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EVALUATION OF MICROPHONE NONLINEARITIES IN PROBES FOR MEASUREMENT OF OTOACOUSTIC EMISSIONS

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ABSTRACT

Measurement of Distortion Product Otoacoustic Emissions (DPOAE) relies on evaluating the nonlinear response of the inner ear to two-tone excitation signals, specifically identifying the cubic intermodulation distortion products. However, the accuracy of these measurements can be adversely affected by nonlinear distortions within the electroacoustic measurement chain. This study examines the nonlinear behavior of microphones embedded in probes used for otoacoustic emission measurements. Nonlinearities were characterized using the source harmonic correction method reported in the literature, as there is no perfectly linear source of excitation signal. We focused on the quantification of second- and third-order harmonic distortion, which are key components of the nonlinear response of the microphone. The results are analyzed and compared to similar measurements performed on conventional and MEMS microphones, revealing specific characteristics of the probe microphone's nonlinear response. Strategies for reducing nonlinear distortion in this context, as described in the literature, are also discussed. These findings contribute to the understanding of the limitations and potential improvements in the measurement accuracy of otoacoustic emissions by addressing microphone-induced nonlinearities.

Keywords: *nonlinear distortion, OAE probe, microphone nonlinearities*

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1. INTRODUCTION

Otoacoustic emissions (OAEs) are sound signals generated in the inner ear and transmitted through the middle ear to the external auditory canal [1]. While spontaneous OAEs occur without presenting evoking stimulus into the ear, clinical diagnostics primarily rely on evoked OAEs. Among these, distortion-product otoacoustic emissions (DPOAEs) are widely used [2]. DPOAEs arise from nonlinear interactions in the cochlea when stimulated with two close-frequency tones, f_1 and f_2 ($f_1 < f_2$), with the cubic distortion product at $2f_1 - f_2$ being of primary interest [3]. As a result, any nonlinearity in the measurement chain may compromise the accuracy of the recorded emissions.

The standard OAE measurement probe includes two miniature loudspeakers to separately generate f_1 and f_2, minimizing intermodulation distortion, and a miniature condenser microphone with low self-noise and a flat frequency response. The probe connects to the ear canal via a small tube. This study investigates nonlinearities in the microphone of such probes.

Accurate characterization of microphone nonlinearities is complicated by the absence of a perfectly linear acoustic reference source, making it difficult to isolate the microphone's contribution from that of the source. To overcome this, we apply a harmonic correction method for periodic signals [4], which uses predistortion and a low-distortion reference microphone to suppress source nonlinearities to the noise floor.

The following sections present the theoretical background on microphone nonlinearities, describe the experimental setup, and discuss the measured results along with possibilities for reducing nonlinear distortion.

2. NONLINEAR BEHAVIOR OF CONDENSER MICROPHONES

Nonlinearities in condenser microphones stem from factors such as variable capacitance due to membrane motion, nonlinear damping, and imperfections in mechanical or electronic components [5, 6]. The dominant source is the electrostatic transduction mechanism, which introduces both harmonic and intermodulation distortion [7, 8]. The second harmonic alone accounts for approximately 90% of total harmonic distortion [9], particularly under high sound pressure levels.

Following the model in [10], the analysis focuses on nonlinearities due to electrostatic transduction, assuming other sources are negligible. With negligible charge variation (due to a high polarization resistance), the microphone output voltage is

$$u(t) = -U_0 \frac{\mathrm{d}C(t)}{C}, \tag{1}$$

where U_0 is the polarization voltage, $\mathrm{d}C$ the time-varying change of capacitance, and $C = C_p + C_0$ is the total static capacitance composed of the parasitic capacitance C_p and the static active capacitance $C_0 = \varepsilon_0 S/h_g$ where h_g is the air gap thickness, S the electrode area, and ε_0 the vacuum permittivity.

Assuming the total time-varying capacitance due to the mean membrane displacement $\bar{\xi}(t)$

$$C(t) = C_p + \frac{\varepsilon_0 S}{h_g + \bar{\xi}(t)} = C_p + C_0 \frac{1}{1 + \bar{\xi}(t)/h_g}, \tag{2}$$

can be expressed as $C(t) = C_p + C_0 + \mathrm{d}C(t)$, the time-varying capacitance change can be approximated using Taylor series expansion as

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

Substituting (3) into (1), and defining $y(t) = \frac{\bar{\xi}(t)}{h_g}$ and $K_0 = U_0 \frac{C_0}{C_p + C_0}$, the output voltage becomes

$$u(t) = K_0 \left[y(t) - y^2(t) + y^3(t) - \cdots \right], \tag{4}$$

revealing the nonlinear terms. The key model parameter K_0 must be estimated from measurements.

3. MEASUREMENTS ON OAE PROBE MICROPHONE

This section describes the measurement setup and presents results for the frequency-dependent sensitivity and the levels of the first three harmonics measured at various excitation levels.

3.1 Measurement setup

The measurement setup (Fig. 1) includes the Etymotic ER10C probe with two low-noise microphones (total sensitivity 50 mV/Pa), whose signals are summed to improve accuracy, operating linearly up to 120 dB SPL. A B&K 4135 1/4" laboratory microphone serves as the low-distortion reference, and an earplug acts as the acoustic source. All components are mounted in a small plastic cavity to generate high sound pressure levels. To suppress source-induced nonlinearities, we apply a harmonic correction method for periodic signals [4] using predistortion (see "Harmonic correction" block in Fig. 1).

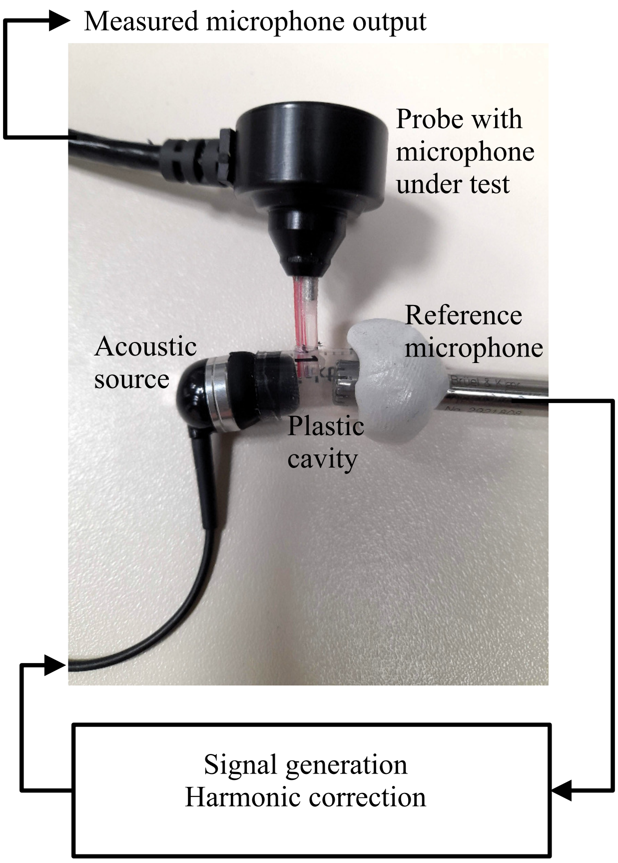

Figure 1. Schematic view of the measuremet setup.

3.2 Sensitivity

The measured frequency-dependent sensitivity is shown in Figure 2 for three different positions of the gain switch on the probe preamplifier. The frequency response is approximately flat between 100 Hz and 10 kHz. In contrast to classical condenser microphones, the phase is not quasi-constant up to the frequency of the first resonance. This is likely caused by unknown, possibly analog, signal processing in the probe preamplifier.

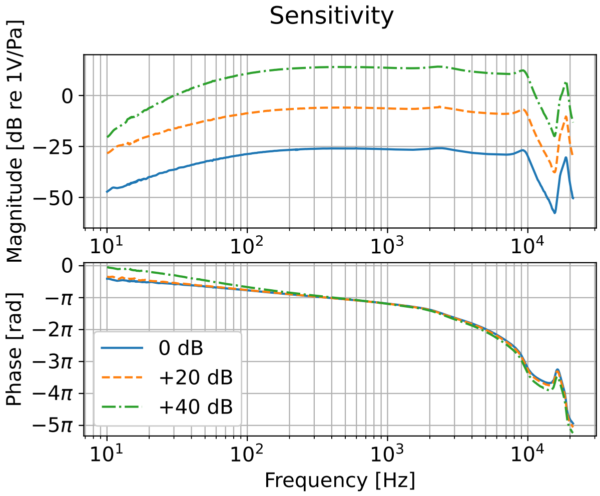

Figure 2. Measured frequency dependence of the magnitude (upper figure) and phase (lower figure) of the microphone sensitivity for the switch position 0 dB (blue solid curve), +20 dB (dashed orange curve) and +40 dB (dash-dotted green curve).

3.3 Nonlinear behavior

In line with previous research [11], the first three harmonics measured at 510 Hz for excitation levels ranging from 70 to 116 dB SPL, recalculated to sound pressure level measured by the microphone under test using its sensitivity, are shown in Figure 3 (points). The dashed lines represent theoretical predictions based on Equation (4) in Section 2, using an estimated value of the parameter $K_0 = 40\ V$. While the measured levels of the first (fundamental) and second harmonics agree well with the theoretical values, the third harmonic is significantly higher than predicted, indicating the presence of additional nonlinear effects not captured by the model. Note that similar results are obtained at higher frequencies [11].

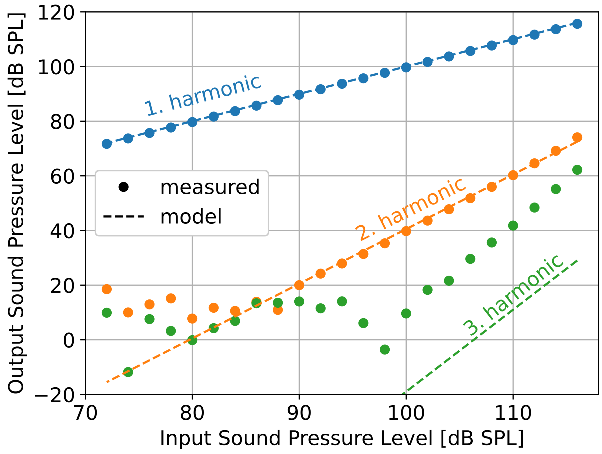

Figure 3. Measured (points) and theoretical (dashed lines) harmonics of the microphone under test at 510 Hz.

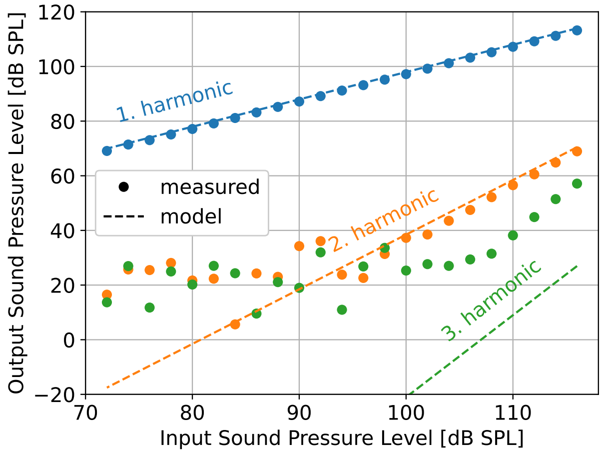

Figure 4. Measured (points) and theoretical (dashed lines) harmonics of the microphone under test at 110 Hz.

Although the frequencies used in DPOAE measurements are usually higher than 510 Hz (typically 1 to 8 kHz), methods have been proposed in the literature [12] that introduce an additional low-frequency component of relatively high amplitude in DPOAE measurements to bias the operating point of the cochlear transducer. It is therefore relevant to examine the nonlinear behavior of the probe at low frequencies. Figure 4 shows the measured and theoretical levels of the first three harmonics at 110 Hz, calculated using the same value of $K_0 = 40\ V$ and taking into account a slightly lower sensitivity (approximately 38 mV/Pa). The results are consistent with those in the previous figure, although the background noise is higher at this frequency.

4. REDUCTION OF NONLINEAR DISTORTION

Previous research [11] has shown that a low-frequency bias tone at 100 dB SPL, combined with the nonlinear distortion of the probe microphone, can generate higher harmonics of non-negligible amplitude at the microphone output. A recently published study [13] proposes a method for reducing harmonic and intermodulation nonlinear distortion in single-backplate condenser microphones by suppressing the quadratic component. This post-processing technique is based on equation (4) and utilizes the parameter K_0. The approximately linearized output voltage u_{lin} is calculated from the microphone output u as follows [13]

$$u_{lin}(t) \approx u(t) + \frac{1}{K_0} u^2(t). \tag{5}$$

In this work, we apply this simple technique to the output of the OAE probe microphone.

Figure 5 shows the level of the second harmonic component (upper plot) and the Total Harmonic Distortion (THD) parameter (lower plot) after applying the distortion reduction technique for varying values of K_0, at an excitation level of 108 dB SPL and a frequency of 510 Hz. The second harmonic exhibits a sharp minimum near the estimated value $K_0 = 40$ V, decreasing from 56 dB SPL (unprocessed value, blue solid line) to 12 dB SPL, corresponding to a reduction of 44 dB. The THD is reduced from $0.26\,\%$ to $0.026\,\%$, representing a tenfold improvement.

Figure 6 presents the same type of result at 110 Hz. Here, the second harmonic is reduced from 52 dB SPL to 42 dB SPL, resulting in a decrease of only 10 dB. Similarly, the THD parameter is reduced from $0.224\,\%$ to $0.074\,\%$, representing an improvement by approximately a factor of 3. Additionally, the positions of the minima for both the second harmonic and the THD appear to be shifted toward lower values of K_0, even though the original estimate showed good agreement between measurement and theory in Figure 4.

We propose the hypothesis that the significant change in the efficiency of the distortion reduction with frequency

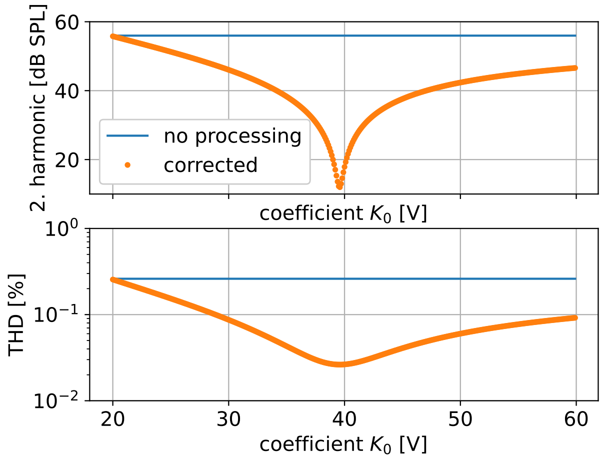

Figure 5. Reduced value of the 2^{nd} harmonic (upper figure) and THD (lower figure) at 510 Hz (orange points) compared with the unprocessed value (blue solid line).

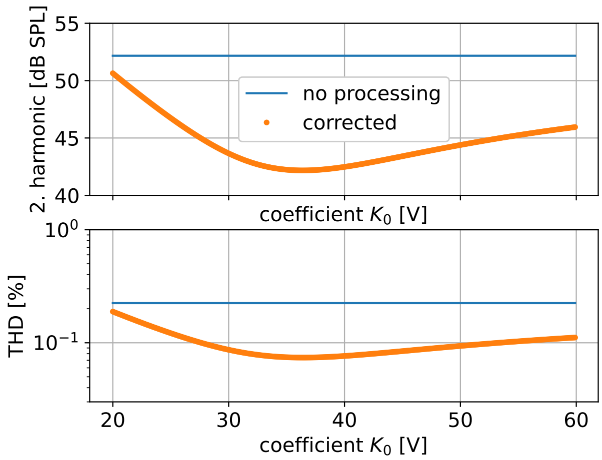

Figure 6. Reduced value of the 2^{nd} harmonic (upper figure) and THD (lower figure) at 110 Hz (orange points) compared with the unprocessed value (blue solid line).

is caused by a phase shift, possibly introduced by post-processing of the microphone output signal in the probe preamplifier. Figure 2 has shown that the phase is not quasi-constant across the entire frequency range. When the phase of the measured signal is extracted from the FFT (not unwrapped) and incorporated into the model, the phases of the first and second harmonics are predicted correctly at 510 Hz, as shown in Figure 7. Note that the third harmonic is not predicted correctly, either in amplitude or phase, for reasons discussed in Section 3.3.

At 110 Hz, as shown in Figure 8, the phase of the second harmonic shows a discrepancy between the measured data and the model, likely due to an additional frequency-dependent phase shift originating from analog signal processing in the probe preamplifier. We hypothesize that this phase shift affects the efficiency of the distortion reduction technique, which performs better at frequencies where the additional phase shift is negligible.

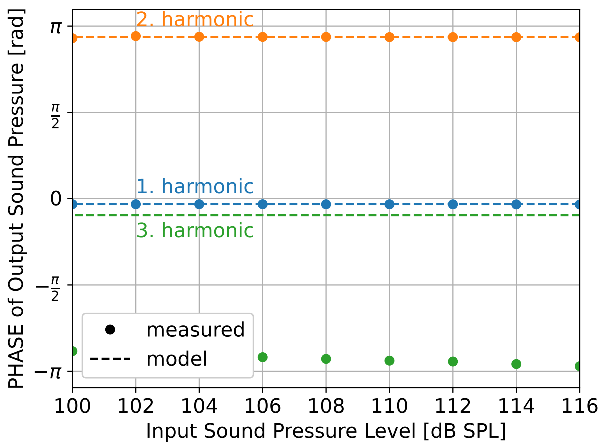

Figure 7. Phase of first three harmonics: measured (points) and theoretical (dashed lines) at 510 Hz.

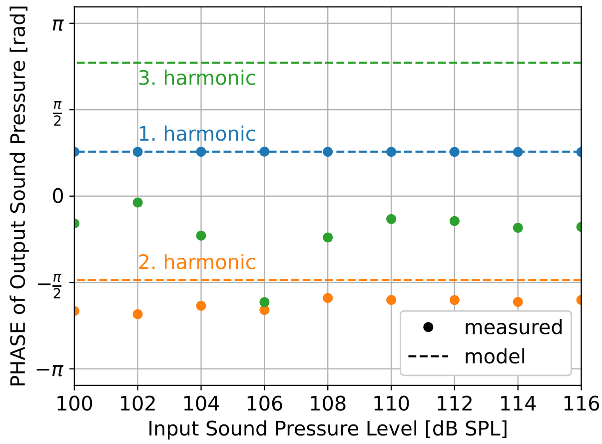

Figure 8. Phase of first three harmonics: measured (points) and theoretical (dashed lines) at 110 Hz.

5. CONCLUSION

This study examined the nonlinear behavior of condenser microphones used in otoacoustic emission (OAE) probes, focusing on its impact on measurement accuracy. A previously published analytical model based on the electrostatic transduction mechanism was applied and shown to predict the measured levels of the first and second harmonics with good accuracy. Furthermore, a distortion reduction technique from the literature, based on this model and parameterized by K_0, was evaluated. When applied as a simple post-processing step, the method significantly reduced the second harmonic component and decreased total harmonic distortion (THD), particularly at 510 Hz.

However, the efficiency of the distortion reduction technique was shown to be frequency-dependent. At 110 Hz, both the suppression of the second harmonic and THD improvement were noticeably lower. This behavior was attributed to an additional phase shift, likely introduced by analog signal processing in the probe preamplifier. Incorporating the measured signal phase into the model improved the agreement for the first and second harmonic phases at higher frequencies, while a clear discrepancy remained at lower frequencies.

These findings highlight the importance of considering frequency-dependent phase characteristics when applying nonlinear distortion reduction techniques to microphone signals. Further investigation of the internal signal processing in probe preamplifiers may help improve modeling accuracy and enable more effective compensation across a broader frequency range.

6. ACKNOWLEDGMENTS

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