JASA EXPRESS LETTERS ARTICLE asa.scitation.org/journal/jel

Laser-based comparison calibration of laboratory standard microphones

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Abstract: A precision laser-based comparison calibration method for laboratory standard microphones is described that uses reference microphones calibrated by the pressure reciprocity method. Electrical drive current and diaphragm velocity are measured while the microphones are driven as transmitters/sources of sound; the diaphragm velocity is measured using scanning laser Doppler vibrometry. Sensitivities determined using this method display very good agreement with those determined directly by reciprocity for seven such test microphones at 250 and 1000 Hz. At these frequencies, the expanded (coverage factor $k = 2$) uncertainties of this comparison calibration method for these microphones are ±0.05 dB.

[Editor: Mark Sheplak] https://doi.org/10.1121/10.0005919

Received: 2 June 2021 **Accepted:** 2 August 2021 **Published Online:** 30 August 2021

1. Introduction

Microphones are calibrated to determine their sensitivities for sound pressure measurements and to calibrate other microphones as well as sound calibrators, which apply known sound pressures to calibrate acoustical measurement equipment used in the laboratory or field. Such equipment includes sound-level meters, personal sound exposure meters (i.e., noise dosimeters), noise monitoring stations, sound power measurement systems, audiometric equipment, hearing aid test setups, and measuring microphone systems. The sensitivity of a microphone is expressed in SI units of V/Pa, but often it is expressed instead as a sensitivity level in dB with respect to a reference of 1 V/Pa.

Primary microphone calibrations which are carried out without the need for a reference to another standard of sound pressure (e.g., a calibrated microphone), are performed at national measurement institutes and other organizations worldwide using the reciprocity method.[1–4] For the calibration of laboratory standard (LS) microphones which are designated as type LS1P (nominal 18.6-mm diameter, flat pressure response) or type LS2P (nominal 9.3-mm diameter, flat pressure response),[5,6] this method is standardized.[7,8]

Standardized methods for secondary calibrations of microphones[9] are implemented by simultaneously or sequentially exposing a calibrated reference microphone and the test microphone to nominally identical acoustic fields. The ratio of the pressure sensitivities of the two microphones is then assumed to be equal to the ratio of their output voltages. A critical element of successful implementation of these methods is ensuring that the two microphones are exposed to identical acoustic fields. The applicable standard describes several mounting arrangements for both microphones to achieve such fields. At the National Institute of Standards and Technology (NIST), a reciprocity-based comparison method is used where a calibrated reference microphone serves as a transmitter electrically driven to produce sound in an acoustic coupler cavity that is sensed by the receiver microphone which is an uncalibrated test microphone.[10] The sensitivity of the test microphone is determined from drive-to-receive voltage ratio measurements, the reference microphone sensitivity and driving point electrical impedance, and the acoustic transfer impedance of the cavity.

One approach that has been investigated for microphone calibration as an alternative to the reciprocity method involves laser Doppler vibrometer (LDV) measurements of the velocity at different points on a microphone diaphragm to determine its volume velocity when acting as a transmitter/source of sound driven with a current through its electrical terminals.[11–13] This approach utilizes the fact that the magnitude of the pressure sensitivity of a reciprocal transducer is the same regardless of whether it is used as a receiver of sound or a source of sound. The former is expressed in terms of open-circuit output voltage for a given incident sound pressure uniformly distributed across the diaphragm, whereas the latter is expressed in terms of output volume velocity for a given drive current. Both expressions reduce to the same SI base units. These investigations have clearly demonstrated the feasibility of implementing primary microphone calibrations

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with laser-based velocity measurements of diaphragm vibration, but the results obtained were not established to be as accurate as the results typically obtained with the reciprocity method. Along similar lines, a technique that utilizes microscope-mounted laser vibrometers to measure displacements across the diaphragms of piezoelectric microelectromechanical system microphones and dynamic pressure sensors during electromechanical actuation has been developed to replace shock tube measurements as a means for calibrating these piezoelectric devices.[14]

In preliminary scanning LDV velocity measurements done at NIST of type LS1P microphones, coarse scans were made across the entire diaphragm of each microphone to develop velocity profiles as a function of the radial distance from the center. Figure 1 shows such a velocity profile for one of the microphones driven with a current of 0.676 μA at a frequency of 1000 Hz. The data with best repeatability were acquired in the central region of the diaphragm where the motion is greatest and where the data are relatively uniform spatially. Based on these observations, a model and equations originally developed for calibration utilizing a single-point measurement at the diaphragm center, without a reference microphone,[13] were applied to develop the precision laser-based comparison calibration method discussed herein that uses a reference LS1P microphone calibrated by reciprocity. Application of this model therefore led to the acquisition of velocity data with a fine spatial resolution in a relatively small scan area around the diaphragm center to optimize the scanning procedure for the comparison calibration method.

The magnitude of the frequency-dependent pressure sensitivity $|M|$ of a microphone in transmitter mode is expressed as

$$|M| = \left| -\frac{q}{i} \frac{Z_a + Z_r}{Z_a} \right|, \tag{1}$$

where q is the volume velocity, i is the drive current through the terminals of the microphone, Z_a is the acoustic impedance of the microphone, and Z_r is the radiation impedance of the microphone. For microphones of the same type, the model assumes that the distribution of vibration on the surface of the diaphragm and the volume velocity normalized to the velocity at the center of the diaphragm are consistent from sample to sample in terms of the normalized frequency, which is equal to the drive frequency divided by the resonance frequency of the microphone sample. To apply the model, Eq. (1) is rewritten as

$$|M| = \left| -\frac{q_n u(r_0)}{i} \frac{Z_a + Z_r}{Z_a} \right|, \tag{2}$$

where q is replaced by the product of the normalized volume velocity q_n and the velocity at the diaphragm center $u(r_0)$. Values of q_n, derived empirically from LDV velocity measurements across the diaphragms of LS1P microphones driven in transmitter mode, are available as a function of the normalized frequency in the forms of graphical data[13] and tabular data.[15]

For the comparison calibration work described herein, a version of Eq. (2) is applied for a reference (calibrated) microphone with a known pressure sensitivity M_R, and another version is applied for a test (uncalibrated) microphone with an unknown pressure sensitivity M_T. After dividing the equation for M_T by the one for M_R and solving for $|M_T|$, the equation

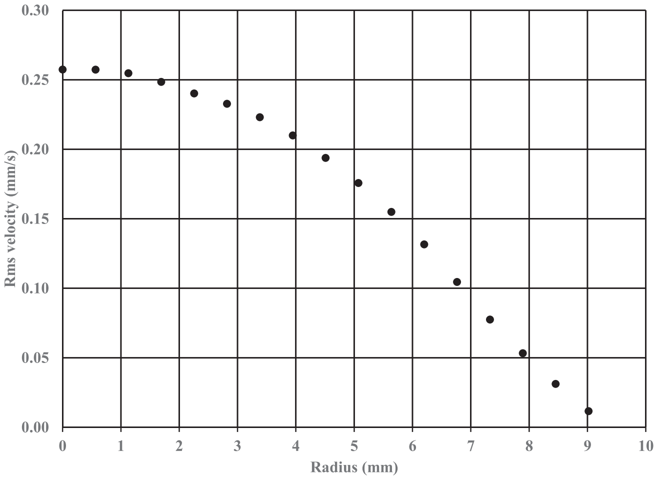

Fig. 1. Diaphragm rms velocity (mm/s) profile as a function of the radius (mm) from the diaphragm center for a type LS1P microphone driven with a current of 0.676 μA at a frequency of 1000 Hz. The microphone diaphragm has a radius of 9.3 mm.

$$|M_T| = \left| M_R \left(\frac{i_R}{i_T}\right) \left(\frac{u(r_0)_T}{u(r_0)_R}\right) \left(\frac{(q_n)_T}{(q_n)_R}\right) \left(\left(\frac{Z_a + Z_r}{Z_a}\right)_T \Big/ \left(\frac{Z_a + Z_r}{Z_a}\right)_R \right) \right| \tag{3}$$

is obtained, where the subscript T designates a parameter associated with the test microphone and the subscript R designates a parameter associated with the reference microphone. For type LS1P test and reference microphones at relatively low frequencies (1000 Hz and below), the last two terms in the product of Eq. (3), which are the ratio of impedance terms and the ratio of normalized volume velocities, can both be assumed to be equal to 1; uncertainties related to these assumptions are included as discussed in Sec. 4. As the measurements discussed herein were conducted at frequencies of 250 and 1000 Hz, the applicable equation reduces to

$$|M_T| = \left| M_R \left(\frac{i_R}{i_T}\right) \left(\frac{u(r_0)_T}{u(r_0)_R}\right) \right|. \tag{4}$$

These frequencies were chosen because of their widespread use in specifications for acoustical instrumentation and in sound calibrators, which usually limit their available frequency options to one or both of these two. Rather than perform an absolute calibration at multiple frequencies, it is often more practical for many acoustical measurement setups to use an absolute calibration performed with a sound calibrator at a single frequency in combination with a microphone frequency response determined by an electrostatic actuator[16] or the manufacturer's specifications for frequency response/flatness.

2. Measurement procedure

Figure 2 shows the experimental setup. The microphone drive current is produced and determined in a manner similar to that described for reciprocity calibrations done at NIST.[17] A Hewlett-Packard (HP) 8904A Multifunction Synthesizer (Certain commercial equipment, instruments, or materials are identified in this paper to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by NIST or intended to imply that the materials or equipment identified are necessarily the best available for the purpose.) (HP, Palo Alto, CA) supplies a sinusoidal 1.0-V test signal to a Brüel & Kjær (B&K) Type 5998 Reciprocity Calibration Apparatus (RCA; B&K, Nærum, Denmark). The RCA amplifies the test signal by 6 dB and directs it to the microphone through a B&K Transmitter Unit ZE 0796, which contains a calibrated capacitor in series with the microphone. The RCA also provides the microphone with its 200-V polarization voltage. An HP 3458A Multimeter configured as an alternating current voltmeter measures the voltage across the capacitor through an output of the RCA. A trigger circuit synchronized to the test signal from the synthesizer is used to provide a trigger to the voltmeter. After the voltage across the capacitor is measured, the microphone drive current is calculated from the known capacitance. The coherence measured between the synthesizer output and the capacitor voltage at each frequency was effectively unity (value consistently measured either 0.999 999 or 1.000 000), indicating low noise and a linear relationship between the two voltages.

The microphone diaphragm velocity measurements are made with a Polytec PSV-400-H4-S Scanning Vibrometer that includes a Polytec OFV-5000 Vibrometer Controller used with a VD-07-S velocity decoder set to its most sensitive range of 2 (mm/s)/V, a Polytec PSV-I-400 Sensor Head with a PSV-A-410 close-up unit, and a PSV-400 Junction Box (Polytec, Irvine, CA). By performing automated measurements while scanning the laser beam over the desired area of the diaphragm, this system acquires velocity data at multiple scan point locations on the diaphragm. At each scan point, the velocity is measured from the decoder signal using fast Fourier transform (FFT) signal processing. For a given scan,

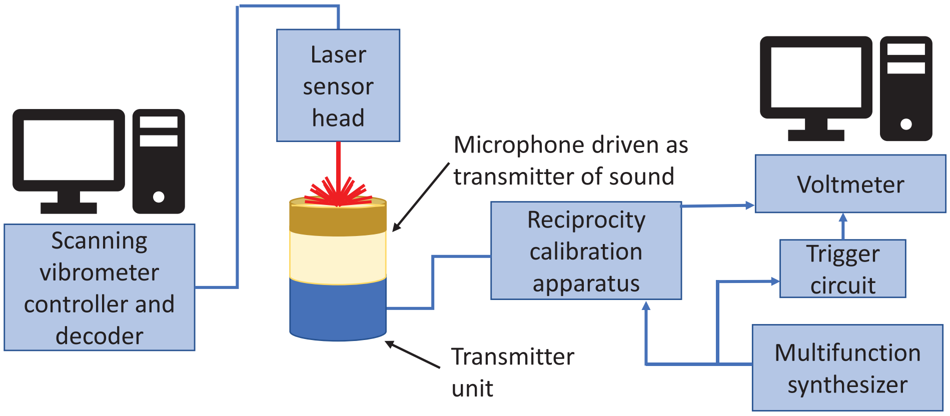

Fig. 2. Block diagram of the experimental setup.

only the FFT data for the single-frequency bin containing the sinusoidal test frequency are utilized because the microphone is driven during the entire scan at that single frequency.

The velocity was measured in a circular grid of 129 points in the central 7% of the total diaphragm area. The grid consisted of a single center point and 16 rings with eight points each, with 0.15-mm spacing between rings. In addition, there were four diaphragm edge points used only as visual aids to set the alignment.

Nine B&K 4160 microphones, which are type LS1P microphones, were used to acquire the data to develop the comparison calibration method. Each of these microphones was also calibrated at 250 and 1000 Hz by the reciprocity method using the NIST plane wave coupler reciprocity calibration system. On a given day, the current and velocity measurements were made at both test frequencies on all microphones sequentially to develop a single complete set of data for the microphone group. Seven such datasets containing a trial for each microphone were acquired for the group of nine microphones.

Barometric pressure and temperature data were also acquired during the measurements to ensure that these parameters did not drift outside allowed limits. For a given day, the ambient barometric pressure is required to stay within a range of 10 millibars. The temperature requirement is 23 ± 2 °C.

3. Data reduction and experimental results

Two of the nine microphones, the two with the best repeatability in velocity divided by current with all velocity points included, over all trials at 250 Hz were chosen as reference microphones. At a given frequency, the sensitivity of each test microphone was calculated as the average of the two sensitivities determined using these two reference microphones.

For each test microphone and frequency, the variance of the sensitivities measured from all seven comparison calibration trials was calculated. For each frequency, the relative pooled standard deviation was determined from the relative pooled variance calculated by pooling the variances for all seven test microphones. This standard deviation characterizes the repeatability of the comparison calibration method and is a component of the combined standard and expanded uncertainties of the measured sensitivity discussed in Sec. 4. The relative pooled standard deviation of the sensitivities measured across all trials is shown in Fig. 3 for both frequencies as a function of the radius of the circular center region (i.e., number of rings) included in the calculations. Due to the higher velocity signal at 1000 Hz, the repeatability is better at this frequency compared with 250 Hz for any given radius. For both frequencies, as the radius of the scanned area increases, the relative pooled standard deviation improves until it reaches a minimum at a radius of 1.65 mm (11th ring) for 250 Hz and a minimum at a radius of 1.50 mm (10th ring) for 1000 Hz. Including the additional data points out to the 16th ring beyond these smaller areas slightly worsens the repeatability. The following results were therefore determined only from data obtained from the points within these smaller scanned areas (3% of the total diaphragm area).

Sensitivities of the seven test microphones as measured with the laser-based comparison calibration method were compared with the sensitivities as measured via the reciprocity method. The differences are shown in Fig. 4(a) for 250 Hz and Fig. 4(b) for 1000 Hz, where positive values indicate that the sensitivities measured by the comparison method are greater than the sensitivities measured by reciprocity. The expanded (coverage factor $k = 2$) uncertainty[18] U is displayed separately for each method, as bars at each data point for the comparison method ($U = \pm 0.05$ dB at both frequencies), and as dashed lines symmetric about the zero-difference line for the reciprocity method ($U = \pm 0.03$ dB at both frequencies). For 250 Hz, the average absolute difference is 0.027 dB, and the largest difference is 0.042 dB; for 1000 Hz, these values are 0.026 dB and 0.050 dB, respectively. For both frequencies, the differences indicate very good agreement between the

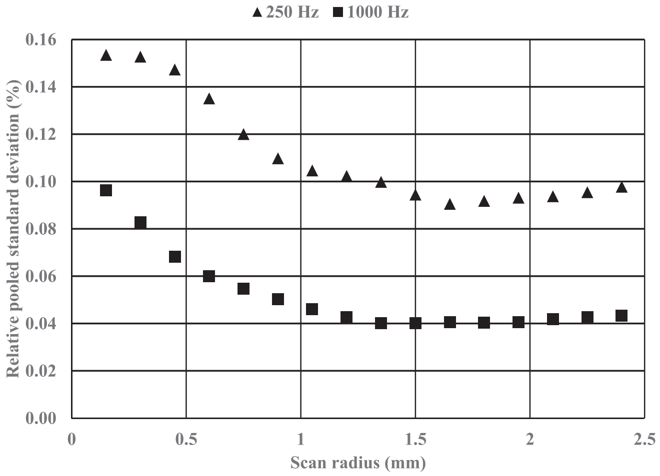

Fig. 3. The relative pooled standard deviations of the sensitivities measured across all trials for 250 and 1000 Hz as a function of the radius of the scanned circular center region (i.e., number of rings) of the microphone diaphragms included in the calculations.

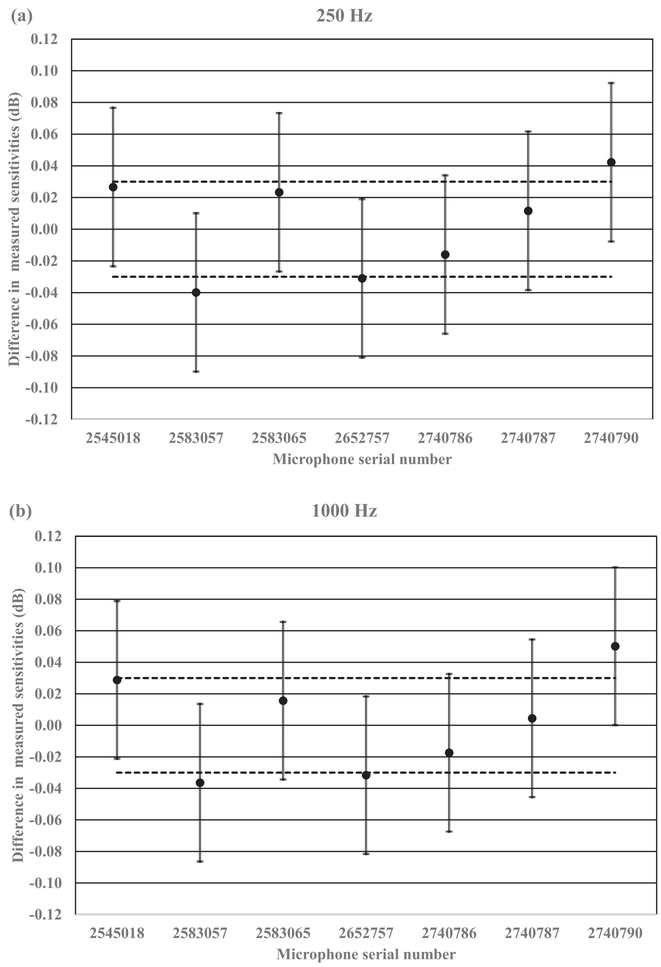

Fig. 4. Differences between the sensitivities of the seven test microphones as measured with the laser-based comparison calibration method and the sensitivities as measured via the reciprocity method for each microphone. (a) 250 Hz. (b) 1000 Hz. A positive value indicates that the sensitivity measured with the comparison method is greater than the sensitivity measured by reciprocity. Uncertainties of reciprocity calibration indicated by dashed lines; uncertainties of laser-based comparison calibration indicated by vertical bars.

two methods. Two statistical tests were performed to verify the observed agreement. At each frequency, a paired *t* test showed that the calculated *t* value is less than the critical *t* value, indicating that the means are not significantly different (with a probability of 95%). In addition, results from the two methods were compared with each other by calculating normalized deviations, an approach utilized for comparing measurement results obtained by laboratories participating in an interlaboratory comparison with the comparison reference value.[19] A normalized deviation is the difference between the values being compared divided by the root-sum-square of their uncertainties. If the absolute value of a normalized deviation is less than unity, the measurement result is considered to be in agreement with the reference value. If the absolute value of a normalized deviation is greater than unity, the difference between the measured result and the reference value is considered to be greater than what would be expected based on the uncertainties of both. At each frequency, all the normalized deviations were less than unity, indicating agreement between the two methods.

4. Uncertainty evaluation

Published guidelines for evaluating uncertainties[18] were applied to determine the standard and expanded ($k = 2$) uncertainties for the laser-based comparison calibration results. These uncertainties are reported and summarized in Table 1 for both frequencies. For each frequency, a standard uncertainty is shown for each individual contributing component along with the expanded uncertainty calculated for the measured sensitivities by combining the component standard uncertainties according to these guidelines. In addition, the type designations (A or B) of the component uncertainties are listed.

A type A standard uncertainty u_{A1} was determined by calculating the variance of the sensitivities measured for each test microphone over all seven of the trials and pooling the variances obtained for all seven microphones. This

Table 1. Standard and expanded (coverage factor $k = 2$) uncertainties of the laser-based comparison calibration sensitivity measurements for 250 and 1000 Hz.

Standard uncertainties (%)			
Symbol: description	Type	250 Hz	1000 Hz
u_{A1}: repeatability/pooled variance	A	±0.091	±0.040
u_{A2}: long-term drift of references	A	±0.092	±0.092
u_{B1}: sensitivities of references	B	±0.173	±0.173
u_{B2}: velocity ratio	B	±0.136	±0.093
u_{B3}: current ratio	B	±0.046	±0.046
u_{B4}: normalized volume velocities	B	±0.052	±0.073
u_{B5}: polarization voltage	B	±0.001	±0.001
u_{B6}: barometric pressure drift	B	±0.003	±0.003
u_{B7}: temperature drift	B	±0.013	±0.013
u_{B8}: ratio of impedance terms	B	±0.000	±0.001
Expanded ($k = 2$) uncertainties (%)			
U		±0.53	±0.47
Expanded ($k = 2$) uncertainties (dB)			
U		±0.05	±0.05

standard uncertainty is equal to the standard deviation derived from the pooled variance. It characterizes the repeatability of the comparison calibration method.

An additional type A standard uncertainty u_{A2} was determined based on the results of a previous statistical analysis[20] of the long-term stability of type LS1P microphones calibrated at NIST. It is included to account for the drift that can occur in the sensitivities of the reference microphones between periodic reciprocity calibrations, which historically have been done routinely at NIST every two years.

A type B standard uncertainty u_{B1} is included to account for the uncertainty of the reference microphone sensitivity at a given frequency as determined by reciprocity. It is equal to one half of the expanded ($k = 2$) uncertainty of this sensitivity, which was derived in the same manner as previously described for type LS2aP microphone calibrations done at NIST.[17]

All of the additional standard uncertainties considered to arise from various other effects were determined from type B evaluations by establishing values for the upper and lower bounds of symmetric rectangular probability distributions based on estimated limits of the effects on the measurement results due to each source of uncertainty.[18] In the absence of any information concerning the shape of the probability distribution, a rectangular distribution is a reasonable default model to assume. The standard deviation of a rectangular probability distribution is equal to one half of the width of the distribution divided by the square root of 3. To determine the standard uncertainties for these type B evaluations, the standard deviations were calculated for each of the rectangular probability distributions developed.

To derive the standard uncertainty u_{B2} of the velocity ratio measured between the test and reference microphones, velocity measurements were performed on three different microphones at four different drive voltages (0.60, 0.84, 1.0, and 1.1 V) measured at the output of the synthesizer to investigate the linearity of the velocity measurements. This range in drive voltages more than covers the range (4 dB) of sensitivities specified for type LS1P microphones at the two frequencies used.[5,6] For all three microphones, the various velocity ratios calculated for a given microphone from the velocities measured for the microphone at the different drive voltages were calculated and compared with the values expected based on the ratios of the measured drive voltages. The largest discrepancy found was used to establish bounds for a symmetric rectangular probability distribution. The same approach was used to develop the standard uncertainty u_{B3} for the current ratio measured between the reference and test microphones by using the voltage data measured across the reference capacitor instead of the velocity data.

The standard uncertainty u_{B4} of the ratio of normalized volume velocities for the test and reference microphones is included to account for potential deviations of this ratio from 1. Such deviations could potentially be caused by differences in resonance frequencies from the nominal value of 8200 Hz provided for the type LS1P microphone samples.[21] Bounds were established for a symmetric rectangular probability distribution based on deviations in values of measured resonance frequencies reported for type LS1P[13] and type LS2P[22] microphones from nominal values in combination with values of q_n as a function of normalized frequency available as graphical data[13] and tabular data.[15]

To determine the standard uncertainty u_{B5} associated with the uncertainty of the polarization voltage, bounds were established for a symmetric rectangular probability distribution from the multimeter manufacturer's accuracy specifications for direct current voltage measurements and the 1-mV difference allowed in the setting of the voltage.

The standard uncertainties u_{B6} and u_{B7} are included to account for effects due to drift in the ambient barometric pressure and temperature, respectively, that could occur during the course of the comparison calibration between reference microphone and test microphone measurements. Bounds were established for symmetric rectangular probability distributions based on published data[23] regarding the static pressure and temperature coefficients of laboratory standard microphones and allowed drifts in the measured pressure and temperature.

The standard uncertainty u_{B8} of the ratio of impedance terms for the test and reference microphones is included to account for potential deviations in this ratio from 1. An analysis of these terms[11] was applied in conjunction with potential deviations in the acoustic impedances of the nine microphones from a value determined using nominal equivalent volume parameters of type LS1P microphones.[21] These potential deviations were inferred from the results obtained by applying an iterative fitting procedure[17,21] that was performed during the reduction of reciprocity calibration data for these nine microphones.

5. Summary

A laser-based method for comparison calibrations of microphones has been described that uses scanning LDV velocity measurements at and near the center (central 3% of the diaphragm area) of the type LS1P test and reference microphones when the microphones are driven as transmitters with measured drive currents. The sensitivities determined with this comparison method at 250 and 1000 Hz for a group of seven test microphones using two reference microphones calibrated by the reciprocity method were found to be in very good agreement with the sensitivities determined for those test microphones directly by the reciprocity method. For 250 Hz, the largest difference in sensitivities determined by the two methods for any of the microphones is 0.042 dB, and the average absolute difference, which was calculated using the difference for all test microphones, is 0.027 dB. For 1000 Hz, the largest difference is 0.050 dB, and the average absolute difference is 0.026 dB.

The expanded ($k = 2$) uncertainties for the laser-based comparison method are ±0.05 dB at 250 and 1000 Hz. These uncertainties compare favorably with those of the reciprocity-based comparison calibration service conducted at NIST with a large-volume acoustic coupler, which are ±0.08 dB at 250 and 1000 Hz. In addition, the laser-based method is simpler and faster to implement, especially at 1000 Hz where the coupler is hydrogen filled for the reciprocity-based comparison service. The expanded ($k = 2$) uncertainties for the laser-based comparison method also compare favorably with those specified (±0.08 to ±0.10 dB) for a commercial system that implements the method of the relevant international standard.[9]

Measurements of the resonance frequencies for each individual microphone used were not necessary at 250 and 1000 Hz to obtain the relatively low uncertainties for the laser-based comparison method. Future work to extend these comparison measurements beyond 1000 Hz will require determining the resonance frequencies for each individual microphone because the normalized volume velocity varies significantly over small ranges of the normalized frequency as the microphone resonance frequency is approached.

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