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PRESSURE-COMPARISON CALIBRATION OF MEMS MICROPHONES IN THE REVERBERATION CHAMBER

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ABSTRACT

The demand of metrological traceability to the International System of units (SI) for Micro-Electro-Mechanical Systems (MEMS) microphones poses new challenges for the development of reliable, fast, and cost-effective calibration methods. This work proposes novel solutions to meet these requirements, improving the capabilities of secondary calibration methods by pressure-comparison. Specifically, it addresses the effects of acoustic field irregularities and different frequency response of microphones under comparison in the determination of MEMS microphone sensitivity in the reverberation chamber. We present numerical techniques for predicting the sound pressure distribution within the narrow gap between reference and test microphones, along with the experimental evaluation of the deviation of calibration results when microphones of different frequency response characteristics are compared. The validity of the measurements in the reverberation chamber, is demonstrated comparing the calibration results obtained by different implementations of the pressure-comparison method, like in closed pressure-couplers and in the anechoic chamber.

Keywords: *MEMS microphone, sound field corrections, pressure-comparison calibration, reverberant chamber, diffuse field.*

1. INTRODUCTION

MEMS microphones are critical components in various acoustic applications, prized for their compact size, low power consumption, and cost-effective production [1, 2]. They are commonly used in consumer electronics and wireless sensor networks, playing a vital role in urban and natural soundscape analysis [3, 4]. Additionally, their small size makes them ideal for sound source localization in applications like seismic detection, traffic monitoring, and security systems.

Traditional calibration methods, like the pressure-comparison method, struggle to fully account for geometric differences between MEMS and reference microphones, leading to systematic errors, especially at high frequencies. These methods also fail to consider the complex acoustic interactions within pressure-couplers, affecting accuracy and repeatability. To overcome these issues, proper correction methods are essential to handle geometric discrepancies [5, 6].

This study integrates Finite Element Method (FEM) simulations with experimental implementations of the pressure-comparison technique for the calibration of MEMS microphones within a reverberation chamber. It addresses the challenges associated with the compensation of acoustic field irregularities between reference and test microphones using FEM, as well as the comparison of microphones exhibiting significantly divergent sensitivity responses across the frequency interval. The results obtained in the reverberation chamber demonstrate good consistency with those from other applications of the pressure-comparison method, including closed pressure-coupler and anechoic chamber set-ups.

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2. PRESSURE-COMPARISON CALIBRATION OF MEMS MICROPHONES

The comparison method is crucial for calibrating non-conventional microphones, including miniaturized MEMS microphones, ensuring traceability to primary standards. It uses a reference microphone with known sensitivity, often determined by the reciprocity technique. For smaller microphones, especially MEMS, calibration under pressure-field conditions has the advantage to replicate real operating environments. Studies highlight the importance of using small-size Laboratory Standard (LS) microphones that can ensure the traceability of measurements.

2.1 Numerical simulation of sound field non-uniformities

FEM is widely used to solve complex acoustics problems, especially in cases where analytical solutions are impractical. It is particularly useful for modeling sound fields between microphones in scenarios involving intricate geometries, such as the small sensing areas of MEMS microphones. The acoustic pressure distribution p is governed by the Helmholtz equation:

$$\Delta p + k^2 p = 0 \tag{1}$$

where $k = \omega/c$ represents the wave number, ω is the angular frequency, and c is the speed of sound in air. FEM effectively handles boundary conditions, including rigid, vibrating with finite acoustic impedance, and sound source boundaries with known particle velocity distributions, which are crucial for simulating real-world microphone configurations.

Recent studies demonstrate the effectiveness of applying FEM with a lumped-parameter approach to model acoustic impedance boundaries [5, 6], simplifying a 3D problem to a 2D axisymmetric one. This approach aids in simulating MEMS microphones during pressure-comparison calibration, ensuring reproducible results. Numerical models have been proposed to correct sensitivity differences caused by acoustic pressure non-uniformity between reference and test microphones, which become more significant at high frequencies and as size dissimilarity of transducers gets more pronounced.

FEM results show the radial distribution of acoustic pressure, influenced by the impedance characteristics of microphones and boundaries, and are validated with experimental data. Fig. 1 illustrates the sound pressure distribution between a reference LS microphone and a MEMS test microphone under pressure-comparison at 6.3 kHz sine-type acoustic excitation, as obtained by FEM. The simulation mesh has a maximum element size of $\lambda/30$, being λ the sound wavelength, with 7214 elements covering an area of $12.12\,\mathrm{mm}^2$. The highest simulation frequency is $f_{max} = 30\,\mathrm{kHz}$.

2.2 Differences in microphones frequency response

The choice of the type of acoustic excitation and signals analysis for microphones calibration by the pressure-comparison method depends on the time efficiency of the measurement procedure, the type of acoustic environment, and the discrepancy of frequency responses of reference and test microphones' sensitivities. Broadband noise sources and third-octave bands analyses are advisable for fast calibrations, but if there are significant differences in microphones frequency responses, the use of sine-type signals and FFT analysis is recommended, especially for MEMS microphones calibration against LS reference microphones. In reverberation chambers, care should be taken in narrowing the bandwidth of the analysis with broadband noise sources, particularly as far as the degradation of the signal-to-noise ratio is concerned. Furthermore, long time-averaging of microphones signals and multi-position measurements should be performed to increase calibration accuracy.

3. REVERBERATION CHAMBER SET-UP

The pressure-comparison method for the calibration of MEMS microphones has been implemented inside the INRiM reverberation chamber of 294 m^3 volume, able to maintain the conditions of an acoustic diffuse field in the frequency range from 250 Hz to 12.5 kHz. The acoustic excitation is provided by two omnidirectional sound sources, placed at specific positions inside the chamber. The reference microphone was an LS2 type (LS microphone of 13.2 mm outer diameter, and 9.3 mm diaphragm diameter) HBK 4180, calibrated by the pressure reciprocity method at the centre frequencies of third-octave bands. The test microphone was an analog MEMS microphone on the evaluation board STMicroelectronics STEVAL-MKI139V5 fit into a custom cartridge that mimics the typical shape of LS2 microphones with a front recessed cavity. Reference and test microphones were coaxially aligned, facing each other with a very small separation gap lower than 2

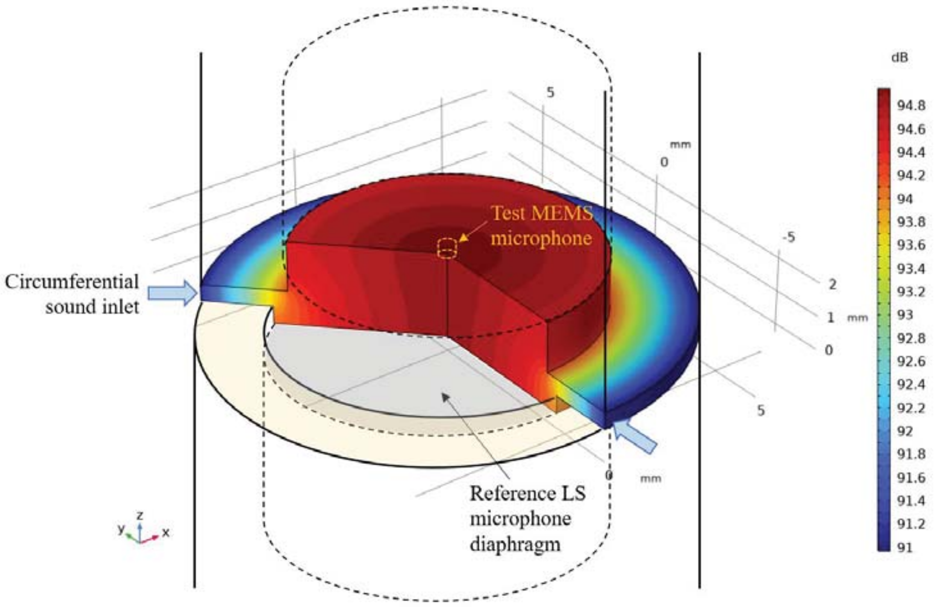

Figure 1. FEM simulation of the acoustic field for pressure-comparison calibration of a test MEMS microphone against an LS2 type reference microphone (LS microphone of 13.2 mm outer diameter, and 9.3 mm diaphragm diameter) with sine-type excitation at a frequency of 6.3 kHz.

mm. The coaxial alignment of the two microphones was realized along a direction non-parallel to any of the walls of the room as show in Fig. 2.

Signal acquisition and analysis were carried out using the ONO SOKKI DS-3200 data station, acting as a spectrum analyzer in third-octave bands. A 15-minute time-averaging was applied, with measurements repeated at various positions within the chamber to account for the diffuseness of the environment. A custom signal conditioner for the MEMS microphone, along with an HBK 2673 preamplifier for the reference microphone connected to the power and polarization module through a custom switch box, allowed applying the insert voltage technique to compensate for gain differences.

4. RESULTS

A broadband noise signal in the frequency range from 100 Hz to 16 kHz, properly amplified and equalized, was supplied to the sound sources to get a uniform sound pressure level (SPL) of about 80 dB over the third-octave bands from 250 Hz to 12.5 kHz. Because of the electro-acoustic characteristic of the sound sources, the SPL at the third-octave band of 16 kHz resulted of around 70 dB, still high enough with respect to the background noise, which was lower than 30 dB in the whole spectrum.

The frequency response of the sensitivity of the MEMS test microphone differs significantly from that of the LS2 reference microphone, as observed in previous calibrations by pressure-coupler and free field implementations of the pressure-comparison method. The dependence of calibration results on the bandwidth of the analysis was investigated by comparing the results obtained in the reverberation chamber with broadband noise stimuli analyzed in third-octave bands, with calibrations in pressure-coupler (active coupler) and free field (anechoic chamber) implementations using sine-type signals at the centre frequencies of third-octave bands. Fig. 3 shows the deviation of the calibration results due to the band-averaging in the reverberation chamber, calculated with respect to the average sensitivity curve of the MEMS microphone normalized to 1 kHz. Results are shown from 500 Hz to 16 kHz.

A marked deviation has been observed at frequency higher than 10 kHz, with a frequency response of about

Figure 2. Reference LS2 HBK 4180 microphone (right) faced to the test STEVAL-MKI139V5 MEMS microphone fit into the custom cartridge (left) for pressure-comparison calibration inside the reverberation chamber.

5 dB lower than those obtained with sine-type excitation. To evaluate the influence of the bandwidth of the analysis on the calibration results, sine-type signals have been used instead of broadband noise, along with the FFT analysis of microphones signals. Despite the possible onset of standing waves would be enhanced by such a tone excitation, the signal-to-noise ratio was higher compared to the case of a broadband noise source with bandwidth analysis narrower than third-octave. Fig. 4 shows the deviations from the mean sensitivity curve of the MEMS microphone normalized to 1 kHz, as obtained from pressure-comparison calibrations with sine-type signals in all acoustic environments: closed pressure-coupler (active coupler), free field (anechoic chamber), and diffuse field (reverberation chamber).

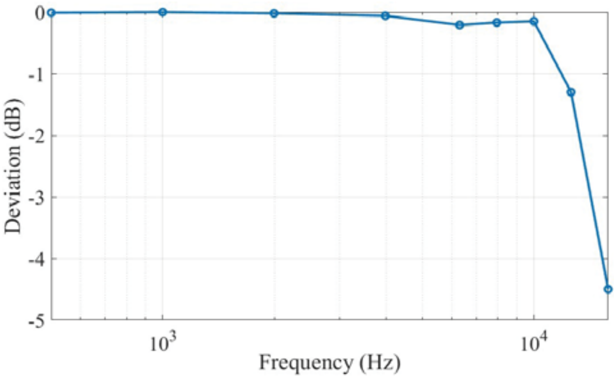

Figure 3. Deviation of pressure-comparison calibration results in the reverberation chamber with respect to the results obtained in pressure-coupler and free field implementations, due to third-octave band-averaging error.

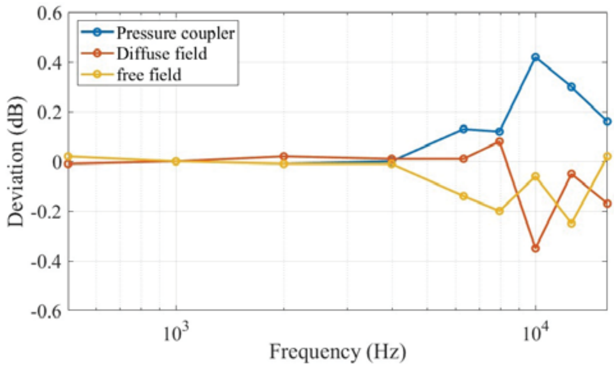

Figure 4. Deviation of pressure-comparison calibration results using sine-type signals in pressure-coupler, free field, and diffuse field implementations.

With sine-type signals excitation all calibration results were observed consistent within 0.5 dB. The increasing deviations above 4 kHz are likely due to the worse repeatability of measurements in the reverberation chamber, and to the uncertainty associated to the evaluation of the sound field corrections for the compensation of acoustic field non-uniformities between reference and test microphones.

5. CONCLUSION

This study presents a detailed analysis of pressure-comparison calibration of MEMS microphones in a reverberation chamber. Although this approach can be time efficient, it is critical to account for significant differences in frequency response between reference and test microphones, which is common for MEMS microphones. In such cases, a trade-off between accuracy and time must be considered, as sine-type excitation provides more accurate results but requires longer measurements. However, sine-type signals can be affected by standing waves in the acoustic field. The results obtained in the reverberation chamber show good agreement with previous pressure-comparison calibrations performed in pressure-coupler and free field implementations. Improvements can be achieved by optimizing the numerical evaluation of sound field corrections and by implementing automatic positioning systems to improve the repeatability of the measurements.

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