Acoustic Intensity Techniques for Airplane Cabin Applications

G. A. Dalan* and R. L. Cohen†
Boeing Commercial Airplane Company, Seattle, Washington

A technique to measure surface radiation from an airplane cabin in flight using a two-microphone acoustic intensity system is described. The technique addresses the problems of high background levels and surface absorption that have in the past complicated cabin radiation measurements. Two probe types were used: a bare probe for the reflective sidewall and ceiling regions and a shielded probe for the absorptive carpet. Laboratory tests were conducted to establish the accuracy and tolerance to background noise for the flight measurement system. From these tests the operating range for each probe was determined in terms of the difference in sound pressure and intensity levels. This difference, called the signal-to-noise indicator, was used to screen out flight data saturated by the background field. From the cabin surveys, several strong radiation areas, such as the ceiling panel and the air distribution and air return grills, were measured quantitatively. Small area sources were distinguished from adjacent areas, and other weak sources were identified.

Background and Statement of Problem

THE acoustic intensity technique referred to in this article is based on the two-microphone method and uses a fast Fourier transform (FFT) signal analyzer. The so-called "cross-spectral" method of acoustic intensity measurement was described by Fahy[1] and Chung.[2] The sources of error in the intensity measurement were discussed by Seybert[3] and Thompson and Tree.[4] Previous applications of this method have been in the areas of automobile diagnostics[5] and source identification on heavy machinery.[6] For aircraft components, the acoustic intensity approach was used by Forssen et al.[7] and McGary[8] to evaluate the transmission loss of sidewall structures in a laboratory environment. Laboratory measurements using a complete Piper Cherokee fuselage and a large reverberation chamber were reported by Wang and Crocker[9] to evaluate transmission paths using acoustic intensity. The Danish firm of Brüel and Kjaer has surveyed several small aircraft interiors using a real-time intensity analyzer.

Weight-efficient design of cabin noise treatment requires knowledge of noise source locations and relative magnitudes. Noise sources in airplane cabins are often difficult to measure with sufficient accuracy.

The problem of accurately measuring radiated intensity in aircraft interiors in flight is made difficult by such factors as the background noise, irregularity of radiating surface shapes, and variation in surface absorptivity. Experimenters have attempted to reduce background noise in laboratory tests by adding absorbing panels or wedges.[8,9] This approach, however, is not practical for flight testing and the background noise problem must be solved by other means, primarily by providing good rejection capability for the intensity measuring instrument.

The two problems of surface irregularity and absorptivity are solved in slightly different ways. When the intensity probe is "scanned" or "swept" over an irregular surface, the result is a measurement of the area-averaged intensity where any radiation variations are included in the average. Care must be taken to ensure that the scan rate is uniform and that all subareas of the test area are included. This averaged value is useful for ranking large surfaces such as sidewall panels and ceilings. More resolution within a single cabin area is also possible when the test area is made smaller. Scanning then eliminates the measurement problems associated with the use of accelerometers and other transducers where radiation from large area sources is estimated from the radiation or vibration measured at a single point.

The problem of surface absorptivity can be stated in terms of the influence of the background noise field. Where there is no significant background field, the intensity method will successfully measure the radiation levels from all surface types, from reflective ($\alpha \cong 0$) to absorptive ones ($\alpha \to 1$). The problem begins when the background field increases and the surface begins to absorb this energy. The bare intensity probe, which measures the net energy flow (outgoing radiation less absorbed energy from background sources), will underestimate the radiated intensity, the degree depending on the absorptivity of the surface and the strength of the background field. For a highly absorptive surface, such as a carpeted floor, an acoustic shield is needed to provide a reasonable estimate of the radiated intensity. For a reflective surface, it is assumed that the bare probe provides adequate rejection, because the net energy flow due to the background field is negligible; i.e., incident and reflected sound waves have approximately equal energy near the measurement surface and the radiated intensity measurement is to a large degree unaffected by the extraneous background sources. These concepts will be discussed later.

Acoustic Intensity Algorithm

In the cross-spectral intensity method, the component of the intensity vector along the axis of two microphones with a separation Δr is

$$I = \mathrm{Im}(G_{12})/2\pi f \rho \Delta r \qquad (1)$$

where $\mathrm{Im}(G_{12})$ is the imaginary part of the cross spectrum between the two microphone channels, ρ the density of air, and f the frequency.

To obtain sound power, the area-averaged intensity is multiplied by the area of the surface scanned, so that

$$W_{\mathrm{source}} = \langle I \rangle \times S \qquad (2)$$

Presented as Paper 83-0716 at the AIAA 8th Aeroacoustics Conference, Atlanta, GA, April 11-13, 1983; received Jan. 14, 1985; revision received May 23, 1985.

*Specialist Engineer, Noise Technology Laboratory (currently Propulsion Technology Research).
†Specialist Engineer, Noise Technology Research (currently 767 Airplane Noise Staff).

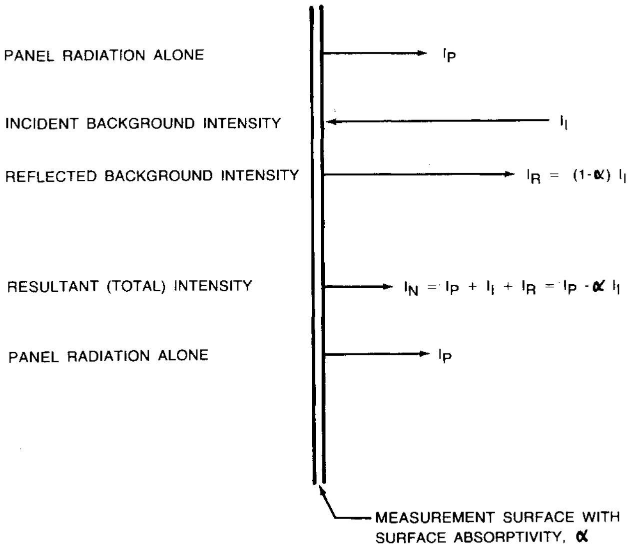

Fig. 1 Background noise effects on measurement of panel radiated intensity.

where the average intensity $\langle I \rangle$ is given in watts/square meter and the source strength W_{source} in watts.

In decibel form the intensity level (IL) is defined as

$$\mathrm{IL} = 10\log\,(I/I_{ref}) \tag{3}$$

where $I_{ref} = 1 \times 10^{-12}$ W/m^2.

The power level (PWL) becomes:

$$\mathrm{PWL} = \mathrm{IL} + 10\log[S] \tag{4}$$

where S is the surface area in square meters and PWL is in decibels re 10^{-12} W.

Verification of Intensity Measurement Accuracy

Laboratory measurements were made over both reflective and absorptive surfaces to establish the accuracy of the portable measurement system designed for flight use. Other researchers have compared the results of surveys with far-field estimates of sound power[6] or with theoretical predictions[8,9] to establish some accuracy verification.

In work done in the Boeing Noise Technology Laboratory, a reference measurement based on reverberation chamber sound power was used, where test panel radiation levels could be compared using the acoustic intensity and room sound power methods. The reflective surface radiator was a 68×68×¼ in. aluminum plate driven by a piezoelectric transducer. The absorptive surface radiator consisted of an airplane floor panel and carpet assembly mounted over an enclosure driven to high sound power levels (SPL) by a speaker. The receiving space for both radiators was a reverberation room.

Background noise was provided by another speaker mounted in a corner of the room and by an air jet. These sources were intended to simulate the background noise of the airplane cabin during flight.

Two types of intensity probes were tested, depending on the measurement environment. For the low background case, where the interest was in verifying measurement accuracy of the intensity method for the different radiators, a bare probe type was used. This bare probe consisted of a pair of Brüel and Kjaer ½ in. type 4166 microphone cartridges aligned in a facing orientation. An aluminum spacer was positioned between the grid caps of the two microphones, and a special sleeve assembly was used to maintain compression against the spacer. Details of this probe design are available from the author in Ref. 10.

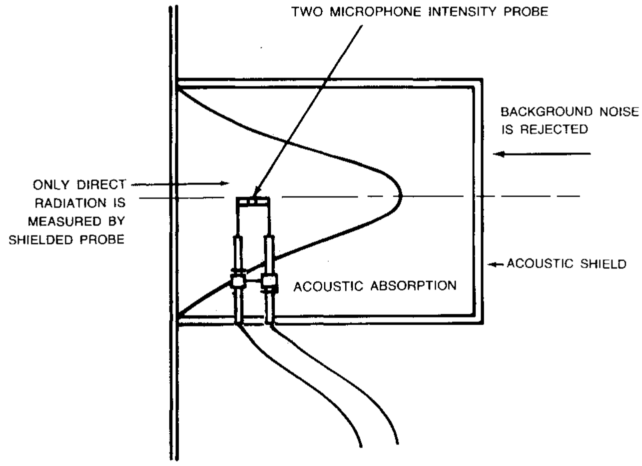

Fig. 2 Concept of acoustic shield used to measure radiation from absorptive surfaces.

Table 1 Accuracy of intensity measurements compared with reverberation room sound power

	Power via intensity measurement re room power measurement, dB	
Octave band frequency, Hz	¼-in.-thick aluminum plate	Carpeted honeycomb floor panel
1000	−1.2	+1.3
2000	−0.7	−1.3
4000	−0.8	−0.3

When the reverberation room levels were increased, the bare probe was used on the reflective surface as before, while the absorptive carpet measurements were made with the probe fitted with an acoustic shield. Earlier measurements with no background had verified that the shield produced little distortion of the sound field. The need for the shield will be discussed in the next section.

To verify the accuracy of the no background measurements, panel sound power was measured using room SPLs and the following equation from Beranek[11] was applied:

$$\mathrm{PWL}_{source} = \mathrm{SPL}_{room} + 10\log[V] - 10\log[T_{60}] + 10\log\left[1 + \frac{S\lambda}{8V}\right] - 13.5\ \mathrm{dB} \tag{5}$$

where S and V are the room surface area and volume, respectively, T_{60} the reverberation time, and λ the wavelength of the analysis band center frequency. The frequency range covered the 1, 2, and 4 kHz octave bands.

A comparison of the plate power from the acoustic intensity method and the room power method showed excellent agreement for both the reflective aluminum plate and the absorptive floor panel. See Table 1.

Measurement Quality Indicator

When a high-level background noise field is added to the measurement environment, greater care must be taken to assure an accurate survey. As mentioned earlier, both background noise levels and surface absorption characteristics influence the intensity reading. From Fig. 1, it can be noted that for a plate having a radiation strength I_p in the presence of background noise where the normal component of the incident background wave is I_I, the following relation holds:

$$I_{meas} = I_N = I_p - \alpha I_I \quad (6)$$

where I_N is the net intensity measured by the probe and α is the surface absorption coefficient.

This equation suggests that for the low background case (i.e., where $I_I \ll I_p$) the true radiation I_p is approximated well by the measured intensity I_N. Likewise, if the surface is highly reflective ($\alpha \cong 0$), the background field may be high and still not influence the plate radiation measurement. In this case, the limiting factor becomes the quality of the instrument phase match with nonsymmetry of the field due to the presence of the probe also having an effect. The importance of instrument phase matching for the two-microphone method has long been recognized and several methods have been suggested to correct for any mismatch. In the test described here, the phase error was corrected by the transfer function method described in the literature.[12]

It was concluded that, to achieve maximum background rejection over a reflective surface, the instrument should be phase matched and phase corrected as well as possible and that the incident and reflected waves should be free to pass over the open intensity probe.

For the absorptive case, Eq. (6) suggests that the measured net intensity will change by 0.5 dB when the term αI_I is greater than 10% of the radiated intensity I_p. The net intensity will always be lower than the radiated intensity and may even be negative, depending on the magnitudes of α and I_I. For this reason, a bare (unshielded) probe cannot be used to measure radiated intensity from a radiator having some degree of absorptivity when significant background noise is present.

For the absorptive surface case, background rejection was achieved by enclosing the intensity probe in an acoustic shield, as illustrated in Fig. 2. The shield used for flight surveys distorted the sound field only slightly when compared with the open-probe intensity levels over the same floor panel area.

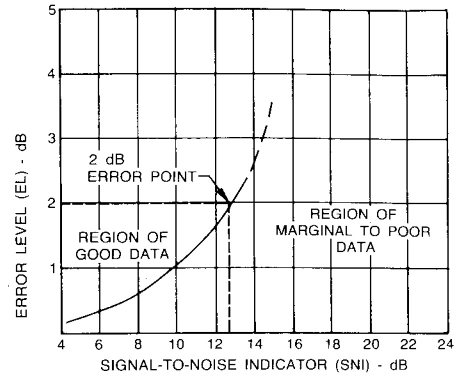

Fig. 3 Error level for the bare probe in the 1 kHz octave band as a function of signal-to-noise indicator derived from measurements over the aluminum plate.

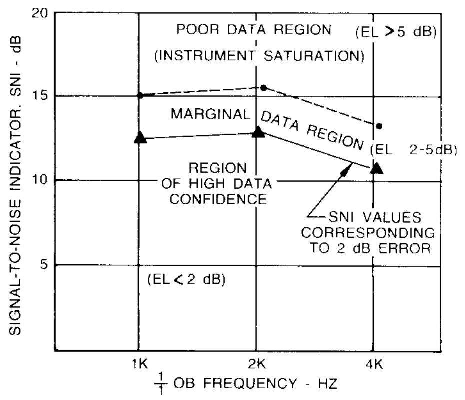

Fig. 4 Operating range of bare intensity probe.

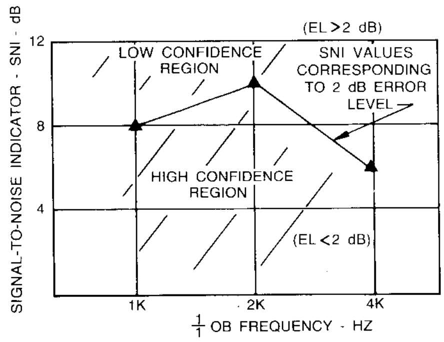

Fig. 5 Operating range of shielded intensity probe.

The Signal-to-Noise Indicator

Once the measurement environment was understood and a suitable system chosen to make the intensity measurement, the problem of assessing the measurement error was addressed. Specifically, it was desired to know when the instrument had measured incorrectly. At some point, instrumentation saturation will occur for the reflective radiators because the phase error is always nonzero and perfect cancellation of the incident and reflective waves is never achieved. For absorptive surfaces, the acoustic shield will have an operating limit beyond which the background field will influence the measurement.

With these factors in mind, a way of determining the saturation point for a high-noise background environment was sought. The plate and floor panel radiators were measured with background noise provided in the test chamber. For the floor panel measurements, the probe having the acoustic shield was used in anticipation of the net-intensity problem mentioned earlier. The background noise was increased until the instrument became saturated—that is, until the intensity differed significantly from the low-noise background reading.

In order to relate the laboratory data to flight measurements, the following relation was used and termed the signal-to-noise indicator (SNI):

$$\text{SNI} = 10\log\frac{(P_{ref}^2/\rho C)/I_{ref}}{I_N/I_{ref}} \quad (7)$$

where ρC is the impedance of the medium in mks rayls and P^2 is the mean squared pressure at the microphone. Now since, $(P^2/\rho C)/I_{ref} \cong P^2/P_{ref}^2$, Eq. (7) can be written in the more convenient form as

$$\text{SNI} = \text{SPL} - \text{IL} \quad (8)$$

where the SPL and IL are quantities measured at the same time and place by the intensity probe. To understand how saturation is measured, the following definition of error level (EL) is given:

$$\text{EL} = \text{IL}_{\text{with background}} - \text{IL}_{\text{no background}} \quad (9)$$

For the intensity system used in these tests, an error level magnitude of 2 dB or less on an octave band basis was considered acceptable. A plot of the error level vs SNI for the bare probe over the reflective surface for the 1 kHz octave band (Fig. 3) illustrates that error level increases with SNI. The point on the SNI axis where a 2 dB error occurs becomes the important feature of this curve because it indicates the instrument threshold. Maximum permissible SNI values (corresponding to a 2 dB error level) for the bare and shielded probes are given on a frequency basis in Figs. 4 and 5, respectively. The SNI values falling below the 2 dB error line represent a region of high-confidence measurements, while data above the line become questionable. The quality of data measured in an airplane cabin environment can now be assessed for each area surveyed. If the SNI is low, the data are acceptable as measured; if high, additional interpretation is required.

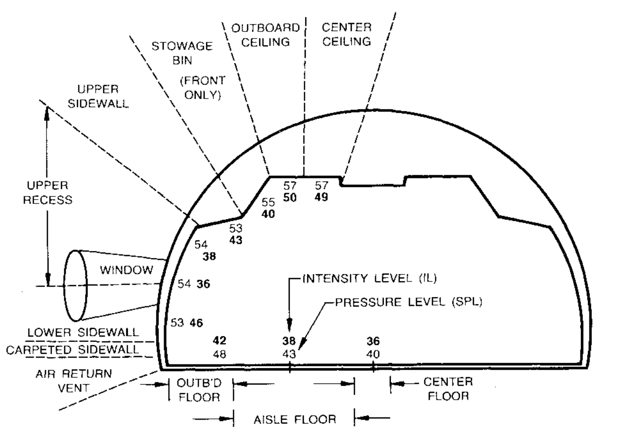

Fig. 6 Normalized pressure and intensity values for selected cabin surfaces at one body station in 1 kHz octave band.

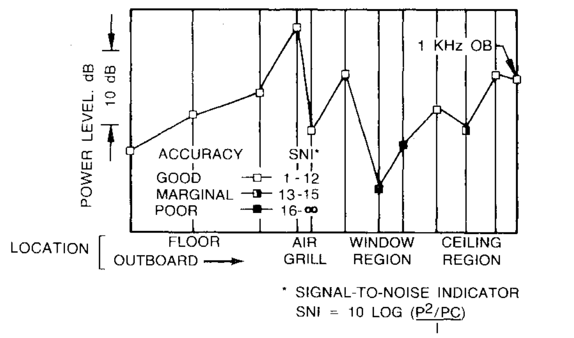

Fig. 7 Relative sound power levels as a function of a cabin circumferential position in 1 kHz octave band.

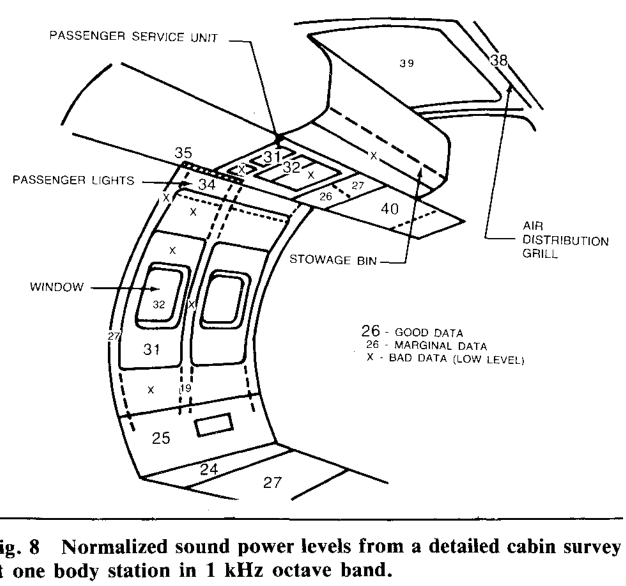

Fig. 8 Normalized sound power levels from a detailed cabin survey at one body station in 1 kHz octave band.

Results of Airplane Cabin Tests

Acoustic intensity surveys of Boeing commercial transports were made and maps of the cabin interiors were produced that located noise sources (or weak transmission areas) and quantified the sound radiation levels of the areas surveyed. Measurements were made on the floor, sidewall, window, and ceiling regions. The acoustic shield was used on carpeted areas, while all other surfaces were scanned using the bare probe. It was assumed that the reflectivity of the noncarpeted surfaces was generally high.

Normalized sound intensity levels are shown in Fig. 6 for several small areas within a single body station along with the local sound pressure reading. The frequency range is the 1 kHz octave band. It is interesting to note that the pressure field displays uniform strength over much of the sidewall region, whereas the intensity field shows differences of several decibels between adjacent areas.

The sound power levels $[\mathrm{IL} + 10\log(S)]$ from this survey are computed and plotted in an alternate form in Fig. 7. In this figure, the cabin air conditioning system return grill is seen as the principal radiator (despite its small size relative to the other areas), with the levels decreasing considerably near the window. Levels rise again in the areas above the window, such as the upper sidewall and the ceiling panels. Floor radiation levels increase from inboard to outboard.

In another cabin survey, detail components such as frames and light fixtures were measured and the results are illustrated in Fig. 8. Several irregular areas were scanned, presenting a detailed picture of the surface radiation. In Fig. 8, the large numerals indicate high-quality data (low SNI) and the smaller numerals indicate data of marginal quality. The Xs indicate areas where the SNI (or background noise) exceeded the allowable limit by several decibels.

Some interesting details emerge from Fig. 8. Window radiation is higher relative to the floor and lower sidewall (in contrast to data shown in Fig. 7). Radiation from the stowage bin is low and from the ceiling panel it is high. On the passenger service unit, the air gaspers represent the strongest radiation point, while below this service unit the passenger lights and air distribution grills are also strong radiators. Another air distribution grill mounted on the cabin ceiling is also strong, similar to the data of Fig. 7. These data are useful in understanding the radiation mechanisms that determined the sound pressure levels at the passenger seat locations.

Conclusion

A technique to accurately measure cabin surface acoustic radiation has been developed and successfully applied in a series of airplane cabin surveys. First, the problems of high background noise and surface absorption had to be understood before meaningful measurements could be made in flight. Testing in the laboratory with controlled radiators and a simulated background noise field was performed to evaluate two flight measurement systems—a bare probe system designed for the reflective ceiling and sidewall regions and a shielded probe for the absorptive carpet. As a result of those tests, the accuracy and tolerance to background noise was established for each system. Using the difference of sound pressure level minus intensity level, called the signal-to-noise indicator (SNI), data acquired in the cabin in flight was evaluated in terms of possible saturation. With these systems, it was possible to accurately measure radiated intensity as opposed to net energy flow. From the flight surveys, several strong radiators were identified, including the air distribution and return grills and the ceiling panels. Several small area sources were distinguished from adjacent areas. These flight results provided the basis for a better understanding of cabin radiation patterns and their effect on sound pressure levels measured at nearby passenger seats.

References

[1]Fahy, F. J., "Measurement of Acoustic Intensity Using the Cross Spectral Density of Two Microphones," *Journal of the Acoustical Society of America,* Vol. 62, No. 4, 1977, pp. 1057-1059.

[2]Chung, J. Y. and Pope, J., "Practical Measurement of Acoustic Intensity—The Two Microphone Cross-Spectral Method," *Inter-Noise 78 Proceedings,* Poughkeepsie Institute of Noise Control Engineering, 1978, pp. 893-900.

[3]Seybert, A. F., "Statistical Errors in Acoustic Intensity Measurement," *Journal of Sound and Vibration,* Vol. 75, No. 4, 1981, pp. 519-526.

[4]Thompson, J. K. and Tree, D. R., "Finite Difference Approximation Errors in Acoustic Intensity Measurements," *Journal of Sound and Vibration,* Vol. 75, No. 2, 1981, pp. 229-238.

[5]Lambrich, H. P. and Stahel, W. A., "A Sound Intensity Meter and its Applications in Car Acoustics," *Inter-Noise 77 Proceedings,* Zurich Institute of Noise Control Engineering, 1977, pp. B142-B147.

[6]Croker, M. D., Tyrrell, R. J., and North, M. P., "The Application of Acoustic Intensity to Engine Noise Reduction," *Proceedings from International Congress on Recent Developments in Acoustic Intensity Measurement,* Senlis CETIM, 1981, pp. 193-199.

[7]Forssen, B., Wang, Y. S., Raju, P. K., and Crocker, M. J., "A Study of Methods of Prediction and Measurement of the Transmission of Sound Through the Walls of Light Aircraft," Herrick Laboratory, Purdue University, West Lafayette, IN, Rept. HL81-19, 1981.

[8]McGary, M. C., "Noise Transmission Loss of Aircraft Panels Using Acoustic Intensity Methods," NASA TP-2046, Aug. 1982.

[9]Wang, Y. S. and Crocker, M. J., "Direct Measurement of Transmission Loss of Aircraft Structures Using the Acoustic Intensity Approach," *Noise Control Engineering Journal,* Vol. 19(3), Nov.-Dec. 1982, pp. 80-89.

[10]Sego, D. J. and Dalan, G. A., "Intensity Measurement System Verification—Test Report," Boeing Co., Seattle, WA, Doc. T6-6635, Feb. 1983.

[11]Beranek, L. L., *Noise and Vibration Control,* McGraw-Hill Book Co., NY, 1971, pp. 149-150.

[12]Krishnappa, G., "Cross Spectral Method of Measuring Acoustic Intensity by Correcting Phase and Gain Mismatch Errors by Microphone Calibration," *Journal of the Acoustical Society of America,* Vol. 69, No. 1, 1981, pp. 307-310.