

**Free-field calibration of the pressure sensitivity of microphones  
at frequencies up to 80 kHz**

G. C. Herring, Allan J. Zuckerwar

NASA Langley Research Center, Hampton, VA 23681

and

Brian R. Elbing

University of Michigan, Ann Arbor, MI 48109

Received:

Electronic mail: [g.c.herring@larc.nasa.gov](mailto:g.c.herring@larc.nasa.gov)

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## **Abstract**

A free-field (FF) substitution method for calibrating the pressure sensitivity of microphones at frequencies up to 80 kHz is demonstrated with both grazing and normal-incidence geometries. The substitution-based method, as opposed to a simultaneous method, avoids problems associated with the non-uniformity of the sound field and, as applied here, uses a ¼-inch air-condenser pressure microphone as a known reference. Best results were obtained with a centrifugal fan, which is used as a random, broadband sound source. A broadband source minimizes reflection-related interferences that often plague FF measurements. Calibrations were performed on ¼-inch FF air-condenser, electret, and micro-electromechanical systems (MEMS) microphones in an anechoic chamber. The accuracy of this FF method is estimated by comparing the pressure sensitivity of an air-condenser microphone, as derived from the FF measurement, with that of an electrostatic actuator calibration and is typically  $\pm 0.3$  dB (95% confidence), over the range 2-80 kHz.

PACs:           **43.58 Vb, 43.38 Kb**

## **ABBREVIATIONS**

EA	electrostatic actuator
FF	free field
MAC	multifunction acoustic calibrator
MEMS	micro-electromechanical systems
SNR	signal-to-noise ratio
SPL	sound pressure level in dB

## **I. INTRODUCTION**

Society has an interest<sup>1,2</sup> in noise reduction for those airports that are in or near large metropolitan areas. The frequency range 1-5 kHz is of key importance when considering the reduction of the public annoyance due to commercial air traffic. Furthermore, a significant fraction of noise-reduction research is done by means of wind tunnel testing, rather than more expensive field testing. Depending on the situation, the acoustic wavelength may scale with Strouhal number ( $\sim r$ ) or Reynolds number ( $\sim \sqrt{r}$ ), where  $r$  is a characteristic length scale. In cases where jet engine and boundary layer noise are unimportant, the acoustic wavelength of airframe noise will scale with Strouhal number. Confident interpretation of wind-tunnel data is possible only if Strouhal number remains unchanged<sup>3</sup> between full-scale flight conditions and scaled-down facility conditions. For example, in testing a 1/20-scale model, the 1-5 kHz region is transformed to the 20-100 kHz region when scaled appropriately. Thus the acoustic frequency range 20-100 kHz becomes important for noise reduction work carried out with small-scale models in wind tunnels. Microphones used in these studies must be calibrated at these ultrasonic frequencies before they can be used to measure unknown sound sources.

Historically, an electrostatic actuator (EA) has been used to calibrate air-condenser microphones at these high frequencies.

If imaging of unknown acoustic sources is also of interest, then microphone cost becomes an issue. A typical acoustic array may use 100 or more microphones at a substantial cost per microphone channel. To address the cost issue, low-cost Panasonic WM-60A electret microphones have recently been considered<sup>4</sup> for acoustic arrays. However, these electret microphones are not adaptable to the EA. In addition, other technologies such as micro-electromechanical systems (MEMS) microphones, which would allow higher packing densities in microphone arrays, are also not adaptable to the EA.

Thus the need arises for high-frequency calibration techniques for microphone types that are not compatible with the venerable EA. In this paper, a substitution-based, free-field (FF) calibration method is demonstrated to derive the pressure sensitivity of the amplitude response of various microphones out to frequencies of 80 kHz. A standard air-condenser pressure microphone is used as the known reference. Two sound sources, a centrifugal fan and a tweeter driven by either frequency sweeps or random noise, were used. FF calibration design issues, procedures, results, and uncertainties for several of the above-mentioned microphones are discussed.

## **II. MICROPHONE CALIBRATION METHODS**

Over the years, several methods have been used for microphone calibration. A summary of the more common methods is presented in left-hand column of Table I. In the second column, the type of sensitivity that the method gives is noted. The pressure sensitivity of a microphone is the voltage per unit sound pressure that the microphone

will produce when a completely uniform pressure is incident on the microphone diaphragm. For example, in a small cavity, where the driving frequency is very low, the sound field is such that any test microphone inserted into this cavity will see an identical pressure increase at all locations on the diaphragm at any given time. In contrast, the FF sensitivity of a microphone is the voltage per unit sound pressure produced when a traveling wave incident on the diaphragm is isolated from boundaries. This FF sensitivity is different from the pressure sensitivity because of diffraction of the incident wave. The diffracted wave about the test microphone interferes with the incident wave to give a total resultant sound field that varies over the face of the diaphragm. This FF pressure distribution over the diaphragm is distinctly different than the uniform distribution in the cavity (i.e., coupler) case. When a microphone is mounted flush in a baffle, diffraction is nonexistent and the microphone exhibits its pressure sensitivity. If the microphone is mounted in free space with minimal mounting hardware, it exhibits its diffraction-related FF sensitivity. The difference between a microphone's FF and pressure responses is shown in Fig. 1. Thus measurements in the FF require a frequency-dependent correction  $C$  to yield the pressure response.

In the right-most column of Table I, important limitations of each technique are listed. For the FF technique, it is relatively easy to provide an approximately uniform *incident* sound pressure over the diaphragm by placing the test microphone at large distances from the sound source. In contrast, all methods which utilize small cavities have the problem that standing waves are generated inside the test cavity. At sufficiently high frequencies, standing waves produce a nonuniform sound field inside the cavity and thus an unknown sound pressure level on the test microphone diaphragm. For example,

in the case of a 6.35 mm diameter by 2.14 mm long cylindrical cavity, Fig. 2 shows the distribution of the lowest-lying axial, radial, and azimuthal cavity modes.<sup>5</sup> In this case, calibration of the microphone becomes problematic at frequencies approaching 30 kHz or higher. Smaller cavities will push the lowest-lying mode to higher frequencies, but with correspondingly greater modal density, and become increasingly impractical for most calibration purposes. One type of coupler calibrator is a pistonphone. Such a device provides a constant and known volume velocity to a microphone inserted in a cavity at a variety of fixed frequencies over the audio range, but is limited to low frequencies.

In the third column of Table I, the frequency range of applicability for the different methods is given. For higher frequencies, the electrostatic actuator (EA) has long been used to calibrate air-condenser microphones up to frequencies exceeding 100 kHz. However, many newer microphone types are not compatible with the EA. This is the appropriate situation for the FF technique to be considered for high-frequency calibration. In the FF method, it is important for the geometry (size and shape) of any reference microphone to match that of the unknown microphone that is being tested to ensure similar diffraction effects about both devices. Another problem with the FF method is reflections that produce interference phenomena between the incident wave and the reflected wave. Specific precautions to minimize or eliminate this particular problem are discussed in more detail in a later section of this article.

Both the coupler and FF methods can both be executed using reciprocity, substitution, or simultaneous procedures. In the simultaneous method, both the known reference and unknown test microphones are tested at the same time, requiring the sound field to be spatially uniform. The method discussed in this paper is the substitution

method, where the two microphones are tested sequentially in the same location, to avoid this potential spatial nonuniformity problem. However, with the substitution method, a temporally stable sound source is now required since the two measurements are no longer made simultaneously. A third possible procedure is reciprocity, which uses a total of three transducers, one unknown and two references that are known. The three transducers are sequentially cycled through the source and receiver duties. This procedure requires more time, but can lead to a more accurate calibration. One potential difficulty with the reciprocity method is to find a reciprocal transducer that operates efficiently as both a transmitter and a receiver at high frequencies, especially in the FF. In this paper, the substitution method was chosen to avoid this difficulty and to minimize the required time for executing the calibration procedure.

Time selective techniques have been demonstrated to remove the reflections from the time response and thus eliminate the attendant contribution to the measurement uncertainty.<sup>6,7</sup> These, however, have not been applied to calibration of the microphone pressure sensitivity nor to measurements above 30 kHz.

### **III. CALIBRATION STANDARDS AND KEY SPECIFICATIONS**

Upon close inspection of existing standards<sup>8-10</sup> for microphone calibration, it is apparent that all are written with low-frequency calibrations and FF sensitivity in mind. Thus there is no published national or international standard for microphone pressure-sensitivity calibration in the ~ 20-100 kHz frequency range other than the EA. In this section, several parameters that will affect the quality of a high-frequency, FF microphone calibration are discussed.

One important problem that arises in a typical FF calibration is a frequency-dependent systematic error that generates an oscillatory pattern on the microphone response spectrum. An example of this oscillatory systematic error is shown in Fig. 3 for a FF calibration of a Panasonic WM60A electret microphone. A distinct modulation of the sensitivity is seen at frequencies of 10 kHz and higher. In this study, five possible different frequency-dependent causes were considered as origins for this sensitivity variation: (1) interference from room resonances; (2) reflections from nearby mounting structure and subsequent interference between the incident and reflected acoustic waves; (3) modal breakup<sup>11</sup> in the diaphragm of the sound source; (4) difference in diffraction<sup>12</sup> between the unknown test and the known reference microphones; (5) differences in the acoustic center location<sup>13</sup> and acoustic impedance between the unknown test and the known reference microphones. It was determined that item (2), reflections and subsequent interference, was the primary reason for the occurrence of the oscillatory systematic errors that can occur. In this study, the other four effects were not generally important relative to number (2).

Five different countermeasures can be used to help minimize or eliminate the systematic error due to these interference effects: (1) to perform the calibrations in a suitable anechoic chamber and cover the mounting structure with an absorbing foam to minimize reflections; (2) to keep all mounting hardware far away from, or behind, the test microphone to minimize significant reflections; (3) to choose the source-microphone separation distance  $L$  such that  $d^2/(\lambda L) \gg 1$ , where  $d$  = source size and  $\lambda$  = acoustic wavelength, to ensure placement of the test microphone beyond the Fresnel region of the source; (4) to use a broadband source that exhibits minimal phase coherence at all



frequencies of interest, in order to suppress the build-up of standing waves, and to minimize interference between any reflected and incident waves near the microphone diaphragm; (5) if a phase-coherent tonal source must be used to achieve a large enough signal-to-noise ratio (SNR), then to use a grazing-angle, rather than a normal-angle, incidence to minimize interference effects in the vicinity of the microphone diaphragm. Thus key specifications for any FF calibration procedure should include the geometry (i.e. normal or grazing incidence), the bandwidth characteristics of the source, SNR, and the source-microphone separation distance. Because the microphone response to grazing incidence more closely matches the pressure response, the correction from FF to pressure sensitivity is accordingly smaller than the correction for normal incidence.

#### **IV. PRINCIPLE OF THE FF SUBSTITUTION METHOD**

Figure 4 illustrates the principle of the substitution method. The calibrations are performed in an anechoic chamber with a sound source, the test and reference microphones, and a remotely located signal analyzer. The reference and test microphones are tested sequentially. The symbols in the figure are defined as follows:

- $P$  = the acoustic pressure in the undisturbed sound field
- $M_R^{FF}, M_X^{FF}$  = the FF sensitivity of the reference and test microphones,
- $V_R, V_X$  = the output voltage of the reference and test microphones,
- $M_R^o, M_X^o$  = the sensitivity of the reference and test microphones at a reference frequency, as determined for example by a pistonphone at 250 Hz,
- $P_R, P_X$  = the pressure reading for the reference and test microphones as displayed by the analyzer.

Then it follows:

$$P_R = \frac{V_R}{M_R^o} = \frac{M_R^{FF} P}{M_R^o} = \frac{CM_R^P P}{M_R^o}, \quad (1)$$

$$P_X = \frac{V_X}{M_X^o} = \frac{M_X^{FF} P}{M_X^o} = \frac{CM_X^P P}{M_X^o}, \quad (2)$$

where  $C$  is the correction factor for converting from FF to pressure sensitivity. Upon taking ratios, and expressing the result in dB, one finds the pressure sensitivity  $M_X^P$  of the test microphone:

$$M_X^P = L_X - L_R + M_R^P + M_X^o - M_R^o, \quad (3)$$

where

$L_R, L_X$  = the measured FF pressure levels  $P_R, P_X$ , expressed in dB,

$M_R^P$  = the known pressure sensitivity of the reference microphone, as determined by the electrostatic actuator.

The validity of Eq. (3) rests upon two assumptions: first, that the sound pressure is the same at the reference and test microphone diaphragms. This implies that the microphone-diaphragm distance and diaphragm height is matched for the two microphone measurements as closely as possible; that the source and microphone are fixed firmly to the chamber floor or to a common base plate (to make their separation immune to displacement by foot traffic); and finally that the source remain sufficiently stable between the two measurements so as not to cause significant measurement error. It is imperative that the measurements on the reference and test microphones take place with minimum delay after the exchange of microphones.

The second assumption is that the correction factor  $C$  for diffraction be the same for both microphones. Since diffraction is primarily a geometric effect, this implies that

both microphones must present the same surface geometry to the sound field. If the test microphone is not of a cylindrical shape, then it must be fitted into a cylindrical adapter. If the resulting diameter of the test adapter exceeds that of the reference microphone, then that latter will also have to be fitted into a matching adapter. Further, it is important that the size of the microphone holder and stand be minimized as much as practical.

An advantage of the substitution method is that the frequency calibration does not depend upon the frequency spectrum of the source, for frequency-dependent variations in amplitude are expected to cancel. However, if the source spectrum has structure, as may be expected of a piston-like source (e.g. loudspeaker), then the error related to source stability is most sensitive in the regions where structure is most prominent. A disadvantage of the substitution method is that the sound source must be very stable and repeatable over the time period between testing of the test and reference microphones.

## **V. EXPERIMENTAL SETUP**

The experimental setup for the FF calibration method, indicated schematically in Fig. 4, consists of a sound source, microphone, the associated mounts, and a data acquisition system. The two sound sources used for testing were a centrifugal fan (Campanella Associates RSS-10U) and a tweeter (Motorola KSN1078). A signal analyzer (B&K 2035), remotely located in a control room, was used to record the data. This performs a fast Fourier transform on the signal, which allows for the data to be recorded in the frequency domain on a 3.5 inch floppy disc for subsequent processing on a spreadsheet. All calibrations were performed in a 1.9×2.4×3.7-m anechoic chamber in order to minimize the formation of standing waves.

### **A. Sound sources**

The centrifugal fan is a wideband noise source that produces approximately random noise. A wideband source minimizes the chance of interference between the incident wave and unwanted reflected waves, and allows for data to be collected simultaneously over the entire frequency range. The disadvantage of this sound source is that the SNR is small compared to a typical tonal source. This ratio can be increased by moving the microphone closer to the centrifugal fan. The manufacturer's specifications state that a microphone should not be used within 0.5 m of the fan to prevent systematic errors due to windage from the fan. Calibrations were typically much better when moved inside of the half-meter separation because the SNR was larger. Figure 5 shows a typical experimental setup for an air condenser microphone. Figure 6a shows the emission spectrum of the centrifugal fan, which reveals no structure except for a small region near 10 kHz. A “1-over-R” test was performed to verify that the centrifugal fan behaves as a point source. Figure 6b shows the results of the “1-over-R” test. The results show that the centrifugal fan still acts as a point source with a separation of 0.4 m, which is less than the separations used for all calibrations presented here.

The response of the tweeter was inconsistent below 1 kHz, but had exceptional performance above 1 kHz until the output rolled off at about 60 kHz; it could still be used at 80 kHz. Two types of electrical input were used to excite the tweeter: swept tones and random noise. With tones, testing could be done with either a frequency-sweep function or temporally-fixed tones. Sweeping of the tones is superior because the time interval required to complete the calibration is significantly reduced when compared with using fixed tones. The reduced time is an advantage because heating of the voice coil affects the input impedance (and hence the acoustic output) of the tweeter. The only advantage

to using fixed tones is that it allows the maximum SNR, which, for example, is important for the calibrating low-sensitivity piezoresistive microphones. The disadvantage of using fixed tones is that the chance of generating interference effects on the response profile, as in Fig. 3, is increased.

The random-noise input signal has the advantage of being able to complete the calibration faster than sweeping tones, but the accuracy of the calibration is reduced due to the lower SNR of the acoustic input.

## **B. Microphones and their mounting**

An air-condenser ¼-in. pressure microphone (B&K type 4136) was used as the reference microphone for every calibration. The dual-channel microphone power supply (B&K type 2807) was turned on at least 24 hours prior to a calibration. The second channel was used for the calibration of other air-condenser microphones.

For the non-air condenser microphones (MEMS & electrets) an alternative setup was used. These microphones were powered from a dc power supply (Agilent E3630A), located in the anechoic chamber. The output signal from the microphone was then fed into a single channel instrumentation amplifier (Pacific Instruments SA1A), having a very low output impedance, and from there to the signal analyzer.

The setup for the tweeter was the same for both the white noise and tone signals, with the exception of the input-signal generator. The white-noise signal generator was a multifunction synthesizer (Agilent 8904A) and the tonal signal generator was a function generator (HP 3314A). The driver-signal was amplified with a wideband power amplifier (B&K 2713).

Mounting of the microphone is a critical step in the FF calibration method. One of the primary assumptions is that both the reference and test microphones encounter the same pressure field. Two factors dictate the validity of this assumption: temporal stability of the sound source and repeatable positioning of the microphone. The positioning of the microphones entails both the orientation to the sound source and the geometry of the microphone.

The orientation of the microphone to the sound source has to be carefully implemented because variations between tests can have significant effects on the results. To improve the ability for the microphones to be accurately positioned, both the sound source and the microphone stand were fixed to a base-board. This kept the setup rigidly fixed in place throughout testing. Even with the sound source stand and the microphone stand being fixed in place, careful measurements still had to be used when mounting the microphones. The height from the ground to the microphone, distance from the microphone diaphragm to the source and to the mounting post, were all adjustable. The height from the ground to the microphone diaphragm center was fixed at 1.25 m, which also corresponds to the center of the sound source. The distances between the microphone diaphragm and source and between the microphone diaphragm and the mounting post are summarized in Table II. With the distances listed in Table II, typical sound SPLs (128 Hz band) generated at the microphone diaphragm were the following: centrifugal fan, 55-60 dB at 10 kHz and 33-38 dB at 80 kHz; tweeter, 75-80 dB at 10 kHz and 60-68 dB at 80 kHz, sweep being slightly higher than white noise excitation.

The other aspect of proper microphone mounting is the geometry of the microphone mount. Since the pressure sensitivity was determined here by FF

measurements, the geometry associated with the test and reference microphones had to be nearly identical. Through experience it was determined that there are two key considerations when considering the geometry of the microphone mount. First is the shape and size of the microphone diaphragm surface. Testing was done with both ¼-inch microphones as well as with varied diaphragm arrangements. These variations included a recessed diaphragm (electret) and a rectangular shaped surface with the diaphragm mounted in the middle (MEMS). The variations produced good results when careful consideration was given to replication of the shape and size. The second key consideration for the microphone mount is the presence of normal surfaces near the microphone diaphragm. In practice any solid surface, like the microphone stand, should be placed at least 10 diaphragm diameters behind the microphone.

### **C. Procedure**

A requirement for the FF method is that a reference microphone be selected that can be calibrated using the EA method. Reliance of the FF method upon the EA is acceptable since the purpose of the FF method is to calibrate “special microphones” that can not be mated to the EA. This requires that the reference microphone have a flat, conducting diaphragm. Once the reference microphone has been properly calibrated with the EA, the FF calibration can be performed on the test microphone.

Before the FF calibration, both the reference and test microphones were calibrated with a fixed pistonphone at 250 Hz. These pistonphone measurements were taken immediately prior to the FF calibration. Measurements of the chamber environment were also recorded. The main environmental parameters are temperature, atmospheric

pressure, and relative humidity. These data are used to make small corrections to the calibration and in the uncertainty analysis.

The method for the start up of the sound source varies based on the source. If the centrifugal fan was used, then the fan should be left on for approximately 5 minutes to allow the source to reach an equilibrium state. The tweeter can be used shortly after being turned on. It is important to note that the tweeter should be employed in a regular routine. Since the output can vary over time as a result of an increase in temperature of the tweeter, the accuracy of the calibration will depend on the time duration from start to finish. Thus if the time delay between starting the tweeter and data acquisition is repeatable and if there is adequate time for the tweeter to cool down in between runs, the calibration will be more accurate.

Four data runs are required for a calibration of the test microphone. The first two runs are done with the test microphone, first with the sound source on and second with the sound source turned off. The latter two runs were done for the reference microphone. Then the acoustic pressure  $P_R$  for the reference microphone in Eq. (1) is corrected to

$$P_R = \sqrt{P_R^2(meas) - P_R^2(bg)},$$

where *meas* and *bg* refer to the runs with and without the source turned on. The acoustic pressure  $P_X$  for the test microphone in Eq. (2) is corrected similarly. In this work, the background subtraction was always carried out, even if the signal was more than 20 dB above the background.

After the FF data had been collected for all four test runs a second pistonphone reading was taken for each microphone. The first pistonphone reading and this later reading are used for an average sensitivity at a fixed frequency of 250 Hz. Thus the



absolute sensitivity over the entire spectrum is fixed to the pistonphone reading. In addition to the pistonphone measurements, the environmental conditions (temperature, pressure, relative humidity) were also repeated.

An independent calibration is desirable for additional confidence and validation of the FF method. The calibrator used here, B&K type 4226 Multifunction Acoustic Calibrator (MAC), operates over the range of 31.5 Hz to 16 kHz at octave intervals (except for an intermediate frequency at 12.5 kHz). The FF method did produce some calibrations that were stable down to 1 kHz (i.e., agree with the MAC), but the 1 kHz endpoint could not be consistently obtained with the FF method.

## **VI. RESULTS**

The Results Section is organized into two parts: (A) proof of the FF calibration concept, whereby the FF calibration method is tested on a microphone for which the electrostatic actuator (EA) calibration is known; and (B) FF calibrations on microphones having geometries unsuited to an EA calibration. For all FF tests the reference microphone was a 1/4" pressure condenser microphone (B&K 4136) with the protective grid removed. The signal analyzer was operated in the "Autospectrum" mode over the frequency range 0-102.4 kHz with a frequency resolution of 128 Hz. Corrections for differences in temperature, pressure, and humidity proved much less than 0.1 dB, because these parameters showed little change within the brief time between the reference and test microphone measurements.

### **A. Proof of the free-field calibration concept**

To prove the concept, a series of calibrations was performed on a test microphone for which the wideband pressure sensitivity by the EA method is known, namely a 1/4-

inch FF air-condenser microphone (B&K type 4939). The first test was performed with the centrifugal fan at normal incidence, in accord with the specification of prior standards.<sup>8-10</sup> The result is shown in Fig. 7(a). Agreement between the FF and EA spectra is excellent, the difference not exceeding  $\pm 0.5$  dB. The difference is greatest in the vicinity of 10 kHz, where the emission spectrum reveals structure (Fig. 6a). The FF spectrum follows the inflection point at about 20 kHz, the sensitivity minimum at 50 kHz, and in this case appears to remain well-behaved at frequencies down to 1 kHz. The discrete calibration points (triangles) obtained with the multifunction acoustic calibrator (MAC) also reveals excellent consistency with the other two calibration methods. Figure 7(b) shows the results for grazing incidence. Here agreement between the FF and EA spectra lies within  $\pm 0.5$  dB only within the interval 3-50 kHz.

For some test microphones it is desirable to increase the SPL to ensure adequate SNR. Here the use of a tweeter will prove useful. However, there will be some sacrifice in accuracy because the tweeter response shows structure across the frequency spectrum. In Fig. 8 the tweeter is excited by white noise. The FF pressure sensitivity of the microphone at (a) normal and (b) grazing incidence shows agreement with the EA to  $\pm 1$  dB, except in a small region near 80 kHz. A small oscillatory pattern is evident, especially in the normal response.

Alternatively, one can drive the tweeter with a frequency sweep, which improves the SPL especially at the higher frequencies. In Figs. 9(a) and (b) the sweep frequency ranges from 5-102.4 kHz linearly over a sweep time of 120 s. The responses are similar to those obtained from white noise. They may be somewhat better in the low-kHz range,

but show spikes at the upper end of the spectrum. Otherwise, agreement with the EA appears to lie also within  $\pm 1$  dB.

### **B. Free-field calibrations on microphones unsuited to an EA calibration**

A calibration was performed on an electret condenser microphone, Panasonic WM-60A. The cartridge is 6 mm in diameter and contains a small hole ( $\sim 2$  mm) for acoustic access to a recessed diaphragm. A felt pad covering the hole was removed prior to calibration. The unavailability of access to the diaphragm precluded the possibility of an EA calibration. The cartridge was installed in a tube of dimensions 6.35 mm OD x 50.8 mm length, which contained a circuit board to accommodate the needed circuit components. The supply voltage was 5.00 V in series with an 8.2 k $\Omega$  resistor on the circuit board. The assembled microphone was fitted into a microphone holder, which was tapered on the microphone end to resemble a conventional 1/4-inch condenser microphone adapter, as shown in Fig. 10(a).

The results of the calibrations using the centrifugal fan, tweeter excited by white noise, and tweeter excited by a frequency sweep, are shown in Figs. 11(a), (b), and (c) respectively. The heavy and light lines represent normal and grazing incidence in each figure. Results for grazing are for the most part slightly lower than for normal. Figure 11(a) shows the adverse effect of low SNR for grazing incidence as early as 40 kHz, where nevertheless the sensitivity lies well beyond the -3 dB point. Grazing shows slightly better agreement with the MAC the whole way down to 1 kHz. Figures (b) and (c) reveal good agreement between normal and grazing, as well as with the MAC, at frequencies down to about 3 kHz. The normal incidence, however, shows an unexplained spike in the response slightly below 50 kHz. Except for the spike, the calibration from 3

kHz to the frequency where the sensitivity drops 20 dB is accurate to within  $\pm 1$  dB (to which the EA contribution to the uncertainty must be added).

A second microphone is a micro-electromechanical system (MEMS) capacitive microphone, SiSonic SP0101Z, manufactured by Emkay Innovative Products. The rectangular cartridge has dimensions of  $6.50 \times 6.25 \times 2.37$  mm. A small hole on one face renders acoustic access to the recessed diaphragm, an arrangement unsuited to an EA calibration, while the opposite face contains four solder pads for electrical contacts. A cylindrical adapter, 12.7 mm (1/2 in.) in diameter, was fabricated with a rectangular recess to seat the cartridge flush with the surface, and provided with spring-loaded contacts to make electrical contacts through an access hole in the adapter [See Fig. 10(b)]. Finally a sleeve pressing against the corners of the cartridge provided enough tension to hold the cartridge in place. The adapter was designed to permit calibration with the MAC; but an unfavorable length-to-diameter ratio did not appear to have an adverse influence on the FF calibration, at least by the centrifugal fan. A matching cylindrical adapter was made for the 1/4-inch reference microphone.

The results are shown for the centrifugal fan and tweeter in Figs. 12(a) and (b). The centrifugal fan yields excellent agreement among normal incidence, grazing incidence, and the MAC, all within  $\pm 1$  dB of each other. The calibration reveals diaphragm resonances near 15 and 35 kHz. The tweeter calibrations meet the  $\pm 1$  dB uncertainty specification only from 3 kHz to just over the first peak at about 18 kHz. Significant differences occur in the region between the peaks from 18 to 35 kHz. Below 3 kHz the white noise calibration (dotted line) veers far astray. The unfavorable length-to-diameter ratio of the adapter may be the culprit.

The final microphone unsuited to an EA calibration is another MEMS microphone, “SiSonic Ultrasonic Prototype,” having the same size but a greater bandwidth than the above. The microphone, as delivered, was mounted on a small rectangular circuit board, 24.2 mm L. × 11.7 mm W. Since the microphone could not be detached from the circuit board, the latter was inserted into a rectangular fixture at the end of a support rod, which provided adequate separation from the microphone stand. This arrangement is shown in Fig. 10(c). The fixture, 26.8 mm L. × 14.2 mm W., served as an acoustic baffle. The reference microphone was flush-mounted in a similar baffle of the same dimensions. The geometry is unsuited to a MAC calibration. Because the baffle precluded a conventional pistonphone calibration as well, the sensitivity of the test microphone at a reference frequency was obtained by matching FF sound pressures between the test and reference microphones at 2 kHz. The result is  $M_X^o = 4.2 \text{ mV/Pa}$ .

The best results of the FF calibration were obtained using the centrifugal fan and tweeter excited by white noise, as shown in Fig. 13. The fundamental diaphragm resonance is seen to be shifted to about 30 kHz. Agreement between the two sound sources is within  $\pm 1 \text{ dB}$  from 2-50 kHz.

## **VII. ESTIMATE OF THE CALIBRATION UNCERTAINTY**

Contributions to the uncertainty of the FF method fall into three categories: (1) deviation of the FF sensitivity from the EA sensitivity. This category includes imperfect cancellation of effects due to environmental conditions, diffraction, and acoustic pressure mismatch at the microphones; (2) relative uncertainty of the EA from one frequency to the next. The dominant contribution, as least at frequencies below

diaphragm resonance, is attributed to “cross-talk”<sup>14</sup>; and (3) uncertainty of the calibration standard used to determine the absolute EA response at the reference frequency.

The results obtained on the FF condenser microphone, described in Sec. VI(A), exemplify the achievable uncertainty specifications by the FF method. The first contribution (1) was determined by computing the rms deviation of the FF from the EA sensitivity over the frequency range 1-80 kHz. The results are 0.3, 0.8, and 1.0 dB for the centrifugal fan, tweeter with white noise, and tweeter with frequency sweep, respectively. The second contribution (2) was determined through a measurement of the EA response with and without the polarization voltage. The rms contribution of the cross-talk signal (without the polarization voltage), computed over the frequency range 1-80 kHz, was found to be 0.15 dB. The final contribution (3) is the uncertainty of the calibration standard, the B&K type 4228 pistonphone used here. According to the manufacturer’s specification, after corrections for temperature and pressure, the uncertainty is listed as 0.2 dB. A low-frequency reciprocity calibration could possibly reduce this contribution considerably.

Thus the total uncertainty attributed to the contributions considered here amounts to  $\pm 0.65$  dB for the centrifugal fan,  $\pm 1.15$  dB for the tweeter with white noise, and  $\pm 1.35$  dB for the tweeter with frequency sweep.

## **VIII. SUMMARY**

The free-field substitution method has proved effective for calibrating microphone pressure sensitivity at frequencies out to at least 80 kHz and is applicable to microphones unsuited to an EA calibration. Best results were obtained with a centrifugal fan at normal incidence. For a microphone with a relatively low SNR, however, a

tweeter excited either by white noise or a frequency sweep will be more suitable but with reduced accuracy.

The selection of specific instruments for testing does not imply endorsement by the National Aeronautics and Space Administration.

## **IX. ACKNOWLEDGEMENTS**

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Table I. Common methods of microphone calibration.

Method	Sensitivity type	Frequencies	Limitations
Coupler Reciprocity Substitution Simultaneous	Pressure	Low-frequency	Cavity modes
Pistonphone	Pressure	Low-frequency	Limited no. of frequencies, SPLs
Electrostatic actuator	Pressure	Wideband	Accessible, conductive diaphragm
Free-field Reciprocity  Substitution Simultaneous	Free-field	Wideband	Diffraction/reflections High-frequency reciprocal transducer Source stability Uniformity of pressure field

Table II. Typical distances (meters): diaphragm-source and diaphragm-mounting post.

Source	Normal incidence		Grazing incidence	
	Diaphragm-source	Diaphragm-mounting post	Diaphragm-source	Diaphragm-mounting post
Centrifugal fan	0.4064 <sup>a</sup>	0.1016 <sup>b</sup>	0.5080	Not applicable
Tweeter	0.4064	0.0889 <sup>b</sup>	0.4953	Not applicable

<sup>a</sup> Measured to center of fan.

<sup>b</sup> For the SiSonic microphone SP0101Z the diaphragm-mounting post distance was 0.0508 m.

## FIGURE CAPTIONS

1. Typical pressure sensitivity (P) and free-field sensitivity (FF) of an air-condenser microphone. The correction  $C$  is the frequency-dependent difference between the two sensitivities.
2. Mode locations of a cylindrical cavity having a diameter of 6.35 mm  $\times$  height of 2.14 mm. The modal designations ( $ijk$ ) refer to the axial, radial, and azimuthal modes, respectively.
3. Free-field measurement of the pressure sensitivity of an electret condenser microphone using a tweeter excited at discrete frequencies. Open circle: datum point at a discrete frequency.
4. Principle of the free-field substitution method.
5. Calibration setup using the centrifugal fan (right) and microphone (left) in an anechoic chamber. The centrifugal fan platform and microphone stand are attached rigidly to a base-plate (not shown) on the floor to prevent displacement due to foot traffic.
6. Properties of the centrifugal fan (Campanella Associates Reference Sound Source RSS-101U): (a) acoustical emission spectrum calibrated by the manufacturer with a Larson-Davis type 2520 microphone at a distance of 0.5 m; (b) sound pressure versus reciprocal distance from the fan at frequencies of 10, 30, and 50 kHz. Circles: in-house measurement. Lines: best fit.
7. Pressure sensitivity of a B&K type 4939 1/4-inch free-field microphone as calibrated by the free-field method (heavy line), EA (light line), and

- Multifunction Acoustic Calibrator (B&K type 4226, triangles). Source: centrifugal fan. Incidence: (a) normal, (b) grazing.
8. Pressure sensitivity of a B&K type 4939 ¼-inch free-field microphone as calibrated by the free-field method (heavy line), EA (light line), and Multifunction Acoustic Calibrator (B&K type 4226, triangles). Source: tweeter excited by white noise. Incidence: (a) normal, (b) grazing.
  9. Pressure sensitivity of a B&K type 4939 ¼-inch free-field microphone as calibrated by the free-field method (heavy line), EA (light line), and Multifunction Acoustic Calibrator (B&K type 4226, triangles). Source: tweeter excited by linear frequency sweep (5-102.4 kHz over a sweep time of 120 s). Incidence: (a) normal, (b) grazing.
  10. Mounting arrangement of test microphones unsuited to an electrostatic actuator calibration: (a) Electret condenser microphone (Panasonic WM-60A), (b) MEMS microphone (SiSonic SP0101Z) in adapter, (c) MEMS microphone (SiSonic Ultrasonic Prototype) on circuit board/adapter.
  11. Pressure sensitivity of electret condenser microphone (Panasonic WM-60A). Sound sources: (a) centrifugal fan, (b) tweeter excited by white noise, (c) tweeter excited by swept tones. Triangles: multifunction acoustic calibrator data (B&K type 4226). Light line: grazing incidence. Heavy line: normal incidence.
  12. Pressure sensitivity of MEMS microphone (SiSonic SP0101Z). Sound sources: (a) centrifugal fan, (b) tweeter excited by swept tones (solid lines) and white noise (dotted line, normal incidence). Triangles: Multifunction Acoustic Calibrator

data (B&K type 4226). Light line: grazing incidence. Heavy line: normal incidence.

13. Pressure sensitivity of MEMS microphone (SiSonic Ultrasonic Prototype). Sound sources: centrifugal fan at normal incidence (heavy line), tweeter excited by white noise at normal incidence (light line).