



Audio Engineering Society

Convention Paper 10225

Presented at the AES 158th Convention
2025 May 22–24, Warsaw, Poland

This paper was peer-reviewed as a complete manuscript for presentation at this convention. This paper is available in the AES E-Library (<http://www.aes.org/e-lib>), all rights reserved. Reproduction of this paper, or any portion thereof, is not permitted without direct permission from the Journal of the Audio Engineering Society.

IMPro – Method for Integrated Microphone Pressure Frequency Response Measurement Using a Probe Microphone

John Cozens¹, Matti Hämäläinen², and Mikko Pekkarinen²

¹*JCooustics*

²*Nokia Technologies*

Correspondence should be addressed to John Cozens (john.cozens@jcooustics.fi)

ABSTRACT

A method to measure the pressure sensitivity frequency response of an integrated microphone device is proposed. The measurement can be conducted in a normal office environment rather than under anechoic conditions. To test the validity of the proposed method, a MEMS microphone integrated into a rigid spherical shell was measured in an office room and in an anechoic chamber. The resulting pressure frequency response was filtered with analytically derived scattering data, and directly compared against the measured free-field directional responses of the microphone. The derived results were found to match the free-field data. We conclude that the proposed method can be used to successfully measure the pressure response within the two stated environments.

1 Introduction

The rapid advancement of Large Language Models (LLMs) is opening a new era of consumer devices, characterized by increasingly sophisticated voice-activated interfaces. This transformative trend is driving a surge in the integration of microphones into a wide range of devices such as kitchen appliances, home automation systems, robots, gaming devices, toys, etc. Smartphones have been driving investment in the development of robust and high performance MEMS microphone technologies, enabling the integration of microphones into compact mechanics and providing reliable audio capture even in harsh environmental conditions. New materials and manufacturing technologies have reduced manufacturing tolerances which is crucial for mass produced devices.

In practice, the frequency response of a device microphone is typically influenced more by the microphone integration than by the transducer characteristics. The integrated microphone frequency response is a product of the device shape, microphone integration-related mechanics, assembly tolerances, gaskets, and ingress protection features such as membranes or meshes. Partly due to industrial design and ingress protection requirements, the microphone integration is intentionally hidden or made quite invisible; a typical microphone inlet is a small 0.8–1.5 mm diameter hole in the device surface.

This paper proposes a measurement method and laboratory setup for integrated device microphone frequency response characterization. Traditional measurement methods require specialized acoustic laboratory facilities, such as an anechoic chamber. Acoustic labora-

tory spaces are generally expensive and large facilities, which is a barrier to manufacturers wanting to build high quality audio products.

In this paper, we propose a novel application for probe microphones in the measurement of integrated product microphones. For convenience, we call this measurement method **Integrated Microphone Pressure Frequency Response Measurement using Probe microphone**, abbreviated as **IMPro**.

The IMPro method uses a probe microphone to measure the sound pressure at the sound inlet of the integrated microphone. This information is combined with the microphone transducer output signal to calculate the pressure frequency response of the integrated microphone. We will also show that this measurement can be conducted in a typical office environment without the need for an expensive anechoic chamber. We will test the method using a MEMS microphone integrated into a simple rigid spherical prototype with known analytical sound scattering properties. Measurement results are validated with measurements conducted both in a $5\text{ m} \times 5\text{ m} \times 5\text{ m}$ anechoic chamber and in an audio laboratory control room that has acoustics comparable with that of a typical quiet office environment.

This research presents a method to measure microphone frequency responses after the microphone components themselves have been integrated into device mechanics. In product development it is advisable to prototype new designs with rapid prototyping techniques. However, it is known that different manufacturing processes have mechanical tolerance differences, and so there is still a need to validate a design using final product hardware. Small consumer electronics devices are easy to carry into acoustic lab spaces, but the situation becomes very different when the product is large, for example an integrated microphone within an automotive interior or vehicle cockpit. The new measurement method proposed in this paper enables measurement of integrated microphone pressure responses in arbitrary product mechanics and within complex acoustic environments. We believe that the proposed method is useful in the electro-acoustic optimization of products with integrated microphones and in improving product audio quality.

The paper has the following structure. In Section 2 we describe a simplified model for integrated microphone acoustics. Section 3 describes how probe microphones

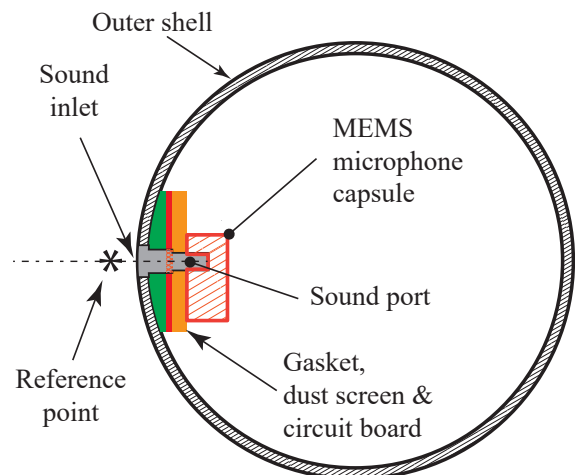


Fig. 1: Typical features of an integrated (bottom port) MEMS microphone.

can be used for pressure response measurements. Calibration of the probe microphone is discussed in Section 4. The prototype tested and the equipment used are listed in Section 5. In Section 6 we introduce the IMPro measurement method and apply the method in the office environment. These measurements are compared against laboratory anechoic measurements. Measurement results are presented and discussed in Section 7. We conclude the paper with some recommendations on possible applications of the IMPro method in commercial product design.

2 Integrated microphone acoustics

A typical embodiment of an integrated microphone device can be seen in Figure 1. The sound inlet is a small opening in the outer shell of the device, and is the outer-most extent of the microphone sound port. The sound port consists of a series of holes cutting through the outer shell, a gasket sealing material and a printed circuit board as well as the microphone capsule's own sound port. The gasket will typically include a dust and water ingress shield. The illustrated structure pertains to bottom port MEMS microphones, which have their sound port on the PCB contact face, but corresponding acoustic structures can be found for other microphone types.

The sound port may have a number of different cross-sectional shapes along its length and effectively adds

series acoustic inertia to the sound inlet of the microphone capsule. This added mass changes the total mass of the microphone resonance system, and results in a downward shift of the resonance frequency [1]. It is generally recommended that the microphone integration utilizes a simple and short sound port structure [2], but it is not uncommon that design limitations in product mechanics lead to more complicated structures with acoustic resonances that need to be compensated for by filtering the microphone signal. A designer can predict these problems and simulate the combined response with either the lumped acoustic component (LEM) approach [3] or with more complex finite element (FEM) methods. It may be difficult to determine the appropriate design parameters of the sound port structure model, especially in the case of ingress screens.

During the development of a microphone device integration LEM, it is useful to compare the response of the model to a free-field response specification in order to verify the correct assignment of the model parameters. Thus, the LEM must also include any effects of the external sound field to successfully predict the radiation characteristics of the microphone system. Oversimplification of the external radiation model may lead to a failure of the LEM to predict physical measurements. If the LEM can be verified with measurement data that disregards the external effects of the device's shape then the model should be more reliable, since the external radiation model components can be removed. The next section discusses how probe microphone measurements can be utilized to provide this verification measurement data.

3 Pressure response measurement with a probe microphone

The pressure frequency response of a microphone is essentially the frequency characterization of the microphone output signal to a known input pressure [4]. This is different from the free-field frequency response, where only the sound pressure at a reference position in the absence of the microphone object is known. The pressure response of the microphone is independent of the external sound field, so using this response as a target for microphone design would negate the need to simulate the external sound field.

Typically, the pressure response of a microphone is measured by placing the microphone and a sound

source in a small enclosing cavity, which has dimensions small compared to the sound wavelength within the measured frequency band. It is assumed that the pressure within the enclosing volume is of a constant known value, or at least accurately predictable at a point within the volume; hence the pressure at the sound port of the microphone is known. Clearly, for larger objects this is not a feasible procedure, or at least is limited to low frequency measurement.

The pressure response of an integrated microphone can be thought of as the free-field response with any scattering effects caused by the device removed. Wiener [5] used a probe microphone to measure the scattering effect of objects in an anechoic environment, and the proposed IMPro method will use a probe microphone to measure the same acoustic phenomenon, but for a different purpose.

The underlying assumption in the IMPro method is that sound pressure at the reference point shown in Figure 1 is equal to the sound pressure entering the microphone sound port. This assumption should be valid if the reference point is very close (≈ 1 mm) to the sound inlet. To verify that at this distance the pressures are sufficiently equivalent, the analytical pressures at the microphone sound port $r + \delta r$ and at the probe reference point r for a sound source producing freely traveling spherical waves were determined [6]. The ratio of these two pressures is

$$\frac{p(r + \delta r)}{p(r)} = \frac{r}{r + \delta r} e^{-ik\delta r} \quad (1)$$

This equation shows that the phase difference between the two points is frequency dependent upon the distance between the two points. The magnitude difference is dependent upon the ratio of the two absolute distances and that the microphone sound port to reference point distance must be small compared to the source to reference point distance. At a measurement distance of $r=0.5$ m and with a probe distance from the microphone sound inlet of $\delta r=1$ mm, the magnitude and phase values of the pressure ratio at 25 kHz is -0.02 dB and -26° .

The complex frequency response of the integrated microphone for constant input pressure, *i.e.* the pressure frequency response, H_m is

$$H_m = \frac{u_m}{p_{in}} \quad [\text{units}/\text{Pa}]^1 \quad (2)$$

¹units refers to either voltage or for this paper as the digital signal level.

where u_m is the measured integrated microphone output signal's response to the loudspeaker sound source, and p_{in} is the sound pressure at the reference point.

The pressure p_{in} at the reference point is determined by measuring the output signal u_p of a probe microphone to the same source loudspeaker stimulus, and correcting the measured signal with the calibrated sensitivity frequency response of the probe microphone H_{probe} (see Section 4 for the definition):

$$p_{in} = \frac{u_p}{H_{probe}} \quad [\text{Pa}] \quad (3)$$

Using (2) and (3), the desired pressure response H_m of the integrated microphone is simply

$$H_m = H_{probe} \frac{u_m}{u_p} \quad [\text{units/Pa}] \quad (4)$$

For the assumption of equivalent pressures at the sound inlet and measurement reference to be valid, the probe tip must be placed as close as possible to the sound inlet. Ideally, the probe tip would be touching the surface. However, if the probe tip is placed too close to the sound inlet, the physical size of the probe tip may distort the end correction of the microphone sound port, which would result in a change in its acoustic mass and resistance and inadvertently modify the resonance characteristics of the integrated microphone. For a circular outlet, the probe should not be placed closer than the diameter of the outlet.

If the probe tube is oriented such that the sound inlet and probe tube axes are orthogonal, the probe tip will sample pressures over a range of distances ± 0.5 mm from the probe tube central axis, which may cause phase smearing at high frequencies. With the probe tube and sound inlet axes aligned, the probe tube samples pressure at the same distance from the inlet. Since the sound inlet is of similar diameter to the probe tip, the pressure should be constant over the probe tip area. Differences in probe tube orientation should only be noticeable at very high frequencies.

Probe microphones may be supplied with a variety of different probe tube lengths. With a shorter probe tube, the sensitivity at higher frequencies is improved. However, short tubes bring the probe microphone body closer to the device being measured, which increases the strength of reflections. Longer tubes may begin to

vibrate due to the loudspeaker stimulus, and this vibration may cause resonances to appear in the measured responses which are not characteristic of the integrated microphone.

If it is a valid assumption that the sound inlet and the reference point pressures are equal, then it should be possible to successfully measure the integrated microphone pressure response in any room, such as in an office, rather than under anechoic conditions. In an office room, there may be problems if either the loudspeaker or the reference point is located at a pressure nodal point, as the pressure level at the reference point may be below the noise floor of either of the two microphones. This could be predicted by measuring the background noise spectrum for each microphone at the measurement position, and ensuring that the measured spectra with sound stimulus are sufficiently above the background noise levels.

4 Probe microphone calibration in an office environment

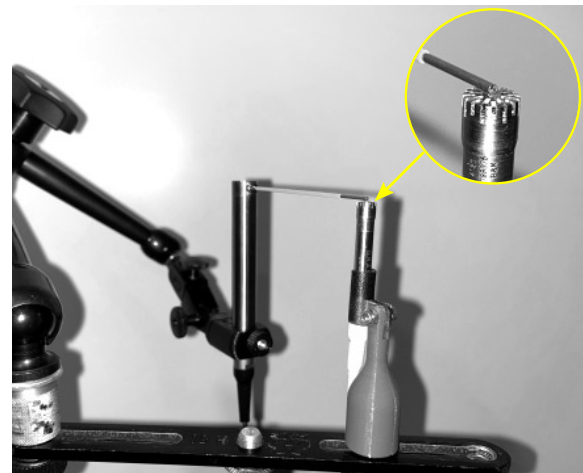


Fig. 2: Reference 1/4 in. pressure-field microphone and probe microphone positioning for frequency response calibration.

Probe microphones have frequency responses that are dependent upon the attached probe tube and require calibration against a reference microphone. Suppliers of probe microphones provide calibration adapters to facilitate measurement of the frequency response of the probe microphone within a closed volume according to standard practice [7]. A small sound source

and a reference microphone are required and typically a measurement microphone is used in reverse as the sound source. This necessitates a second measurement grade microphone capsule and a sound source adapter as well as a polarization power supply, amplifiers and cabling, all of which are used for a very limited purpose. Free-field calibration of the probe microphone does not need this special miniature sound source but does unfortunately require an anechoic test chamber.

A probe microphone calibrated following the free-field simultaneous standardized method [8] places the probe tip and the reference microphone close together, and assumes that both microphones measure exactly the same pressure. For the same reasons outlined in Section 3, measurement of the probe microphone frequency response could be performed in any normal room rather than restricted to an anechoic environment. The pressure measured by the probe tip should be equal to the average pressure over the sensing area of the reference microphone membrane. This is a reasonable assumption if the reference microphone is sufficiently small compared to the measurement wavelength, and should be the case for a $\frac{1}{4}$ in. measurement microphone at frequencies in excess of 20 kHz.

The reference microphone of sensitivity S_{ref} [units/Pa] and the probe microphone are placed together, with the probe tip offset about 0.5 mm from the outer surface of the reference microphone's protection grid and the center points of the tip and the reference microphones coincident (see Figure 2). The output signals of the reference microphone u_r and the probe microphone u_c in response to the source loudspeaker stimulus are measured. The probe microphone calibration frequency response H_{probe} , which is used in (4), is defined as follows:

$$H_{\text{probe}} = S_{\text{ref}} \frac{u_c}{u_r} \quad [\text{units/Pa}] \quad (5)$$

A key assumption made in comparison calibration methods is that the reference microphone has a known response in a well defined measurement environment. In a normal office room, this is not the case. Therefore, corrections to the reference microphone response should be made to account for the measurement environment mismatch. A normal office room is neither a free-field nor diffuse-field environment, but falls somewhere in between. For a $\frac{1}{4}$ in. microphone the deviation from diffuse to free-field/pressure-field responses at 20 kHz is small but not insignificant, and dependent upon the incident angle of the arriving sound. Hence,

there may be slight differences in the implied response of the reference microphone, depending on the measurement location within the room, and the strength of the different reflections arriving at the reference microphone. By spatially averaging the measurement, the reference microphone's assumed response will tend towards a random incidence response, thereby reducing the effect of the measurement environment. Corrections for a random incidence response could then be applied to the reference microphone response, or a suitable random-incidence measurement microphone could be used as the reference microphone.

The mean frequency response $\bar{H}_{\text{probe}}$ and confidence interval data presented in Figure 3 show that it is possible to calibrate a probe microphone using this modified free-field method. The differences between the reference microphone response measured in the anechoic and office environment sound fields are clearly seen. If neither an anechoic chamber, nor pressure calibration equipment is available, a probe microphone can be calibrated in a normal office room.

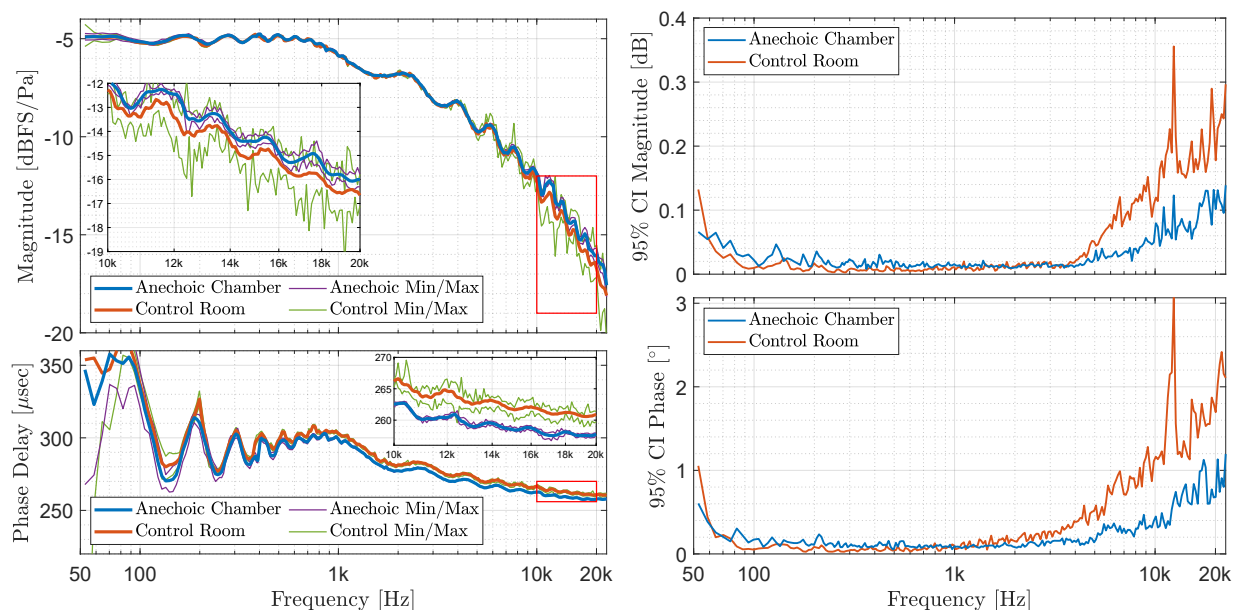
5 Prototype and measurement equipment

5.1 Sphere microphone prototype

In order to test the validity of the IMPro methodology, an integrated microphone prototype was constructed and measured. The prototype consisted of a digital MEMS microphone (Knowles SPH0644LM4H-1DS) housed in a rigid hollow sphere (Figure 4), with similar internal structures to those depicted in Figure 1.

The MEMS microphone with a bottom-facing (PCB side) sound port was soldered onto a small circuit board. The circuit board was attached and sealed to the inner surface of the spherical shell with a gasket. A hole of 1.0 mm in diameter was drilled through the shell cover, of thickness 1.0 mm, within the gasket area, thus creating a short sealed sound port connection to the microphone membrane. The internal diameter of the gasket seal was large compared to the sound port diameter.

The sphere diameter was 90.0 mm, and the microphone sound inlet was positioned at the spherical coordinates (r, θ, ϕ) of $(45 \text{ mm}, 0^\circ, 35.3^\circ)$. A $\frac{3}{8}$ -16 UNC threaded insert, located at $(45 \text{ mm}, 0^\circ, -90^\circ)$, allowed the sphere microphone to be easily connected to a microphone



(a) Probe microphone magnitude and phase delay frequency responses. (b) Statistical variation in the probe microphone calibration frequency response, showing the 95% confidence intervals for the magnitude and phase responses.

Fig. 3: Probe microphone calibration mean frequency responses $\bar{H}_{\text{probe}}$ and confidence intervals in anechoic and control room environments. Magnitude and phase plots share the same x-axis

stand or stereo T-bar. This insert also set θ as the rotational axis for the sphere microphone. The MEMS microphone was connected to a custom computer USB interface, which allowed direct capture of the microphone's digital signal.

5.2 Equipment

The equipment required for the IMPro measurement consists of signal acquisition hardware, a reference microphone, a probe microphone, a loudspeaker, and mechanical hardware to reliably position the probe microphone's tip at the required position (Table 1).

The probe microphone was fitted with an 80 mm long probe tube. Positioning the tip is challenging, as small movements of the microphone body result in much larger movements of the tip. A dial gauge positioning arm, used by machinists, allows easy general positioning of the tip and locks rigidly in place when required. The arm used also included some fine adjustment of the probe tip in one axis. When placing the probe tip a measurable distance from the sound inlet surface, displacement adjustment along the length of the probe

Table 1: Measurement equipment for IMPro

Item	Part
Probe microphone	GRAS 40SA
Reference microphone	B&K 4136
Loudspeaker	Genelec 8010A
Microphone PSU	B&K 2829
Acquisition hardware	RME UFX
Microphone stands	K&M 201A/2
Stereo T-bar	K&M 23550
Tripod universal ball-joint	K&M 19695
Dial gauge positioning arm	Noga MG60103
Thread adapter M8 to $\frac{3}{8}$ -16 UNC	Custom
Probe microphone holder	3-D printed part

tube is needed, and a simple 3-D printable jig was developed to enable the required fine adjustments² (Figure 5). Feeler gauges, used in automotive repair, can be used to accurately assess the distance between the

²3-D model available from <https://github.com/nokiotech/impro>



Fig. 4: Sphere microphone and probe microphone positioning for pressure frequency response measurement.

probe tip and the integrated microphone sound inlet surface.

The integrated microphone being tested (or the reference microphone for probe calibration measurements) were mounted to a stereo T-bar, to which the positioning arm was also securely mounted using an appropriate thread adapter. The T-bar was attached to a microphone stand. Figure 4 shows an example of the positioning setup. The arrangement allows rigid positioning of the two microphones relative to one another but allows easy rotation of the microphone assembly about the microphone stand shaft axis. The source loudspeaker is mounted on a separate microphone stand. Placing the loudspeaker and microphone assembly on different microphone stands helps to reduce vibrational coupling

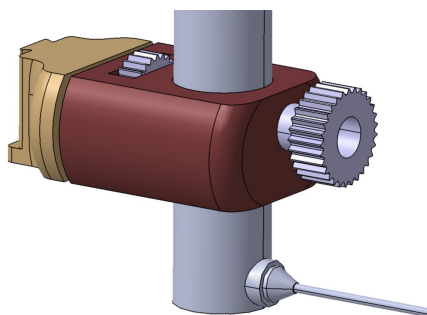


Fig. 5: Probe positioning device to displace the probe tip along the probe tube axis

between the source and the microphone assembly.

6 IMPro method

The IMPro measurement setup is illustrated in Figure 4. In the nominal position of the microphone assembly, the probe tube and loudspeaker radiation axes are aligned. The loudspeaker sound source is placed approximately 50 cm from the microphone assembly. The integrated microphone under test and the probe microphone are assembled together on a microphone stand according to the setup described in the previous section (Section 5.2). The combined loudspeaker and microphone assembly measurement setup is positioned in the test room, away from walls and other strongly reflecting surfaces. For the reported data, measurements were conducted in an acoustic laboratory control room with a hard concrete floor but with otherwise typical office room acoustics.

The probe microphone tip is positioned such that the integrated microphone sound inlet and the center of the probe tip are coincident and aligned to the outward surface normal of the sound inlet. The gap between the device sound inlet surface and probe tip is adjusted such that a 1.0 mm thickness feeler gauge just fits through the gap. The loudspeaker level for the sine sweep is set to be approximately 30 dB above the background noise level.

To assess the reliability of the measured responses, sine sweep measurements are repeated 20 times. For each repetition, the microphone assembly is slightly rotated within a 20-degree range ($\pm 10^\circ$). This rotation helps determine the confidence intervals of the measurements. In situations where the microphone assembly cannot be rotated, the sound source should be repositioned within the measurement environment to achieve equivalent rotations.

For the reported data, the logarithmic sine sweep recordings were processed according to the method described by Müller [9] to obtain the signal response functions u_m and u_p for the sphere and probe microphones, respectively, and used to determine the pressure response H_m of the sphere microphone (4). The sphere and probe microphone signals were not acquired with the same hardware. Time alignment of the impulse responses was achieved by quadratic fitting of the subsampled impulse to $1/64^{\text{th}}$ of a sample. Alignment was ensured between the two microphone signals, and also

between the repeated measurements, thus minimizing issues caused by sample clock rate differences.

To evaluate the statistical variance of the pressure response measurement H_m , the set of repeated measurements of u_m and u_p as well as the set of measurement data obtained for the probe microphone response calibration H_{probe} were individually combined to create a set of all possible pressure responses. $\log_{10}$ magnitude and unwrapped phase forms of the H_m data set were processed using the bootstrap bias and accelerated percentile method [10] to determine, for each frequency point, the mean response components and their 95% confidence intervals, based on a bootstrap count of 2000.

6.1 Anechoic verification measurements

Verification measurements of the IMPro method were conducted on the sphere microphone under anechoic conditions. The microphone assembly setup was identical to that used in the control room. However, the loudspeaker source distance was 1.21 m, and only 11 repeated measurements were made within a range of $\pm 10^\circ$ of microphone assembly rotation.

In order to verify that the IMPro measurement method correctly identifies the pressure response of the integrated microphone, a reference measurement is required. The free-field directional response H_{ff} of the sphere microphone was deemed suitable, since an analytical model similar to this measurement setup is available. Measurements of the sphere microphone's free field response H_{ff} , conducted according to IEC 60194:8 [8], were obtained for source incident angles between 0° and 350° at 10° intervals in the horizontal plane.

Equivalent data to the measured directional responses (H_{ff}) were generated by combining the measured pressure response H_m with data from an analytical model of the primary and scattered pressures surrounding a rigid sphere due to acoustic radiation from a point source [11]. The sound pressure at a point on the horizontal plane (r, α) due to radiation from a point source of strength U_0 is determined from the sum of the primary (p_d) and scattered (p_s) pressures:

$$p_t(r, \alpha) = p_d(r, \alpha) + p_s(r, \alpha) \quad (6)$$

For the total pressure p_t to be equivalent to the free-field measurement data (H_{ff}) that we wish to compare

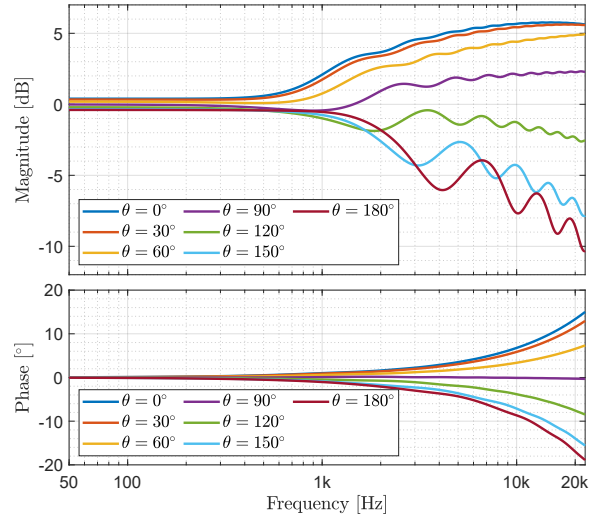


Fig. 6: Analytical pressure response p_t for the external sound field at the sphere microphone reference point, normalized with the sphere center point pressure p_{ref} for different sound source incident angles (8)

against, this pressure should be normalized with the sound pressure p_{ref} which is produced by the same point source at the free-field reference position in the absence of the sphere microphone:

$$p_{\text{ref}} = ik\rho c U_0 \frac{e^{-ikd}}{4\pi d} \quad (7)$$

Here, k is the wavenumber and d is the distance from the point source to the sphere center, *i.e.*, the reference point. If the point p_t is chosen to be the same measurement reference point for which the pressure frequency response H_m is measured with the probe microphone, then the product of these two quantities gives the signal output of the sphere microphone. Thus the response function H_f of the sphere microphone signal to the reference pressure p_{ref} is

$$H_f = \frac{H_m p_t(r, \alpha)}{p_{\text{ref}}} \quad [\text{units/Pa}] \quad (8)$$

and H_f should be equivalent to measurements of the directional free-field sphere microphone frequency response H_{ff} . For the prototype sphere microphone, the H_m reference point is located 1.0 mm from the sphere surface, with spherical coordinates $(46 \text{ mm}, 0^\circ, 35.3^\circ)$.

The analytical model determines p_t for a point at (r, α) lying on the horizontal plane. As the sphere micro-

phone sound inlet is not located on this plane, the rotation angle θ of the sphere microphone about the vertical axis, *i.e.*, the source incident angle, is not equivalent to the angle α required to determine p_t . Conversion of the angle θ to α is determined by

$$\alpha(\theta) = \cos^{-1}(\cos \phi \cos \theta) \quad (9)$$

where $\phi=35.3^\circ$ for the probe reference point. The calculated values of H_f for the 90 mm diameter sphere, at a distance 1.21 m from the point source at various rotation angles θ , are shown in Figure 6.

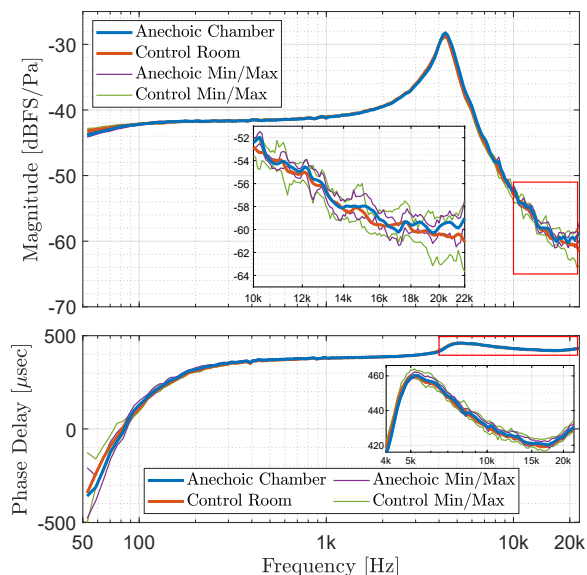
7 Results

This section presents the measured pressure frequency responses (H_m) of the sphere microphone in both anechoic and control room environments obtained using the IMPro method, along with the measured free-field directional responses (H_{ff}) and their synthesized versions (H_f) using the analytical scattering model data.

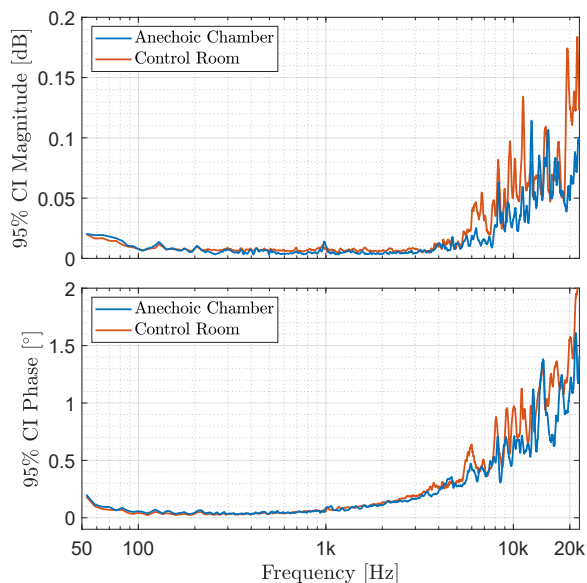
Figure 7 shows the pressure frequency response of the sphere microphone, with 1/36-octave smoothing, measured in both the anechoic chamber and in the control room. In Figure 7(a) the mean responses are plotted along with the maximum and minimum measured frequency point values. The 95% confidence intervals of the magnitude and phase components for the measurements are reported in Figure 7(b).

To determine the pressure response of the sphere microphone (H_m), we used the probe calibration data (H_{probe}) obtained from measurements in the anechoic chamber (see Figure 3). We observe virtually no difference between the measurements made in the two environments. The range between the maximum and minimum frequency point values is slightly higher in the magnitude and phase delay responses for measurements made in the control room. This may be the result of higher background noise levels in the control room compared to the anechoic chamber. The confidence intervals for the measurements in both environments were relatively low and similar. This means that the measurements were consistent and reliable, with a maximum confidence interval of 0.2 dB in magnitude and 2° in phase. The measured phase delay is similar to the phase delay of a typical MEMS microphone of the same manufacturer [12].

The IMPro method demonstrates considerable robustness against variations in measurement environment



(a) Pressure frequency responses H_m



(b) Confidence intervals

Fig. 7: Sphere microphone pressure sensitivity frequency responses H_m for anechoic and control room measurements.

due to the cancellation of the room effects resulting from the close proximity of the probe microphone to the integrated microphone sound inlet. Our results show that pressure frequency response measurements obtained in a typical office environment closely resemble those acquired in an anechoic chamber. Whilst an anechoic chamber remains the ideal setting for acoustic measurements, the comparable results achieved in a more modest office environment highlight the IMPro method's ability to produce reliable data even under less controlled acoustic conditions.

Figure 8 presents the free-field response (H_f) of the sphere microphone, generated using the IMPro method, alongside the directly measured responses from the anechoic chamber (H_{ff}) for three difference source incident angles. Both the free-field and IMPro data were processed using 1/36-octave smoothing, and the deviations from linear phase responses are shown for clarity.

The IMPro method accurately predicts the free-field response for incident angles up to 90° , closely matching the measured data. The differences between the responses of the sphere microphone for rotation angles between 0° and 60° are so small that only the 0° on-axis data is illustrated.

For the 180° angle of rotation, the IMPro method fails to accurately predict the peak frequency and peak level in the magnitude response, and the deviation from linear phase response exhibits significant discrepancies at high frequencies. These discrepancies can be attributed to a combination of factors. Addressing the difference seen at the resonant frequency, Figure 6 shows a dip in the analytical external pressure at the probe measurement point near 4 kHz for the 180° rotation condition, which also coincides with a resonance seen in the sphere microphone's pressure response in Figure 7(a). These two frequency characteristics are independent of each other. The microphone pressure response resonance results from the resonant system arising from the combination of the sound port and microphone capsule. The frequency and magnitude level of the external pressure dip is dependent upon the radius of the sphere. The gradients for both responses at 4 kHz are steep, and so small shifts in the frequency of these resonances will lead to large errors. Similarly, at frequencies above 10 kHz, small ripples in the pressure response may also coincide with high-order harmonics in the scattered pressure response, and give rise to the high frequency differences observed.

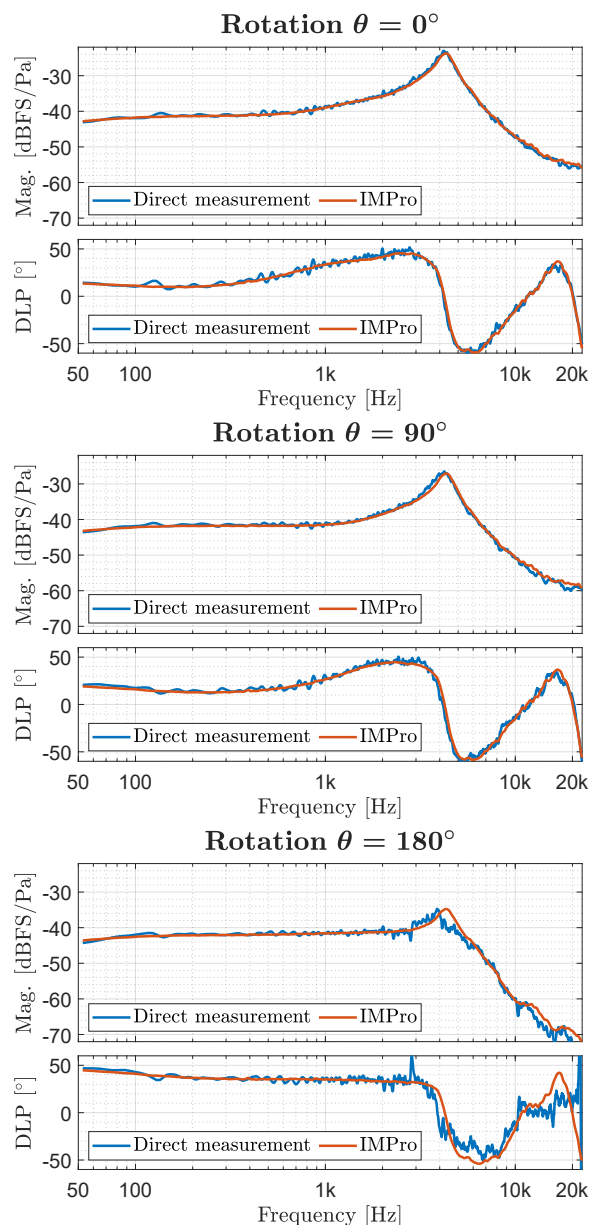


Fig. 8: Sphere microphone directional free field responses, showing both direct measurement data H_{ff} and IMPro H_f (8) for the stated source incident angle θ . Log magnitude and deviation from linear phase (DLP) plots are shown.

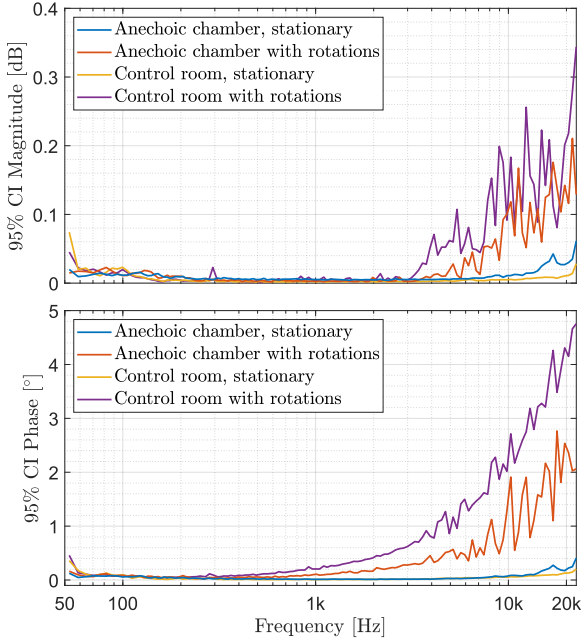


Fig. 9: Confidence intervals of $\bar{H}_m$ for stationary and rotated microphone assemblies

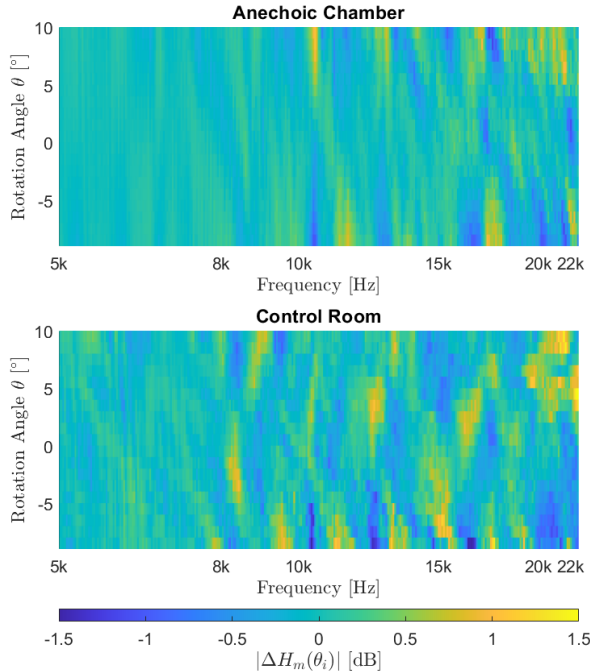


Fig. 10: Variation of $|\Delta H_m(\theta_i)|$ for each rotation θ_i

The IMPro method recommends the rotation of the microphone assembly between N repeated measurement of signals u_m and u_p (4). To verify this recommendation, a series of measurements were made in both anechoic and control room environments. Within each environment, 2 sets of 20 sine sweep samples were acquired. The integrated microphone pressure response for each individual direction θ_i is defined as

$$H_m(\theta_i) = \bar{H}_{\text{probe}} \frac{u_m(\theta_i)}{u_p(\theta_i)}, \quad (10)$$

where $\theta_i = [\theta_1, \dots, \theta_N]$. During the first measurement set the microphone assembly remained in exactly the same position throughout the measurement. For the second measurement set the microphone assembly was incrementally rotated about the microphone stand axis within the range of $\pm 10^\circ$ in about 1° steps. Note, since the rotational axis of the microphone stand and the probe reference point were not coincident, rotation of the microphone assembly resulted in both rotation and displacement of the probe reference point with respect to the sound source. Figure 9 shows the magnitude and phase confidence intervals for the stationary and rotated microphone assembly measurement cases in both environments. The stationary measurement cases clearly show that there is very low variation, suggesting that measurement noise in both environments was not an issue. The rotational measurement results show larger variation, with confidence intervals of up to 0.35 dB in magnitude and 5° in phase for the control room measurement. It can be seen that the IMPro method provides isotropic measurement results at low frequencies but has slight spatial dependency above 7 kHz.

Figure 10 shows the variation from mean response $\bar{H}_m$ and defined in the following equation

$$\Delta H_m(\theta_i) = \frac{H_m(\theta_i)}{\frac{1}{N} \sum_{i=1}^N H_m(\theta_i)} = \frac{H_m(\theta_i)}{\bar{H}_m}, \quad (11)$$

for measured $N = 20$ directions. The figure shows that at frequencies above 7 kHz the results are affected by measurement geometry. This may be from reflections caused by the measurement hardware within the sound field, and from subtle non-uniform directional characteristics of the probe microphone. Even though the variations are small, the suggested spatial averaging method is recommended either by rotating the microphone setup or alternatively by moving the sound source for full frequency band IMPro measurements.

Table 2: f_0 and Q-factor values for H_f at different incident angles, including mean and standard deviation and corresponding values for the mean pressure response $\bar{H}_m$

$\theta(^{\circ})$	f_0 (kHz)	Q-factor
0	4.330	4.48
90	4.342	4.55
180	4.336	4.07
mean	4.328	4.40
σ	0.023	0.16
$\bar{H}_m$	4.359	4.77

Resonance frequency f_0 and Q-factor values were calculated from the synthesized H_f data for all measured rotation angles 0° to 180° at 10° intervals. The means and standard deviations of f_0 and Q were determined (see Table 2). Often design criteria for a device may include the specification of f_0 and Q , and our data clearly demonstrates that the measurement direction should also be included in the specification. The variation of Q for different incident angles may not occur for other exterior shapes, but this is difficult to predict beforehand. Specification of f_0 and Q with reference to the pressure response would avoid this outcome.

8 Conclusions

The results show that the IMPro method is suitable to measure the pressure response of an integrated microphone with a small sound inlet that is typical of commercial devices. The proposed method is expected to perform well across different measurement environments and be insensitive to changes in instrumentation and stimulus types. Measurements can be made without expensive acoustic facilities such as an anechoic chamber. IMPro can be applied to more complex mechanical structures, whose diffraction characteristics cannot be modeled analytically, by using well known numerical acoustic methods. This opens the possibility of specifying integrated microphone performance requirements that are independent of product shape and usage environment.

References

- [1] Knowles Electronics, LLC, *Technical bulletin - Effects of sound inlet variations on microphone response*, 2017.
- [2] Suvanto, M., *The MEMS microphone book*, Mo-somic, 2020, ISBN 978-952-94-5660-4.
- [3] Olson, H., *Elements of Acoustical Engineering*, chapter IV, D. Van Nostrand Company Inc., 1940.
- [4] IEC, *61094:1 (2000): Measurement microphones - Part 1: Specifications for laboratory standard microphones.*, International Electrotechnical Commission, 2000.
- [5] Wiener, F. M., “Sound Diffraction by Rigid Spheres and Circular Cylinders,” *The Journal of the Acoustical Society of America*, 19(3), pp. 444–451, 1947, doi:10.1121/1.1916501.
- [6] Beranek, L. and Mellow, T., *Acoustics: Sound Fields and Transducers*, chapter 2.8, Elsevier Science, 2012, ISBN 9780123914217.
- [7] IEC, *61094:5 (2016): Measurement microphones - Part 5: Methods for pressure calibration of working standard microphones by comparison*, International Electrotechnical Commission, 2016.
- [8] IEC, *61094:8 (2012): Measurement microphones - Part 8: Methods for determining the free-field sensitivity of working standard microphones by comparison*, International Electrotechnical Commission, 2012.
- [9] Müller, S. and Massarani, P., “Transfer-function measurements with sweeps—Director’s cut including previously unreleased material and some corrections,” *Journal of the Audio Engineering Society*, 49, p. 443–471, 2001.
- [10] Efron, B. and Tibshirani, R., *An Introduction to the Bootstrap*, Chapman & Hall/CRC Monographs on Statistics & Applied Probability, Taylor & Francis, 1994, ISBN 9780412042317.
- [11] Beranek, L. and Mellow, T., *Acoustics: Sound Fields and Transducers*, chapter 12.4, Elsevier Science, 2012, ISBN 9780123914217.
- [12] Knowles Electronics, LLC, *Application note AN22 - Frequency response and latency of MEMS microphones: Theory and practice*, 2017.