CHAPTER 8

# Laboratory Microphone Calibration Methods at the National Institute of Standards and Technology, U.S.A.

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## 8.1 PRESSURE CALIBRATION BY THE RECIPROCITY METHOD

### 8.1.1 Microphone Types Calibrated

Pressure calibrations are performed on type *L* laboratory standard microphones satisfying the requirements of ANSI S1.12-1967 [1] and its impending revision. Such microphones, which are 23.77 mm (0.936 in.) in diameter and are called 1-in. microphones, include the Western Electric Company type 640AA, Tokyo Riko type ECL MR103, Bruel and Kjaer type 4160, Bruel and Kjaer types 4144 or 4132 with DB0111 adapter, and others.[1] Pressure calibrations are also performed on microphones 12.7 mm (1/2 in.) in diameter, such as Bruel and Kjaer type 4134, Tokyo Riko type ECL MR112, or equivalent, which are called 1/2-in. microphones. All microphones are calibrated with their protection grids removed.

[1]Throughout this section, instruments are identified only to specify experimental apparatus and procedures. The presence of an instrument on this or other lists does not imply recommendation or endorsement of any product by the National Institute of Standards and Technology, nor does it imply that this instrument is necessarily the best available for the purpose.

### 8.1.2 Apparatus and Procedure

Three microphones are used in the reciprocity procedure. Two are reciprocal and are used as both transmitters and receivers, and the third is used as a transmitter only [2]. At each frequency, the pressure response levels of the two reciprocal microphones are the results of calibration.

Calibrations are performed in a quiet, ground-level, windowless room separated from the rest of the NIST Sound Building by concrete block walls approximately 0.3 m (1 ft) thick. The only doors to this room are 10 cm (4 in.) thick, and are of wood, with compliant seals at all edges to minimize sound transmission. The mechanical HVAC equipment is located at the opposite end of the building, and HVAC ducts to the calibrating room are oversized to minimize flow noise.

The insert voltage technique is used for all electrical measurements involving receiving microphone output voltage. This technique requires specific ground shield dimensions to achieve reproducible results. Ground shield dimensions for type *L* microphones shown in Figs. 6 and 13 of [2] are used for the receiving and transmitting microphones, respectively. The ground shield dimensions used with 1/2-in. microphones are described in [3,4], and are the same for both the pressure and free-field [5] calibrations of 1/2-in. microphones. Details of the electrical measurement apparatus, couplers, and procedures used for the pressure calibration of 1/2-in. and type *L* microphones are given in [4,6].

At frequencies from 50 Hz to 700 Hz, measurements are performed in a relatively large air-filled coupler, of 20 $cm^3$ nominal cavity volume, shown in Fig. 6 of [2]. This coupler is essentially similar in its interior dimensions to the large IEC coupler [7] of similar nominal volume. The same air-filled coupler is used for occasional special calibrations, with greater uncertainties, at frequencies as low as 10 Hz. For measurements at frequencies from 1 kHz to 10 kHz, this coupler is filled with hydrogen gas. A smaller coupler of 3.8 $cm^3$ nominal cavity volume, shown in Fig. 10(a) of [2], is filled with hydrogen gas and used for measurements in the frequency range 10 kHz to 20 kHz. Frequency-dependent corrections for the effects of capillary tubes, heat conduction, and wave motion in these cavities on the pressure response levels determined during calibration are described in [6]. The influence of the frequency-dependent equivalent volumes of the microphones on these pressure response levels is also discussed in [6].

### 8.1.3 Results from NIST Participation in the Recent IEC Interlaboratory Comparison

The participation of calibration laboratories in interlaboratory comparisons of calibration results can be especially useful in finding unexpected sources of systematic error. The 1986–1987 interlaboratory comparison of pressure calibrations of type *L* laboratory standard microphones was conducted through the International Electrotechnical Commission (IEC) Technical Committee 29 Electroacoustics, Working Group 5, on microphone calibration. Each of 17 participating laboratories in 17 nations exchanged pressure calibrations of two of its microphones with the host laboratory, the National Physical Laboratory (NPL) in the U.K. A partial summary of results [8] was written by representatives of the host laboratory, for which data and editorial support were provided by the participating laboratories. The results for one microphone from each pair submitted by a given laboratory are included in this partial summary.

The comparison of NIST and NPL calibrations of both microphones for all 23 frequencies of calibration (63 Hz to 10 kHz at intervals of one-third octave) is of particular interest because of significant differences between the methods used in the two laboratories. At NPL, the air-filled IEC plane-wave coupler [7], of nominal volume 3 $cm^3$, was used throughout the frequency range 63 Hz to 10 kHz, while the much larger 20 $cm^3$ coupler at NIST was filled with air at low frequencies, and with hydrogen gas at high frequencies, as described above. Other aspects of the apparatus and procedures, including the electrical instruments and methods for determining the volumes of the front cavities and the equivalent volumes of the microphones, were also dissimilar in the two laboratories. Consequently, the individual uncertainty components associated with frequency-dependent corrections for the effects of capillary tubes, heat conduction, and wave motion in the couplers, as well as the uncertainty components associated with the equivalent volumes of the microphones, signal-to-noise ratios, and so on, were significantly different in the two laboratories.

Nevertheless, for both microphones, the absolute values of the differences between pressure response levels determined at NIST and at NPL were 0.02 dB or less at frequencies from 200 Hz to 4 kHz, inclusive. From 63 Hz to 200 Hz, and from 4 kHz to 10 kHz, these absolute values were no greater than 0.05 dB. This remarkably close agreement, which at high frequencies is probably somewhat fortuitous, is discussed in [6], and demonstrates the close agreement that can be achieved under nearly ideal circumstances, such as using stable microphones handcarried by visitors between NPL and NIST and relatively similar ambient barometric pressure and temperature during the calibrations of these microphones at the two laboratories.

## 8.2 FREE-FIELD CALIBRATION BY THE RECIPROCITY METHOD

### 8.2.1 Microphone Types Calibrated

Free-field calibrations are performed at normal incidence on 1/2-in. condenser microphones such as the Tokyo Riko type ECL MR112, Bruel and Kjaer types 4133, 4134, 4165, 4166, 4180, or equivalent. For the most precise calibrations, protection grids are removed from the microphones. However, the grids are left in position if a calibration is needed for that microphone configuration, due to the measurement applications anticipated for the microphones.

### 8.2.2 Apparatus and Procedure

As in the pressure calibration procedure, three microphones are used, two of which are reciprocal, and the third of which is used as a transmitter only. At each frequency of calibration, the free-field response levels of the two reciprocal microphones are determined.

The insert voltage technique is used for all electrical measurements involving receiving microphone output voltage with the same ground shield dimensions that are used for the pressure calibration of 1/2-in. microphones. Details of the electrical measurement apparatus, anechoic chamber, and procedures are described in [5].

The frequency range of calibration is usually 2.5 kHz to 20 kHz, although, on request, calibrations are performed at frequencies from about 1.25 kHz to greater than 50 kHz. Calibrations at frequencies greater than 50 kHz are usually performed by using a different lock-in amplifier and bandpass filter than the ones described in [5].

The 1/2-in. microphones are mounted on 12.7 mm diameter rods, which pass through bearings on opposing walls of the chamber and protrude through the walls. A screw-driven mechanical slide with a linear position indicator is mounted on the rod supporting the receiving microphone and containing its preamplifier, so that the distance of the receiving microphone from the transmitting microphone can be adjusted with a repeatability of about 0.1 mm. The separation between transmitting and receiving microphones is typically 200 mm during calibration, but can be adjusted to more than 300 mm. The chamber dimensions, measured between wedge tips in opposite walls, are 2.1 m (width), 1.6 m (height), and 1.6 m (depth); the volume of the chamber is 5.4 m$^3$. The fiberglass wedges are 0.3 m deep, and cover all interior surfaces of the chamber.

This chamber is supported by elastomeric blocks that provide vibration isolation from the ground-level concrete floor of a quiet, windowless control room separated from the rest of the NIST Sound Building by reinforced concrete walls approximately 0.3 m (1 ft) thick. The door from this room to the hallway exterior is fabricated of a steel layer over a built-up core including plywood, lead compound, and mineral corkboard, with compliant seals between the door edges, the door frame, and the floor, to minimize sound transmission. This room is located as far as possible from mechanical HVAC equipment, which is at the opposite end of the building. All HVAC ducts to this room are oversized to minimize flow noise.

Determinations of the effects of divergence from anechoic conditions in the chamber, and of frequency-dependent atmospheric attenuation of sound, are described in [5]. The determination of the acoustic center positions of the microphones is also discussed in [5].

## 8.3 PROCEDURES BASED ON DIFFERENCES BETWEEN THE FREE-FIELD AND PRESSURE RESPONSE LEVELS

The frequency-dependent difference between the calibrated free-field response level for a plane wave at normal incidence and the calibrated pressure response level is of interest for two principal reasons.

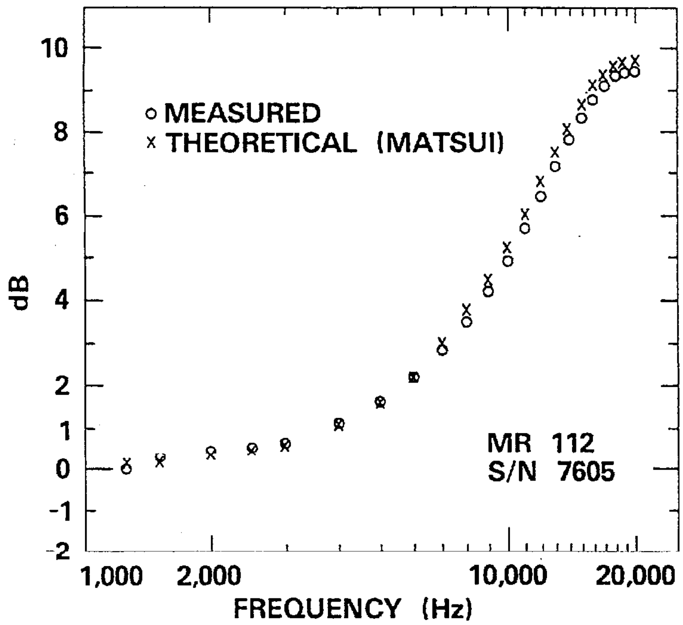


**FIGURE 8.1.** Comparison of experimentally and theoretically determined normal-incidence plane-wave free-field corrections (free-field response level at normal incidence minus pressure response level) for a Tokyo Riko type ECL MR112 1/2-in. microphone with a recessed diaphragm configuration (protection grid removed) [5].

First, this difference, called the experimentally determined normal-incidence plane-wave free-field correction, can be compared with the theoretically determined normal-incidence plane-wave free-field correction for a given microphone type. This theoretical correction and the pressure calibration are both considered most accurate at frequencies well below the fundamental resonance frequency of the microphone diaphragm. The free-field calibration is considered least accurate for the lowest frequencies, because of relatively low signal-to-noise ratios and imperfections in the anechoic chamber at these frequencies during calibration. Consequently, comparing the differences between the experimental free-field and pressure response levels with the theoretical plane-wave free-field correction is a strong test of the validity of the free-field calibration at these frequencies. Figure 8.1, reproduced from [5], compares experimentally and theoretically determined normal-incidence plane-wave free-field corrections for a Tokyo Riko type ECL MR112 microphone with a recessed diaphragm configuration (protection grid removed). The theoretical correction was obtained from Matsui's theoretical expressions [9,10], evaluated at most frequencies by Miura *et al.* [11], and from a low-frequency approximation [10] evaluated by the author of this chapter at other frequencies (e.g., 1.25 kHz, 1.5 kHz, and 2.5 kHz). At frequencies less than 7 kHz, sufficiently less than the nominal fundamental resonance frequency of the microphone for the theoretical correction to apply to a microphone of this type, the experimentally and theoretically determined corrections agree within 0.15 dB.

Second, for certain laboratory standard microphone types, the experimentally determined plane-wave free-field corrections, sometimes weighted to include results of theoretical calculations at low frequencies, have been tabulated [2,12]. Customers who have received (for example) pressure calibrations of their microphones from NIST sometimes use these tables and the calibration pressure response levels to infer the free-field response levels. However, the accuracy of such inferences depends on how well the characteristics, including the acoustic impedance of the diaphragm, of the microphone match the characteristics typical of its type. Uncertainties of about 1 dB can occur when a standardized correction for a microphone type is applied to a particular microphone of that type [13]. Consequently, the most accurate free-field measurements traceable to NIST are achieved by obtaining the NIST free-field calibration of a microphone by the reciprocity method [5].

## 8.4 PRESSURE CALIBRATION BY THE RECIPROCITY-BASED COMPARISON METHOD

Pressure calibrations can be carried out by the comparison method described in Sec. 6 of [2], in which a microphone is used as a sound source to generate identical (after accounting for possible differences in the equivalent volumes of microphones and the influence of changes in ambient conditions, as necessary) sound pressures in a coupler in which, first, a reference microphone of known pressure response level, and then the microphone of unknown sensitivity, are inserted. However, this procedure requires measuring two voltage ratios at each frequency of calibration and two sealings and fillings of a coupler with hydrogen gas for performing measurements at its upper frequency limit. Since two couplers are used, one for frequencies up to 10 kHz and the other for frequencies from 10 kHz to 20 kHz, performing a comparison calibration over the entire audio-frequency range by this procedure is laborious.

The labor required for such wideband calibration can be reduced by a comparison procedure developed and routinely used at NIST, described in detail in [4]. For each calibration against a reference microphone, this procedure requires measuring only one voltage ratio at each frequency and only one sealing and filling of each coupler with hydrogen gas for performing measurements at the coupler's high-frequency limit. A standard reference microphone, for which both the pressure response level and the modulus of the driving-point electrical impedance are known from a reciprocity calibration, is used as the sound source in the same couplers in which the reciprocity calibration was performed, and the microphone of unknown sensitivity is used as the receiver. The ratio of the open-circuit voltage at the receiving microphone terminals to the voltage driving the sound source is the only ac electrical measurement that must be performed at each frequency of calibration. Because the same couplers are used at the same frequencies in both the calibration of the reference microphone by reciprocity and in the comparison calibration, some systematic components of uncertainty, which are associated with the acoustic transfer impedance relating the sound pressure at the diaphragm of one microphone to the volume velocity at the diaphragm of the other, are partially cancelled [4] in the comparison calibration, and are only as large as they would be in a reciprocity calibration. In practice, the microphone of unknown sensitivity is given two essentially independent calibrations, by comparing separately with two calibrated reference microphones, and the results are averaged to reduce the random component of uncertainty. Consequently, for a given expenditure of labor, this procedure permits a more accurate calibration of a microphone than can be achieved by the substitution calibration method described in Sec. 6 of [2].

## 8.5 FREE-FIELD CALIBRATION BY THE RECIPROCITY-BASED COMPARISON METHOD

As in Sec. 8.4, in principle, a standard microphone, for which both the modulus of the electrical driving-point impedance and the free-field response level have been determined by the reciprocity method, can be used as a sound source to calibrate a receiving microphone of unknown free-field sensitivity. However, the sound pressure levels obtained from standard microphones as sound sources are impractically low at reasonable working distances in the free field, especially at low frequencies. Consequently, electrodynamic sound sources are most frequently used to produce a good approximation to a plane wave at the position of a reference microphone that has been calibrated by the reciprocity method. After the output voltage of this microphone is measured, the reference microphone is removed, and the test microphone of unknown sensitivity is placed with its acoustic center (or other reference point) at the position that had been occupied by the acoustic center of the reference microphone. With the same signal driving the sound source, the free-field response level of the test microphone is determined by comparing its output voltage with the output voltage and the free-field response level of the reference microphone. In this procedure, the influence of modern, precision electronic instruments, such as the preamplifier and (if needed) filters, amplifiers, and so on, is sufficiently well characterized and small relative to other sources of uncertainty, such as the stability of the sound source and imperfections in the anechoic chamber, that the open-circuit voltages from the microphones can be determined to sufficient accuracy with only occasional insert-voltage calibration of the gain of these instruments. In many cases, the free-field calibration of the entire test microphone system, including these electronic instruments, is desired and obtained, so that the open-circuit output voltage of the test microphone need not be determined.

Possible excitation signals for the sound source include singly presented sine-wave signals, random noise, periodic noise, and transient signals such as band-limited impulses, "chirps" (rapidly swept sine-wave signals), and bursts of random noise. The microphone output voltages may be measured with analog filters and rms voltmeters, lock-in amplifiers, real-time digital filters, and dynamic signal analyzers incorporating FFT (fast Fourier transform) or other signal processing [14–18].

The validity of an experimental arrangement for free-field comparison calibration can be evaluated by comparing such calibrations with those obtained from the primary NIST calibration method (reciprocity). Such an evaluation is the most practical way to validate an arrangement containing particularly complex instruments such as real-time digital filters or dynamic signal analyzers. Features incorporated in such analyzers may include autoranging, analog input signal conditioning, and anti-alias filtering followed by analog-to-digital conversion, digital filtering, digital signal processing such as FFT analysis of time records weighted by a variety of user-selectable window functions, several user-selectable data-averaging methods, including root-mean-square (rms) and linear methods, and a variety of built-in, user-selectable source signals for exciting the sound source. No standards or generally recognized methods are available for characterizing such complex devices to determine experimental uncertainties in specialized applications such as free-field comparison calibrations. Consequently, validating the apparatus and procedures in these applications requires evaluating them against established, well-characterized methods and systems.

For example, a pair of 1/2-in. laboratory condenser microphones was calibrated by the free-field reciprocity method using the small NIST anechoic chamber and apparatus described in Sec. 8.2. One of these microphones was then used as the reference microphone, and the other was used as the test microphone of "unknown" sensitivity, in several trial calibrations by the free-field comparison method in the large, general purpose NIST anechoic chamber. For each trial calibration, a different source signal was used. Each signal type possessed specific advantages and disadvantages. These signals were specifically selected to point out different degrees of deviations from anechoic conditions in the chamber due to different standing wave patterns caused by slight reflections from interior surfaces of the chamber. For each trial, electrical signals from the microphones, preamplifier, and measuring amplifier were measured with a single-channel dynamic signal analyzer [14,15,16,17,18] providing FFT analysis of an anti-alias-filtered, digitized time record. In one trial, the source signal was random noise, the Hanning window weighting function was applied to each time record on which FFT analysis was performed, and 5000 rms averages of data were obtained [14]. (This averaging does not improve the signal-to-noise ratio, but does reduce the variance of the measurement.) In each of the other two trials, the uniform window weighting function was used, and linear averaging, also called time averaging [14], was performed in synchrony with the periodic source signal to increase the signal-to-noise ratio by a factor equal to the square root of the number of averages. In one of these trials, with 500 data averages, the source signal was periodic noise, comprising spectral lines at the FFT analysis frequencies. In the other trial, with 4000 data averages, the source signal was a train of band-limited impulses (one for each time record captured for analysis); each impulse was composed of frequencies in the FFT analysis range. The periodic noise contained discrete sine-wave signals capable of producing standing waves due to slight reflections from the chamber boundaries. The random noise spectrum contained a continuum of sine-wave signals considered less likely to strongly excite specific standing-wave patterns. For the band-limited impulses, the time record length and synchronous trigger delay were chosen so that these records, upon which FFT analysis was performed, contained no significant reflections from interior surfaces of the chamber. Consequently, the trial using the impulse source is considered least likely to be influenced by standing-wave patterns. The trials using band-limited impulses and periodic noise, however, are more likely to be influenced by nonlinearities in the sound source, microphone system, and analyzer. For each trial calibration, the difference between the response levels of the "unknown" and reference microphones was subtracted from the corresponding difference obtained from the reciprocity calibration at each of 15 frequencies from 2 kHz to 40 kHz. The smaller the absolute value of these remainders, the more closely the comparison calibrations approximate the reciprocity calibration of the "unknown" microphone. At frequencies from 2 kHz to 20 kHz, the largest absolute values of these differences are 0.27 dB for the periodic noise source trial, 0.29 dB for the random noise source trial, and 0.21 dB for the impulse source trial. At frequencies from 20 kHz to 40 kHz, the largest absolute values are 0.60 dB for periodic noise, 0.38 dB for random noise, and 0.34 dB for the impulse source. In these initial measurements, despite short-term instabilities of 0.1 dB to 0.15 dB in the electrodynamic sound source used for the comparison calibrations, good agreement has been obtained between comparison calibrations in the large anechoic chamber using all three signal types and reciprocity calibrations in the small anechoic chamber using sine-wave signals. Considering the entire frequency range, 2 kHz to 40 kHz, this agreement is closest for the comparison calibration trial using the impulse source, next closest for the trial using random noise, and least close for the trial using periodic noise; that is, the comparison calibration method that is considered least vulnerable to standing-wave patterns from slight reflections from the chamber walls produces the closest agreement. This result suggests that these reflections, rather than nonlinearities or instabilities in the sound source, microphone system, and analyzer, can compose the principal source of uncertainty in comparison calibrations.

## 8.6 LINEARITY OF MICROPHONE SYSTEMS

As noted in Sec. 5.6, a microphone must be a linear system to undergo a valid primary calibration by the reciprocity technique. Such calibrations are usually carried out over a limited dynamic range. However, for most applications, the linearity of a microphone or microphone system must be demonstrated throughout a much wider dynamic range. One of the most common methods for verifying the linearity of a microphone or microphone system is to measure its output as a receiver responding to a sound source as the drive voltage level to the source is changed in accurately controlled increments, usually by means of a calibrated precision attenuator. The sound source may be another microphone, especially of different size or type, or a dissimilar transducer considered to be linear throughout the dynamic and frequency ranges of interest. In a strict sense, changes in the output level of the receiver that match the increments by which the source drive voltage level is changed indicate that the system comprising the source-receiver pair and the acoustic coupling between them behaves as a linear system, not necessarily that the receiver is itself linear. In practice, however, linearity of this system, but nonlinearity of the receiving microphone, would require another nonlinearity in the system, namely, in the sound source, that would be the inverse of the nonlinearity of the receiver and that would compensate for the effects of receiver nonlinearity throughout the frequency and dynamic ranges of measurement. Such accurate (but unintentional!) compensation would be highly unlikely, especially if the sound source and receiver are of dissimilar construction, if the acoustical coupling between them can be considered linear, and if electrical crosstalk between the source signal and the receiving microphone's electrical terminals can be considered negligible. Consequently, in a well-designed system characterized by linear acoustical coupling and negligible crosstalk, verification of system linearity constitutes very strong evidence that the source and receiver both perform as linear transducers.

One linearity verification at very low sound pressure levels was performed in the NIST large anechoic chamber using an electrodynamic sound source that had been calibrated and characterized with a reference microphone (Tokyo Riko type ECL MR112). This microphone had undergone primary free-field calibration as described in Sec. 8.2. The source was electrically driven to produce a progressive sound wave normally incident on the test condenser microphone (Bruel and Kjaer type 4145) placed in the far field at the position that had been occupied by the reference microphone. The test microphone output was followed by a preamplifier, measuring amplifier, bandpass filter, and lock-in amplifier. This test microphone system had been calibrated by comparison with the reference microphone. For a sine-wave signal at 4 kHz, the applied nominal free-field SPL (sound pressure level, in dB, reference: 20 $\mu$Pa) of this wave at the reference position was varied from 84.3 dB to $-25.7$ dB, in 10 dB increments, by means of the output level control of the signal generator (Hewlett-Packard model 3325A) and a properly terminated and calibrated precision attenuator (Daven type VT-795-G) in the sound source signal path. The SPL of the progressive wave indicated by the test microphone system (rounded to the nearest 0.1 dB) agreed with the nominal SPL within 0.1 dB at all test levels within the dynamic range of measurement (110 dB). When the sound source signal was turned off, the output of the test microphone system, expressed as the equivalent SPL of a normally incident progressive wave at the reference position, was $-54$ dB to $-55$ dB, so that the signal-to-noise ratio at the lowest level of measurement was about 28 dB to 29 dB.

Another example of a linearity verification at very low sound pressure levels was performed on a type *L* laboratory standard microphone (Bruel and Kjaer Type 4160) that had been calibrated by the pressure reciprocity method described in Sec. 8.1. This microphone was to be used in a system for calibrating the acoustic output of audiometers and audiometric earphones at low hearing levels, including those well below the threshold of normal hearing. These measurements were needed in the U.S.A. to support particularly demanding audiometric measurements involving studies of human hearing threshold levels in large population samples and the etiology of differences in threshold between sample groups. These studies require accurate audiometric measurements of a large number of individual pure-tone hearing thresholds, including those more sensitive than the normal hearing threshold level for pure tones. This normal level is often called audiometric zero, or zero hearing level (hearing level, abbreviated HL, is expressed in dB relative to audiometric zero, for example, −10 HL at a given frequency corresponds to a hearing threshold 10 dB more sensitive than normal for that frequency) [19].

This type $L$ microphone was placed as a receiving microphone in a plane-wave coupler of nominal volume 3 $cm^3$. A condenser microphone (Bruel and Kjaer type 4136) of nominal diameter 6.35 mm (1/4 in.) was sealed into the coupler with suitable adapters, and was driven electrically with sine-wave signals to serve as the sound source. The microphones and coupler, as well as the preamplifier and measuring amplifier for the receiving microphone, were placed in an audiometric test booth in the control room of the NIST large anechoic chamber, further to reduce the background acoustical noise in this quiet control room. A two-channel dynamic signal analyzer [20] outside the test booth was used in its swept-sine mode [21], with a properly terminated and calibrated precision attenuator (Daven type VT-795-G) in its source output signal path, to determine the intracoupler sound pressure levels indicated by the receiving microphone system, as the level of the voltage driving the source microphone was adjusted in 10 dB increments. For a perfectly linear, noise-free system in the absence of background noise, indicated intracoupler SPL measurements at a given frequency, but for different source attenuations, should be separated by the appropriate multiple of 10 dB. At frequencies from 0.2 kHz to 8 kHz, Fig. 8.2 shows these indicated SPLs as the source signal was adjusted over a range of 90 dB. The peak at −15 dB SPL in the noise floor occurs at just more than 400 Hz (not a frequency of audiometric measurement), and is attributed to the remaining ambient acoustic noise. To calibrate audiometers using TDH-50P earphones on the NBS-9A coupler [22] at very low hearing levels, the most difficult calibration frequencies are 1 kHz and 1.5 kHz, for which the lowest reference equivalent sound pressure levels are produced [19]. At these frequencies, linearity of the microphone system is demonstrated in Fig. 8.2 at levels as low as about −18 dB SPL, and the noise floor is approximately at or less than −35 dB SPL. During calibration of audiometers with TDH-50P earphones on the NBS-9A coupler, at 1 kHz and 1.5 kHz the level −18 dB SPL corresponds to the −25.5 hearing level, and the noise floor −35 dB SPL corresponds to the −42.5 hearing level [19]. Consequently, even at the frequencies at which the lowest sound pressure levels must be measured, a laboratory standard microphone system can calibrate audiometers and earphones used to measure hearing threshold levels that are much lower than audiometric zero. Special microphone types with better signal-to-noise ratios, but with less stability and with inferior frequency response characteristics, need not be employed, although they may be required in the absence of an excellent filter or dynamic signal analyzer.

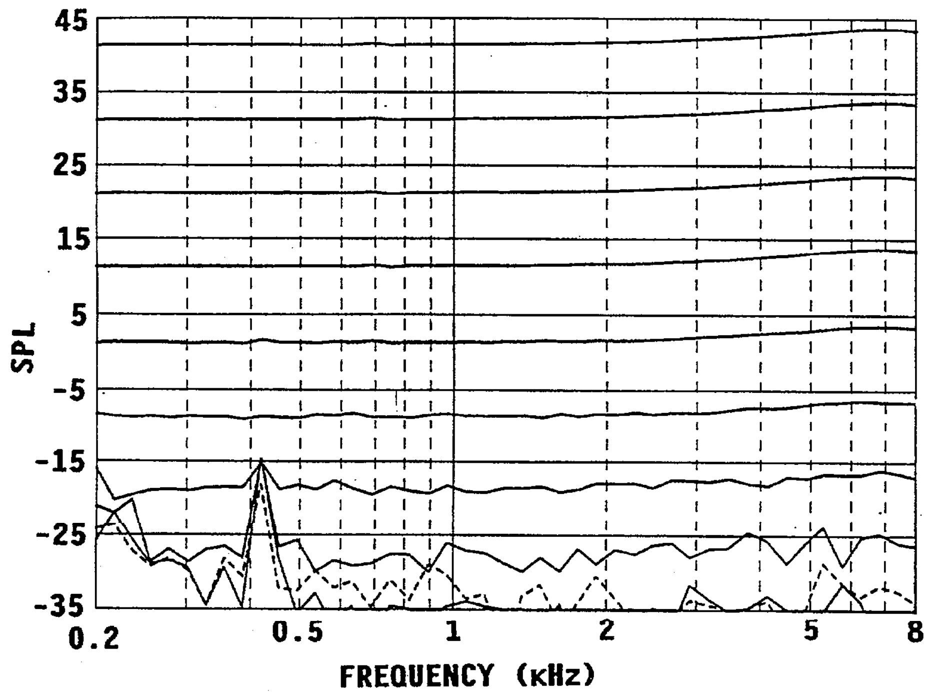


**FIGURE 8.2.** Linearity and equivalent noise floor measurements on a type *L* (1-in.) condenser microphone system. For each curve, sound pressure level (SPL, in dB, reference: 20 $\mu$Pa) was measured at a given sound source signal attenuator setting, using sequentially presented sine-wave signals at discrete frequencies, evenly spaced on the logarithmic frequency scale at the rate of 28.1 data points per decade. The source signal attenuation was incremented by 10 dB after each curve was taken.

## 8.7 ELECTROSTATIC ACTUATOR MEASUREMENTS

An electrostatic actuator measures the relative frequency response of a microphone simply and conveniently [23]. However, the distance between microphone and actuator must be small to obtain adequate signal-to-noise ratios using dc bias voltages (applied between actuator and microphone diaphragm) of about a kilovolt or less. Because this small distance is difficult to measure and to maintain sufficiently well, the accuracy of electrostatic actuator measurements is limited. At frequencies less than 800 Hz, accuracies of about 0.5 dB have been attained [24].

Furthermore, the true pressure response level of a microphone and its approximate pressure response level as measured by an actuator may differ considerably at high frequencies because the force $f_D$ acting on the microphone diaphragm differs from the electrostatic force $f_E$ applied by the actuator in a manner that depends on the relation between the mechanical impedance $Z_m$ of the microphone diaphragm and the effective mechanical radiation impedance $Z_r$ loading the diaphragm in the presence of the actuator [25]. Only when $|Z_m| \gg |Z_r|$ does $f_D$ very nearly equal $f_E$.

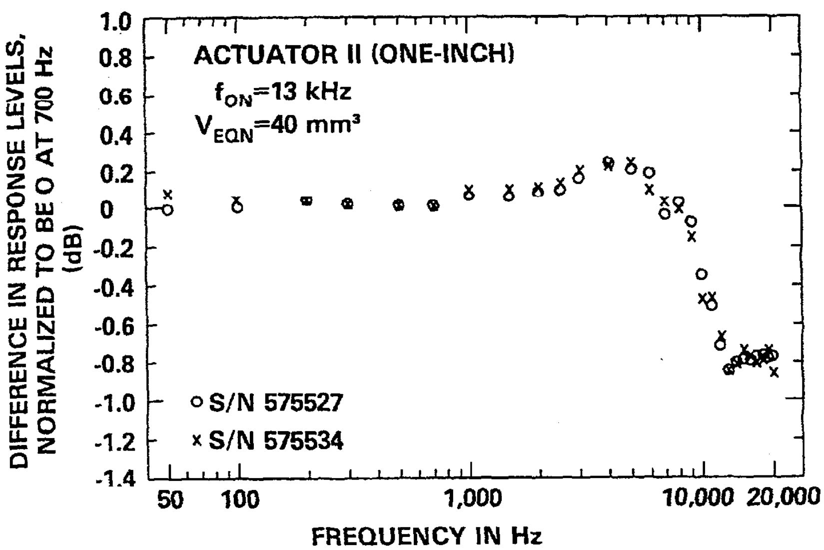


**FIGURE 8.3.** Difference in response levels between calibration using a slotted 1-in. electrostatic actuator and pressure calibration in standard couplers, for two 1/2-in. microphones of 13 kHz nominal resonance frequency $f_{0N}$, and 40 mm³ nominal equivalent volume $V_{EQN}$. This difference has been normalized so that its value is 0 at 700 Hz.

Such is apparently the case at frequencies sufficiently below the fundamental resonance of the diaphragm, where $Z_m$ is stiffness-dominated [26] and is large compared to $Z_r$ [27,28]. At higher frequencies, absolute values of the differences between actuator-determined calibrations of type $L$ microphones and pressure calibrations determined in couplers by reciprocity can be as large as about 1.5 dB [27,28].

At NIST, the corresponding differences have been examined for some commonly used 1/2-in. microphones and actuators. These differences are not the same when the same actuator is used to calibrate two microphones having different diaphragm impedances and fundamental resonance frequencies [3]. Moreover, these differences are not the same when different actuators are used to calibrate the same microphone. For two microphones of nominal resonance frequency $f_{0N} = 13$ kHz and nominal equivalent volume $V_{\text{EQN}} = 40$ mm³, Fig. 8.3 shows the normalized difference $D_n$ in response levels between a calibration performed using an adapter and a slotted actuator intended for use with 1-in. microphones, and a reciprocity-based comparison calibration in couplers. For each microphone, $D_n$ has been normalized so that its value is 0 at 700 Hz, and $|D_n|$ can be as large as about 0.9 dB at high frequencies. The same microphones were used without an adapter so that a perforated actuator intended for use with 1/2-in. microphones could be employed (Fig. 8.4). In this case, $|D_n|$ can be as large as about 1.3 dB.

How well a calibration of a microphone performed using an actuator approxi-

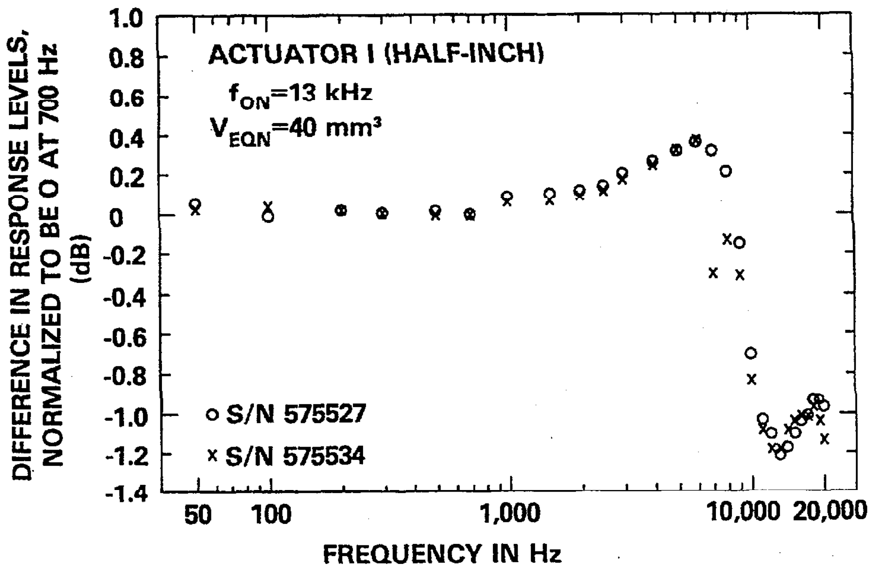


**FIGURE 8.4.** Difference in response levels between calibration using a perforated 1/2-in. electrostatic actuator and pressure calibration in standard couplers, for the two microphones in Fig. 8.3. This difference has been normalized so that its value is 0 at 700 Hz. [3].

mates a pressure calibration performed using the reciprocity method with couplers depends upon both the actuator and the microphone type. Consequently, there are no current ANSI or major international standards for the primary or secondary calibration of microphones by means of electrostatic actuators, and NIST does not advertise measurement services based upon electrostatic actuators. However, actuator methods are so convenient and readily performed in a semi-automated fashion that they are widely used by manufacturers, and such methods may be applied even in calibration laboratories for specialized purposes or for less demanding calibrations. For most laboratory condenser microphones at the highest frequencies of interest, the actuator shapes are not analytically tractable, and determining $Z_r$ accurately is difficult. Consequently, when an electrostatic actuator has been used with a microphone to approximate a pressure calibration, the accuracy of the result should be verified by reciprocity-based calibrations performed in couplers.

## 8.8 METHODS INVOLVING THE PHASE ANGLE OF MICROPHONE RESPONSE

Methods involving phase angles of microphone response are the subject of active research, but a brief description of some approaches examined to date can be given here.

The approximate phase angle of the pressure response of a microphone system within and somewhat beyond the audible-frequency range can be obtained by the electrostatic actuator method, particularly if a microphone of high diaphragm mechanical impedance $Z_m$ and very high nominal resonance frequency $f_{0N}$ is selected. The same microphone system can be calibrated with actuators presenting substantially different radiation impedances; a degree of confidence in the accuracy of the method can be attained by observing how well these calibrations agree. As in pressure calibrations performed in couplers, this approach assumes that only the diaphragm of the microphone, not its ambient pressure equalization vent, is exposed to the sound field when the microphone is used to measure sound pressure. In typical calibrations using an actuator, however, sound radiated by actuator-induced microphone diaphragm motion may be incident upon this vent, possibly causing slight differences between the actuator response and the pressure response. The actuators are used only to determine the approximate phase angle and relative amplitude-frequency characteristic of the pressure response. The absolute amplitude at one or more selected frequencies is obtained by means of comparison calibrations in couplers, or by means of pistonphones or other acoustic calibrators of the closed coupler type that have been calibrated themselves by microphones traceable to primary calibration by the reciprocity method. For example, these actuator techniques have been applied to a system including a 3.2 mm (1/8-in.) diameter condenser microphone (Bruel and Kjaer type 4138, $f_{0N}$ = 160 kHz, and $V_{\mathrm{EQN}}$ less than 0.1 mm$^3$), a preamplifier (Bruel and Kjaer type 2618), and measuring amplifier (Bruel and Kjaer type 2607). Appropriate microphone adapters and three actuators of different nominal diameters and shapes were used: a 6.35 mm (1/4-in.) solid actuator, a perforated actuator intended for 1/2-in. microphones, and a slotted actuator intended for 1-in. microphones. At frequencies from 20 Hz to 40 kHz, measurements with all three actuators agreed within the range (+0.6, −0.8) dB in amplitude. From 20 Hz to 50 kHz, these measurements agreed within the range (+0.6, −1.5) dB in amplitude, and were within ±7° of the same given phase response representing a pure time delay (characterized by a straight line plot of phase angle vs frequency).

Methods for determining the relative phase response of microphone systems in the free field include comparison calibration in the NIST large anechoic chamber. A microphone system is positioned in the far field of a sound source. Here, the far field is defined as the region of the sound field sufficiently distant from the source that the wavefronts of sound are approximately spherical, the sound pressure and acoustic particle velocity are essentially in phase, and the sound wavefronts resemble plane waves well enough for use in calibrations of acceptably small uncertainty. The system output voltage is measured as a transfer function in response to a source excitation signal. This system is then replaced by the second microphone system, so that the acoustic center of the second microphone is at the same position that had been occupied by the acoustic center of the first microphone. Then the output voltage of the second system is measured as a transfer function in response to the same source excitation signal. The ratio of the transfer functions obtained for the two microphone systems is their relative frequency response, which is typically displayed in two plots: amplitude vs frequency, and phase angle vs frequency. If the sound source and measuring instruments are sufficiently accurate and stable, absolute measurements of the outputs of the microphone systems can be used instead of transfer functions. Initial experiments have been performed using a dynamic signal analyzer [20] in its FFT-based measurement modes [21] to determine the amplitudes and phase angles of the outputs of the microphone systems and their ratios, as well as to generate the source excitation signals, at relatively low frequencies where anechoic chamber imperfections and signal-to-noise constraints are probably most critical for many practical experiments. For example, the relative free-field response at normal incidence of a pair of microphone systems (not specially selected for matched characteristics), each consisting of a 1/2-in. microphone (Bruel and Kjaer type 4134) and preamplifier (Bruel and Kjaer type 2619) was measured. These two systems matched in phase response within 1.5° from 53 Hz to 100 Hz, within 1° from 100 Hz to 200 Hz, and within 0.25° from 200 Hz to 2000 Hz. More elaborate and more nearly optimized calibration procedures, based upon further experimentation with source excitation signal parameters, sound source characteristics (such as directivity, stability, and maximum undistorted output level), positioning apparatus, and choice of source and microphone positions, could reasonably be expected to improve the accuracy and extend the frequency range of these measurements. Such improvements are needed to make the most demanding measurements, such as determining the relative response of pressure-sensing microphone systems used in pairs for the measurement of acoustic intensity, especially at higher frequencies, where coupler-based measurements have greater uncertainty. Because of these greater uncertainties and the influence of diffraction, coupler-based measurements become unreliable for free-field applications at these higher frequencies.

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