INTER-NOISE 2006

3-6 DECEMBER 2006
HONOLULU, HAWAII, USA

Development of a Calibrator for Simultaneous Calibration of Multiple Microphones on an Acoustic Energy Density Probe

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ABSTRACT

This paper presents the theory, design, and development of a microphone calibrator used to calibrate multiple microphones simultaneously. This work was done in conjunction with the development of an acoustic energy density (ED) probe, which is used to measure the acoustic pressure and particle velocity of a sound field. The probe of interest in this paper was developed to measure ED using multiple microphones to acquire the data needed to compute the ED quantity. The microphones used are ¼ inch electret microphones which do not have an ideal “flat” response over a wide range of frequencies. These characteristics prompted the need for calibration. The idea behind the calibration process was to simultaneously subject each microphone on the probe to the same known acoustic pressure and frequency. This is done using equal length small diameter tubes connected to a single source and each microphone independently. It has been shown that the microphones on the probe can be calibrated within 0.5 dB up to 2000 Hz which is the frequency range of the probe.

1 INTRODUCTION

An acoustic energy density probe is a sensor that can use multiple pressure transducers to measure acoustic energy density (E.D.). Calibrating each pressure transducer of an acoustic energy density probe at the same time is a difficult problem because the pressure transducers have a unique location and orientation. The objective was to calibrate the probe within ± 0.5 dB re 20 μPa over the probe’s operational frequencies. Calibrating to this metric would classify the probe as a class 1 probe.[1]

Two main challenges arise when simultaneously calibrating multiple microphones. The first is creating a uniform pressure at each microphone. The effective distance between the microphones on the probe is the same distance used to calculate the pressure gradient. This distance restricts simultaneous calibration to a uniform pressure field. A uniform pressure field exists in a chamber when the largest dimension of the chamber is less than $1/10^{th}$ of a wavelength of the frequency being used to calibrate. This means for a 5.08 cm (2 inch) probe being calibrated at 1000 Hz, the largest chamber dimension would need to be less than 3.43 cm

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(1.35 inches). Fitting a spherical probe with a 5.08 cm (2 inch) diameter into a 3.43 x 3.43 cm (1.35 x 1.35 inch) chamber is physically impossible.

The second challenge is creating a seal for the calibrator microphone interface. It arises from the probe/calibrator interface which must be sealed the same at each probe microphone. This issue has no effect if the probe is in a uniform pressure field.

2 BACKGROUND

2.1 The Energy Density Probe

The probe of interest for this research is spherically shaped with four pressure transducers mounted in the sphere. The sphere is 5.08 cm (2 inches) in diameter. A hollow shaft is used to connect the sphere to the Digital Signal Processor (DSP) housing. Wires pass through the shaft to connect the microphones to the DSP. The z axis or the axis which runs down the length of the shaft is considered the natural axis of the sphere. One sensor microphone is mounted on the sphere opposite the shaft, and shares the same z axis as the shaft. This microphone is known as the pole microphone. (See Figure 1)

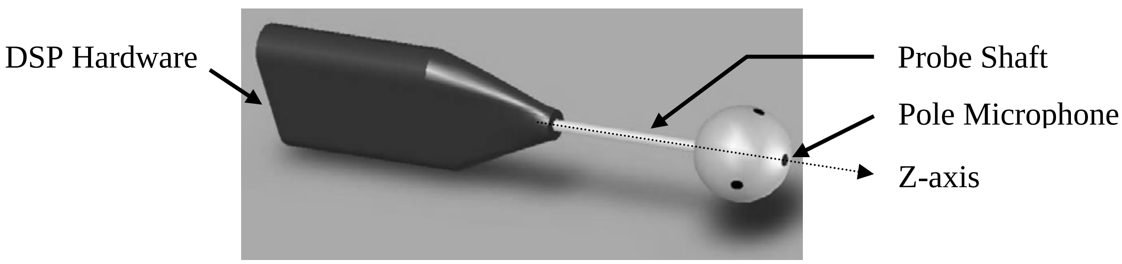


Figure 1: Energy Density Probe

The other three transducers are located 68.75˚ off the z axis as measured from the pole microphone. These three side microphones are spaced equally around the sphere at 120˚ increments. (See Figure 2)

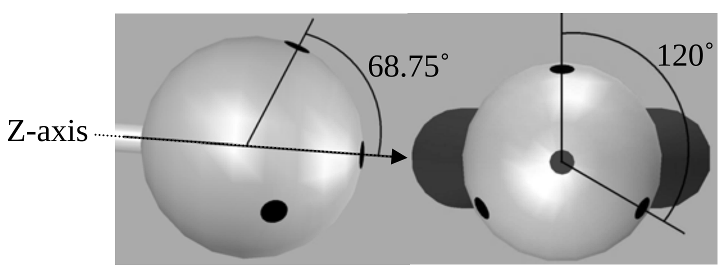


Figure 2: Microphone Locations

All four microphones are mounted perpendicular to and flush with the surface of the sphere at their locations. In order for the probe to accurately measure acoustic energy density, each microphone must be accurately calibrated.

2.2 Acoustic Energy Density

Total acoustic energy density is the sum of the acoustic potential energy density and the acoustic kinetic energy density as shown in Eq. 1[2].

$$w_{Total} = w_p + w_k \tag{1}$$

In Eq. 1, w_{Total} is the total acoustic energy density, w_p is the acoustic potential energy density, and w_k is the acoustic kinetic energy density. The probes relevant to this research compute energy density using pressure transducers. The potential energy density is calculated directly from the pressure measurements produced by the transducers as shown by Eq. 2.

$$w_p = \frac{1}{2\rho_o c^2} p^2 \tag{2}$$

In Eq. 2, ρ_o is the ambient fluid density, c is the acoustic phase speed, and p is the acoustic pressure. The acoustic kinetic energy density is calculated using this particle velocity as shown in Eq. 4.

$$w_k = \frac{\rho_o}{2} u^2 \tag{4}$$

The particle velocity is calculated using the pressure difference between two of the microphones. This technique is referred to as the two-microphone technique and can be expressed as shown by Eq. 3[3].

$$u \approx \frac{p_1 - p_2}{j\omega\rho_o \Delta x} \tag{3}$$

In Eq. 3, u is the acoustic particle velocity, p_1 and p_2 are the pressure at the two microphones, ω is frequency of oscillation, Δx is the effective distance between the two microphones[4], and j is $\sqrt{-1}$. Since the particle velocity of the sound is directional, the two microphones used to get this pressure difference are used to obtain the component of particle velocity along the axis of the two microphones. It is worth noting that in this case a particle refers to a group of air molecules that are moving in the same direction at the same speed and not the individual molecules of the median. Also worth noting is that particle velocity is produced only by the sound and not Brownian motion[5]. Both the kinetic energy density and the potential energy density rely on the pressure measurements of the microphones. It is this dependence that produces a need for calibrated microphones.

2.3 Calibration

Calibration is the process of comparing the output value produced by a measuring device to a known or desired output. Typically the device being calibrated is subject to a known input value or measurement standard. This comparison will yield a correction or calibration factor that when applied to the output results, scales the results to match the known output, allowing for calibrated measurements.[6]

Currently two calibration techniques for the probe specific to this research have been attempted. These two techniques yielded insurmountable challenges that prompted a new approach. In the first technique, each microphone on the probe was calibrated individually. This technique had the potential to introduce large errors in calibration. These errors resulted from the microphones sensitivity to small changes in pressure. Therefore, the seal around every microphone during each calibration must be the same. Forming a seal at each microphone calibration proved difficult to repeat. If each microphone could be compared to a known reference in a uniform pressure field then the seal issue becomes obsolete. The next technique is an attempt to eliminate this seal problem.

The second calibration technique was based on a lumped parameter model, which is founded on the assumption that when distances are small compared to wavelength, pressure changes are minimal. This technique involved a calibration chamber that encloses the entire probe. The lumped parameter model is valid as long as $ka << 1$, where a is the largest chamber dimension and k is the acoustic wave number. This means the largest chamber dimension needs to be much less than ($1/10^{th}$) the size of the acoustic wavelength of the frequency used to calibrate[7]. If the lumped parameter model is valid, the acoustic pressure in the chamber is uniform. With a uniform pressure surrounding the probe, each microphone could be calibrated simultaneously. This technique is hindered, however, by the physical limitations on the size of the cavity due to the size of the spherical probe. This size constraint limits the frequencies at which the calibrator can operate, limiting the frequencies at which the probe can measure accurately.

Both of these techniques have been implemented in an attempt to calibrate the probe of interest in this research. The first technique failed to accurately compare each microphone to a known reference thus leaving the probe un-calibrated. The second technique resulted in valid calibration results at low frequencies (less than 250 Hz). However, for frequencies greater than 250 Hz, the error in calibration between the microphones was much greater than the objective of ± 0.5 dB re 20 μPa. The probe is designed to be used up to 2000 Hz and needs to be calibrated over this entire range.

3 CONCEPT THEORY

A new concept where each path to each microphone would be identical was developed. The theory behind the concept was derived from an equivalent circuit model shown in Figure 3.

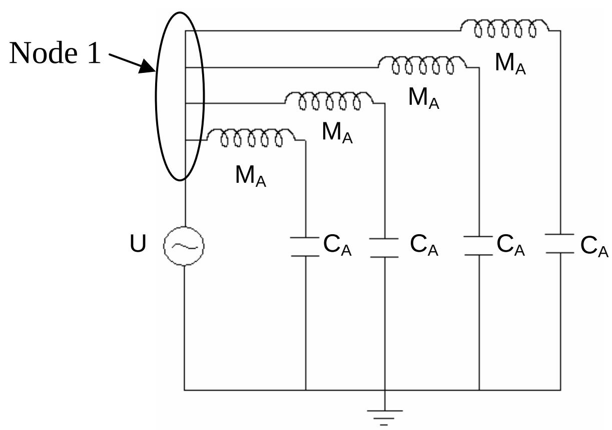


Figure 3: Equivalent Circuit Model

In Figure 3, U is the volume velocity (m^3/s), C_A is the acoustic compliance (m^5/N), and M_A is the acoustic mass (kg/m^4).This model conceived an individual sound path for each of the microphones. In theory, if each of these paths is identical, has the same termination impedance, and originates from the same source, then the same acoustic pressure will result at the end of each path. This solution would be completely independent of the wavelength-dimension interaction. The validity of this concept rested upon the practicality of node 1. If the signal could not successfully be divided into equal parts, the concept would not be valid.

4 NODE 1

To verify that the pressure could be divided into separate paths, a driver was attached to a small piece of acrylic with five holes located symmetrically about the axis of the speaker. This piece was called the pentagon. Figure 4 is a computer model drawing of the pentagon, and shows the speaker side (front) and then tube side (back). Four ports were included for the four microphones on the probe. The fifth port was included for the reference microphone.

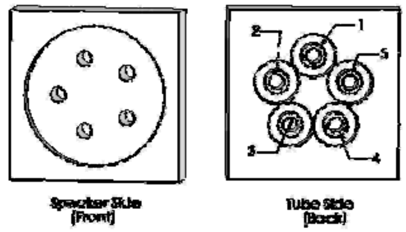
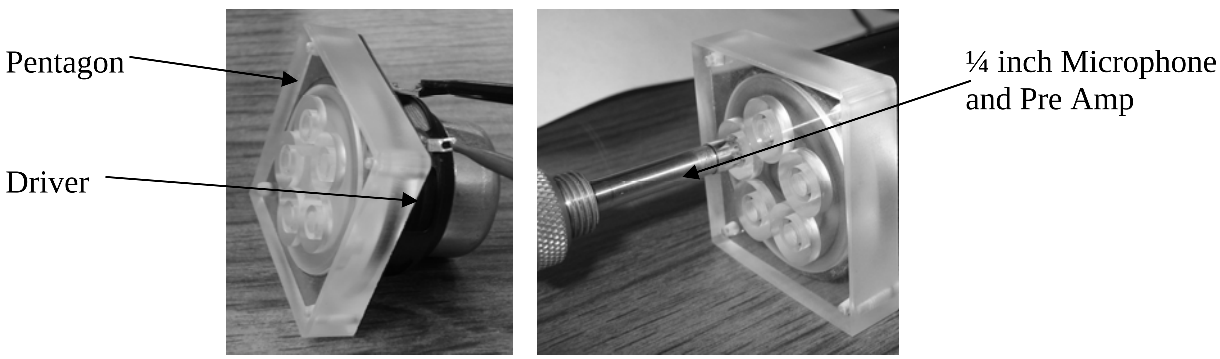


Figure 4: Pentagon Drawing

Figure 5 a) shows the pentagon attached to the driver. Figure 5 b) shows the pentagon and a microphone measuring the pressure at one of the ports. The microphone was held in place using a piece of latex tubing, not shown in Figure 5 b).



a) b)

Figure 5: a) Microphone Measuring Pressure at Pentagon port b) Pentagon Attached to Driver

The pressure was measured at each of the five ports of the pentagon as shown in Figure 5 b). An Agilent 35670A two channel analyzer was used with a 0.635 cm (1/4 in) precision microphone to measure the pressure at each port. The analyzer evaluates signals under 102.4 kHz, with a dynamic range of 80 dB, a real time rate of 25.6 kHz, and 400 lines of resolution. Since the data was clean only five measurements were made at each port. The five measurements at each port were averaged, and the largest difference (in dB) between any two of the five ports was calculated. This process was repeated on the pentagon at every 500 Hz, from 500 Hz to 6 kHz. The results are plotted in Figure 6.

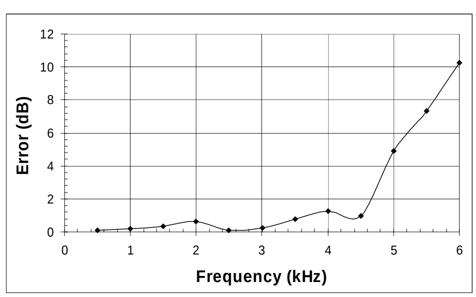


Figure 6: Frequency Sweep of the Pentagon

The error near 2 kHz was significant. It was postulated that the curved shape of the speaker diaphragm was creating the error. To attenuate any cross modes that may have been resulting from the diaphragm, a plane wave tube was attached to the speaker extending the five ports away from the driver. The length of the plane wave tube was calculated to be about 14 cm (5.512 in). This length corresponded with 95 dB of cross mode attenuation at 1000 Hz, leaving only plane waves in the tube, which are uniform across the cross-section of the tube. The same test used to produce Figure 6 was conducted and the results are plotted in Figure 7. The error was decreased below the 0.5 dB metric at 2 kHz, and remained below 0.5 dB up to 3 kHz. The increase in error at 3.5 kHz was not investigated, because it is beyond the operational limits of the probe.

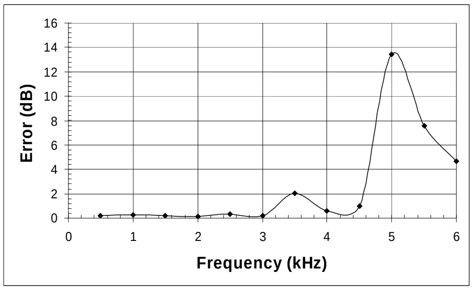


Figure 7: Frequency Sweep of Pentagon with Plane Wave Tube

5 ACOUSTIC MASSES

With the feasibility of generating an equal pressure at node 1 verified, the concept was further tested by the addition of the acoustic masses. Flexible PVC tubes with an outside diameter of 1.19 cm (15/32 in) were added to the end of each port. Since the microphones on the probe are 0.635 cm (¼ in) diameter, the tubes were chosen to have an inside diameter of 0.635 cm (¼ in). (See Figure 8)

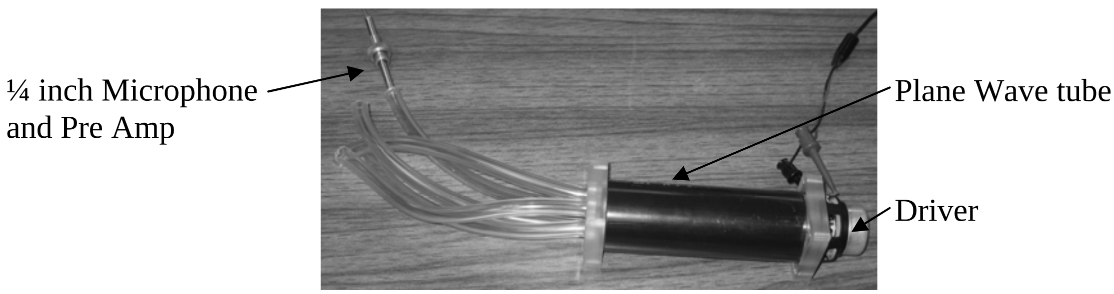


Figure 8: PVC Tube Test Setup

These tubes were tested using frequencies of 250 Hz, 300 Hz, 400 Hz, 500 Hz, 600 Hz, 700 Hz, 800 Hz, 900 Hz, 1000 Hz, 1500 Hz, and 2000 Hz. This upper limit was chosen based on the operational limit of the probe. The error in dB was then calculated and plotted at each of these frequencies. Figure 9 shows the results of this test. The goal was to limit the error to less than 0.5 dB, and as can be seen from Figure 9, this was accomplished for the frequencies of interest for this probe.

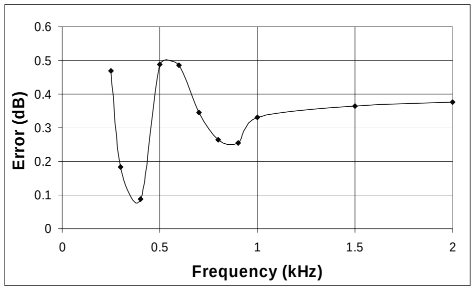


Figure 9: Frequency Sweep of Acoustic Masses (PVC Tubes)

6 ATTACHMENT DESIGN

The next step in advancing the concept was attaching the tubes to the probe. Each microphone needed to line up with a tube. In order to reach each microphone on the probe, the tubes would need to be bent. The question of how much error will be introduced as a result of bending the tubes was addressed with a simple test. The pressure at the end of each tube was measured with the tube straight, and bent at 30, 60, and 90 degrees. The pressure was measured at the end of each tube in each position five different times. An average was calculated at each orientation. Using these averages at each orientation the largest error in dB between any two orientations was calculated to be 0.03 dB. The overall average pressure measurement was 13.35 volts with a standard deviation of 4.59 volts. This small error was considered to be measurement variability.

The tube attachment apparatus was designed using two halves with spherical cavities that come together and enclose the probe. The top half is equipped with a groove that allows the probe shaft to pass through to its center. The bottom half, where the microphones on the probe are, is equipped with four ports. Each port lines up with a microphone on the probe. Each port has an attachment insert that is fit with an o-ring to seal the probe attachment interface. The attachment insert is held in place by a bolt that has a hole in the center to allow the attachment insert to pass through it. The bolts screw into threaded holes in the attachments bottom half. (See Figure 10)

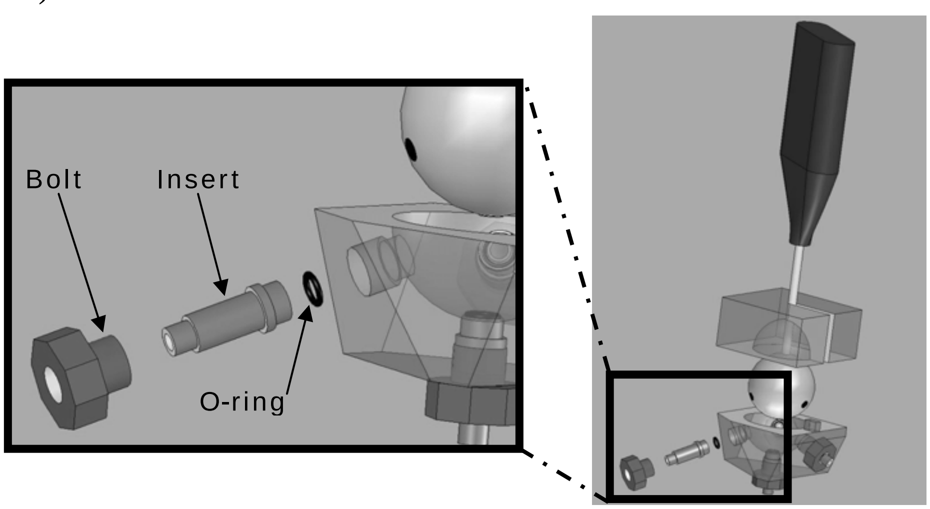


Figure 10: CAD Model of Attachment

The tubes, which are attached to the driver via the pentagon and plane wave tube shown in Figure 4, are connected to the attachment inserts. The two halves are held together with latches. Figure 11 is a photograph of the entire calibrator.

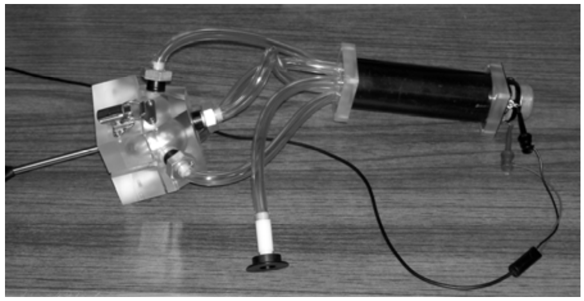


Figure 11: Attachment Test Setup

Figure 12 shows the probe inside the top half of the attachment. Figure 12 also shows a close up view of the inside of the bottom half of the attachment. When calibrating these halves come together to surround the probe.

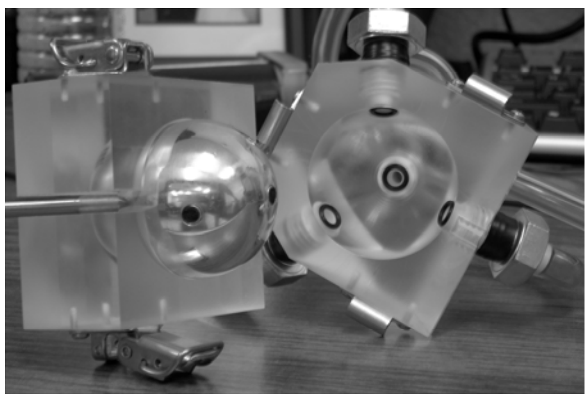


Figure 12: Probe-Attachment Interface

7 RESULTS

The driver was excited with a 114 dB (as measured with the reference microphone) harmonic wave at 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz. The probe was inserted into the attachment and a one second time signal was recorded for each microphone on the probe, and the reference microphone. The probe was taken out and rotated so that the three side microphones on the probe were connected to a different tube. The pole microphone and the reference microphone remained connected to the same tube. Another time signal was recorded and the rotation was repeated. The data for each of the three measurement configurations were then normalized about the first position. The error at the second and third positions relative to the first position was then plotted. This entire process was repeated for the four frequencies mentioned above. It is worth noting that physical limitations of the driver reduced the amplitude of the harmonic wave at 2 kHz to 110 dB. The error plots for each of the four frequencies can be seen in Figure 13, Figure 14, Figure 15, & Figure 16.

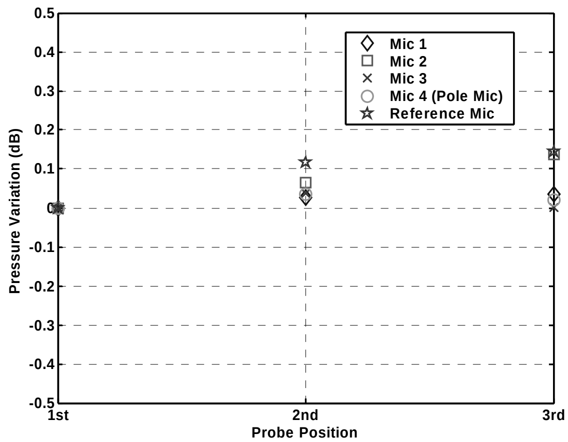


Figure 13: Calibration Error at 250 Hz and 114 dB

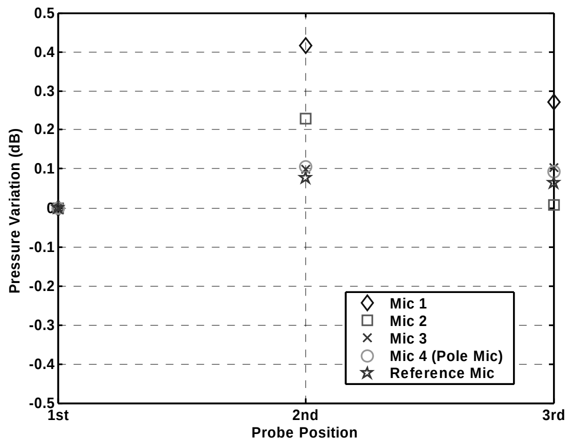


Figure 14: Calibration Error at 500 Hz and 114 dB

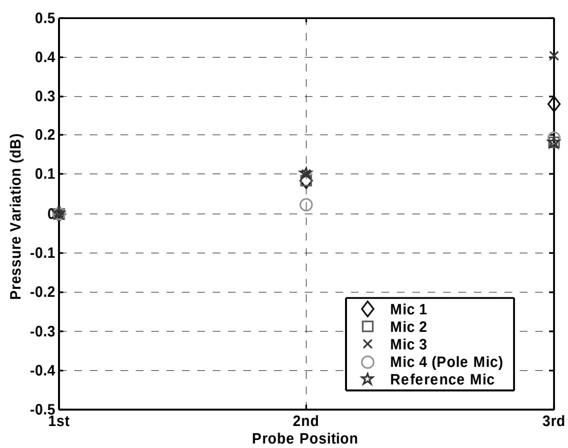


Figure 15: Calibration Error at 1000 Hz and 114 dB

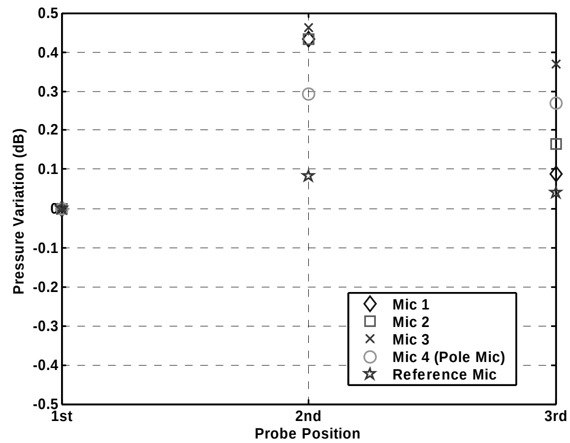


Figure 16: Calibration Error at 2000 Hz and 110 dB

The error at 250, 500, and 1000 Hz was less than the 0.5dB target value. At 2000 Hz the error was near, but still less than, the 0.5dB limit, and the error at 3000 Hz (not shown) was slightly above the 0.5 dB limit. These results are consistent with the results in Figure 7 and Figure 9.

8 CONCLUSIONS

The probe can be accurately calibrated over its entire operating range. This calibrator is for a specific probe; however, the concept could be applied to different probes using attachments unique to those probes. The concept could also be applied to multiple microphone arrays with specific attachments.

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