Measurement of nonlinear distortion of MEMS microphones

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Abstract

An experimental investigation on the nonlinear behaviour of the MEMS microphones is of rising interest as their use is growing rapidly not only in the domain of consumer audio devices but also in the measurement applications where higher precision is needed. The present work uses a recently published method allowing a distortionless harmonic excitation at high-pressure levels to measure and examine the distortion of single backplate MEMS microphones. The measured distortion is compared with the values predicted by a simple model of the nonlinearities originating in the electrostatic transduction principle. A good agreement between the predicted and the measured values of the second harmonic is shown. The level of the third harmonic is influenced by nonlinear effects not taken into account in the simple model and therefore deviates from the predicted values.

1. Introduction

MEMS microphones have become popular for their properties, such as small dimensions, very low price, relatively high sensitivity, low inherent noise, and low power consumption. Their use is growing rapidly over recent years, particularly in the domain of mobile phones and consumer audio devices, but also in the measurement applications such as noise monitoring sensor networks [1] and microphone arrays [2]. It is then of great interest to explore the nonlinear behaviour of these microphones since the nonlinear distortion originating in the microphone can have a significant impact on the precision of the measurement results. A contribution to such a study is proposed in this paper.

Because an overwhelming majority of the commercially available types of MEMS microphones is based on the electrostatic transduction principle (although piezoelectric types exist) and most of them consist of single backplate structure, this study is limited to the condenser microphone types with single backplate (note that dual bacplate microphones present different nonlinear behaviour than the single bacplate ones). The output signal of such devices can take the classical analog form (analog output voltage) or a digital form with a given format of output data (I2S, PDM, TDM). The transducer parts of the devices with these two output types are very similar. From a nonlinear distortion point of view, the only difference is the presence of hard-limit saturation of the A/D converter in the digital type microphones, usually appearing at input sound pressure levels near 120 dB SPL.

There are many sources of nonlinear distortion in a condenser microphone [3] that can originate from the mechanical properties of the diaphragm [4], damping in the air gap between the diaphragm and backplate varying with its thickness, acoustic nonlinearities due to potentially high acoustic pressure in the air gap, stiffness of the cavity, preamplifier, and nonlinear capacitance of the capsule [5, 6]. The latter is the primary source of the distortion, and its analytical description is known for both harmonic [5, 6] and inter-modulation [7] distortion. Section 2 of this paper provides a short overview of its theoretical description.

Characterisation of the non-linear behaviour can be done either indirectly, measuring the inter-modulation distortion of independent sources [8, 9, 10], or directly measuring the harmonic distortion. The direct method necessitates a reference microphone and a loudspeaker (or similar excitation device [11]) whose nonlinear distortions are much lower than the one of the microphone under test. While there exist low-distortion microphones (condenser microphones with low sensitivity or piezoresistive microphones), low-distortion loudspeakers are much more difficult to achieve, especially at high sound pressure levels [12]. One of the solutions to provide high-pressure levels while keeping the source distortion low is to use a system of cavities and tubes with standing waves [13, 14]. Such a system is usually frequency limited to very low frequencies (<200 Hz) [11, 15], or tuned to a specific frequency (e.g., 500 Hz [14]) at which the pressure is maximized. This approach, limited for a given frequency, is also used in a commercially available product [14, 16].

A recently developed method [17] allows for correcting a harmonic distortion caused by an excitation device and reducing its higher harmonics to the level of background noise. This adaptive method is used in this paper to reduce the distortion caused by the loudspeaker and to ensure a pure sinusoidal pressure signal, measured by a low-sensitivity, low distortion, and small-sized reference measurement microphone. Such an approach allows a direct measurement of the harmonic distortion of MEMS microphones tested at different levels (up to the limit of the MEMS microphone) and for different frequencies (20 Hz, 200 Hz, 2 kHz). The experimental bench is presented in Section 3.

The results of harmonic distortion measurement of an off-the-shelf MEMS microphone are presented in Section 4.

2. Model of Condenser Microphone Distortion

Distortions of condenser microphones have different origins. Some of them can be modelled fully analytically, such as the electrical distortion due to the electrostatic principle of the microphone [18, 5, 6], other types of distortions such as the acoustic one due to the dynamic change of the air gap thickness may require a numerical solution [19]. Since the inherent distortion of the electrostatic transduction is considered to be predominant, a brief review of its theoretical description is provided hereafter.

The charge in a capacitor is given by $Q = CU$, where U is a charging voltage. The total static capacitance of the condenser microphone (at rest) $C = C_0 + C_P$ is composed of the parasitic capacitance C_P and the active static capacitance $C_0 = \varepsilon_0 S_a / h_g$ with ε_0 being the permittivity, S_a the active surface and h_g the thickness of the air gap between the diaphragm and the backplate. The total differential of the charge can be then expressed as

$$\mathrm{d}Q = \mathrm{d}CU + C\mathrm{d}U. \tag{1}$$

The total voltage at the output of the condenser microphone $U = U_0 + u$ is composed of the static component U_0 representing the polarization voltage and the varying component u caused by the change of the capacitance dC. Since the level of the varying component of the microphone output voltage u is significantly lower than the static polarization voltage U_0, we can assume that $\mathrm{d}U \approx u$ and $U \approx U_0$. This approximation along with the effect of the polarization resistor of huge value $(G\Omega)$ causing the charge variation to be negligible, $\mathrm{d}Q \approx 0$, give the output voltage of the microphone directly in the form

$$u = -U_0 \frac{\mathrm{d}C}{C}. \tag{2}$$

The time-dependent non-uniform displacement of the diaphragm $\xi(\vec{r}, t)$ is supposed to be outwardly directed (such as in many models of electrostatic transducers [20]), the time-dependent total capacitance $C_t(t)$ can be then calculated from the displacement averaged over the active surface $\bar{\xi}(t) = \left(\iint_{S_a} \xi(\vec{r}, t)\ \mathrm{d}S_a\right) / S_a$ as follows

$$C_t(t) = C_P + \frac{\varepsilon_0 S_a}{h_g + \bar{\xi}(t)} = C_P + C_0 \frac{1}{1 + \bar{\xi}(t)/h_g}. \tag{3}$$

In using the Taylor series expansion $1/(1+y) = 1 - y + y^2 - y^3 + \ldots$ and assuming that the total capacitance is given by $C_t(t) = C_P + C_0 + \mathrm{d}C(t)$, the time-dependent capacitance variation $\mathrm{d}C(t)$ can be expressed as

$$\mathrm{d}C(t) = -C_0 \left[\frac{\bar{\xi}(t)}{h_g} - \left(\frac{\bar{\xi}(t)}{h_g}\right)^2 + \left(\frac{\bar{\xi}(t)}{h_g}\right)^3 - \ldots \right]. \tag{4}$$

Substituting this expression to Eq. (2) the time-dependent output voltage of the condenser microphone becomes

$$u(t) = U_0 \frac{C_0}{C_P + C_0} \left[\frac{\bar{\xi}(t)}{h_g} - \left(\frac{\bar{\xi}(t)}{h_g}\right)^2 + \left(\frac{\bar{\xi}(t)}{h_g}\right)^3 - \ldots \right], \tag{5}$$

where the nonlinear behaviour is clearly visible.

In line with Eq. (5) and similarly to [5] the distortion at the electrical output of the microphone can be modelled in its simplest form as

$$u(t) = K_0 \left[y(t) - y^2(t) + y^3(t) - \ldots \right], \tag{6}$$

where K_0 is a constant depending on capacitance and polarization voltage, and y is a relative mean diaphragm displacement to the gap thickness. According to [5, 6] this model can be refined by taking into account the diaphragm deformation. In [3] Dessein investigated several nonlinear models of diaphragm deformation and stated that "the difference between the results given by the different models is only a vertical shift of the curves" (curves

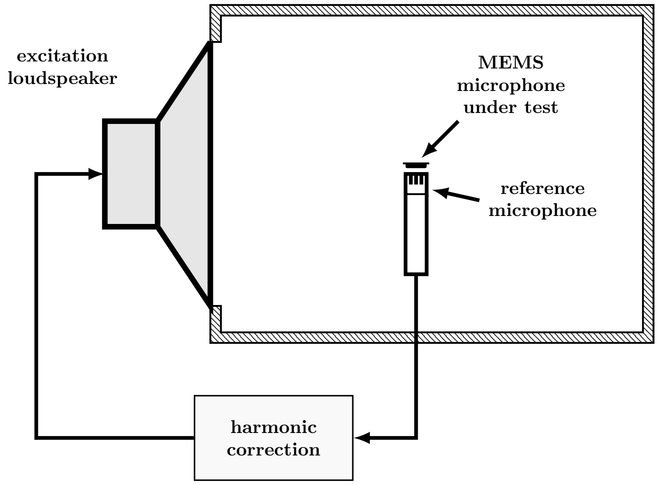


Figure 1. Simplified schema of the measurement setup.

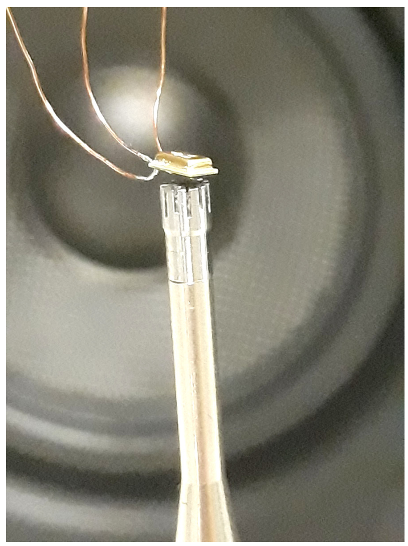


Figure 2. A picture of both microphones inside the sealed box.

referring to higher harmonics in dB as a function of dB SPL). In other words the ratio between the harmonics remains proportional to power series of Eq. (6).

The model (Eq. (5)) uses physical parameters of the MEMS microphone under tests such as gap thickness, capacitance, or polarization voltage, to provide the right prediction. Unfortunately, these parameters are not usually known for the commercially available MEMS microphones. However, since the relation between the relative displacement $y(t)$ and the output voltage $u(t)$ from Eq. (6) contains only one parameter K_0, it can be fitted to the measured data without the knowledge of any of the physical parameters.

An experimental setup for the MEMS microphone nonlinear distortion measurement, described in the following section, is next used to estimate the harmonic distortion for several frequencies and several levels. The results are then compared with the simple model provided by Eq. (6) to show its ability to predict the distortion of MEMS microphones.

3. Experimental Setup

The MEMS microphone under test and the reference 1/8" Pressure Microphone GRAS 40DP are placed approximately 2mm apart inside a sealed box of dimensions [cm] (18.7 x 18.6 x 19). An 8" loudspeaker, together with an off-the-shelf amplifier, provides the pressure excitation inside the box. A preamplifier GRAS Type 26AC and a conditioning amplifier Brüel&Kjær Type 2609 are used to ensure proper handling of the reference microphone signal. The signal generation and acquisition are provided using an RME Fireface 400 sound card. A simplified schematic representation of the experimental setup and a picture of both microphones inside the box are shown in Figs. 1 and 2 respectively.

A sinusoidal signal is used to measure the harmonic distortion of the MEMS microphone under test at three frequencies (20 Hz, 200 Hz, 2 kHz) and different sound pressure levels going from 90 to 128 dB SPL with a 2 dB step set up using the reference microphone with known sensitivity. A harmonic correction [17] is applied to ensure a pure harmonic acoustic pressure inside the box. Consequently, the pressure signal measured with the reference microphone (distortion of which is negligible at the above mentioned levels) contains no higher harmonics (suppressed to the noise level) as illustrated in Fig. 3(a).[1]

We measured several MEMS microphones with analog output of different manufacturers available on the market. The acoustic overload point (value after which the total harmonic distortion rises above 10%) given in the datasheets is between 120 and 130 dB SPL. Since the results for all of the measured microphones share common characteristics and the conclusions presented in this paper apply to all of them, we present in this paper the results for only one measured microphone.

4. Results

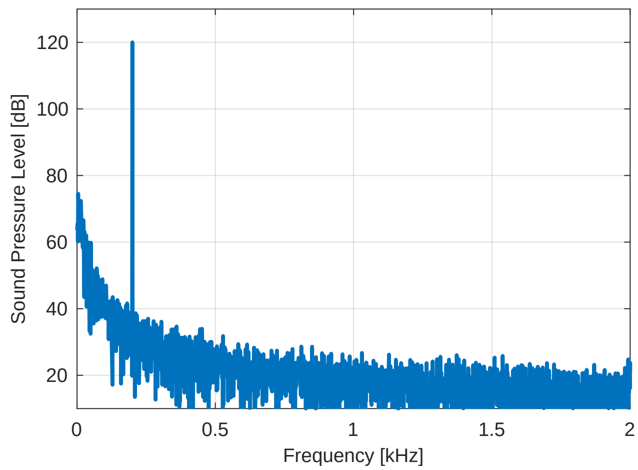
First, the acoustic pressure sensitivity σ of the MEMS microphone under test was estimated as a ratio of its output voltage u and the incident acoustic pressure p_{inc} measured by the reference microphone, as $\sigma = u/p_{inc}$. The sensitivities estimated at the incident pressure level of 80 dB SPL for 20 Hz, 200 Hz, and 2 kHz sinusoidal excitation are 12.2, 13.6 and 13.9 mV/Pa respectively.

Next, the measurement of the distortion is made using the sinusoidal signal generated by loudspeaker and processing of the drive signal to compensate its distortion (harmonic correction). An example of the measurement with the harmonic correction is shown in Fig. 3. The spectra of the acoustic pressure are depicted for both the reference microphone and the MEMS microphone under test. Note, that in the case of the reference microphone (Fig. 3(a)) all the higher harmonics are suppressed to the noise floor. The higher harmonics measured by the MEMS microphone (Fig. 3(b)) are thus originated only from the microphone itself and not from the loudspeaker. For this particular case of the sine excitation (200 Hz, 120 dB SPL), the second and third harmonics of the MEMS microphone under test correspond to the level of 83 dB SPL and 70 dB SPL.

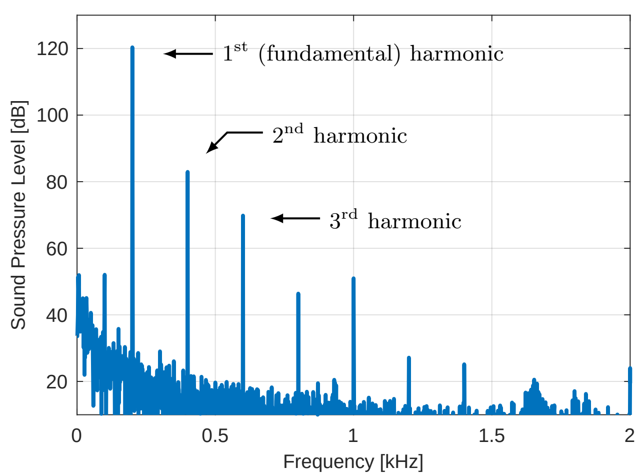
The same measurement is next performed for three frequencies 20 Hz, 200 Hz, and 2 kHz, and sound pressure levels going from 90 to 128 dB SPL with a 2 dB step. The results depicted in Fig. 4 show the measured harmonic distortion. The 1st (fundamental) harmonic is plotted with black circles, blue x-marks are used for the 2nd harmonic, and red plus markers for the 3rd harmonic. The model prediction is depicted with a solid black line for the 1st harmonic, with a blue dashed line for the 2nd harmonic, and with a red dot-dashed line for the 3rd harmonic.

In this model a linear relation between the harmonic incident acoustic pressure and the diaphragm displacement was assumed (which means neglecting other sources of nonlinearities then the one caused by the electrostatic transduction). First, relation $y(t) = y_m \sin(\omega_0 t)$ where $\omega_0 = 2\pi f_0$ is the angular frequency at excitation frequency

[1]Note that the reference 1/8" Pressure Microphone GRAS 40DP has a THD 3% at 174 dB SPL. Considering the same model of condenser microphone as the one presented in section 2, the higher harmonic components of the reference microphone excited with a 128 dB SPL sinusoidal wave should be below 6 dB SPL which is way below the noise floor of the measurement.



(a) reference microphone



(b) MEMS microphone under test

Figure 3. Spectra of the measured sound pressure (a) with the reference microphone, (b) with the MEMS microphone under test. Note that thanks to the harmonic control, there are no higher harmonics measured by the reference microphone.

f_0 and where $y_m = p_{inc}\sigma/K_0$, was substituted to Eq. (6). The coefficient K_0 was estimated by fitting the second harmonic measured data. The same fitted value of K_0 was used for all the three frequencies 20 Hz, 200 Hz, and 2 kHz.

We can note that the measured second harmonics behaves in a very predictable way above the background noise up to the level of 120 dB SPL. The model (Eq. (6)) predicts the 2nd harmonic behaviour very accurately from the background noise to 120 dB SPL. As shown in Fig. 5, the time-domain signal shows clipping at sound pressure levels higher than 120 dB SPL. The clipping probably comes from the built-in amplification part of the MEMS microphone, or from the diaphragm touching the stoppers on the backplate preventing the diaphragm from collapsing to the backplate. Note that the diaphragm displacement towards the backplate provokes negative output voltage, see Eq. (2), which could lead to asymmetric clipping. Since the model does not account for clipping phenomena, a deviation of the model from the measured data is expected.

The levels of third harmonics are higher than the predicted values by approximately 20 dB at 200 Hz and 2 kHz and more than 30 dB at 20 Hz. This is probably related to the effects which were not taken into account in the model used herein, such as another nonlinear phenomena of the electrostatic transduction, the acoustic distortion associated to the dynamic change of the air gap thickness [19, 21] due to the potentially high level of acoustic pressure in the air gap, or to nonlinearities originating from the deflection of the diaphragm with a built-in residual stress [4]. Yet much more research is needed to test these hypotheses.

5. Conclusion

Harmonic distortion of low-cost single backplate MEMS microphones available on the market has been experimentally studied in this paper. The results show that the predominant distortion component in the single backplate MEMS microphones is the second harmonic and that its variation with sound pressure level is in a good agreement with an existing model for condenser microphones (for the output levels under the signal saturation which does not originate from the transduction principle). The model predicts well the second harmonic for all the measurements at studied frequencies 20 Hz, 200 Hz, and 2 kHz. On the other hand, the third harmonic distortion product deviates from the model prediction.

This leads to the conclusion that the nonlinearities arising from the electrostatic principle are the predominant source of distortion in single backplate condenser MEMS microphones and that they affect mainly the second harmonic. The others sources of distortion are much less important and mainly affect third and possibly higher harmonics.

These conclusions can be generalized for several tested single backplate MEMS microphones of different manufacturers.

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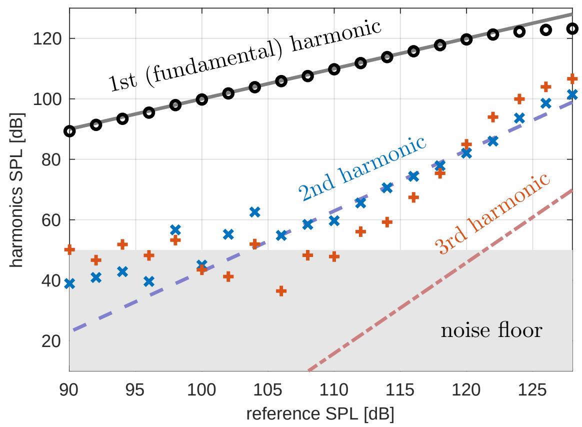
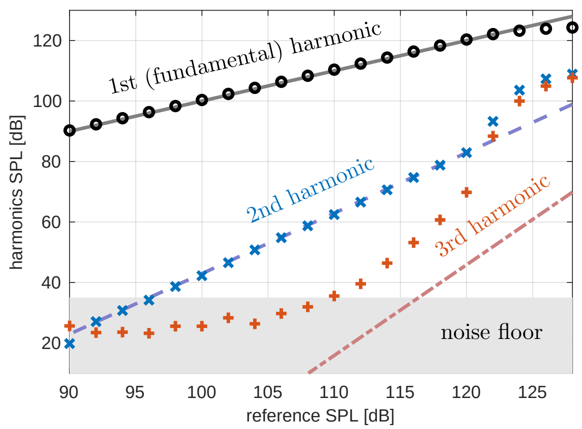
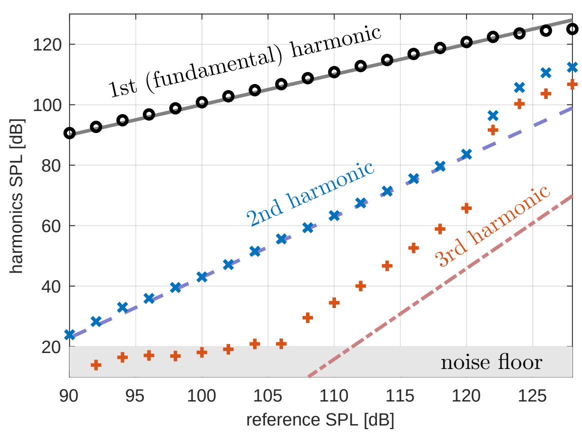


(a) 20 Hz



(b) 200 Hz



(c) 2 kHz

Figure 4. Measured and model predicted harmonic distortion of the MEMS microphone under test for (a) 20 Hz, (b) 200 Hz, and (c) 2 kHz. Black: first (fundamental) harmonic (measured: circles, model: solid line), blue: second harmonic (measured: x-marks, model: dashed line), red: third harmonic (measured: plus markers, model: dot-dashed line). The gray area denotes a noise-floor.

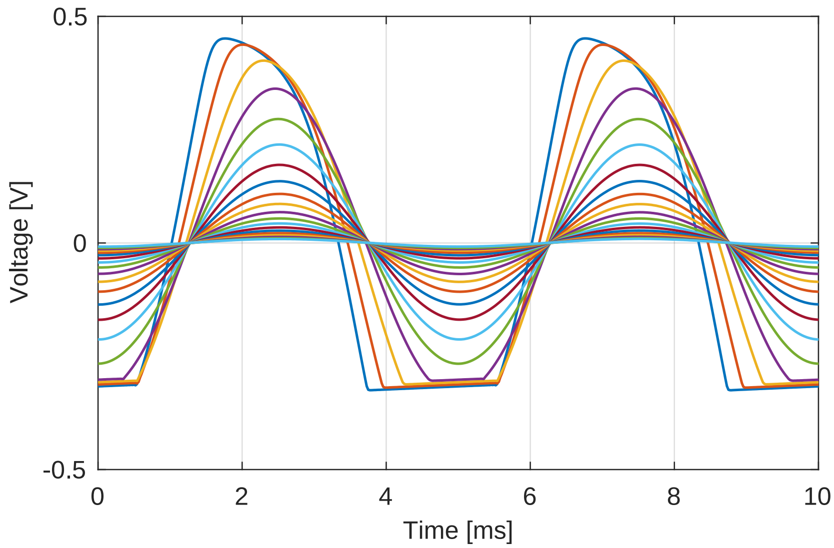


Figure 5. Time-domain signal of the voltage at the output of the MEMS microphone under test for different levels from 90 dB SPL to 128 dB SPL. Note that the electrical signals for the four highest sound pressure levels (122, 124, 126, and 128 dB SPL) are saturated.

References

[1] C. Mydlarz, J. Salamon, J. P. Bello, The implementation of low-cost urban acoustic monitoring devices, Appl. Acoust. 117 (B) (2017) 207–218. doi:10.1016/j.apacoust.2016.06.010.

[2] I. Hafizovic, C.-I. C. Nilsen, M. Kjølerbakken, V. Jahr, Design and implementation of a MEMS microphone array system for real-time speech acquisition, Appl. Acoust. 73 (2) (2017) 132–143. doi:10.1016/j.apacoust.2011.07.009.

[3] A. Dessein, Modelling distortion in condenser microphones, Ph.D. thesis, Technical University of Denmark, DTU, DK-2800 Kgs. Lyngby, Denmark (2009).

[4] S. Chowdhury, M. Ahmadi, W. C. Miller, Nonlinear effects in MEMS capacitive microphone design, in: Proc. - Int. Conf. MEMS, NANO Smart Syst. ICMENS 2003, 2003, pp. 297–302. doi:10.1109/ICMENS.2003.1222013.

[5] E. Frederiksen, W. Bolton, Reduction of non-linear distortion in condenser microphones by using negative load capacitance, Tech. Rep. 3 (1996). doi:10.1007/BF01830739.

[6] H. Pastillé, Electrically manifested distortions of condenser microphones in audio frequency circuits, J. Audio Eng. Soc. 48 (6) (2000) 559–563.

[7] M. T. Abuelma'atti, Improved analysis of the electrically manifested distortions of condenser microphones, Appl. Acoust. 64 (5) (2003) 471–480. doi:10.1016/S0003-682X(02)00140-8.

[8] M. Hibbing, H.-J. Griese, New Investigations on Linearity Problems of Capacitive Transducers, in: Audio Eng. Soc. Conv. 68, Vol. 1752, 1981.
URL http://www.aes.org/e-lib/browse.cfm?elib=12001

[9] S. Temme, Audio Distortion Measurements (1992).

[10] M. T. Abuelma'atti, Large signal performance of micromachined silicon inductive microphones, Appl. Acoust. 68 (10) (2007) 1286–1296. doi:10.1016/j.apacoust.2006.06.006.

[11] H. Dahlke, G. T. Kantarges, Investigation of Microphone Nonlinearities, Using the High-Intensity Pistonphone, in: J. Acoust. Soc. Am., Vol. 40, 1966, p. 1966.

[12] W. Klippel, Tutorial: Loudspeaker nonlinearities - Causes, parameters, symptoms, J. Audio Eng. Soc. 54 (10) (2006) 907–939. arXiv:arXiv:1011.1669v3, doi:10.1017/CBO9781107415324.004.

[13] H. Pastillé, An Approach to Analyze the Linear Movement of Condenser Microphone Membranes, in: Collect. Pap. from Jt. Meet. Berlin, 1999, pp. 1–4.

[14] E. Frederiksen, System for measurement of microphone distortion and linearity at very high sound levels, Tech. rep. (2002). doi:10.1121/1.4777118.

[15] D. C. Aldridge, D. R. Jarvis, B. E. Jones, R. T. Rakowski, A Method for Demonstrating the Linearity of Measurement Microphones at High Sound Pressures, Acta Acust. united with Acust. 84 (6) (1998) 1167–1171.

[16] E. Frederiksen, Verification of High-pressure Linearity and Distortion of Measurement Microphones, Tech. rep. (2004).

[17] A. Novak, L. Simon, P. Lotton, A simple predistortion technique for suppression of nonlinear effects in periodic signals generated by nonlinear transducers, J. Sound Vib. 420 (2018) 104–113. doi:10.1016/j.jsv.2018.01.038.
URL http://dx.doi.org/10.1016/j.jsv.2018.01.038

[18] S. V. Djuric, Distortion in microphones, in: ICASSP'76. IEEE Int. Conf. Acoust. Speech, Signal Process., Vol. 1, IEEE, 1976, pp. 537–539.

[19] M. Pedersen, W. Olthuis, P. Bergveld, Harmonic distortion in silicon condenser microphones, J. Acoust. Soc. Am. 102 (3) (1997) 1582–1587. doi:10.1121/1.420070.

[20] P. Honzík, M. Bruneau, Acoustic fields in thin fluid layers between vibrating walls and rigid boundaries: Integral method, Acta Acustica united with Acustica 101 (4) (2015) 859–862. doi:10.3813/AAA.918880.

[21] M. Pedersen, W. Olthuis, P. Bergveld, R. J. Hill, S. Brillante, P. J. Leonard, On the simulation of subminiature condenser microphones using finite differences, WIT Trans. Built Environ. 12 (1995).