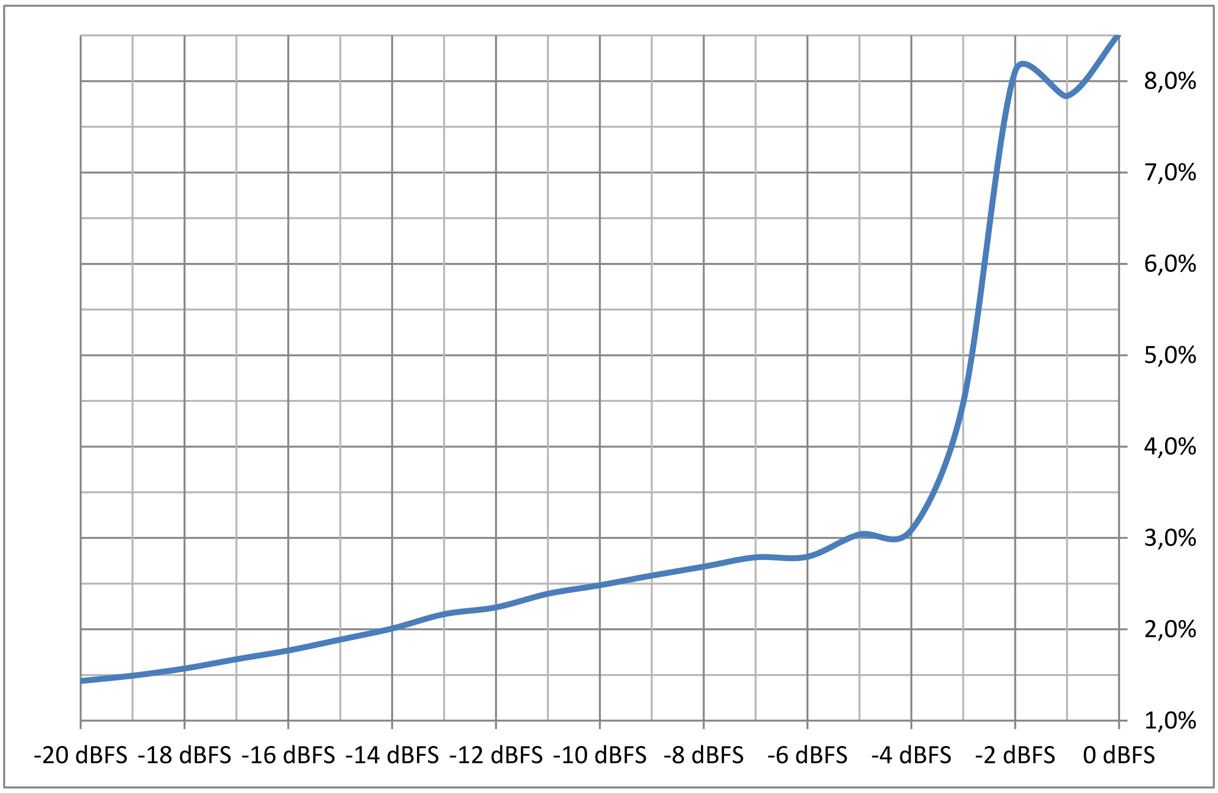

Figure 7 – THD ratio, measurement with throat adaptor

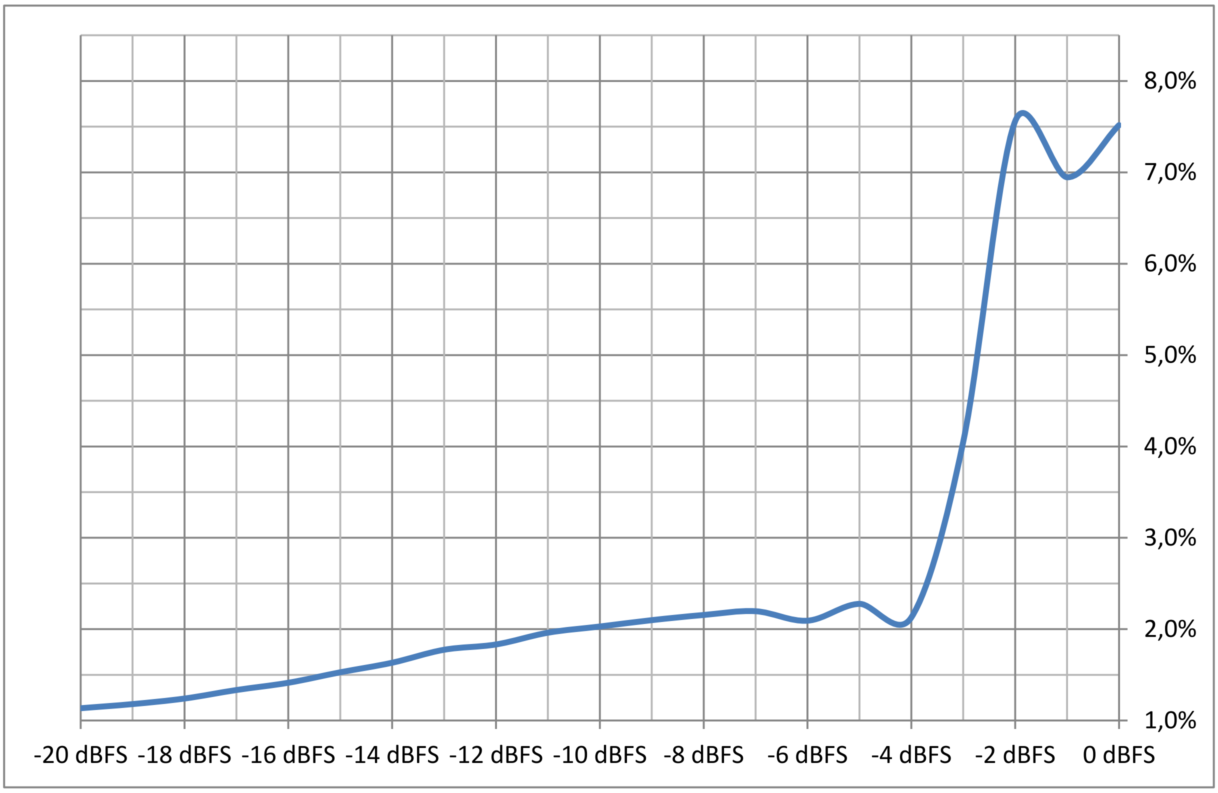

Figure 8 – THD ratio, calculated throat chamber harmonic distortion contribution relative to measured fundamental level with throat adaptor

5. CONCLUSIONS

The use of a compression chamber results in predicted increase of harmonic distortion, the contribution is increasing with pressure level, especially after reaching certain pressure value in the throat. Comprehensive measurements of pressure levels inside the throat adaptor are being planned, utilizing 3.175 mm (1/8 inch) microphone designed for high SPL. This research will hopefully help determine the pressure limit value. This number could be a base for theoretical model evaluation and calibration.

The variation of pressure in function of frequency for a few highest power input measurements (Figure 5) indicate possible turbulences, however those variations were not observed when the microphone was placed inside the throat adaptor. This is probably a result of sudden pressure drop outside the adaptor, measurements with full size horn are scheduled. The application of an acoustic transformer will solve the turbulence problem and will have a significant impact on pressure inside the throat adaptor as well as diaphragm displacement.

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