157

CALIBRATION OF PRESSURE AND GRADIENT MICROPHONES

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1 INTRODUCTION

Calibration of a microphone establishes the quantitative relation between the signal (usually, the voltage) at the electrical terminals of the microphone and the acoustical signal at its diaphragm or other specified reference position. This chapter deals with microphones used in gases, principally in air, for which this signal may be sound pressure, its first or higher order gradient, or a combination of these quantities. Calibration is necessary for accurately measuring potentially hazardous noise, as well as desired acoustical signals. National and international legal, regulatory, and quality control measurements for health, safety, and commerce depend on various acoustical instruments and systems calibrated or characterized by calibrated microphones.

To accommodate the wide variety of microphone types, characteristics, and applications, various calibration procedures greatly differ in complexity, uncertainty, and the labor and equipment costs required to realize given frequency ranges and accuracies. This chapter briefly describes only some calibration methods of fundamental importance or currently in widespread use and some factors important in determining calibration uncertainties. Reciprocity and reciprocity-based primary laboratory methods of the highest accuracy are included, as well as less complicated, less costly, and, usually, less accurate methods based on comparisons, calibrators of the closed-coupler type, and electrostatic actuators. Selected references are provided.

2 CATEGORIES OF MICROPHONES

To some degree, all microphones exhibit compromises in their essential mechanical and electroacoustical performance characteristics. These characteristics include size, frequency range, uniformity of sensitivity with frequency (usually for a specified type of sound field), dynamic range, directionality of response, stability, ruggedness, the degree to which performance characteristics are influenced by changes in ambient environmental conditions (e.g., static pressure, temperature, relative humidity), and sensitivity to extraneous influences such as electromagnetic fields, ionizing radiation, and vibration. Some of these compromises are related to cost, and most are closely related to the applications intended for a given microphone, as well as its transduction mechanism and design.

Microphones are frequently categorized by their intended applications and transduction mechanisms, as in Chapters 159 and 162. For calibration purposes, however, it is essential to consider the acoustical signal for which the microphone is intended, as well as certain general characteristics and applications closely related to calibration.

Four relatively broad categories are considered here: laboratory standard, pressure, pressure-gradient, and combination microphones. The first two categories are sometimes grouped together and termed pressure (or pressure-sensing) microphones, but here we consider laboratory standard microphones, which are specifically designed for the most accurate calibration purposes, to be a separate category. The categories pressure-gradient microphones and combination microphones are some-

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times grouped together and termed pressure-gradient microphones, or, simply, gradient microphones. Each category has its distinctive characteristics and applications, although in some cases a given microphone may correctly be classified in more than one category. Some categories can also be divided into subcategories: for example, pressure microphones include working standard and other measuring microphones, as well as pressure-sensing communications microphones. Differences in microphone design and performance characteristics often, but not always, indicate the use of calibration methods particularly appropriate to given categories.

2.1 Laboratory Standard Microphones

Critical mechanical and electroacoustical characteristics have been standardized[1,2] for these microphones, which are intended for calibration by primary methods to the highest attainable accuracies. Laboratory standard microphones that are handled carefully are very stable, so that their sensitivity changes very little with passage of time. Consequently, after calibration, they can be used in comparison methods to calibrate other microphones and instruments. At present, every available laboratory standard microphone is a condenser microphone, to which a polarizing voltage, usually 200 V DC, is applied from an external source. These microphones respond to sound pressure; that is, the microphone output voltage is intended to be proportional to the sound pressure at the microphone diaphragm in a given type of acoustic field.

2.2 Pressure Microphones

Pressure microphones also respond to sound pressure but are not necessarily as stable in their sensitivity, with regard to time and changes in environmental conditions, as laboratory standard microphones. Working standard microphones are externally polarized condenser microphones that approach the stability of laboratory standard microphones and, after calibration, are used to calibrate other microphones and instruments, often on a frequent and regular basis. Working standard microphones are a subject of an international standard[2a] and of an American standard being developed by the Standards Committee S1, Acoustics, Working Group 1, Standard Microphones and Their Calibration, accredited by the American National Standards Institute (ANSI) and administered by the Acoustical Society of America (ASA). Measuring microphones are used in custom-designed systems, sound level meters, and personal sound exposure meters (noise dosimeters) to determine sound pressure or sound exposure in laboratory or field applications. These microphones include externally polarized condenser microphones, as well as electret, piezoelectric, and electrodynamic microphones. Many working standard and measuring condenser microphones are sufficiently similar to laboratory standard microphones to warrant calibration by reciprocity techniques. However, most are calibrated by secondary methods.

Some pressure microphones typically are not used to measure sound pressure but to transduce it to an electrical signal for communication or recording purposes, as in telephones, many hearing aids, and some radio broadcasting and audio recording applications. When necessary for design prototype testing, production quality control, comparative performance evaluation, and so forth, most of these microphones are calibrated by secondary techniques.

2.3 Gradient and Combination Microphones

For a gradient (also termed pressure-gradient) microphone, the electrical response corresponds to a spatial gradient of sound pressure. The response of a first-order gradient microphone corresponds to the difference in sound pressure between two points in space. Over much, if not all, of the intended range of operating frequencies, these points are usually separated by a sufficiently small distance compared to the wavelength that the pressure gradient corresponds to the acoustic particle velocity. Such microphones are often called velocity microphones. Higher-order gradient microphones are those in which the electrical response corresponds to a second, or higher, order spatial gradient of the sound pressure. Gradient microphones of the first and higher orders are directional, discriminate against random-incidence (diffuse) components of the sound field, and are useful in many applications for which such discrimination is often desirable,[3–5] as in sound recording, broadcasting, and communications systems.

In a combination microphone, desired directionality and frequency response characteristics related to those of both pressure and gradient microphones are achieved by a variety of methods.[3–5]

3 SELECTION OF CALIBRATION METHODS AND SCHEDULES

3.1 Selection of Calibration Methods

Practical microphones are seldom sufficiently small that the effects of diffraction can be considered negligible throughout the entire frequency range of operation. Consequently, a microphone is usually characterized by different frequency-dependent sensitivities when it is used in different sound fields, such as a spatially uniform sound pressure, a plane sound wave at a specified angle of incidence in the free field, or a diffuse field. Different calibration procedures have evolved so that an appropriate calibration is available calibration is available for each field type. These issues, and many others, must be considered in selecting a calibration method.

Sufficiently detailed, rigorous general rules for selecting appropriate calibration methods for specific tasks in every nation cannot be given in this brief chapter. Despite international standardization, national standards and regulations are not always identical in different nations. Detailed procedures for many of the most accurate and expensive, as well as frequently performed and inexpensive, calibrations vary among laboratories and manufacturers, and are not fully documented in accessible form. The user of an instrument must consider the microphone category, its intended application, the range of operating frequencies, the dynamic range, and the frequency-dependent and level-dependent uncertainties that need to be achieved, so that the calibration complexity and cost are commensurate with the acceptable degree of uncertainty. A laboratory standard microphone or working standard microphone that is used by a calibration laboratory to calibrate other standard microphones, acoustical calibrators (including pistonphones), and instruments over a broad frequency range may need the best available reciprocity or reciprocity-based calibration, but if lesser accuracy is acceptable, a secondary method may be appropriate. Examples for which secondary methods are commonly employed include microphones used in sound level meters, integrating-averaging sound level meters, and personal sound exposure meters for which exhaustive data establishing the design integrity of the instrument models are already available. Applicable secondary methods include calibration by comparison with a calibrated working standard microphone, the use of a properly calibrated multifrequency acoustical calibrator, or the use of a single-frequency calibrator and an electrostatic actuator method. The manufacturer's recommendations and advice from national and private calibration laboratories, as well as regulatory and legal authorities, should be carefully considered, along with the experience of the instrument users.

There is one cardinal, succinct rule: The conditions of calibration must correspond, as closely as is necessary and practical, to the pertinent critical conditions of intended use of the microphone, so that the calibration method is appropriate to the applicable kind of measurement and sound field.

Most microphones contain a cavity behind the diaphragm. To prevent fluctuations in ambient barometric pressure from mechanically biasing the diaphragm, and thereby affecting the microphone sensitivity, this cavity is almost always equalized to this pressure by a high-acoustic-impedance vent that has only a small effect on the acoustical performance of the microphone. However, for purposes requiring high accuracy at low frequencies, this effect is usually not negligible. For such purposes, if the vent is exposed to the sound field, as in most free-field and diffuse-field measurements, the vent must also be exposed during calibration. If the vent is not so exposed, for example, during measurements of sound pressure in nearly all standardized couplers, the vent should not be exposed during calibration.

For some calibrations, especially those using laboratory standard microphones, the desired sensitivity involves the open-circuit output voltage of the microphone itself (sometimes called the microphone cartridge). In other calibrations, the sensitivity may involve the output voltage of the preamplifier, or the combined preamplifier and amplifier, to which the microphone is connected and used in a system. The Thevenin equivalent electrical network impedances (also called source impedances) of most condenser, electret, and piezoelectric microphones are not negligibly small compared with the input impedances of the preamplifiers with which they are used. Consequently, a system usually should be calibrated as it is used or reliable corrections should be applied for the loading and other effects (including gains) of the preamplifier and amplifier, which cause the voltages at the preamplifier and amplifier outputs to differ from the open-circuit output voltage of the microphone.

3.2 Selection of Calibration Schedules

Selection of calibration schedules depends on the microphone category, its application and treatment, the necessary accuracy of measurement, the cost or penalty of inaccurate measurement, and the stability of the microphone as demonstrated by a history of its calibrations, preferably performed at regular intervals. These issues are familiar to calibration laboratories and have been described in some detail.[6] For example, a laboratory standard microphone that is handled carefully, used only occasionally as one of several available reference standards, and has an excellent record of stability may be calibrated only every 12–18 months or more, with its calibration interval overlapping those of the other such microphones, so that at least one has been calibrated every 6–12 months. However, a sound level meter or personal sound exposure meter used daily in a hostile industrial environment such as underground mining may require weekly calibration with a multifrequency, multilevel acoustical calibrator and field checks at a single frequency and a single level at the beginning and end of each day. The recommendations of the microphone or instrument manufacturer, the national and private calibration laboratories, and regulatory and legal authorities in a nation, as well as practical experience acquired by the users of the instruments in specific circumstances, should be carefully considered.

4 PRIMARY CALIBRATION OF LABORATORY STANDARD MICROPHONES BY ELECTROACOUSTICAL RECIPROCITY TECHNIQUES

Nearly all of the major national standards laboratories of the world use these techniques. Except for the relatively undeveloped and less accurate determination of diffuse-field sensitivity by the reciprocity method discussed in Section 4.4, these are the most highly developed and cost-effective methods available for achieving the highest attainable absolute accuracies of laboratory standard microphone calibration over a wide range of operating frequencies. Such calibrated microphones are needed to perform the most accurate sound pressure measurements and to calibrate other microphones and acoustical instruments, so that nearly all critical measurements of sound pressure are traceable to these methods.

Electroacoustical reciprocity techniques permit calibration based on fundamental principles and constants, and typically involve measurements of AC voltages, transfer impedances, and the quantitative determination of the acoustical coupling between transmitting (electrically driven to serve as a sound source) and receiving microphone pairs.

4.1 Insert-Voltage Technique and Ground Shield Dimensions

The insert-voltage technique[7,8] is used to determine the open-circuit sensitivity of the microphone when it is connected to a practical preamplifier. Usually, the open-circuit sensitivity of a laboratory standard microphone is reported, so that highly accurate measurements can be made with this microphone at different laboratories, essentially independently of interlaboratory differences between preamplifiers. However, critical microphone-to-preamplifier mounting and ground-shield dimensions have been standardized[7,8] for these microphones to avoid the influence of significantly differing stray capacitances associated with differences in these dimensions.

4.2 Determination of Pressure Sensitivity by the Reciprocity Technique

In the method using two microphones and an auxiliary transducer the sensitivities of two microphones are determined.[7,8,9] One of these microphones must be reversible, that is, must be used as a transmitter, as well as a receiver. The auxiliary transducer, which may be a microphone more sensitive than the other two, is used only as a transmitter to determine the ratio of their sensitivities.

Another method determines the sensitivities of three microphones. Each is used as a transmitter as well as a receiver. From a sequence of pairwise measurements, the sensitivities of the microphones are determined.[8]

Uncertainties in Pressure Sensitivities Determined by the Reciprocity Technique Generalizations concerning these uncertainties are difficult because they are not only frequency-dependent but also critically dependent on particular choices made in different laboratories with regard to rather complicated details of method and apparatus. Furthermore, different laboratories have used different methods of combining individual systematic and random uncertainty components to estimate overall calibration uncertainty. Consequently, comparisons of calibration results obtained at different laboratories are invaluable for establishing the approximate uncertainties in primary calibrations. The 1986–1987 comparison[10] of pressure calibrations of IEC Type LS1P (ANSI Type L) laboratory standard microphones[1,2] among 17 laboratories in 17 different IEC member nations indicated that, at frequencies from 63 Hz to 10 kHz, agreements in calibration results of approximately 0.1 dB (often better at frequencies from a few hundred hertz to a few kilohertz, and sometimes a bit worse at the highest frequencies) were usually obtained. Particularly noteworthy was the agreement obtained from 63 Hz to 10 kHz (23 frequencies at one-third-octave intervals) between calibrations at the National Physical Laboratory (UK) (abbreviated NPL), which used an air-filled "plane-wave" coupler, and the National Bureau of Standards (U.S.A.) (renamed the National Institute of Standards and Technology in 1988, abbreviated NIST), which used a larger coupler filled with air at low frequencies and with hydrogen at higher frequencies. Other aspects of the apparatus and procedures, and consequently tradeoffs among individual uncertainty components during calibration, were also significantly different in the two laboratories. For both microphones in this comparison,[11] the absolute values of the differences between pressure response levels determined at NPL and at NIST were 0.02 dB or less at frequencies from 200 Hz to 4 kHz inclusive. At the remaining frequencies from 63 to 200 Hz, and from 4 to 10 kHz, these absolute values were no greater than 0.05 dB. This is perhaps the closest agreement in such calibrations ever achieved by laboratories using independent and significantly dissimilar apparatus and procedures, and is probably somewhat fortuitous, especially at high frequencies. However, these results demonstrate the kind of agreement that can be achieved under nearly ideal circumstances.

4.3 Determination of Free-Field Sensitivity by the Reciprocity Technique

Analogous to the corresponding method for pressure calibration using two microphones and an auxiliary transducer, the sensitivities of two microphones are determined, and an auxiliary transducer, which may be a microphone more sensitive than the other two, is used only as a transmitter.[7,9,12] Instead of being sealed into an acoustic coupler, however, each microphone pair, or each microphone and the auxiliary transducer, are placed in an anechoic chamber. A method using three microphones in a sequence of pairwise measurements, analogous to the corresponding procedure for pressure calibration, has also been standardized for free-field calibration,[12] and this IEC standard additionally considers IEC Type LS2P microphones.

Uncertainties in Primary Free-Field Calibration Uncertainties in primary free-field calibration are very dependent on the type of microphone being calibrated, as well as on specific details of calibration apparatus and procedures. The quality of the anechoic chamber, signal-to-noise ratios, and electrical crosstalk are all particularly important. The best anechoic chambers introduce uncertainty components of approximately 0.1 dB, and the worst may introduce components of more than 1 dB. Probably the most useful laboratory microphones routinely given free-field reciprocity calibrations are 12.7 mm (0.5 in.) nominal diameter, primarily because the useful amplitude-frequency responses of these microphones are more nearly constant to higher frequencies than are the amplitude-frequency responses of the larger Type LS1P microphones. Among all interested IEC member nations, extensive interlaboratory comparisons involving the free-field response levels of 12.7-mm nominal diameter microphones such as the IEC Types LS2F, LS2aP, and LS2bP have not yet been conducted. For some essentially similar condenser microphones of this size, overall uncertainties of approximately 0.1–0.2 dB have been obtained at frequencies from about 1.25 to more than 20 kHz at NIST with microphone separation distances of about 0.2 m.[11,13,14]

4.4 Determination of Diffuse-Field Sensitivity

Reciprocity Method The reciprocity method in a diffuse field has been devised and performed at the PTB (Braunschweig, Germany) by Diestel.[15,16] The procedure is basically similar to the method of pressure or free-field calibration using two microphones, here denoted a and b, and an auxiliary transducer. However, the microphones and transducer are placed in a reverberation room during measurements, and the transmitter is excited by sequentially presented bands (typically one-third-octave) of random noise rather than sine-wave signals. Furthermore, to achieve an adequate signal-to-noise ratio, Diestel used a small electrostatic loudspeaker instead of a reversible microphone for frequency bands below 2 kHz. Diestel's English-language paper[16] expresses the diffuse-field sensitivities $M_{\mathrm{df}a}$ and $M_{\mathrm{df}b}$ of a and b (notation of this chapter) in terms of the diffuse-field reciprocity parameter, J_{df}, and the electrical voltages and currents measured during calibration. (Note that a typographical error occurs in Diestel's Eqs. (21) and (22): The entire right-hand side of each equation should be raised to the exponent $\frac{1}{2}$. The corresponding equations in the German-language paper[15] avoid this error.) Diestel expressed[15,16] $J_{\mathrm{df}} = 2h_0/\rho_0 f$ by considering h_0 to be the "diffuse-field distance,"[16] that is, the distance from an idealized point source at which the energy density of directly radiated sound equals the average energy density in the reverberation room, and by denoting the frequency and ambient air density as f and ρ_0, respectively. Diestel also used the room volume V, the Sabine reverberation time T, and the speed of sound c, to determine $J_{\mathrm{df}} = (2.1/\rho_0 f)(V/cT)^{1/2}$, another useful expression.

While the significance of Diestel's accomplishment has been recognized, this method has not been widely used or standardized, for at least two reasons. First, the reverberation room must provide a very good diffuse field and must be extremely well characterized. Even with a good room at PTB, Diestel apparently needed to average results from measurements using three different positions of the microphones/loudspeakers to estimate the microphone sensitivity level with a standard error less than 1 dB at frequency bands from 0.5 to 16 kHz. Second, because even the best reverberation rooms are imperfect, it is difficult to include the effects of sound absorption by the air in the room on calibration results, especially at high frequencies, where such absorption can be sufficiently large and dependent on environmental conditions (especially humidity) to compromise primary calibration accuracy. Consequently, there is ambiguity in the determination of J_{df}, and, therefore, in the determination of $M_{\mathrm{df}a}$ and $M_{\mathrm{df}b}$.

Method from Free-Field Measurements of Directivity and Reference Sensitivity Of two important primary methods of diffuse-field calibration, this is the more widely used method, has long been available,[17] and has appeared in both an IEC standard[18] on diffuse-field calibration of sound level meters and in established

ANSI standards.[7,19] This IEC standard formally distinguishes between the random-incidence and diffuse-field sensitivities of a microphone, using the term "diffuse-field" differently than the ANSI standard[7] for microphone calibration. However, the IEC standard considers the random-incidence and diffuse-field sensitivities to be equivalent, so that they can be used as synonyms. Brinkmann and Goydtke[20] discuss this issue in detail and describe experimental procedures and apparatus for determining random-incidence and diffuse-field sensitivities in an anechoic chamber and reverberation room, respectively. From results of both kinds of microphone calibrations, they conclude that, when carefully performed, the two methods can be considered equivalent to an accuracy sufficient for most practical sound measurements.

For free-field measurements in an anechoic chamber, a sound source is excited by a sine-wave signal or band of noise. For a sufficient number of angles of incidence sampling the solid angle 4π (or a smaller angle, given a symmetry assumption about the microphone and sound field), the directivity of the microphone is measured. From these and the appropriate reference sensitivity measurements at the specified reference direction of incidence, the diffuse-field sensitivity is calculated, for example, as a correction to the reference free-field sensitivity. This reference sensitivity may be obtained by the reciprocity technique described in Section 4.3. The directivity measurements require a very good and well-characterized anechoic chamber, which a primary standards laboratory must already have for use in the primary and secondary free-field calibration of microphones. If all measurements of directivity patterns in a given calibration are conducted at the same, or nearly the same, ambient environmental conditions, the effects of atmospheric attenuation of sound need not be calculated. If necessary, these effects are much easier to calculate and to include in this method than in reverberation room measurements.

Uncertainties in Determination of Diffuse-Field Sensitivity Level Uncertainties in determination of diffuse-field sensitivity level are particularly dependent on the characteristics of the reverberation room or anechoic chamber in which the measurements are performed. Comparison of the results from different methods is invaluable. Brinkmann's and Goydke's results showed that random-incidence and diffuse-field sensitivity levels of the microphone carefully determined in an anechoic chamber and reverberation room, respectively, were equal with an uncertainty of about 0.1 dB for frequencies as high as about 12.5 kHz. Their methods and measurements in a reverberation room have based on free-field measurements of directivity evidently improved upon the accuracy of the diffuse-field reciprocity method devised by Diestel.

For what is now termed[1,2] an IEC Type LS1Po or ANSI Type L laboratory standard microphone, Diestel[16] compared the sensitivity levels measured by the diffuse-field reciprocity method using one-third-octave bands of noise and the sensitivity levels calculated from the directivity patterns and the free-field response at the midfrequency of each band. Throughout the frequency range 0.5–16 kHz, the agreement was within about 1 dB. At frequencies below 0.5 kHz, the sound wavelength is sufficiently large relative to the dimensions of this microphone-type that diffraction effects are practically negligible, and the pressure, free-field, and diffuse-field sensitivities may be considered essentially equal, provided that the effect of the ambient pressure equalization vent is also negligible.

5 TESTS OF MICROPHONE LINEARITY WITHIN OPERATING DYNAMIC RANGE

Laboratory standard and other condenser microphones are similar to single-sided electrostatic loudspeakers,[21] which do not behave as linear transducers at sound pressures so large that the diaphragm displacement is not small relative to the spacing between the diaphragm and the back electrode (backplate). Consequently, an upper limit to the microphone operating dynamic range is typically specified in terms of the maximum sound pressure level (SPL) that the microphone can measure for a given total harmonic distortion at its electrical output terminals.[1,2] For all microphones, the interaction of the microphone and preamplifier should be considered when measuring or interpreting the dynamic range. Important distinctions may exist between the upper limit of the operating dynamic range and the maximum SPL and static overpressure that the microphone system can withstand (but not necessarily measure) without damage. The lower limit of dynamic range typically is attributable to noise mechanisms, including thermal noise, in the microphone and preamplifier, as well as the type of signal processing used to measure a band-limited or periodic signal in the presence of noise.

The most accurate and convenient measurements of microphone linearity typically involve exciting a sound source such as a condenser microphone or electrodynamic transducer with a precise electrical signal that can be accurately attenuated in known increments. This source is acoustically coupled (in a coupler, or in a free-field, etc.) to the receiving microphone or microphone system, and the received output voltage level is compared with the excitation signal level for each value of attenuation. If the receiver has already been calibrated by a primary or secondary method at one or more given levels, the differential level linearity of the source–acoustical-coupling–receiver combination can be checked.[11]

6 SELECTED SECONDARY CALIBRATION METHODS

6.1 Direct-Comparison (Substitution) Method

A sound source is placed in an acoustical coupler (for pressure calibration) or in an anechoic chamber (for free-field calibration), and the transfer function relating the source excitation signal and the output voltage of a reference microphone (calibrated by a primary method) is determined.[7] The test microphone of unknown sensitivity is substituted for the reference microphone, and the corresponding transfer function for the source and test microphone is determined. From the ratio of these transfer functions, the known sensitivity of the reference microphone, and consideration of certain potentially significant differences between the test and reference microphones, the sensitivity of the test microphone is determined.

6.2 Reciprocity-Based (Reference Sensitivity and Impedance) Comparison Method

A reference microphone or other sound source for which both the receiving sensitivity and the modulus of the driving-point electrical impedance have been determined by the reciprocity method is used as a sound source, and the test microphone is used as a receiver, in an acoustical coupler or an anechoic chamber. The reference source and the test microphone occupy the same positions in the same coupler or anechoic chamber as have been used for the corresponding sources and microphones in the calibration of this reference. From the measured transfer function relating the output voltage of the test microphone to the voltage driving the reference source, the known sensitivity and electrical impedance of the source, and the known properties of the coupler or anechoic chamber (including the acoustic transfer impedance between the source and receiver), the sensitivity of the test microphone is determined.[22]

This method is particularly applicable to the pressure calibration of microphones in acoustical couplers, especially if hydrogen is used for measurements at high frequencies, because only a single assembly and sealing of the microphones into the coupler is needed, practically halving the labor required for a given calibration by the substitution method. Signal-to-noise ratio limitations in free-field comparison calibrations, due to the low output levels available from microphones used as sound sources, typically require the use of electrodynamic sound sources. These are often more directional, and in particular less stable, than microphone sources. Consequently, free-field calibrations are usually performed by the direct comparison (substitution) method, which relies on the short-term (not the long-term) stability of the electrodynamic source.

6.3 Uncertainties in Determination of Pressure Sensitivity by the Reciprocity-Based (Reference Sensitivity and Impedance) Comparison Method

Because the same couplers are used at the same frequencies in the comparison calibration and in the calibration of the reference microphone by reciprocity, some systematic uncertainty components of the comparison calibration that are associated with the acoustic transfer impedance between the transmitting and receiving microphones are partially canceled and are only as large as they would be in a reciprocity calibration. If the reference microphones are sufficiently stable throughout the time intervals between their calibrations by the reciprocity method, and if certain other conditions are met, the overall uncertainty of calibration approaches that of a reciprocity calibration.[11]

6.4 Uncertainties in Free-Field Calibration by the Direct-Comparison (Substitution) Method

Among the most critical factors in the direct-comparison method are the quality of the anechoic chamber and the limitations imposed by the characteristics of the sound source, including its directivity, output level, linearity, and short-term stability. The anechoic chamber and apparatus used for comparison calibrations are often distinct from, and less well characterized than, those used for free-field primary calibration by the reciprocity method. In this case, differences between the sensitivity levels of the test microphone determined in the comparison calibration and of the reference microphone determined in the primary calibration can be compared with the corresponding differences in sensitivity levels determined for both microphones by the primary calibration using the relatively well-characterized, dedicated anechoic chamber and reciprocity calibration apparatus. At each frequency, the difference of these differences provides a check of the degree to which comparison calibration results approach those of the primary calibration by the reciprocity method. Such checks have been performed with 12.7-mm nominal diameter condenser measuring microphones at NIST,[11] using in the comparison calibration a variety of source excitation signal types and signal processing methods. These signals and methods differed in the degrees to which they were influenced by reflections from the chamber walls, transducer/measurement system nonlinearities, signal-to-noise ratios, and so forth. For the case of a band-limited impulse excitation signal, with signal processing [fast Fourier transform (FFT) analysis] configured to eliminate the most significant of the relatively slight reflections from the interior surfaces of the chamber, the absolute values of these differences were about 0.2 dB or less at frequencies from 2 to 20 kHz and about 0.35 dB or less at frequencies from 20 to 40 kHz.

6.5 Calibrators of the Closed-Coupler Type

Closed-coupler type devices, which include pistonphones, as well as other calibrators incorporating electrodynamic, piezoelectric, or combination transducers, produce a sound pressure (usually a sine-wave signal), most commonly at a frequency or frequencies from 250 Hz to 1 kHz.[23,24] The microphone is inserted into these calibrators so that its diaphragm forms part of the walls of a coupler that is enclosed, except for a capillary tube or vent intended to equalize the coupler interior to ambient barometric pressure. Often, the equalization vent of the microphone is not exposed to the sound field. Most frequently, such calibrators are manufactured to serve as convenient, portable devices generating conveniently high SPL (most commonly from 94 to 124 dB, relative to 20 μPa) for secondary and tertiary laboratory and user field checks of the pressure sensitivity of a microphone system, sound level meter, personal sound exposure meter, or other instrument. Typically, calibrated laboratory standard microphones are used to measure the SPL produced by these calibrators, which are then capable of achieving uncertainties of about 0.15–0.3 dB at their primary calibration frequencies and levels in checking the pressure sensitivities of the instruments under test.

6.6 Electrostatic Actuator Method

An electrostatic actuator (typically a slotted or perforated electrically conductive plate), to which are applied an AC signal voltage and a much larger polarizing DC voltage, is placed in close (e.g., 0.5 mm) proximity to the diaphragm of the microphone to be calibrated. Usually, this diaphragm is at ground potential, and the resulting electrostatic force can be calculated and used to determine the approximate pressure sensitivity of the microphone.[25] Because such absolute determination requires precise measurement of the small separation distance between the actuator and microphone diaphragm, this method is usually performed to determine only the relative frequency response of the test microphone. This response is then combined with a single-frequency pressure calibration, for example, by means of a pistonphone or acoustic calibrator, to determine the approximate pressure sensitivity. This method is widely used by instrument manufacturers[26] and others because it can be applied over a broad frequency range to the rapid, relatively low-cost calibration of individual microphones, as in production line testing. However, the degree to which the actuator-determined response approximates a pressure calibration depends on the relation between the mechanical impedance of the microphone diaphragm and the effective mechanical radiation impedance loading the diaphragm in the presence of the actuator.[27] Consequently, the actuator-determined sensitivity of the microphone differs from its pressure sensitivity. For ANSI Type L laboratory standard microphones, this difference may be as large in absolute value as about 1.5 dB within the frequency range 5–20 kHz;[28,29] for condenser measuring microphones 12.7 mm in nominal diameter, this value may be as large as about 1.3 dB at frequencies from 10 to 20 kHz, and depends on both the actuator and microphone type.[11,22] Therefore, there are no current major international or ANSI standards for the primary or secondary calibration of laboratory standard microphones by the actuator method, and the use of a given electrostatic actuator with a given microphone type to approximate a pressure calibration should be validated by reciprocity or reciprocity-based calibrations performed in couplers. The large AC signal electrostatic fields produced by the actuator do not usually cause a serious problem of crosstalk to the high-input-impedance electrical input terminal of a condenser microphone preamplifier for microphones with electrically grounded metal diaphragms and microphone/preamplifier housings, because this terminal is effectively enclosed in a Faraday cage. However, there can be problems in the case of electret and semiconductor condenser microphones with diaphragms that are not good electrical conductors. The electrostatic actuator calibration of such microphones must always be validated by other calibration techniques that are far less susceptible to such crosstalk.

7 SPECIAL CONSIDERATIONS REGARDING GRADIENT AND COMBINATION MICROPHONES

7.1 Types of Sources, Microphones, and Separation Distance

For these microphones, the results obtained in a given application depend on the nature of the source (simple monopole, dipole, quadrupole, etc.), the frequency of the sound radiated by the source, the kind of microphone (first-order, second-order, or higher-order gradient, combination, etc.), and the distance between the microphone and the source. The source itself must be well characterized and its radiation characteristics must be known. Even in the case of a simple (monopole) source, the responses of gradient microphones, as well as the gradient components of the responses of combination microphones, show pronounced increases (relative to their far-field responses to the same source) at frequencies and distances for which the distance becomes significantly smaller than the sound wavelength.[3–5] This relative rise in low-frequency response is sometimes termed the proximity effect and is even more pronounced for high-order gradient microphones than for those of first order. Indeed, this effect is inherent in the design of certain noise-canceling microphones intended for "close-talking" applications.[5]

7.2 Free-Field Calibration by the Direct-Comparison (Substitution) Method

A common method of calibrating gradient and combination microphones is by comparison with a calibrated reference microphone, using a simple (monopole) source of sound at a given distance in the free field. For these conditions, the sound pressure gradients of first and higher orders can be determined from the measured sound pressure and distance from the source by using harmonic excitation of the source and invoking: (1) the solution of the wave equation in spherical coordinates and (2) the definitions of the sound pressure gradients of the first and higher orders. In such calibrations, the source behavior must be characterized, for example, by measuring its directionality and the sound pressure as a function of distance from the source, and by examining the degree to which measured behavior in the region about the microphone position used for calibration approaches the theoretical behavior of such a source.

7.3 Influence of Calibration Environment

Particular attention in the case of gradient and combination microphones must be given to the degree to which the source characteristics and acoustic field approximate the intended calibration situation. For example, if the sound field radiated by a source that is considered a monopole includes dipole, quadrupole, or even more complicated components, the interpretation of calibration results can be substantially in error, especially at frequencies for which the distance between the source and microphone is smaller than the sound wavelength. In this case, for free-field calibrations, anechoic chamber imperfections (such as reflections from the interior surfaces of the chamber) can cause particularly significant errors. These errors can occur both in the calibration at a specific angle of incidence and in the measurement of directionality, especially if the source and receiver are placed too close to these surfaces, so that the microphone effectively responds to the near-field components of image sources as well as the intended source. At such frequencies and distances for diffuse-field calibrations in a reverberation room, room imperfections can introduce very substantial errors, not only in diffuse-field calibration but also in the measurement of other properties such as the noise rejection provided by close-talking microphones.

To examine the calibration uncertainties associated with imperfections in an anechoic chamber or reverberation room, it may be helpful to perform calibrations at two or more different positions for several different source-receiver separations and to compare differences in the calibration results for different positions with the same separation distance, as well as differences in the results for different separation distances. Comparison of calibration results with results obtained in another chamber of known high quality can also be useful. In frequency ranges for which the microphone response does not vary too much with frequency, differences between calibration results using sinusoidal or other periodic signals that would be expected strongly to excite standing waves, and results using frequency bands of random noise that are much less likely to do so, may be valuable. For anechoic chambers, using transient signals and gating techniques to eliminate major sound reflections from interior surfaces of the chamber can also be helpful.

8 PHASE RESPONSE OF MICROPHONES

Numerous needs exist in experimental science, research and development, and engineering practice for determining the absolute and relative (e.g., to another microphone) sinusoidal-steady-state frequency response phase angles as well as the response moduli (magnitudes) of microphones.[30,31] The pressure and free-field sensitivities obtained during the primary calibration of laboratory standard microphones by reciprocity methods[7,8] can be expressed in terms of complex amplitudes. From these expressions and physical considerations resolving mathematically derived sign ambiguity,[14] the microphone phase response can be obtained.[32] However, there must be further development of these primary standard methods, ideally involving interlaboratory comparisons of calibration results, before these methods can be used readily to determine absolute phase response with well-documented frequency-dependent uncertainties.

Relative pressure and free-field phase response calibrations of microphones by secondary methods are particularly important for the measurement of sound intensity using one or more pairs of pressure microphones (often termed the "p-p intensity probe method").

9 RELATIVE RESPONSES OF PRESSURE MICROPHONES USED IN P-P INTENSITY PROBES

The p-p method for measuring sound intensity is critically dependent on microphone system response angles at low frequencies, at which for a given microphone spacing the phase difference due to the acoustic pressure gradient (and, consequently, the acoustic particle velocity) between the microphones is small. This dependence is especially critical for cases in which one must measure time-varying or nonstationary signals, for which switching techniques[33] intended to lessen this dependence are difficult or impossible to implement. Issues regarding the calibration of p-p acoustic intensity probes are discussed in Chapter 156, and are considered in an IEC standard[34] and an ANSI standard[35] that is nearing completion. The measurement of relative phase response remains an active area of ongoing research, but it appears at present that the most accurate measurements of relative amplitude and phase response can be obtained in couplers[36] and standing-wave tubes at low frequencies, and in the free field at high frequencies.

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