Designation: E 1781 – 98

Standard Practice for Secondary Calibration of Acoustic Emission Sensors[1]

This standard is issued under the fixed designation E 1781; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers requirements for the secondary calibration of acoustic emission (AE) sensors. The secondary calibration yields the frequency response of a sensor to waves of the type normally encountered in acoustic emission work. The source producing the signal used for the calibration is mounted on the same surface of the test block as the sensor under testing (SUT). Rayleigh waves are dominant under these conditions; the calibration results represent primarily the sensor's sensitivity to Rayleigh waves. The sensitivity of the sensor is determined for excitation within the range of 100 kHz to 1 MHz. Sensitivity values are usually determined at frequencies approximately 10 kHz apart. The units of the calibration are volts per unit of mechanical input (displacement, velocity, or acceleration).

1.2 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 114 Practice for Ultrasonic Pulse-Echo Straight-Beam Examination by the Contact Method[2]

E 494 Practice for Measuring Ultrasonic Velocity in Materials[2]

E 1106 Method for Primary Calibration of Acoustic Emission Sensors[2]

E 1316 Terminology for Nondestructive Examinations[2]

3. Terminology

3.1 *Definitions*—Refer to Terminology E 1316, Section B, for terms used in this practice.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *reference sensor (RS)*—a sensor that has had its response established by primary calibration (also called secondary standard transducer) (see Method E 1106).

3.2.2 *secondary calibration*—a procedure for measuring the frequency or transient response of an AE sensor by comparison with an RS.

3.2.3 *test block*—a block of homogeneous, isotropic, elastic material on which a source, an RS, and a SUT are placed for conducting secondary calibration.

4. Significance and Use

4.1 The purpose of this practice is to enable the transfer of calibration from sensors that have been calibrated by primary calibration to other sensors.

5. General Requirements

5.1 *Units for Calibration*—Secondary calibration produces the same type of information regarding a sensor as does primary calibration (Method E 1106). An AE sensor responds to motion at its front face. The actual stress and strain at the front face of a mounted sensor depends on the interaction between the mechanical impedance of the sensor (load) and that of the mounting block (driver); neither the stress nor the strain is amenable to direct measurement at this location. However, the free displacement that would occur at the surface of the block in the absence of the sensor can be inferred from measurements made elsewhere on the surface. Since AE sensors are used to monitor motion at a free surface of a structure and interactive effects between the sensor and the structure are generally of no interest, the free motion is the appropriate input variable. It is therefore required that the units of calibration shall be volts per unit of free displacement or free velocity, that is, volts per metre or volt seconds per metre.

5.2 The calibration results may be expressed, in the frequency domain, as the steady-state magnitude and phase response of the sensor to steady-state sinusoidal excitation or, in the time domain, as the transient response of the sensor to a delta function of displacement.

5.3 *Importance of the Test Block Material*—The specific acoustical impedance (ρc) of the test block is an important parameter that affects calibration results. Calibrations performed on blocks of different materials yield sensor sensitivities that are very different. For example, a sensor that has been calibrated on a steel block, if calibrated on a glass or aluminum

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[1] This practice is under the jurisdiction of ASTM Committee E-7 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.04 on Acoustic Emission Method.

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[2] *Annual Book of ASTM Standards*, Vol 03.03.

block, may have an average sensitivity that is 50 % of the value obtained on steel and, if calibrated on a polymethyl methacrylate block, may have an average sensitivity that is 3 % of the value obtained on steel.[3]

5.3.1 For a sensor having a circular aperture (mounting face) with uniform sensitivity over the face, there are frequencies at which nulls in the frequency response occur. These nulls occur at the zeroes of the first order Bessel function, $J_1(ka)$, where $k = 2\pi f/c$, f = frequency, c = the Rayleigh speed in the test block, and a = the radius of the sensor face.[3] Therefore, calibration results depend on the Rayleigh wave speed in the material of the test block.

5.3.2 For the reasons outlined in 5.3 and 5.3.1, all secondary calibration results are specific to a particular material; a secondary calibration procedure must specify the material of the block.[4]

6. Requirements of the Secondary Calibration Apparatus

6.1 *Basic Scheme*—A prototype apparatus for secondary calibration is shown in Fig. 1. A glass-capillary-break device or other suitable source device (A) is deployed on the upper face of the steel test block (B). The RS (C) and the SUT (D) are placed at equal distances from the source and in opposite directions from it. Because of the symmetry of the sensor placement, the free surface displacements at the locations of the RS and SUT are the same. Voltage transients from the two sensors are recorded simultaneously by digital waveform recorders (E) and processed by a computer.

6.1.1 Actual dynamic displacements of the surface of the test block at the locations of the RS and SUT may be different because the RS and SUT may present different load impedances to the test block. However, consistent with the definitions used for primary and secondary calibration, the loading effects of both sensors are considered to be characteristics of the sensors themselves, and calibration results are stated in terms of the free displacement of the block surface.

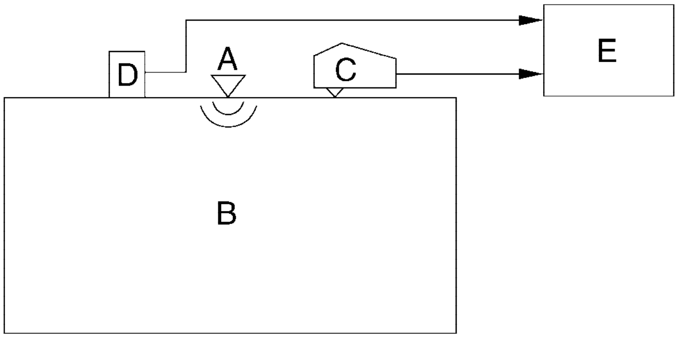

FIG. 1 Schematic of the Prototype Secondary Calibration Apparatus: A = a Capillary-Break Source, B = a 41 by 41 by 19-cm Steel Block, C = the RS, D = the SUT, and E = the Two-Channel Waveform Recorder System

6.2 *Qualification of The Test Block*—The prototype secondary calibration apparatus was designed for sensors intended for use on steel. The test block is therefore made of steel (hot rolled steel A36 material). For a steel block, it is recommended that specification to the metal supplier require that the block be stress relieved at 566°C (1050°F) or greater and that the stress relief be conducted subsequent to any flame cutting.

6.2.1 For a steel test block, there must be two parallel faces with a thickness, measured between the faces, of at least 18 cm. The volume of the block must contain a cylinder that is 40 cm in diameter by 18-cm long, and the two faces must be flat and parallel to within 0.12-mm overall (±0.06 mm).

6.2.2 For a steel test block, the top surface of the block (the working face) must have a rMS roughness value no greater than 1 µm (40 µin.), as determined by at least three profilometer traces taken in the central region of the block. The bottom surface of the block must have a rMS roughness value no greater than 4 µm (160 µin.). The reason for having a specification on the bottom surface is to ensure reasonable ability to perform time-of-flight measurements of the speed of sound in the block.

6.2.3 For blocks of materials other than steel, minimum dimensional requirements, dimensional accuracies, and the roughness limitation must be scaled in proportion to the longitudinal sound speed in the block material relative to that in steel.

6.2.4 The top face of the block shall be the working face on which the source, RS, and SUT are located. These locations shall be chosen near the center so as to maximize the distances of source and receivers to the nearest edge of the face. For a test block of any material, the distance from the source to the RS and the distance from the source to the SUT must each be 100 ± 2 mm (the same as that specified for primary calibration).

6.2.5 The block must undergo longitudinal ultrasonic inspection for flaws at some frequency between 2 and 5 MHz. The guidelines of Practice E 114 should be followed. The block must contain no flaws that give a reflection greater than 12 % of the first back wall reflection.

6.2.6 The material of the block must be highly uniform, as determined by pulse-echo, time-of-flight measurements of both longitudinal and shear waves. These measurements must be made through the block at a minimum of seven locations spaced regularly over the surface. The recommended method of measurement is pulse-echo overlap using precisely controlled delays between sweeps. See Practice E 494. It is recommended that the pulse-echo sensors have their main resonances in the range between 2 and 5 MHz. For the seven (or more) longitudinal measurements, the maximum difference between the individual values of the measurements must be no more than 0.3 % of the average value. The shear measurements must satisfy the same criterion.

6.3 *Source*—The source used in the prototype secondary calibration system is a breaking glass capillary. Capillaries are prepared by drawing down 6-mm pyrex tubing to a diameter of 0.1 to 0.25 mm. Source events are generated by squeezing the

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[3] Breckenridge, F. R., Proctor, T. M., Hsu, N. N., and Eitzen, D. G.,“ Some Notions Concerning the Behavior of Transducers,” *Progress in Acoustic Emission III*, Japanese Society of Nondestructive Inspection, 1986, pp. 675–684.

[4] Although this practice addresses secondary calibrations on test blocks of different materials, the only existing primary calibrations are performed on steel test blocks. To establish a secondary calibration on another material would also require the establishment of a primary calibration for the same material.

capillary tubing against the test block using pressure from the side of a 4-mm diameter glass rod held in the hand.

6.3.1 In general, a secondary calibration source may be any small aperture device that can provide sufficient energy to make the calibration measurements conveniently at all frequencies within the range of 100 kHz to 1 MHz. Depending on the technique of the calibration, the source could be a transient device such as a glass-capillary-break apparatus, a spark apparatus, a pulse-driven transducer, or a continuous wave device such as a National Institute for Standards and Technology (NIST) Conical Transducer driven by a tone burst generator. If the RS and SUT are to be tested on the block sequentially instead of simultaneously, then it must be established that the source is repeatable within 2 %.

6.4 *Reference Sensor*—The RS in the prototype secondary calibration system is an NIST Conical Transducer.

6.4.1 In general, the RS must have a frequency response, as determined by primary calibration, that is flat over the frequency range of 100 kHz to 1 MHz within a total overall variation of 20 dB either as a velocity transducer or a displacement transducer. It is preferred that the RS be of a type that has a small aperture and that its frequency response be as smooth as possible. See 5.3.1 and Fig. 2 concerning the aperture effect.

6.5 *Sensor Under Testing*—The SUT must be tested under conditions that are the same as those intended for the SUT when in use. The couplant, the electrical load applied to the SUT terminals, and the hold-down force must all be the same as those that will be applied to the SUT when in use. The preferred couplant is low-viscosity machine oil, and the preferred hold-down force is 9.8 N. These conditions are all the same as for primary calibration.

6.6 *Data Recording and Processing Equipment*—For methods using transient sources, the instrumentation would include a computer and two synchronized transient recorders, one for the RS channel and one for the SUT channel. The transient recorders must be capable of at least eight-bit accuracy and a sampling rate of 20 MHz, or at least ten-bit accuracy and a sampling rate of 10 MHz. They must each be capable of storing data for a time record of at least 55 µs. The data are transferred to the computer for processing and also stored on a permanent device, for example, floppy disc, as a permanent record.

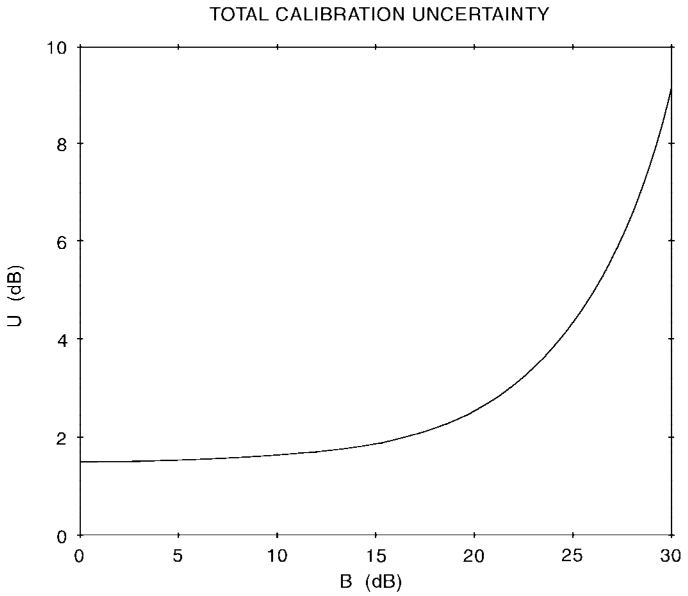
7. Calibration Data Processing

7.1 *Raw Data*—In the prototype secondary calibration system, the triggering event is the Rayleigh spike of the reference channel. By means of pre-triggering, the data sequence in both channels is made to begin 25 µs before the trigger event. The raw captured waveform record of one of the two channels comprises 2048 ten-bit data with a sampling interval t = 102.4 µs. Therefore, the total record has a length of T = 102.4 µs. Reflections from the bottom of the block appear approximately 60 µs after the beginning of the record in both channels (see Figs. 3 and 4). It is undesirable to have the reflections present in the captured waveforms because the reflected rays arrive at the sensors from directions that are different from those intended for the calibration. The record is truncated and padded as follows: data corresponding to times greater than 55 µs are replaced by values, all equal to the average of the last ten values in the record prior to the 55 µs cutoff.

7.2 *Complex Valued Spectra*—Using a fast fourier transform (FFT), complex valued spectra $S(f_m)$ and $U\ (f_m)$ derived from the RS and SUT, respectively, are calculated:

$$S(f_m) = \sum_{j=0}^{n-1} s_j \exp\ (i2\pi mj/n), \tag{1}$$

$$U(f_m) = \sum_{j=0}^{n-1} u_j \exp\ (i2\pi mj/n) \tag{2}$$



NOTE 1—The nulls in the response curves are predicted by the aperture effect described in 5.3.1. The worst case error is approximately 3.6 dB and occurs at the first aperture null (0.3 MHz). Most of the data agree within 1 dB.

FIG. 2 Comparison of Primary and Secondary Calibration Results for Another SUT Having a Nominal Diameter of 0.5 in.

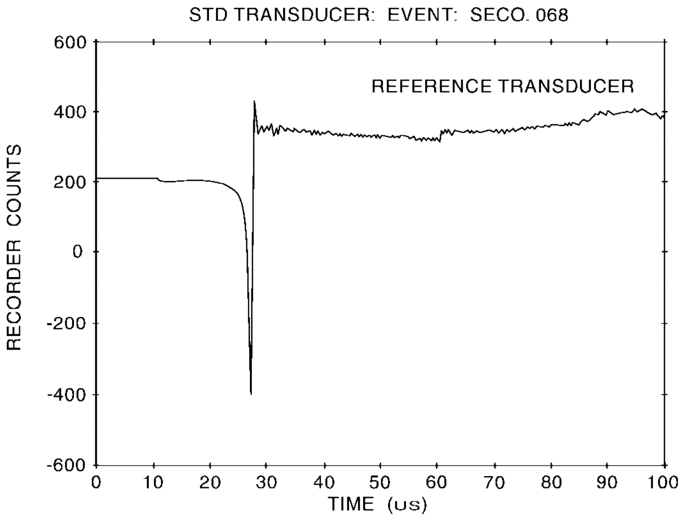


FIG. 3 Waveform of the RS from a Calibration Performed on the Prototype Secondary Calibration System

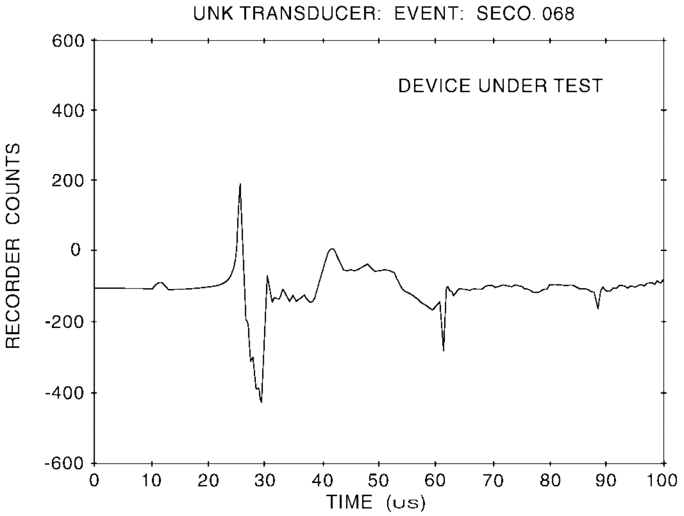


FIG. 4 Waveform of the SUT from Calibration of Fig. 3

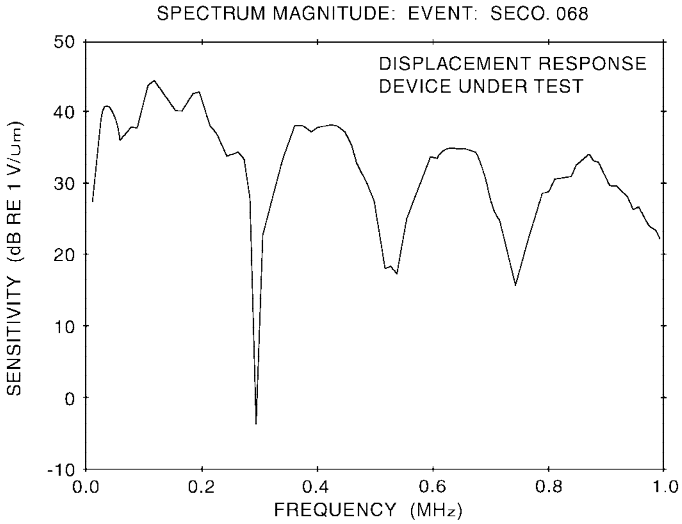


FIG. 5 Magnitude of the Frequency Response of the SUT Derived from the Data of Figs. 3 and 4

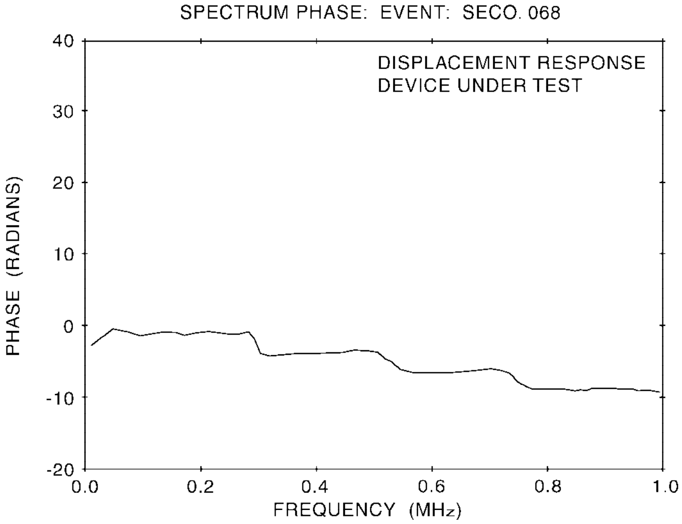


FIG. 6 Phase of the Frequency Response of the SUT Derived from the Data of Figs. 3 and 4

where:

n = 2048,
j = 0, 1, 2, ..., $n - 1$,
s_j = j^{th} sample value in the RS channel,
u_j = j^{th} sample value in the SUT channel,
m = 0, 1, 2, ..., $n/2 - 1$, and
f_m = m/T, the m^{th} frequency in MHz.

The frequency separation is $1/T$ = 9.76 kHz. It is assumed that s_j and u_j have been converted to volts by taking account of the gains of the waveform recorders and any preamplifiers used in the calibration. The (complex valued) response of the SUT is

$$D(f_m) = \frac{U(f_m)S_o(f_m)}{S(f_m)} \tag{3}$$

where $S_o(f_m)$ represents the (complex valued) response of the RS in volts per metre at the frequency f_m. The values of $S_o(f_m)$ are derived from primary calibration of the RS.

7.3 *Magnitude and Phase*—The magnitude, r_m, and phase, θ_m, of D (f_m) are calculated from D (f_m) in the usual way:

$$r_m = |D(f_m)|, \tag{4}$$

$$\theta_m = \text{Arctan}\, \frac{I[D(f_m)]}{R[D(f_m)]} \tag{5}$$

where $I[z]$ and $R[z]$, respectively, denote the imaginary and real parts of a complex argument, z. Calibration magnitude data, w_m, are usually expressed in decibels as follows:

$$w_m = 20 \times \log_{10}(r_m) \tag{6}$$

The values of w_m and θ_m are plotted versus frequency as shown in Figs. 5 and 6.

7.4 *Special Considerations*—The FFT treats the function as though it were periodic, with the period equal to the length of the time recorded. If initial and final values are unequal, a step exists between the last and first data point. The FFT produces data that are contaminated by the spectrum of this step.

7.4.1 The fix that is applied in the prototype system is to add a linear function to the data as follows:

$$s'_j = s_j + (j/n)(s_o - s_{n-1}), \tag{7}$$

$$u'_j = u_j + (j/n)(u_o - u_{n-1}), \tag{8}$$

The modified functions, s'_j and u'_j, have no steps between the last and first data points. It has been shown analytically[5] that this procedure and two other commonly used techniques for dealing with step-like functions are all equivalent except at zero frequency. This linear“ ramp” function is applied to the data after the padding operation.

7.4.2 The phase associated with a complex valued quantity is not uniquely determined. In the prototype system, first a four-quadrant arctangent routine chooses that value of θ_m

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[5] Waldmeyer, J., "Fast Fourier Transform for Step-Like Functions: The Synthesis of Three Apparently Different Methods," *IEEE Transactions on Instrumentation and Measurement*, Vol IM-29, No. 1, pp. 36–39.

which lies in the interval between $-\pi$ and $+\pi$. Using this routine, jumps in θ_m occur whenever the value of θ_m crosses one of its limits, $-\pi$ or $+\pi$. To avoid these jumps, a routine of calculation in sequence of increasing frequency adds some multiple of 2π to θ_m so that each value of θ_m is the nearest to the preceding one. For most sensors, this routine produces smooth phase versus frequency curves except when $D(f_m)$ goes near zero. In this event, phase sometimes jumps by a multiple of 2π. For a sensor with a relatively flat frqeuency response, the routine works well, but if the sensor phase response oscillates wildly, or if the sensor magnitude response goes near zero, there exists a phase ambiguity that is a multiple of 2π.

8. Expected Uncertainty

8.1 *Sources of Uncertainty*—There are several sources of uncertainty that affect the accuracy and repeatability of the prototype secondary calibration method. Uncertainties involved in the (primary) calibration of the RS and variability in the mounting of the SUT as well as uncertainties introduced in the waveform recording and digital processing all contribute to uncertainty of the secondary calibration result.

8.1.1 The repeatability between calibrations of a sensor with remounting is poorer than without remounting. Making a repeatable mechanical coupling of a sensor to a surface is known to be a problem. In a secondary calibration procedure, special care must be taken to minimize variability due to the following: lack of flatness of the mounting face of the transducer, the presence of small burrs on the surface of the test block, dirt in the couplant layer, excessive viscosity of the couplant, and variability in the amount or point of application of the hold-down force.

8.1.2 There is a truncation error arising from the fact that the captured waveform is limited to 55 µs. The SUT is shock-excited primarily by the Rayleigh pulse; the waveform termination is approximately 30 µs later. Electrical output from the sensor is lost if it occurs after this interval. For a sensor that has a ringdown time of less than 30 µs, negligible error will occur; however, to the extent to which there is ringing in progress at the end of the interval, the captured waveform will be an erroneous representation of the true response of the sensor. The assessment of truncation error is difficult. A larger test block would allow longer waveform captures but is not considered practical. For the accuracy statements of this standard to apply, the transducer under test and the reference transducer must both be well enough damped that, for each, the ringing amplitude at the termination of the capture window is no more than 2 % of the maximum peak signal amplitude. Other transducers may be tested by the system but the results may be expected to have reduced accuracy.

8.1.3 The fourier transform yields discrete frequency components separated by approximately 10 kHz. At frequencies below 100 kHz, this scale becomes rather coarse. For sensors that have smooth frequency responses, there is meaningful information in the 10 to 100 kHz range, but it is difficult to establish an expected uncertainty in this range.

8.1.4 Electronic noise and quantization noise become progressively worse at high frequencies. At frequencies above 1.0 MHz, these effects result in variability of several dB in successive calibrations of the same sensor. Therefore, the frequency band within which it is reasonable to establish error limits is from 100 kHz to 1 MHz.

8.2 *Quantitative Assessment of Uncertainty*—For the purposes of this discussion, uncertainty is considered to be the limits of the error band that has a 95 % confidence level.

8.2.1 Uncertainties of the frequency response magnitude data may be classified as follows: (*1*) those that are proportional to signal amplitude from the SUT and (*2*) those that are related to a certain fraction of the dynamic range of the transient capturing equipment.

8.2.2 Uncertainties of the first type are attributed to such variables as variations in sensor coupling, variations of amplifier gain, temperature and aging effects on the sensor, etc. These uncertainties define an error band that is proportional to linear (not dB) signal magnitude and, therefore, may be expressed as a percentage uncertainty applicable to all magnitude data. For the prototype secondary calibration system, the total uncertainty of the first type is estimated to be approximately ±16 %.

8.2.3 Uncertainties of the second type are associated with electrical noise, digital roundoff, aliasing errors, and any other errors associated with the transient capture process. The magnitudes of these errors are fixed in relation to the maximum signal level accepted by the transient recorder. Assuming that amplification and gain settings are chosen for optimal use of the dynamic range of the recorder, then these errors are related to the maximum signal swing from the sensor and related fairly closely to the amplitude of the sensor at the frequency of maximum output. Based on the repeatability of calibration results from tests of a sensor without remounting the sensor between tests, a reasonable allowance for the total uncertainty of the second type is approximately ±2 % of the magnitude of the calibration result at the frequency of maximum output.

8.3 *Expression of Uncertainty in Decibels*—A 16 % uncertainty of the first type, if positive, would be $20 \times \log_{10}(1 + 0.16) = +1.3$ dB and, if negative, would be $20 \times \log_{10}(1 - 0.16) = -1.5$ dB. For simplicity, the error band for the uncertainty of the first type may be specified as ±1.5 dB.

8.3.1 The total uncertainty of the second type varies from frequency to frequency. This uncertainty is of constant magnitude and is, therefore, a greater fraction of the (linear) response magnitude at frequencies at which the SUT has low output. An expression for this uncertainty in decibels is

$$U_m = 20 \times \log_{10}(1 \pm 0.02 \times A_m) \tag{9}$$

where:

A_m = $\exp[(B_m/20) \times \ln(10)]$, and
B_m = $M - w_m$.

and where:

M = maximum value of w_m over the range 100 kHz to 1 MHz,
A_m = ratio of the maximum (linear) response magnitude to the (linear) response magnitude r_m at the m^{th} frequency, and
B_m (a positive number) = decibel representation of A_m.

For the purpose of expressing the uncertainty band as a function of *B*, the "*m*" subscripts are dropped from *U*, *A*, and *B*.

8.3.2 Treating the uncertainties of the first and second types as statistically independent, the resulting total uncertainty is the root sum of squares of the two component uncertainties. The total uncertainty is

$$U = 20 \times \log_{10} \{1 \pm [(0.16)^2 + (0.02 \times A)^2]^{1/2}\} \qquad (10)$$

In the calculation of *U*, the negative sign has been chosen because it represents the worse of the two possible cases. For values of *B* greater than 30 dB, *U* is more than 9 dB, and the data are not reliable. Therefore, no accuracy claim is made for data that are more than 30 dB down from the peak amplitude. Fig. 7 shows total uncertainty, *U*, as a function of *B*.

9. Proof Testing of a Secondary Calibration System

9.1 It must be demonstrated by the calibration of at least three sensors that the secondary calibration system produces repeatable results. For each of the three sensors, 95 % of the calibration frequency response data must fall within an error band defined by ±*U*.

9.2 It must be demonstrated that, for at least one sensor, the results of the secondary calibration are in agreement with those of a primary calibration. For this sensor, 95 % of the calibration frequency response data must agree with the primary calibration data within an error band defined by ±(*U* + 1.5).

10. Typical Calibration Results

10.1 Figs. 3 and 4 show typical waveform captures from the RS and SUT, respectively, as obtained on the prototype secondary calibration system. Figs. 5 and 6 show calibration frequency domain results obtained from the data of Figs. 3 and 4. Fig. 2, Fig. 8, and Fig. 9 show a comparison of the results from primary calibration and from prototype secondary calibration conducted on three sensors. Each of the two curves in each figure displays the results of a single calibration.

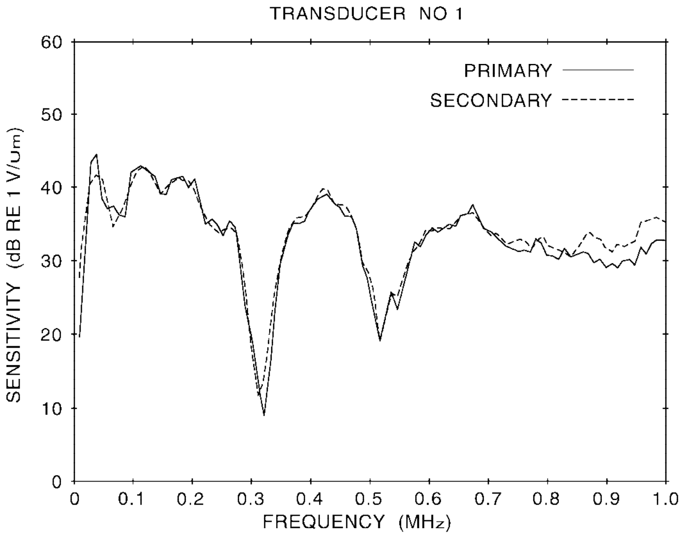

FIG. 7 Estimated Uncertainty, *U*, of the Calibration Frequency Response Data—Let *M* be the Largest Value of w_m over the Range 100 kHz to 1 MHz; Then, for any w_m, $B = M - w_m$, and the Uncertainty of w_m is ±*U*

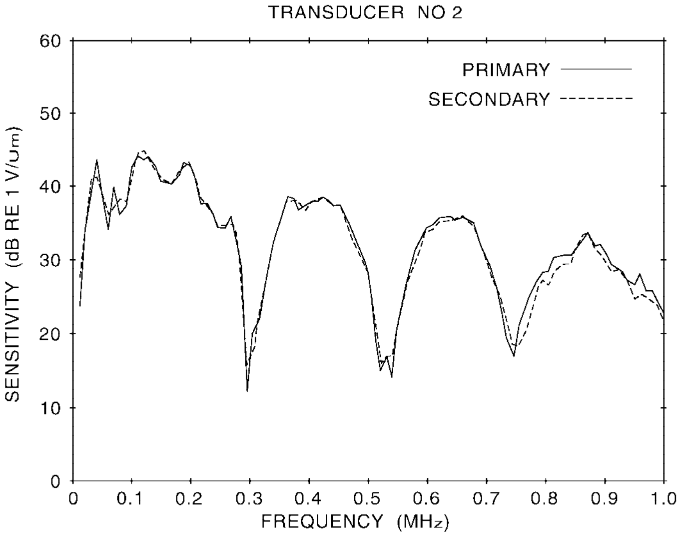

FIG. 8 Comparison of Primary and Secondary Calibration Results for a SUT Having a Nominal Diameter of 0.5 in. (12.7 mm); Worst Case Errors are 3 dB, While Most of the Data Agree Within 1 dB

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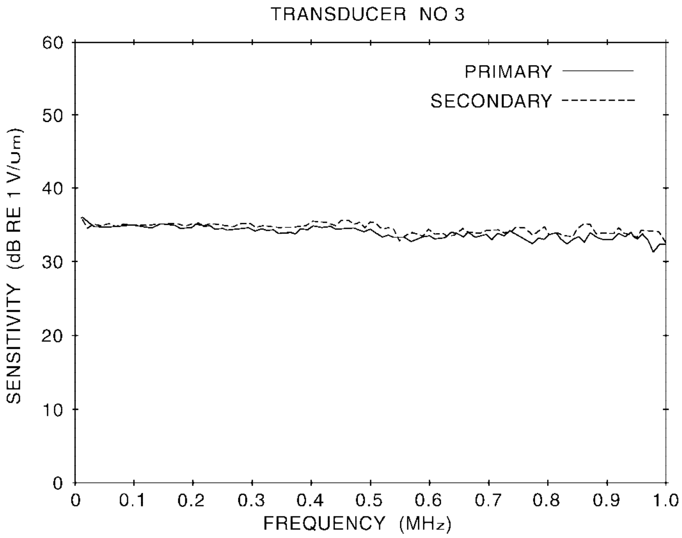

NOTE 1—There is an absence of aperture nulls below 1 MHz, as predicted. The worst case error is approximately 2.7 dB, while most of the data agree within 1 dB.

FIG. 9 Comparison of Primary and Secondary Calibration Results for an NIST Conical Transducer, Having an Aperture Diameter of 1.4 mm

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