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LABORATORY METHODS FOR MEASURING LOW-FREQUENCY SOUND EMISSION

W.T. Chu, Ph.D.

A.C.C. Warnock, Ph.D.
Member ASHRAE

ABSTRACT

ASHRAE research project 624-RP investigated measurement procedures for extending the frequency range of sound power tests in reverberation rooms down to the 63-Hz and 31-Hz octave bands both for broad-band and discrete frequency sound sources. There were four main areas of investigation: (1) a literature review, (2) a detailed study of the sound field in a model reverberation room, (3) a study of the reproducibility of the substitution method for both one-third-octave and single-frequency measurements in a number of reverberation rooms with different sizes and configurations, and (4) calibration of the sound sources used in the investigation by the intensity scan method. The project results suggest that the substitution method is the most suitable method for measuring sound power at low frequencies in reverberation rooms. The reproducibility and accuracy of the method, while larger than the values at frequencies of 100 Hz and above, appear to be acceptable.

INTRODUCTION

Recent changes in building design and construction have created significant noise problems from air-conditioning equipment at frequencies below the 125-Hz octave band. ASHRAE TC 2.6 felt there was a need to extend current ANSI sound power standards for use down to the 31-Hz octave band in reverberation rooms typical of those used by many testing laboratories, rooms with volumes of around 7,000 ft^3 (200 m^3). ASHRAE Research Project 624-RP investigated possible techniques for the measurement of sound power in reverberation rooms and attempted to establish the uncertainties associated with the measurements. This paper summarizes the results of this investigation. Full details are given in the project report.

Before describing the results, some background information on the behavior of sound fields in reverberation rooms at low frequencies will be helpful. Above a frequency known as the Schroeder frequency (Schroeder 1962), the sound field generated by a broad-band source in a room is quite uniform; it does not vary much from point to point. Below this frequency, typically about 400 Hz in a 7,000-ft^3 (200-m^3) room, the sound fields become progressively less uniform, until at very low frequencies, where only a few room resonances exist, the fluctuations from point to point become very large. This is why standards specify procedures to be sure that reverberation rooms have sound fields that are sufficiently uniform and why measurements are only required down to 100 Hz (ANSI 1990a, 1990b). At low frequencies, not only does the sound field vary strongly from place to place but the power emitted by the source can change markedly as it is moved from place to place in the room. Hence, sound power measurements at low frequencies can be expected to have large uncertainties or bias. The aim of the project was to determine if the uncertainties and bias were acceptable, remembering that, at present, no information at all usually exists for sound power below 100 Hz. The investigation was for sources radiating broad-band sound and for those with spectra containing discrete frequency components.

Two methods are routinely used to measure sound power in reverberation rooms. With the *direct* method, the average sound pressure levels and reverberation times in the room are used to calculate sound power. With the *substitution* method, a source of known power replaces the unknown source. The resulting change in sound pressure levels corresponds to the difference in sound power between the sources.

OUTLINE OF PROJECT

Following a review of the literature, the following topics were chosen for study:

1. The direct method, using the room-average sound pressure levels calculated from measurements made throughout the entire room volume, not just in the central room volume as is customarily done.
2. A direct method where sound pressure levels were measured in room corners only.
3. The substitution method, using different methods of sampling the sound field.
4. The sound intensity scanning method for measuring the "true" sound power of the sources.

Using loudspeaker sources, the first two topics were studied in a 1 to 2.5 scale model of an 8,829-ft^3 (250-m^3) reverberation chamber. Thus the model room had a volume of 568 ft^3 (16.1 m^3). Results in a full-size room can be predicted by dividing model frequencies by 2.5. The substitution method was investigated in greater detail using a number of room configurations and four different types of sources. The power of each source was calculated from sound intensity measurements made in an anechoic room

Wing T. Chu and **Alfred C.C. Warnock** are senior research officers at the Acoustics Laboratory, Institute for Research in Construction, National Research Council Canada, Ottawa, Ontario.

and a reverberation chamber with sound-absorbing material added to it to greatly reduce the reverberant field. These investigations and results are presented in the following sections.

SOUND POWER MEASUREMENTS AT LOW FREQUENCY USING THE DIRECT METHOD

Detailed Sound Field Measurements in Model Room

Usually, the average sound pressure level in a room is determined from measurements in the central volume only. Calculations are made to correct for expected concentration of sound close to the room surfaces (Waterhouse 1958). To determine the "true" room-average sound pressure levels in the model room, the whole room, including points on the surfaces of the room, was sampled at 3,040 regularly spaced grid points with a traversing microphone system. The grid points were about 6.8 in. (17.2 cm) apart. Microphone signals were measured with a one-third octave-band real-time analyzer.

The loudspeaker source comprised two 6.5-in. (16.5-cm) woofers set on opposite sides of a 10 in. (25.4 cm) diameter plastic globe. A partition inside the globe separated the two speakers, and the inner spaces were filled with glass fiber. The two speakers were driven in phase to simulate a monopole or in anti-phase to simulate a dipole. These are referred to as the small monopole and dipole. Two source positions (one corner and one mid-floor location) were studied. The sound power of each source was computed using the "true" room-average sound pressure level and the average reverberation time. The latter was measured using interrupted sound from the same source in the same position.

The cases with the sound source located at a corner were compared with similar measurements made according to ANSI (1990a) in the full-size, 8,829-ft^3 (250-m^3) room, which was fitted with fixed and rotating diffusers. Results of the 63- and 80-Hz bands for the full-size room were questionable because of the inadequacy of the Waterhouse correction term at low frequencies (Maa 1989). A modal analysis (Morse 1948) showed that in the 63-Hz, 80-Hz, and 100-Hz bands, there are only one, two, and three modes, respectively, in the model room, but there are 7, 14, and 29 modes, respectively, in the full-size room. Nevertheless, Figure 1 shows fair agreement between the sound powers measured in the two rooms. Scaling the model room results to the full-size room (dividing frequencies by 2.5) suggested that there was a possibility of making reliable sound power measurements down to the 25-Hz band in reverberation rooms of 250 m^3 where there is only a single mode!

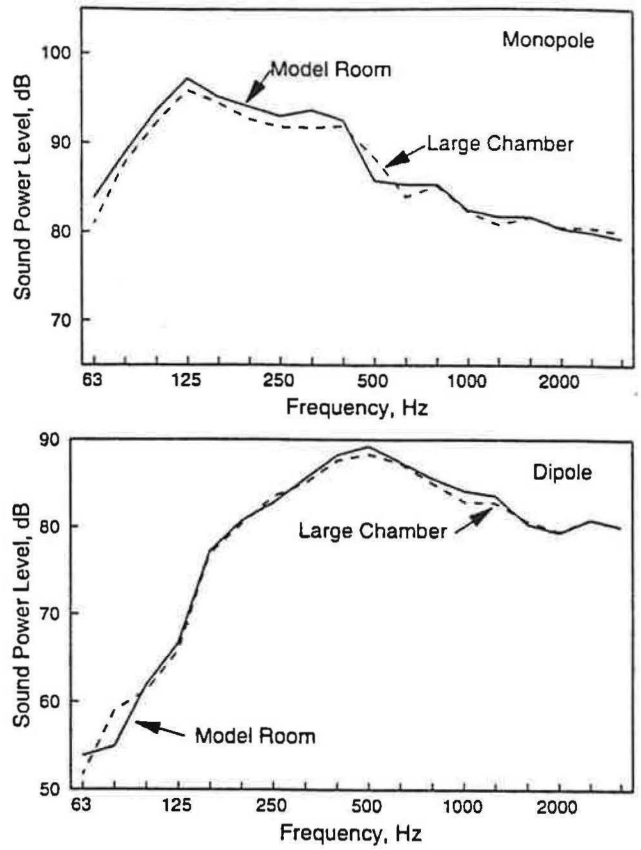

Figure 1 *Comparison of the sound power levels of the small monopole and the small dipole measured at the corners of the 250-m^3 room and the model room.*

Corner SPL vs. "True" Room-Average Sound Pressure Level

As well as the detailed survey of the sound field, sound pressure levels were measured at all eight corners of the model room. Corner microphones are often suggested for the measurement of sound pressure level (SPL) in a room because the room eigenmodes have pressure anti-nodes there. According to theory, the SPL in the corner where three infinite planes meet should be 9 dB greater than the SPL far from the corner. This theory is not expected to apply to sound fields in rooms at low frequencies where there are only a few eigenmodes. Also, when the room is not resonant, the SPL is not the same in each corner.

Figure 2 shows the difference between the room-average SPL and the average corner SPL for the small monopole and dipole located in a corner. For comparison, the result computed from normal mode theory (Chu 1980) for rectangular rooms is also shown. A simple point source located at 5.1 in., 5.1 in., 5.9 in. (13 cm, 13 cm, 15 cm)

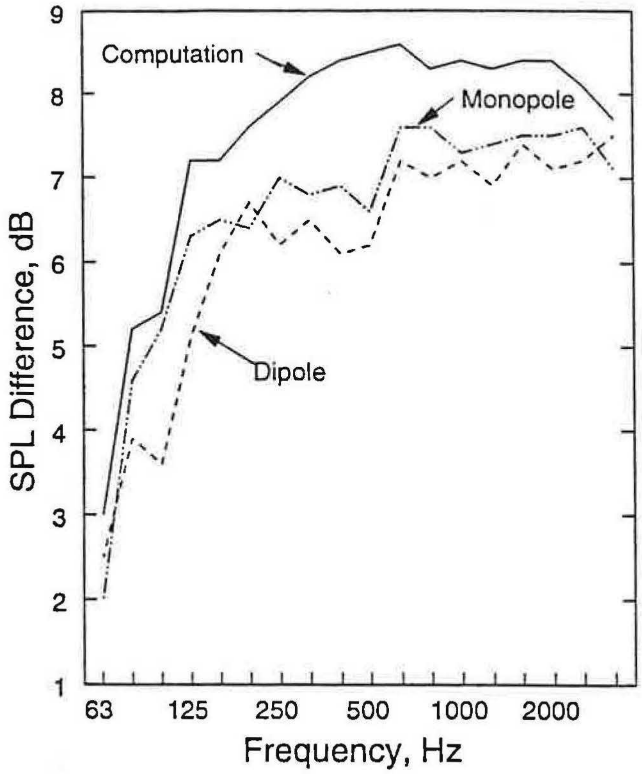

Figure 2 *Comparison of differences between average corner SPL and room-average SPL for two different noise sources in a corner of the model room. The theoretical result is for a monopole at the same position.*

simulated the actual source. The agreement between theory and measurement is only fair. This is possibly due to the inadequate representation of the real finite source by an ideal point source.

Ignoring the difference between theory and measurement, it is still evident that there is no simple relationship between the room-average and corner SPL. Empirical relationships would be needed for individual rooms if the direct method of sound power measurement using corner SPL were to be adopted. These relationships would have to be determined with a number of sources having different characteristics.

Reverberation Time Measurements in Model Room

With the small monopole and dipole located at the same corner and floor position used in the SPL measurements, reverberation times were measured at 20 microphone positions in the central volume of the room and at the eight corners. For a fixed source location, reverberation times measured by the corner and the spatial microphones were similar. However, for frequencies below 800 Hz (corresponding to 315 Hz in the full-size room), the measured reverberation times depended significantly on the source type and location (Figure 3). This is not surprising because the sound field is not diffuse below 800 Hz. (For the model room, the Schroeder frequency [Schroeder 1962], based on a modal overlap of 3, is about 1,000 Hz.) The maximum difference in reverberation time at 63 Hz corresponds to a 3.8-dB difference in the computed sound power of the source.

At low frequencies, where the number of room modes is small, loudspeakers in arbitrary positions in the room cannot reliably measure reverberation times for use in sound power calculations. Not only does the reverberation time depend on microphone and source position, but it also depends on source type. If the loudspeakers do not excite the room in the same way as the source being tested, the reverberation times may not be valid.

In the previous section, the sound powers of the small monopole and dipole sources were calculated using reverberation times measured using interrupted sound from the sources themselves. Agreement with sound powers measured in the large reverberation room was good. This suggests that the correct reverberation time to use is the one measured with the same source at the same location where SPL is measured. However, it is not always feasible to abruptly stop the sound from a source being tested. Thus, the direct method presents two difficulties at low frequencies:

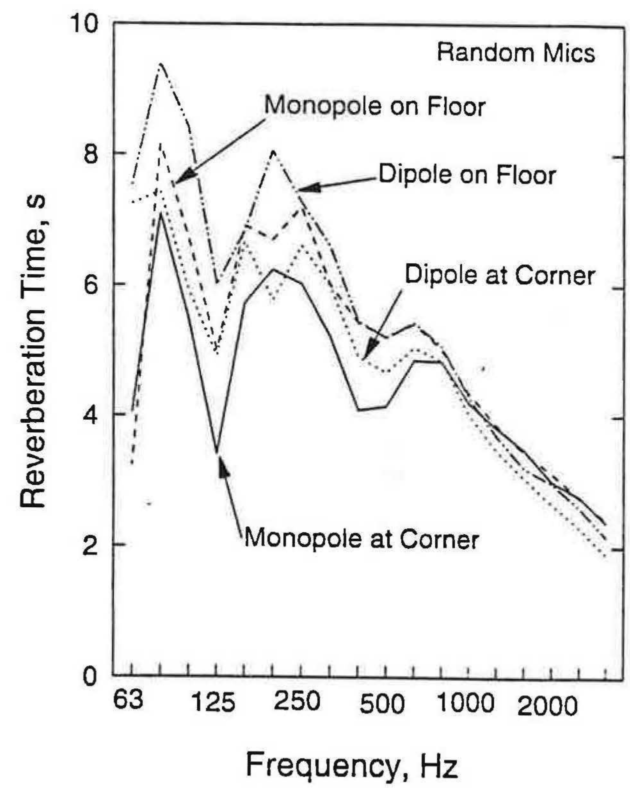

Figure 3 *Comparison of space-average reverberation time in the model room for four different excitation conditions.*

1. Measurement of room-average sound pressure level: Our data show that corner microphones do not make this task any easier, in contrast to other opinions (Bartel et al. 1983; Baade 1988).
2. Measurement of appropriate reverberation times.

Because of these problems, the substitution method was chosen as most likely to be viable for sound power measurements at very low frequencies. It requires no calibration of microphones and no measurement of reverberation time. It does, however, need a reliable calibration of the reference sound source at low frequencies. It also assumes that one type of reference sound source is applicable for the measurement of all other types of sources.

SOUND POWER MEASUREMENTS AT LOW FREQUENCY USING THE SUBSTITUTION METHOD

The precision and accuracy of the substitution method for both one-third octave-band and single-frequency applications were studied extensively in four rooms of different sizes and configurations using different microphone arrangements and source positions. Four different sources were investigated for one-third octave-band excitation and three for single-frequency excitation.

Room Configurations

The test rooms were basically rectangular parallelepipeds except as noted below:

1. The model room had a volume of 568 ft^3 (16 m^3) and was tested empty, with a rotating vane located in a corner, with a rotating vane located near the center, and with two low-frequency tuned absorbers mounted on the rotating vane in a corner.
2. The model room was altered by making two pairs of its walls nonparallel. This reduced the volume to 419 ft^3 (12 m^3). Measurements were made in this room with it empty and with two low-frequency tuned absorbers placed against one pair of nonparallel walls.
3. The large chamber had a volume of 8,857 ft^3 (250 m^3). It was used in its normal configuration with fixed and rotating diffusers. For single-frequency measurements, four additional 80-Hz low-frequency tuned absorbers were hung from the four walls.
4. The small chamber had a volume of 2,349 ft^3 (67 m^3) and was used in its regular configuration with fixed diffusers. This room has two recessed niches about 18 in. (0.5 m) deep where wall and floor specimens are mounted for sound transmission loss tests. These niches added eight extra corners to the "natural" corners in the room.

Sampling Methods

Four methods of sampling the sound field in the rooms were investigated.

1. *Corner microphones:* In the model room and the altered model room experiments, eight 1/4-in. (6.4-mm) microphones were placed about 0.4 in. (1 cm) from each of the eight corners of the room. (The exact location of the microphone is not important for the substitution method as long as it remains unchanged for measuring both the reference and the unknown source.) In the large chamber experiments, only six corner positions could be used. In the small chamber experiments, five natural corners were used and three other microphones were placed in corners inside the wall niche.
2. *Circle microphones:* In the model room and the small chamber experiments, eight 1/4-in. (6.4-mm) microphones were equally spaced in a 3.3 ft (1 m) diameter circle near the center of the room. The plane of the circle was not parallel to the floor. This arrangement was meant to simulate a microphone on a rotating boom. In the large chamber experiments, 10 microphones were used in an 8.2 ft (2.5 m) diameter circle.
3. *Random microphones:* In the model room experiments, eight 1/4-in. (6.4-mm) microphones were placed randomly in the central region of the room. In the large chamber experiments, one 1-in. (25.4-mm) microphone was moved under computer control to sample nine selected positions in the central part of the room.
4. *Edge microphones:* In the model room experiments, eight 1/4-in. (6.4-mm) microphones were equally spaced along the longest edge of the room including the two corners at the ends.

Sound Sources

Five different sources were used for this investigation. In most cases, six source positions were used.

1. A monopole was formed from two 10-in. (25.4-cm) speakers set on opposite faces of a 12-in. (30.5-cm) cubical plywood box and driven in phase. The interior of the box was filled with glass fiber. This is referred to as the large monopole.
2. A dipole was formed from the monopole by driving the speakers in anti-phase. This is referred to as the large dipole.
3. A 12 × 18 × 18 in. (30.5 × 45.7 × 45.7 cm) metal box was made by bending and welding panels of 0.02 in. (0.05 cm) thick sheet metal. Two 6.5-in. (16.5-cm) woofers resting on a foam pad inside generated noise, which was then radiated from the box surfaces. To minimize transmission of low-frequency vibrations to the floor in the anechoic room during sound power

calibration, the box was suspended on rubber bands attached to a wooden frame.

4. A standard fan reference source was modified to minimize the generation of tones at low frequencies. In its normal configuration, the tones emitted by this reference source caused unacceptably large variations in the sound fields in the 40-Hz band.
5. A second vertically mounted fan source with a 12 in. (30.5 cm) diameter fanwheel ran at about half the speed of the standard fan source. This moved troublesome tones below 25 Hz.

Only the monople, the dipole, and the metal box were used for single-frequency measurements.

Calculations

For each source and source position, the average sound pressure level (L_m) and the standard deviation (s_m) of individual sound pressure levels (L_i) were calculated for each sampling method following ANSI (1990a):

$$L_m = 10 \log \left[\frac{1}{N_m} \sum_{i=1}^{N_m} 10^{L_i/10} \right], \quad (1)$$

$$s_m = 10 \log \left[\frac{1}{(N_m - 1)} \sum_{i=1}^{N_m} (L_i - \langle L_i \rangle)^2 \right]^{1/2}, \quad (2)$$

where N_m is the number of microphone positions and $\langle L_i \rangle$ is the arithmetic mean of the individual sound pressure levels L_i.

For sound power computation using the substitution method, a comprehensive sound pressure level (L_p) averaged over microphone and source positions was computed for each source using

$$L_p = 10 \log \left[\frac{1}{N_s} \sum_{j=1}^{N_s} 10^{(L_m)_j/10} \right] \quad (3)$$

where $(L_m)_j$ is the average sound pressure level obtained using Equation 1 when the source is located at the jth position. The corresponding standard deviation (s_s) of the average sound pressure levels was calculated according to

$$s_s = \left\{ \frac{1}{(N_s - 1)} \sum_{j=1}^{N_s} [(L_m)_j - \langle L_m \rangle]^2 \right\}^{1/2} \quad (4)$$

where $\langle L_m \rangle$ is the arithmetic mean of L_m, averaged over all the source positions, and N_s is the number of source positions.

The sound power for each source was also determined independently using the sound intensity scan technique. Sound intensity measurements were made in an anechoic chamber and in the large reverberation room, which was suitably deadened with sound-absorptive material.

Strictly, standard deviations calculated as above cannot be used for the assessment of the measurement precision at the low frequencies of interest because the microphones are too close together to give independent samples. However, the standard deviations still serve as a qualitative indicator of the relative merit of the different sampling methods.

RESULTS AND DISCUSSIONS

In the following sections, the precision of measured sound pressure levels for a single source position is discussed first. A discussion of the precision of measured average sound pressure levels obtained with a number of source positions follows. Then, the reproducibility and the accuracy of the substitution method for sound power measurements are discussed.

One-Third Octave-Band Results, Single Source Position

When only a single position of a sound source emitting broad-band noise was used, examination of the results for different sources in different rooms led to the following general conclusions:

1. Corner microphones gave the lowest variance of sound pressure level (SPL) in the rooms that were rectangular parallelepipeds.
2. Corner microphones did not give as low variances in the two rooms that were not rectangular parallelepipeds as in the rooms that were.
3. Adding the rotating vanes had no significant effect on the spatial variance of SPL.
4. Adding the low-frequency absorbers did not significantly decrease the spatial variance of SPL.

One-Third Octave-Band Results, Multiple Source Positions

Since the sound power emitted at low frequencies by a source in a reverberation room depends on the position of the source in the room, to get a good average of the source sound power, sound pressure levels should be averaged over several source positions. This is termed here the global average sound pressure level. When this is done, the variance in the average SPL due to changes in source position is much greater than the spatial variance of SPL for a single source position. This means that any advantages due to the use of corner or edge microphones are lost. Figure 4, for the empty model room, shows examples of the average standard deviation due to repositioning the source for four different microphone sampling techniques. Standard deviations for the large monopole and dipole, the metal box, and the modified reference fan source were averaged to produce this graph. Similar plots for other room configurations suggest that there is no reason to prefer one microphone system over any other when several source positions

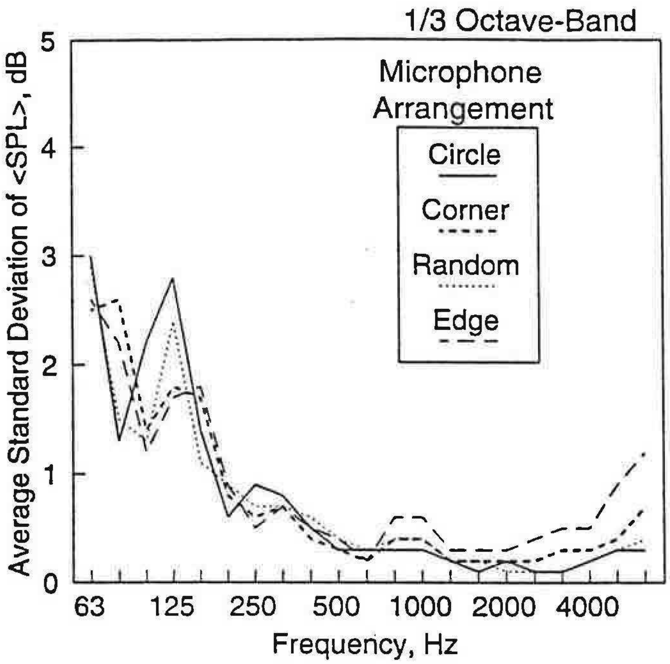

Figure 4 *Average standard deviations of the average SPL, s_s, obtained by four sampling methods in the empty model room (averaged over eight microphone positions for each of four source locations for the four sources).*

are used. This can be viewed as good fortune, since corner microphones are not commonly used and are more inconvenient than a single, moving microphone.

To present a more comprehensive picture of the precision in determining the global average sound pressure level, standard deviations from eight different room configurations are plotted on a single graph using a normalized frequency defined by

$$f_n = f\frac{\sqrt[3]{V}}{c} = \frac{L}{\lambda} \qquad (5)$$

where V is the room volume, f is the frequency, and c is the speed of sound, $L = \sqrt[3]{V}$ is the geometric mean dimension of the room, and λ is the wavelength of sound. A normalized frequency of 0.46 corresponds to 25 Hz in the 250-m^3 chamber or 63 Hz in the model.

Figure 5 shows standard deviations of average sound pressure level as a function of normalized frequency for corner and random microphone arrangements with the modified reference fan as the sound source. The figure gives a rough indication of the precision associated with the estimation of the global average SPL in a laboratory. The main conclusions drawn from data such as these were that all microphone systems work equally well when the source position is changed and that no one room configuration was better than any other.

Reproducibility of Sound Pressure Level Measurements

Using the substitution method, the sound power level produced by a source under test can be calculated as follows:

$$L_w = L_p + (L_{wr} - L_{pr}) \qquad (6)$$

where

- L_w = sound power level of the noise source under test (dB);
- L_p = global average sound pressure level of the noise source under test (dB), determined according to Equation 3;
- L_{wr} = sound power level of reference sound source (dB), known from the calibration of the source; and
- L_{pr} = global average sound pressure level of the reference sound source (dB), determined according to Equation 3.

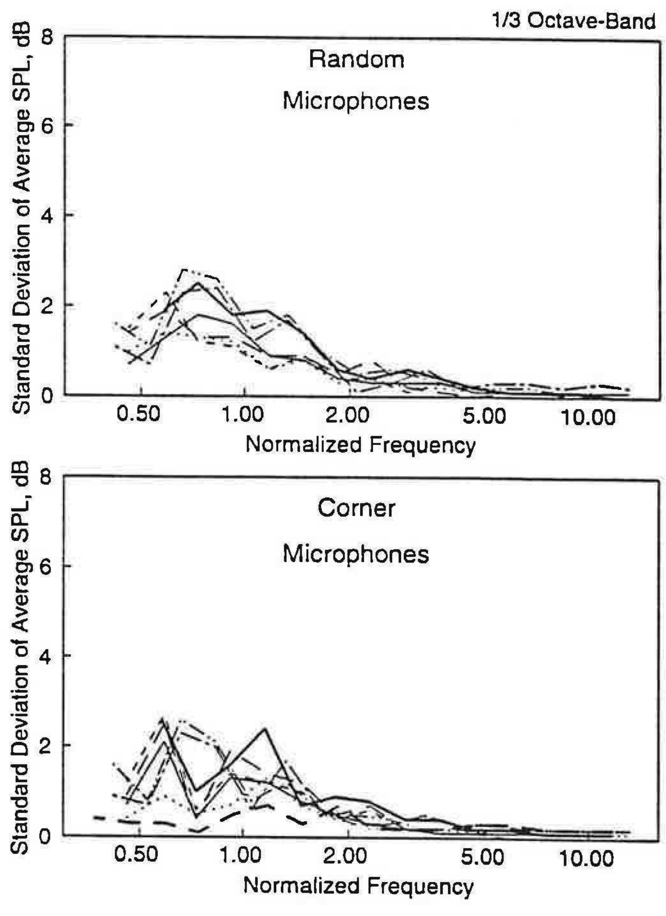

Figure 5 *One-third octave-band standard deviations of the average SPL, s_s, vs. normalized frequency for eight different room configurations excited by the modified ILG. The results are for the random and corner arrangements of the microphones.*

The method relies on an accurate determination of the difference in global average sound pressure level ($L_p - L_{pr}$).

Results for the different room configurations were grouped together to give some indication of the reproducibility of the difference in global average sound pressure levels measured for the unknown sources and for that acting as the reference source. An example of the spread in the data is shown in Figure 6 for a particular pair of sources, the large monopole and the modified reference fan. Differences between powers measured using sound intensity techniques are included as a reference. The agreement between this line and the shaded area indicates the accuracy of the substitution method. Accuracy and reproducibility are dealt with more fully below. These results give a preliminary overview of the measurements at low frequencies. They show that for this source

1. the large chamber results and the intensity results agree well above 80 Hz;
2. translating the model room results to a full-size room (by dividing the frequency scale by 2.5) suggests that the reproducibility of the substitution method should be better than 5 dB down to the 25-Hz band in full-size rooms around 250 m^3;
3. nevertheless, differences of more than 5 dB between the large chamber results and intensity results were seen at and below 63 Hz.

MEASUREMENT PRECISION

Measurement reproducibility is usually found from an interlaboratory or "round robin" investigation using the same source in different rooms. In this study, different rooms were used, but the differences in volume between the small room, the large room, and the model room are too great to consider all of them in one group. The data would not be relevant to typical rooms. The precision associated with the substitution method cannot be calculated using normalized frequency data because, for the same f_n in different rooms, the data would be related to different parts of the source spectra, effectively a different source. Hence, the data are restricted to those from the model room measurements. Although the range of volumes is not great, the set of experimental results in the model room is considered equivalent to an interlaboratory or "round robin" investigation. Nevertheless, because of the restricted range in volumes, estimates of precision should be considered as conservative.

This assumption allows approximate estimates to be made of the precision that can be expected for a standardized test based on the substitution method. The set of results used in the analysis came from the use of

1. four sources: the large monopole and dipole, the metal box with the modified fan source acting as the reference for the one-third octave-band results, and the large monopole as the reference sound source for single-frequency results;
2. six model room configurations;
3. four source positions in each room;
4. eight microphone positions for each source position;
5. two sampling methods: random and corner.

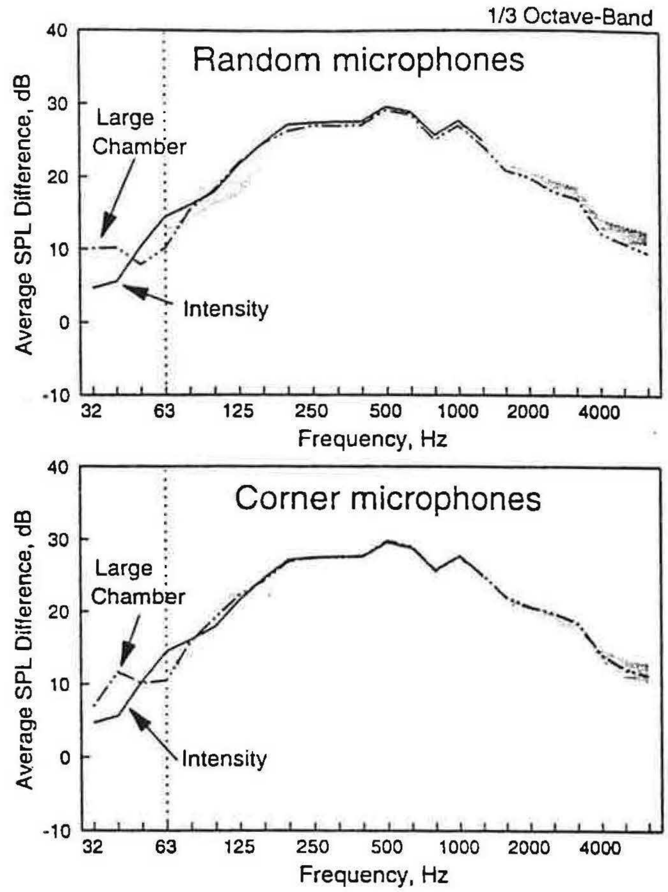

Figure 6 *Differences between the one-third octave-band average SPL for the large monopole and the modified reference fan source—random and corner arrangements of microphones. The shaded area represents the range of results for the six model room configurations. In the corner microphone cases, the shaded area also includes results from the small chamber. The difference in intensity levels for the two sources is shown by the solid line on the graph.*

For the substitution method, the precision in the computed power is a combination of the uncertainties associated with measurements of

1. sound pressure level for the unknown source,
2. sound pressure level for the reference source, and
3. sound power of the reference source.

The precision associated with the SPL measurements can be considered in two parts (ISO 5725-1981 (E) and ASTM E 691-79):

1. the precision for measurements in the same room (within-room repeatability) and
2. the precision for measurements obtained in different rooms (between-room reproducibility).

The precision for the power measurement of the reference source depends on the method used to measure power. In what follows, we ignore uncertainties in measurement of the sound power of the reference source using sound intensity. Statistics that apply to independent samples were used, although in this study microphones are too close together at low frequencies to provide independent samples.

For each source position, the sound pressure level measurements at the different microphone positions have a mean, L_m, and a standard deviation, s_m, given earlier by Equations 1 and 2.

Averaging over N_s source positions, we can define an average s_m as

$$\langle s_m^2 \rangle = \frac{1}{N_s} \sum_{i=1}^{N_s} S_{m_i}^2. \tag{7}$$

The variance of L_m due to changes of source position in a room, s_s, is defined by

$$s_s^2 = \frac{1}{N_s - 1} \sum_{i=1}^{N_s} \left[L_{m_i} - \langle L_m \rangle \right]^2 \tag{8}$$

where $\langle L_m \rangle$ is the arithmetic mean of the L_{m_i}. An average value of s_s can be calculated from the s_s values for each of the six rooms. This is the estimate of the within-room repeatability standard deviation and is labeled s_r. Thus,

$$s_r^2 = \langle s_s^2 \rangle = \frac{1}{N_R} \sum_{i=1}^{N_R} s_{s_i}^2 \tag{9}$$

where N_R is the number of rooms used.

The standard deviation, s_M, of the average SPL for each room is a combination of the variance due to changing rooms, s_L^2 and the variance within a room, s_r^2. Thus,

$$s_M^2 = s_L^2 + \frac{s_r^2}{N_s} \tag{10}$$

and

$$s_M^2 = \frac{1}{N_R - 1} \sum_{i=1}^{N_R} \left(\langle L_m \rangle_i - \langle\langle L_m \rangle\rangle \right)^2 \tag{11}$$

where $\langle\langle L_m \rangle\rangle$ is the overall average value of SPL for all the rooms.

The between-room reproducibility, s_R^2, is the sum of the within-room variance, s_r^2, and the between-room variance, s_L^2, thus

$$s_R^2 = s_r^2 + s_L^2. \tag{12}$$

The variance associated with the substitution method is taken as the sum of the variances for measuring the mean SPL for the unknown and the reference source (Baade 1971; Lubman 1974). The parameters s_r and s_R, derived from the measurements in this study, are presented in Table 1 for one-third octave and octave bands. These are average values based on results obtained for the different sources.

TABLE 1
Estimates of the One-Third Octave-Band and Octave-Band Repeatability and Reproducibility Standard Deviations for the Substitution Method Using the Modified Fan as the Reference Sound Source
(Normalized frequency is defined in Equation 5.)

Normalized Frequency	Corner Mic. $\langle s_r \rangle$	Corner Mic. $\langle s_R \rangle$	Random Mic. $\langle s_r \rangle$	Random Mic. $\langle s_R \rangle$	Corner Mic. $\langle s_r \rangle$	Corner Mic. $\langle s_R \rangle$	Random Mic. $\langle s_r \rangle$	Random Mic. $\langle s_R \rangle$
0.46	4.0	5.7	3.5	5.3				
0.59	3.1	4.7	2.5	4.0	1.7	4.0	1.3	3.1
0.73	2.4	4.9	2.6	4.8				
0.92	2.4	4.5	2.8	4.8				
1.18	2.6	3.6	2.0	3.7	1.3	3.2	1.2	3.4
1.47	1.4	2.8	1.6	3.0				
1.84	0.8	1.9	1.0	1.9				
2.31	0.9	1.4	1.0	1.5	0.5	1.4	0.6	1.4
2.94	0.6	1.5	0.7	1.4				
3.67	0.7	1.3	0.6	1.3				
4.63	0.4	1.4	0.5	1.3	0.3	1.3	0.3	1.2
5.88	0.5	1.3	0.5	1.1				
7.35	0.6	1.2	0.5	1.1				
9.18	0.3	0.9	0.3	0.8	0.3	1.0	0.3	0.9
11.75	0.3	0.9	0.2	0.9				

ONE-THIRD OCTAVE BAND MEASUREMENTS—ACCURACY

To consider accuracy, the sound power levels of the sources measured by the substitution method were compared with the sound power levels measured by the intensity method. In essence, the data were replotted in a different form. An example is shown in Figure 7 using normalized frequency for the same pair of sources. To provide an estimate of the bias errors one can get with different sources in different rooms, the data in Figure 7 and similar data for two other sources have been averaged and are shown in Table 2. Table 3 shows the corresponding octave-band results. These data show that the bias error depends on the type of the unknown source.

To get an overview of the accuracy and reproducibility of the substitution method, the data were condensed further. Figure 8 shows the maximum and minimum range of the differences between the power levels measured by the substitution method and those measured by the intensity method. The differences are for the large monopole and dipole and the metal box measured using the modified fan as the reference sound source in eight room configurations. Data were also analyzed in octave bands and plotted in Figure 8. This figure gives an idea of the range of the errors one might get for unknown sources. For further insight, Figure 9 shows the standard deviations of the differences for the same data. It is interesting that the ranges and standard deviations for octave bands are not significantly less than those for one-third octave bands.

The following observations were made concerning the accuracy of the measured sound power levels:

1. The accuracy of the substitution method at low frequencies varies with the room used but not significantly with microphone arrangement.

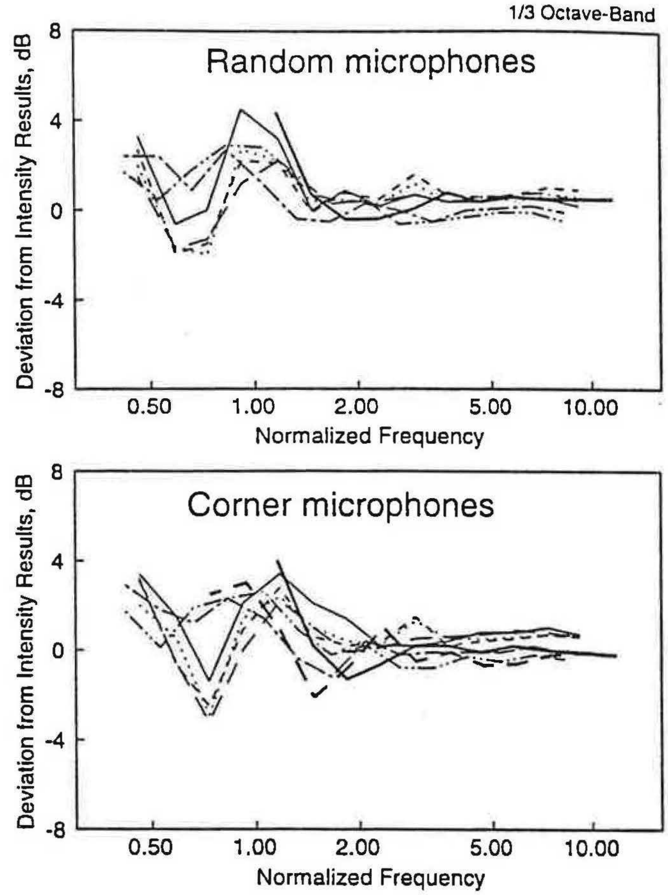

Figure 7 *Differences in one-third octave-band sound power level by the intensity and substitution methods for the large monopole. The modified fan is the reference sound source. Two sampling methods in eight room configurations.*

TABLE 2
Means and Standard Deviations of the Bias Error of the Substitution Method Using the Modified Fan as the Reference Sound Source
("Correct" sound powers were measured by the intensity scan method.)

1/3 Octave band Normalized Frequency	Large Dipole				Metal Box				Large Monopole			
	Corner		Random		Corner		Random		Corner		Random	
	Mean	Sigma	Mean	Sigma	Mean	Sigma	Mean	Sigma	Mean	Sigma	Mean	Sigma
0.46	-2.1	0.9	-2.1	1.0	2.5	1.6	2.5	2.0	2.4	1.0	0.9	0.8
0.59	-0.9	0.5	-1.1	0.6	1.8	2.1	0.8	3.0	0.7	1.1	-0.2	1.9
0.73	-1.6	1.2	-1.4	1.0	2.8	1.0	3.3	1.3	-0.5	2.5	0.6	1.9
0.92	-1.4	0.9	-1.3	1.2	1.9	1.4	2.8	1.2	1.6	1.0	1.3	1.2
1.18	-0.7	0.8	0.3	0.7	3.2	1.1	2.9	1.2	2.2	1.3	1.8	1.3
1.47	-0.1	0.2	0.1	0.4	0.7	1.7	0.9	1.0	0.3	1.3	0.5	0.5
1.84	0.6	0.9	0.8	0.8	-0.1	0.8	0.0	0.6	-0.1	0.8	0.4	0.5
2.31	0.9	1.0	0.7	0.8	-0.7	0.9	-0.9	0.5	0.1	0.5	0.0	0.3
2.94	0.3	0.7	0.4	0.7	-0.5	0.7	-0.4	0.7	0.3	0.8	0.1	0.8
3.67	0.3	0.8	0.5	0.8	-0.8	0.9	-0.8	0.8	0.2	0.4	0.0	0.4
4.63	0.3	0.4	0.6	0.5	-0.3	0.5	-0.4	0.4	0.1	0.5	0.2	0.3
5.88	0.4	0.5	0.6	0.4	-0.4	0.2	-0.4	0.3	0.3	0.5	0.2	0.3
7.35	0.4	0.6	0.7	0.6	-0.8	0.8	-0.7	0.5	0.3	0.5	0.2	0.4
9.18	0.3	0.4	0.4	0.4	-0.5	0.5	-0.5	0.2	0.2	0.5	0.1	0.4

TABLE 3
Means and Standard Deviations of the Bias Error of the Substitution Method
Using the Modified Fan as the Reference Sound Source
("Correct" sound powers were measured by the intensity scan method.)

Octave Band Normalized Frequency	Large Dipole				Metal Box				Large monopole			
	Corner		Random		Corner		Random		Corner		Random	
	Mean	Sigma	Mean	Sigma	Mean	Sigma	Mean	Sigma	Mean	Sigma	Mean	Sigma
0.59	-1.4	0.4	-0.8	0.7	3.2	1.0	3.9	1.1	0.0	1.6	1.1	1.6
1.18	-0.5	0.5	-0.1	0.3	1.7	1.0	2.2	1.3	1.1	0.9	1.3	0.7
2.31	0.5	0.9	0.5	0.7	-0.5	0.8	-0.6	0.9	0.1	0.5	0.2	0.6
4.63	0.2	0.4	0.4	0.4	-0.6	0.5	-0.6	0.4	0.3	0.5	0.5	0.4
9.18	0.5	0.4	0.9	0.2	-0.5	0.7	-0.5	0.3	0.4	0.4	0.7	0.2

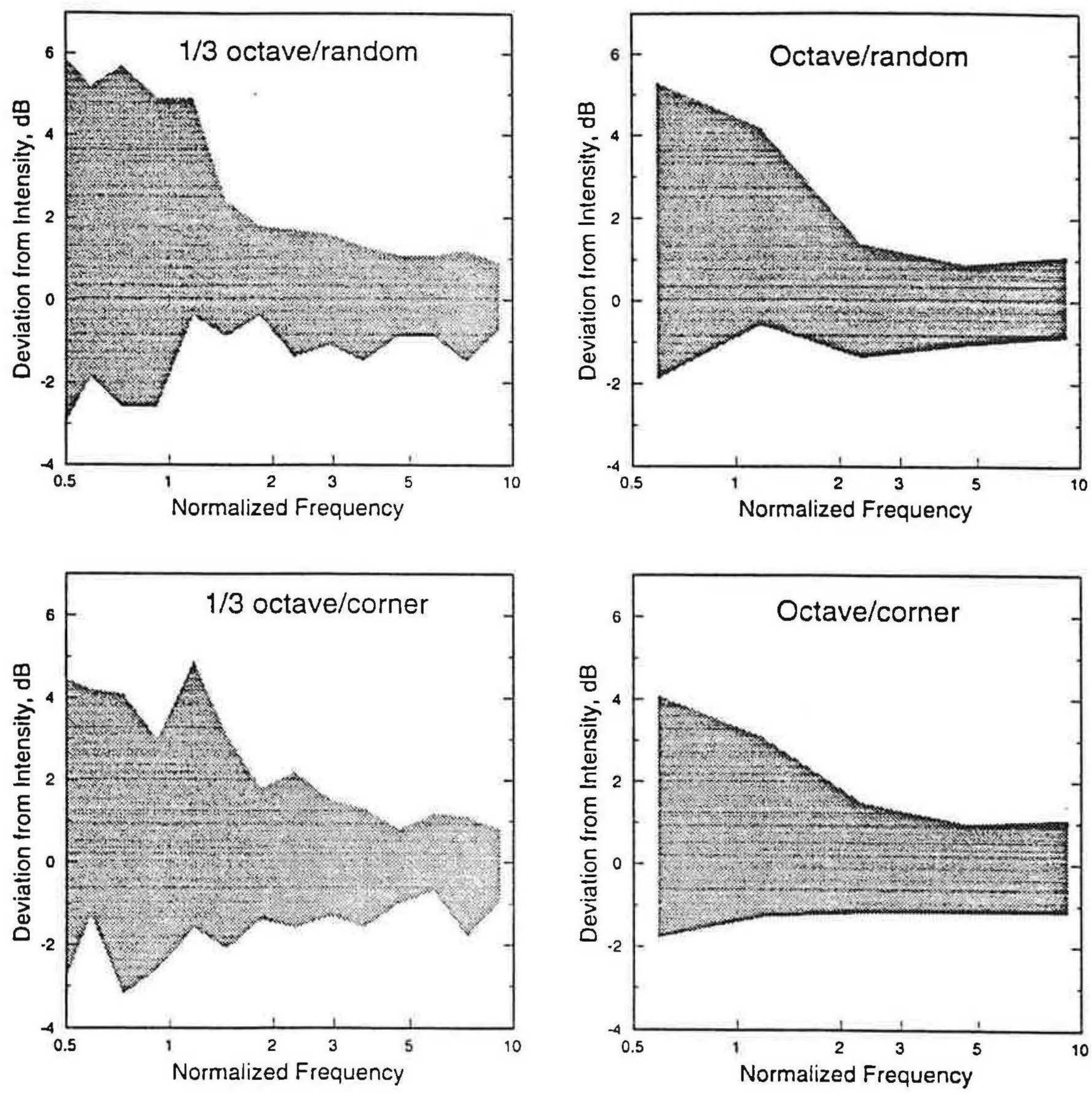

Figure 8 *Maximum and minimum values for the differences in one-third octave-band and octave-band sound power level by the intensity and substitution methods for the large monopole and dipole and the metal box. The modified fan is the reference sound source.*

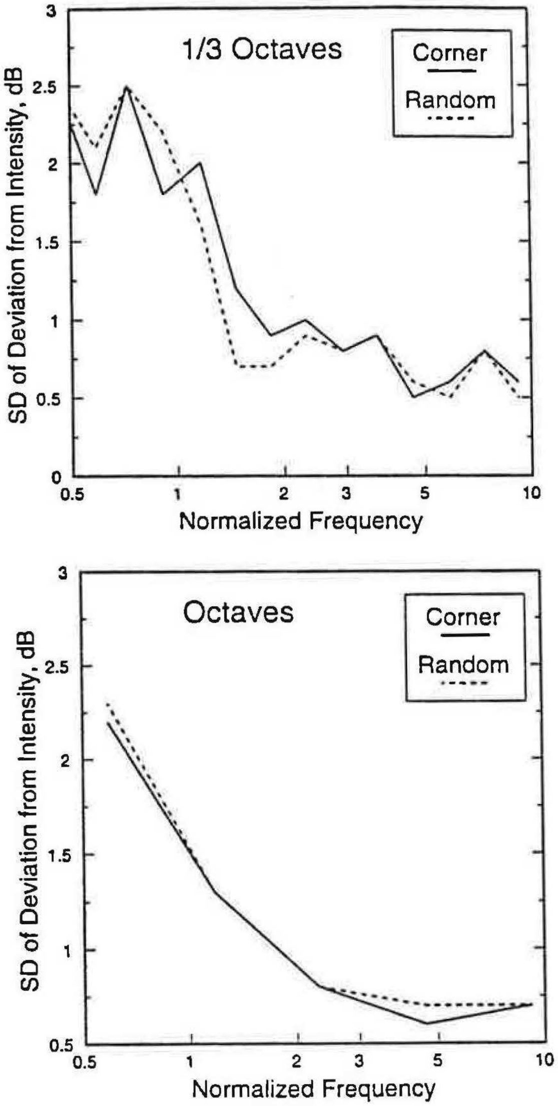

Figure 9 *Standard deviation of the differences in one-third octave-band and octave-band sound power level by the intensity and substitution methods for the large monopole and dipole and the metal box. The modified fan is the reference sound source.*

2. The accuracy of the substitution method at low frequencies depends on the similarity between the unknown and the reference sound source.
3. Taking the sound power from intensity measurements as correct, the data in Figure 9 suggest that 95% of sound power measurements made by the substitution method should be "correct" within ±2 dB above a normalized frequency of 1.5 (80 Hz in the 250-m^3 room) and within ±5 dB below that frequency.

Single-Frequency Results

Results from the single-frequency work were much less satisfactory. In general, plots of the measured standard deviation of sound pressure level for a single source position have a jagged appearance, with standard deviations being much higher at frequencies that did not coincide with the room resonance frequencies. The corner and edge microphones gave slightly lower standard deviations at the room resonance frequencies than the other microphone configurations. A rotating vane was effective only for frequencies whose half-wavelengths were less than the average linear dimension of the vane.

Figure 10 shows the standard deviation of the average SPL (s_s) as a function of normalized frequency for random microphones and the large monopole in several different rooms. The corresponding curves for other microphone arrangements and sources are similar; s_s varies quite strongly with room and source type.

To illustrate the reproducibility and accuracy of the substitution method for single-frequency measurements, differences between average sound pressure levels from two sources for all model room configurations are plotted in Figure 11; the shaded areas indicate the range of results. Differences between the powers determined by the intensity method for the two sources involved are also plotted. As expected, the reproducibility is worse than the one-third octave-band results, and the differences from the intensity results are larger. The following observations can be made:

1. Even with single-frequency excitation, there was no strong evidence that corner microphones were better than randomly spaced microphones when multiple source positions were used.
2. The accuracy of the substitution method for single frequencies at low frequencies depends on the room

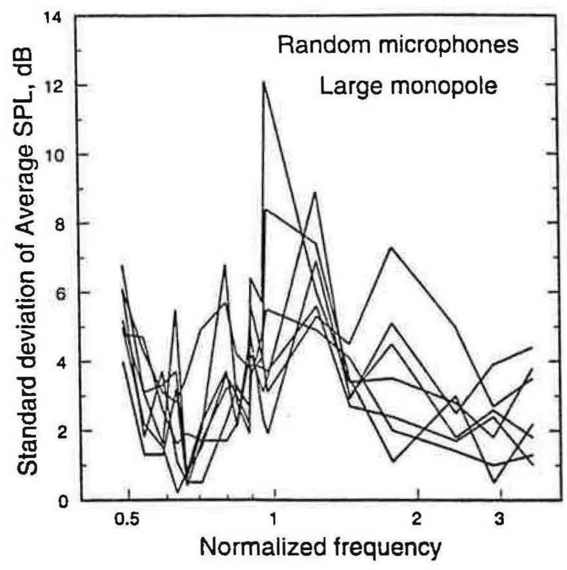

Figure 10 *Single-frequency standard deviations of the average SPL, s_s, vs. normalized frequency for eight different room configurations excited by the large monopole. The results are for the random and corner arrangements of the microphones.*

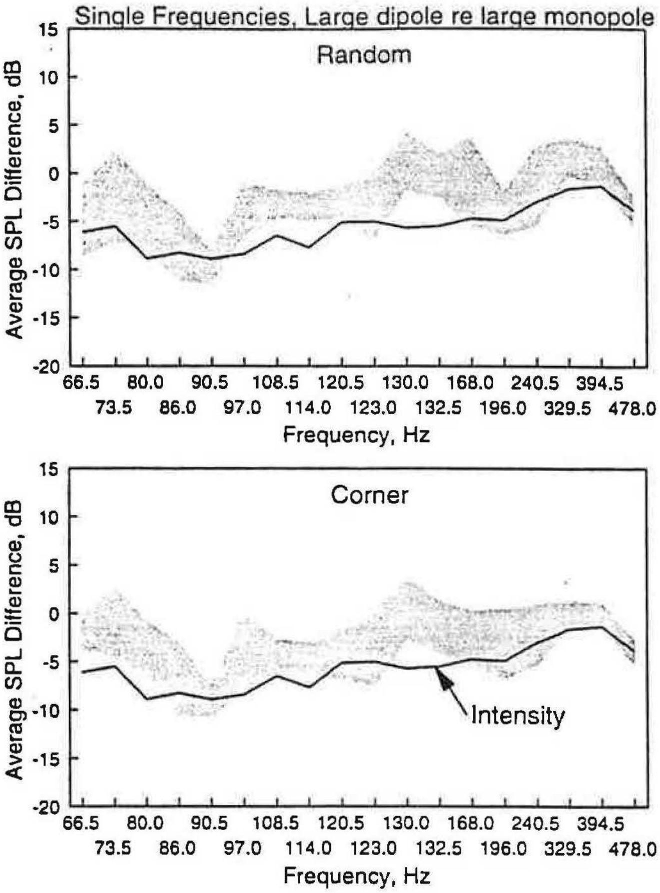

Figure 11 *Single-frequency average SPL differences between the large dipole and the large monopole obtained by the random and corner arrangements of microphones.*

and on the source type. Deviations from the values obtained from intensity measurements ranged from +18 dB to −10 dB.

CONCLUSIONS

The main conclusions from the research:

1. The substitution method is the most suitable method for measuring sound power at low frequencies in existing laboratories. No special room modifications or microphone sampling techniques are required. The accuracy and the reproducibility of the method seem acceptable, although an interlaboratory study is needed to verify this.
2. Requirements for microphone separation and source locations should still be governed by the existing ANSI S12.31 standard, since they would be used in normal sound power measurements. The statistical information in the body of the report can serve as a guide for establishing criteria for the acceptance of rooms for low-frequency sound power measurements.
3. Based on this limited set of results, the accuracy and repeatability standard deviation of the substitution method for one-third octave-band measurements increases from about 2 dB at a normalized frequency of 2 (125 Hz in the 8,857-ft^3 [250-m^3] room) to about 5 dB at normalized frequencies of 0.5 (32 Hz in the 8,857-ft^3 [250-m^3] room).
4. Accuracy for single-frequency measurements was much worse than that for one-third octave bands; differences from intensity measurements ranged from +18 dB to −10 dB.

Some other findings from the research:

a. For a fixed source position, corner microphones gave the lowest spatial variance of sound pressure level for both one-third octave-band and single-frequency measurements. However, when the standard deviation of these average SPLs for different source positions was used as a criterion, no one microphone system was found to be significantly better than any other. The variance in mean sound pressure level caused by moving the source was so large that any benefits due to the use of corner microphones were lost.
b. Rotating vanes or low-frequency absorbers had no significant effect on the spatial standard deviation of SPL for the one-third octave-band measurements, although there was some improvement for the single-frequency measurements. It is difficult to design a rotating vane that is effective at the lowest frequencies of interest because its size is limited by the size of the room.
c. Sources can be calibrated reasonably accurately above 63 Hz using the intensity scan method.

These conclusions apply to the procedures followed in this project, where multiple source positions were used and the sources were all comparatively small. Where a laboratory must estimate the power from a fixed object, such as the outlet of a duct system, then one must expect greater bias in the measurement. It is possible that a correction spectrum could be generated for such a laboratory that would compensate for the use of a single source position. This is, however, speculative and needs further investigation.

RECOMMENDATIONS

There are unanswered questions, and further work needs to be done. Thus, we recommend the following:

1. Interlaboratory measurements of the variation of global average SPL differences between a few more loudspeaker sources and a reference source to determine the reproducibility of the substitution method at low frequencies in typical laboratories.

2. Investigation of the calibration of reference sound sources at low frequencies using the fixed-point intensity method, measurements in large hemi-anechoic rooms, or measurements in very large reverberant rooms or arenas.
3. Some investigation of methods for dealing with situations where measurements must be made with a single source position.

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