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SOME PRACTICAL ASPECTS OF ABSORPTION MEASUREMENTS IN REVERBERATION ROOMS

by A.C.C. Warnock

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RÉSUMÉ

La présente communication décrit les résultats d'une série de mesures commandées par ordinateur, des coefficients d'absorption sonore dans une chambre de réverbération simple. Les effets de facteurs comme la surface des diffuseurs, la position des microphones et l'utilisation de diffuseurs tournants sur les mesures sont analysés. Les variations spatiales du taux de décroissance, des rayons de courbure et des coefficients d'absorption tels que mesurés déterminent la précision des mesures. Les méthodes pratiques requises pour obtenir une précision satisfaisante sont comparées à celles utilisées dans les essais normalisés.

Some practical aspects of absorption measurements in reverberation rooms

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This paper discusses the results of a series of computer controlled measurements of sound absorption coefficients in a single reverberation room. The effects of factors such as diffuser area, microphone position, and rotating diffusers on the measurements are discussed. Spatial variations of decay rate, curvature, and measured absorption coefficients determine the precision of the measurements. The practical procedures necessary to achieve satisfactory precision are compared with those allowed in standard test methods.

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INTRODUCTION

Random incidence sound absorption measurements have been made in reverberation rooms for many years. Since the results are usually used to compare commercial acoustical products, the reproducibility and repeatability of such measurements are of practical as well as scientific interest. Several round robin measurements[1–4] and many other informally reported investigations made over the years have shown that factors such as loudspeaker, specimen, and microphone position, as well as the number, disposition, and size of the diffusing elements in the reverberation room, are important in determining the values of absorption coefficient obtained. In recent years computer-based measurement systems have allowed a detailed look at sound decay in rooms,[5–8] at measurement procedures, and at factors affecting the reproducibility, repeatability, and measured coefficients. The introduction of laboratory accreditation programs in North America makes a careful investigation of the sections in the standards containing suggested or mandatory room performance criteria an urgent task. If these criteria cannot be readily satisfied in typical laboratories, then they should be removed from the standards and replaced with realistic criteria.

Two major standard methods are considered in this paper, American Society for Testing and Materials (ASTM) method C423[9] and the International Organization for Standardization (ISO) draft document R354.[10] They are fundamentally similar but differ in some details. In certain sections of ASTM C423 there are room performance criteria that could be used in accreditation requirements. These criteria deal mainly with the spatial variation of decay rate, decay linearity, and the variation of measured absorption coefficient with microphone and specimen position. ISO R354 contains requirements on decay linearity and the number of microphone and loudspeaker positions to be used, as well as a procedure for adding diffusing elements to qualify the room.

This paper compares the sets of criteria in the two standards with each other and with practical measurements; it also examines the effects of changes in measurement procedures and in diffuser arrangements on measured coefficients. Based on this work, some recommendations for improving standard measurement procedures are made.

I. EXPERIMENTAL PROCEDURES

The measurements were made in the 251-m^3 reverberation room at the National Research Council Canada (NRCC). The physical properties of the room are given in Table I. All measurements were made with a GenRad 1566 multichannel amplifier, a 1925 third-octave band multifilter, and a 1926 real-time analyzer interfaced to a minicomputer that also switched the sound in the room on or off and measured room temperature and humidity. With this system, simultaneous level measurements are made in the one-third octave bands from 100 to 5000 Hz in consecutive intervals of 0.1 s during the decays. The number of microphones in the room varied through the measurement series from a maximum of 22 to a minimum of 9. Microphones were at least 1.2 m apart. The ensemble or decay curve averaging procedure described by Chu[6] was used almost exclusively to obtain the mean decay rate at each microphone. In this procedure a number of decays are averaged together to produce decay curves smoother than the usual jagged curves seen for single decays, especially at the lower frequencies. For convenience, the averaging is done for each time interval by adding together the sound pressure levels in decibels. Jacobsen[11] has pointed out that it is more correct to combine mean square pressures rather than levels, but with the above instrumentation this more complicated procedure made no significant difference to the calculated decay rate or curvature.

To determine the decay rates, straight lines were fitted

TABLE I. Reverberation room characteristics.

Dimensions	7.98×6.48×4.88 m
Floor	51.7 m^2
Height	4.88 m
Volume	251 m^3
Surface area	244.5 m^2
Temperature	21 °C
Relative humidity	∼55%

to the averaged decay curves, usually over a range of 30 dB, using a least mean squares algorithm. The reverberation time calculated from this decay rate is denoted as T_0. The first point used in the fitting procedure was at 0.1 s after the sound had been switched off; i.e., the second level measurement made during the decay. Examination of ensemble-averaged decay curves[5,6] shows that there is no reason for waiting until the sound pressure level has decreased by 5 dB with respect to the steady-state level, thereby rejecting points early in the decay. Each 30-dB decay curve was divided into a top half and a bottom half; the decay rates for each half are used to calculate reverberation times, T_t and T_b, respectively. The percent curvature of the decay is defined for this work as

$$C_1 = 100(T_b/T_t - 1). \tag{1}$$

Since these experiments extended over a few years in a room used for other purposes, the configuration of the microphones, diffusers, and speakers in the room changed as alterations to measurement procedures were made. However, the physical configuration of the room was closely controlled in each measurement subset where comparisons were made.

The specimen used in the absorption measurements consisted of 50-mm-thick panels of glass fiber enclosed in protective aluminum frames faced with an expanded aluminum protective cover. This specimen was constructed for round robin studies in North America in 1964. The specimen panels were assembled in a 2.74- × 2.4-m wood frame. The distance from the upper surface of the panels to the room floor was 405 mm and the enclosed air space was 355 mm deep. This method of mounting is designated as E405 in ASTM E795.[12] The panels could also be laid flat on the floor of the reverberation room, the A mounting described in E795, but most of the measurements were made using the E405 mounting.

At the time these measurements were made the systematic error due to a cavity at the bottom of the frame had not been recognized,[13] but since the frame was not changed during the series, the effect was constant and can be ignored for the purposes of this paper.

The principal room variation studied in these experiments was the effect of different diffusing systems on the measured quantities. At one extreme the room was bare of all diffusing elements except for two small pieces of board to cover the air-conditioning openings when desired. Fixed diffusing panels were added to the room in stages and the specimen absorption and other parameters were measured in each case. Panels were added to a rotating vertical shaft to form a rotating diffuser, which is normally present in the room, and further increased the number of diffusing elements in it. The panels were not surfaces of revolution but acted like paddles and the normal to their surface pointed approximately in the direction of motion. Although they significantly disturb the air in the room, they have a negligible effect on the measurements of sound pressure level and even help to produce a more uniform temperature and relative humidity by mixing the air in the room.

Table II describes all of the diffuser configurations studied. Those connected by brackets in the table are cases where measurements were made with the rotating diffuser both fixed and stationary with all other factors unchanged. Although the loudspeaker boxes could be considered to act as diffusers, they are not included as part of the diffuser area.

TABLE II. Diffuser configurations.

	Area of diffusers (m^2)		
	Fixed	Rotating	Total
A	0.93	0	0.93
B	6.32	0	6.32
C	9.85	0	9.85
D	0	11.90	11.90
E	11.90	0	11.90
F	18.77	0	18.77
G	7.97	11.90	19.87
H	19.87	0	19.87
I	18.77	4.46	23.23
J	18.77	9.50	28.27
K	28.27	0	28.27
L	24.00	4.46	28.46
M	19.87	11.90	31.79
N	32.15	9.50	41.65
O	41.65	0	41.65

II. DECAY CURVATURE

A. General considerations

Both C423 and ISO 354 contain decay curvature criteria and recommend or require the rejection of excessively curved decays. These criteria are based on the assumption that rooms can be adjusted by using diffusing devices to make the decays linear and that the curvature can be measured precisely enough to allow valid rejection of individual or averaged decays.

The visual interpretation of decays on a level recorder is tedious at best at the higher frequencies, but at low frequencies it can be very difficult to arrive at a good estimate for the decay rate of a jagged trace which is apparently curved. There is thus some practical justification for rejecting such traces when the interpretation is done by eye. When a computer analysis system is used, rejecting individual decays is not justified since there is no change in difficulty of interpretation. Nor is it acceptable in principle to reject individual decays from a population because the curvatures exceed some arbitrary value. In the following subsections the problem of curved decays in reverberation rooms is examined from a practical point of view.

B. Effects of diffusers on curvature

The discussions of the decay process at low frequencies by Larsen,[7] Bodlund,[5] and Jacobsen[11] show that one should expect curved decays in bare rectangular rooms, especially at low frequencies, because of the scarcity of modes and the different decay rates associated with them. The extent of the influence of diffusers on room response, the nature of the decays and decay curvature will depend on the size, weight, position, and number of these devices and, if a rotating vane is used, the rotation speed. Many of these factors have not yet been fully investigated, especially for rotating diffusers.

The definition of decay curvature given by Eq. (1) is obviously not the only one possible. Others have been used.

The curvature defined in Eq. (1) can be used to verify that the ISO 354 requirements are met, but so can

$$C_2 = 100(T_0/T_t - 1), \qquad (2)$$

which is less stringent. The ISO 354 criterion for accepting or rejecting decays, which is that C_2 (or C_1) should be less than 10%, may be applied to individual decays or to ensemble averages.

ASTM C423 suggests that the average decay time for the top half of the decay range at any frequency should be the same as the average for the bottom half within precision limits stated in the standard. This implies that decay curvature is checked on some occasion and the room adjusted if the measured curvature is too large.

The definition of curvature in Eq. (1) was adopted because it is convenient and yet corresponds fairly closely to the C423 approach; in any case, the computer program always checks each ensemble average for linearity at all frequencies.

Obviously the value of curvature assigned to a decay depends on the algorithm used and on part of the curve over which the fitting is carried out. However, since the effects described in this paper are qualitative rather than quantitative, the merits of different definitions will not be discussed.

In case A, Table II, no diffusing elements were present in the room. Figure 1 shows for this case the mean percent curvature, C_1, measured in the empty room by 18 microphones distributed throughout it. The figure also shows one standard deviation on either side of the mean. The substantial spatial variations in measured curvature are in qualitative agreement with the predictions and results of Davy *et al.*[14] The formulae given there to predict the spatial standard deviation of percent curvature, $\sigma_s(C)$, can be simplified to

$$\sigma_s(C) \approx 10800/D(fT_0)^{1/2}, \qquad (3)$$

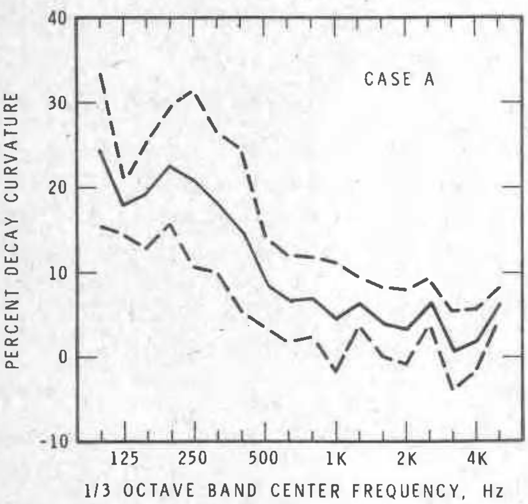

FIG. 1. Mean percent curvature ± one standard deviation (18 microphones) for case A—no diffusers.

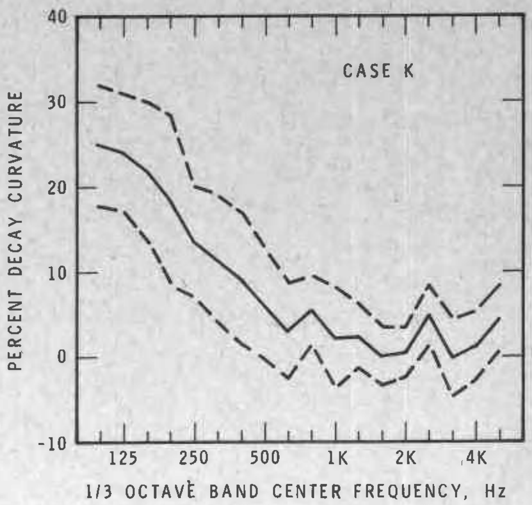

FIG. 2. Mean percent curvature ± one standard deviation (18 microphones) for case K—28.27 m^2 of fixed diffuser.

where f is the center frequency of the one-third octave band filter and D is the range in dB (20 to 30) over which the fitting procedure is carried out. Since the definition of curvature used in this work is not the same as that adopted by Davy *et al.*, no direct comparison with their theory has been made here.

Figure 2 is the corresponding plot for case K where 28.27 m^2 of fixed diffusers was used. The reduction in the mean value of curvature can be attributed to the addition of diffusers; however, the spatial standard deviation is not reduced. On the other hand, Fig. 3 shows for case J the marked improvement that results when the rotating diffuser is set in motion. Not only is the mean value of curvature reduced but also the spatial standard deviation. This is typical of the effect of the rotating diffusers used in this work on the magnitude and spatial variation of curvature.

To illustrate the effects on curvature of all the diffusing systems investigated, Fig. 4(a) and (b) shows mean room cur-

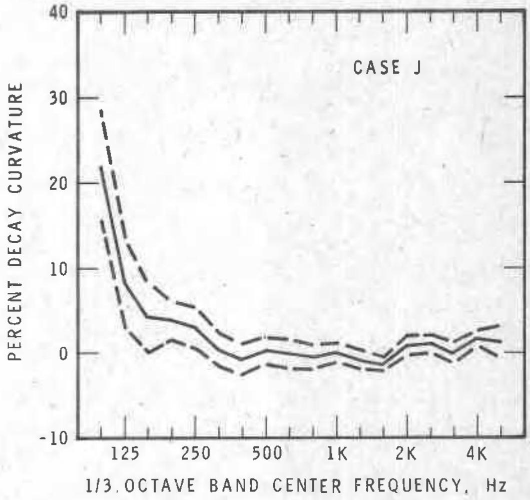

FIG. 3. Mean percent curvature ± one standard deviation (18 microphones) for case J—18.77 m^2 of fixed diffusers and 9.5 m^2 of rotating diffusers.

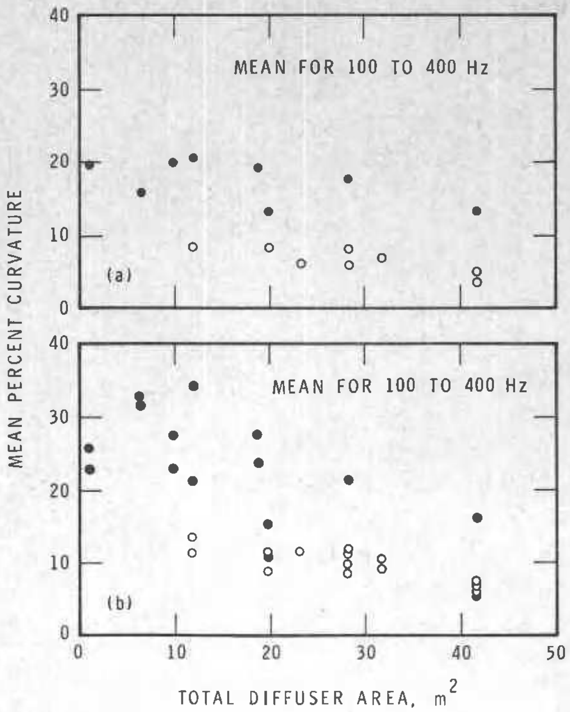

FIG. 4. Mean percent curvature in frequency range 100–400 Hz as a function of diffuser area. ●—fixed diffusers; ○—fixed and rotating diffusers. (a) no specimen in room; (b) specimen in two positions in room.

vature as a function of total diffuser area for the room with and without a specimen. Room arrangements using fixed diffusers only are denoted by dots or triangles, and arrangements using fixed and rotating diffusers are denoted by open circles. The data in both figures are averages for the frequency range from 100 to 400 Hz where the decay curvature is most severe. The data in Fig. 4(b) are for the specimen placed in two floor positions. There is no obvious dependence of curvature on total diffuser area, but it is clear that the rotating diffusers reduce measured curvature. The figures also show that introducing a specimen into the room generally results in a slight increase in curvature in these bands.

This room is not atypical and the data presented in Figs. 1–4 show that when fixed diffusers are used, the criteria in ISO 354 and ASTM C423 are not realistic. Even when rotating diffusers were used, the criteria could not be satisfied at all frequencies for all microphone positions.

C. Precision of curvature measurements and rejection of individual decays

The paper by Davy *et al.*[14] on decay curvature predicts the variance of measured curvature for a single microphone, the ensemble variance $\mathrm{var}_e(C)$. An approximate expression for the room and analysis parameters used here, which agrees adequately with the more exact equation by Davy *et al.*, is

$$\mathrm{var}_e(C) \approx (8.8\times 10^9)/D^3 f T_0. \quad (4)$$

It is thus easy to calculate the number of decays necessary to measure the curvature at a single microphone position to any required degree of precision. Assuming $D = 30$ dB, $T_0 = 7$ s, and $f = 125$ Hz, the equation predicts that the standard deviation of the ensemble of measured curvatures will be 20%. Thus 1600 decays must be collected at a single position in order to specify the mean curvature of the decays there with 10% uncertainty and 95% confidence. This is clearly impractical for routine testing and out of the question unless computer analysis equipment is freely available. Because of the different definition of curvature used here and the use of rotating vanes, individual decays at a single microphone were examined further.

For a single microphone, 1800 decays were collected in each frequency band and stored on magnetic tape. Each decay curve in each band was then individually analyzed; that is, the decay curve averaging procedure was deliberately not used. This resulted in 1800 values of each of the three reverberation times, T_0, T_t, and T_b, defined earlier, and 1800 values of each of the two definitions of curvature [Eqs. (1) and (2)] for each of the 18 frequencies. Figure 5(a)–(e) shows as an example the distribution of these quantities for the 125-Hz third-octave band for one microphone in a particular room configuration. These plots are typical for the low-frequency bands and show the variability between successive decays at the same microphone. As the frequency increases, the distributions become narrower in qualitative agreement with Eq. (4). Measured values of the standard deviation of curvature ranged from about 40% at 125 Hz to 10% at 5 kHz.

The same set of decays was used to examine the effect of decay rejection on mean reverberation time. The correlation coefficient between T_0 and percent curvature was calculated for all of the 18 frequency bands and exceeded 0.1 at only three of the lower frequencies (Table III). The computer was then programmed to reject decays with a curvature of magnitude greater than 10% and to calculate a new mean value of T_0. Both the C_1 and C_2 definitions of curvature in Eqs. (1) and (2) were used as the basis for rejecting decays, and the resulting average decay times are denoted as T_{01} and T_{02}, respectively. The corresponding number of decays used to calculate each mean time is denoted as n_1 and n_2. Values of C_1 and C_2 in Table III are for the entire set of 1800 decays. This table shows that the mean reverberation times calculated are not substantially affected by the rejection. This is to be expected because there is no correlation between the calculated decay rates and the curvatures.

The individual low-frequency decays can be classified as "straight" according to the algorithms used in these experiments. However, the average value or the value calculated from the ensemble-averaged decay curve, using the same algorithms, may exceed the 10% criterion in Draft ISO R354. Thus according to ISO 354, if ones uses ensemble averaging or calculates the mean curvature for many decays, one must reject the entire ensemble because it is excessively curved, yet if the same algorithms are used on individual decays, many of them can be used. This approach is not consistent.

Thus, both theory and experiment show that a very large number of decays must be analyzed before one can make reasonably precise statements about average decay curvature. The measurements also show that, although rejecting decays that do not satisfy some arbitrary curvature

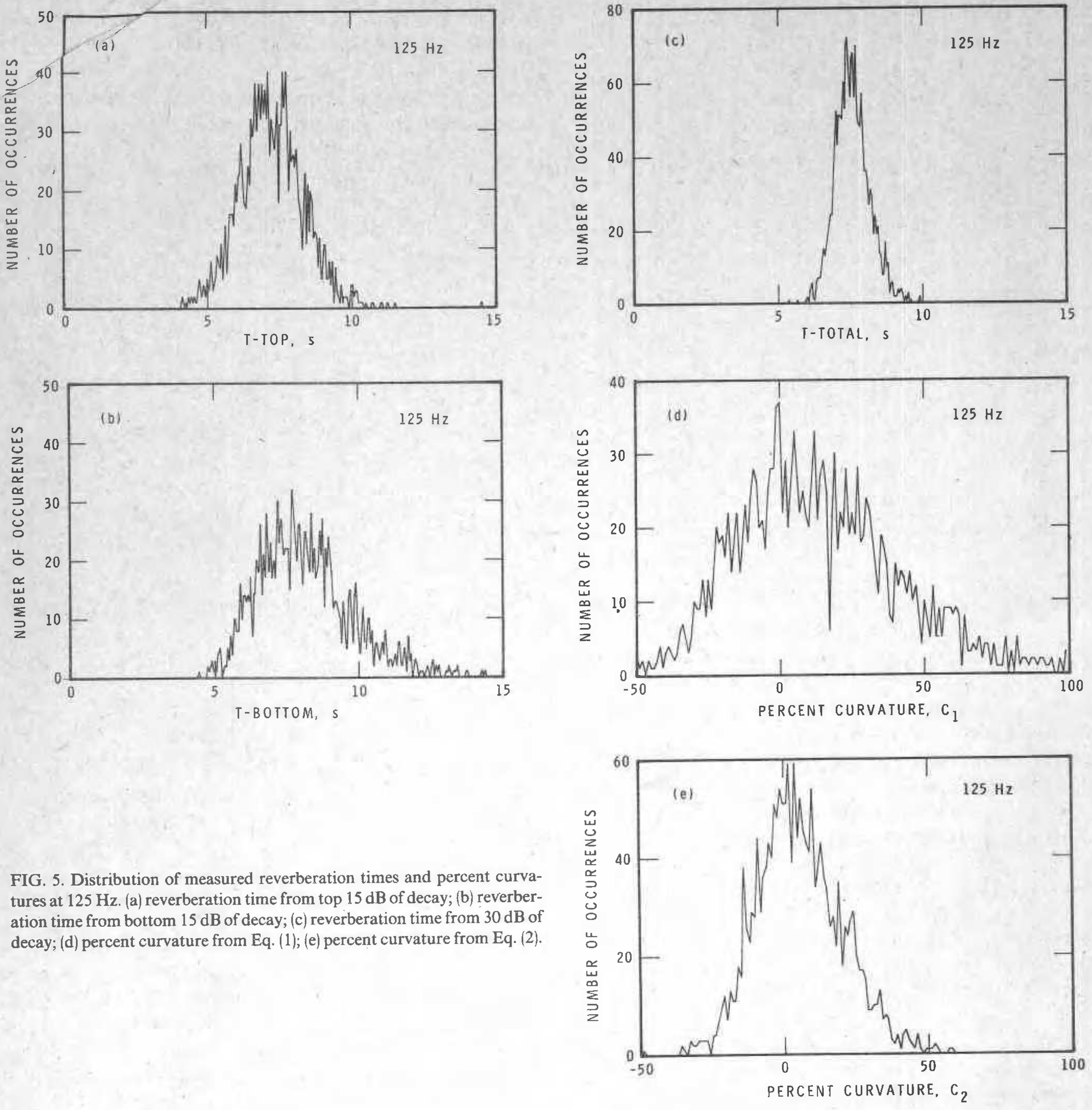

FIG. 5. Distribution of measured reverberation times and percent curvatures at 125 Hz. (a) reverberation time from top 15 dB of decay; (b) reverberation time from bottom 15 dB of decay; (c) reverberation time from 30 dB of decay; (d) percent curvature from Eq. (1); (e) percent curvature from Eq. (2).

criterion may not be good practice, it does not alter the mean reverberation time.

D. Precision of ensemble-averaged measurements

Visual inspection of ensemble-averaged decays might lead one to suppose that their repeatability was very high and that quantities such as percent curvature would therefore exhibit much less variability.

To investigate this, 50 decays were collected and averaged in each frequency band for each of nine microphones. Reverberation times and curvatures were calculated for each set of averaged decays and stored, together with measured room temperature and relative humidity. This procedure was repeated 33 times over many hours. Throughout the measurement period the room temperature and relative humidity remained constant within 0.6°C and 1% relative humidity, respectively. Thus for each frequency there were 33 values of reverberation time for each of nine microphones.

For a given frequency and microphone, the 33 values of reverberation time were averaged to give a mean and standard deviation. The standard deviations for the nine microphones were then averaged to produce s_{mics}, which is thus a typical value.

For one set of 450 decays, the reverberation times at each of the nine microphones can be averaged to give a room-averaged time. The 33 sets of room averages have a distribution with a standard deviation denoted by s_{room}.

The same procedures can be applied to the values of curvature measured at each microphone. Table IV lists these standard deviations for each frequency and shows that for

TABLE III. Correlation between reverberation time and percent curvature C_1 and the effects on reverberation time of rejecting excessively curved decays (see text for explanation of symbols) (1800 decays).

Frequency (Hertz)	r	T_0	T_{01}	n_1	C_1	T_{02}	n_2	C_2
100	− 0.022	6.74	6.68	387	31.0	6.78	638	13.1
125	0.100	7.61	7.58	517	14.3	7.61	892	6.1
160	0.140	7.06	7.02	576	10.2	7.04	944	4.2
200	0.180	6.85	6.85	657	7.0	6.84	997	3.2
250	− 0.022	7.24	7.25	881	6.2	7.24	1262	3.1
315	− 0.035	7.09	7.09	983	3.0	7.09	1425	1.0
400	− 0.065	6.71	6.72	1096	3.0	6.71	1504	1.1
500	0.020	6.21	6.21	1204	2.3	6.21	1622	0.2
630	0.001	5.89	5.89	1042	3.2	5.90	1450	1.0
800	− 0.004	5.82	5.82	1268	4.9	5.81	1654	1.8
1000	− 0.016	5.69	5.69	1337	4.9	5.69	1695	2.3
1250	0.006	5.60	5.61	1334	3.0	5.60	1679	1.7
1600	0.003	5.27	5.28	1479	4.3	5.27	1759	2.4
2000	0.009	4.75	4.75	1288	4.7	4.75	1691	2.0
2500	0.004	4.14	4.14	1427	4.4	4.14	1725	2.7
3150	− 0.027	3.63	3.63	1556	2.6	3.63	1761	2.0
4000	− 0.026	3.04	2.88	1557	1.3	3.04	1766	1.2
5000	− 0.047	2.49	2.33	1510	2.3	2.49	1766	1.1

individual fixed microphones the variation in measured reverberation time is small, even at low frequencies. The room-averaged value is even more stable, especially at low frequencies. In contrast, the corresponding values for curvature are much larger, as can be seen in the last two columns of Table IV.

The values for s_{mics} for percent curvature (Table IV, Col. 3) might of course have been predicted from the values obtained for the ensemble variance [Eq. (4)] or from Fig. 5(d) for curves analyzed individually. This column therefore contains no surprises even though ensemble averaging was used. It merely confirms that even with an ensemble average of 50 decays at each microphone, a fairly large number for practical measurements, one cannot determine the curvature precisely enough to justifiably reject decays that do not comply with the standards (because of excessive curvature). However, in practice it does not seem to matter whether the curvature criteria are adhered to or not because the mean reverberation time measured at the microphone does not change significantly.

TABLE IV. Standard deviations of reverberation time and percent curvature. s_{mics} is an average value for measurements made at a single microphone and s_{room} is the value for the room average (nine microphones).

Frequency (Hertz)	Reverberation time		Percent curvature (C_1)	
	s_{mics}	s_{room}	s_{mics}	s_{room}
100	0.099	0.039	3.88	1.36
125	0.108	0.031	4.25	1.37
160	0.074	0.023	2.79	0.89
200	0.062	0.025	2.70	0.92
250	0.056	0.021	2.60	0.91
315	0.046	0.013	2.41	0.85
400	0.038	0.012	2.21	0.61
500	0.033	0.014	1.89	0.59
630	0.038	0.011	2.23	0.57
800	0.024	0.012	1.75	0.72
1000	0.021	0.009	1.44	0.43
1250	0.023	0.009	1.64	0.53
1600	0.018	0.006	1.25	0.40
2000	0.020	0.008	1.71	0.63
2500	0.013	0.006	1.45	0.48
3150	0.013	0.007	1.51	0.47
4000	0.014	0.010	1.41	0.53
5000	0.013	0.011	1.56	0.42

The s_{room} values for curvature show, as in the case of reverberation time, that the room-averaged value is a more stable quantity and could be used to make more reliable statements about the average room curvature.

E. Application to standards

From this discussion one can see that no matter what definition of decay curvature is used, requiring in the standards that it be measured for all tests is impractical. A requirement limiting the average curvature for a room without a specimen to some specified values could be included in a standard. Then the curvature of empty-room decays would be checked periodically only to ensure compliance and not necessarily during measurements. But even this is an excessive requirement for a laboratory lacking automated equipment, and assumes that one can always obtain linear decays in a reverberation room by adjusting fixed diffusing elements, rotating diffusers, or other devices.

III. SPATIAL VARIATION OF DECAY RATE

The paper by Davy *et al.*[15] calculates the expected variance of decay rates or reverberation time in a reverberation room. It shows that measurements of the variance in a number of rooms with fixed diffusers agreed well with the theory except at the lower frequencies where it was higher than predicted. Bartel and Magrab[16] also found good agreement with this theory but showed that the effect of their rotating diffuser was to reduce spatial variance below that predicted.

A more recent paper by Flenner *et al.*[17] provides further confirmation of the theory. Similar results were obtained in this room, as can be seen from the typical results shown in Fig. 6. The upper curve is for fixed diffusers while the lower one shows the effect of turning on the rotating vane.

The theory in Ref. 15 and the experimental results have an important bearing on the precision of measurements, the number of microphone positions used and on those sections of ASTM C423 dealing with spatial variation of decay rate. It is suggested in C423 that the room be adjusted to make the decay rate independent of position in the reverberation room within certain limits. Using the formulas in Ref. 15 and assuming a decay range of 20 to 30 dB, it can readily be shown that the spatial standard deviation of reverberation time $\sigma_s(T)$ is approximately

$$\sigma_s(T_0)\approx(32.4/D)(T_0/f)^{1/2}. \tag{5}$$

Assuming $D = 30$ dB, $T_0 = 7$ s, and $f = 250$ Hz, then $\sigma_s(T_0) = 0.22$ s. Thus, one expects 95% of measured values to lie in the range 6.56–7.44 s. This range of 12% is much greater than the 4% recommended by C423 at this frequency. Thus, it would not be possible in many cases to satisfy the C423 recommendations in a room with fixed diffusers. If these requirements were to become mandatory in the standard or in accreditation requirements, they would implicitly require a rotating or moving diffuser because, as shown in Fig. 6 and Ref. 16, these devices reduce the spatial variance of decay rate below the value for rooms with stationary diffusers. Yet even with a rotating diffuser, the C423 requirements on spatial variation of decay rate are very stringent.

Because spatial variations of decay rate are inherent in reverberation rooms, even in those with rotating diffusers, measurement standards should specify a minimum number of microphone positions. C423 does not explicitly state this since the room is assumed to be adjustable; ISO R354, on the other hand, requires at least three microphone positions. At 250 Hz, as an example, C423 requires in paragraph 13.2 that the uncertainty in the measurement be less than 2% or

$$\sigma_s(T_0)t/T_0\sqrt{n}\leqslant 0.02, \tag{6}$$

where t = student's t for n microphones.

If uncertainties for measurements at each microphone are ignored and the value of 0.22 obtained above for $\sigma_s(T_0)$ is substituted into this expression, one finds that 12 independent microphone positions should be used in the room. Only about three microphone positions are needed with the rotating vane which reduces the spatial standard deviation, in this case, to about one-third or one-fourth of the theoretical value.

At 125 Hz, however, where the maximum uncertainty allowed by C423 is 4%, Fig. 6 shows that the rotating diffuser reduces the spatial standard deviation to approximately the theoretical value and five microphone positions are necessary to satisfy the uncertainty requirement. Obviously the room with only fixed diffusers requires even more microphone positions at 125 Hz.

IV. CORNER MICROPHONES

For one part of this work four microphones placed in corners of the room were compared with 18 distributed throughout the volume to determine if they had some special advantages. Figure 7 compares the mean absorption coefficient obtained from the 18 space microphones with that obtained from the individual corner microphones for six room conditions at a frequency of 125 Hz. For this frequency, the

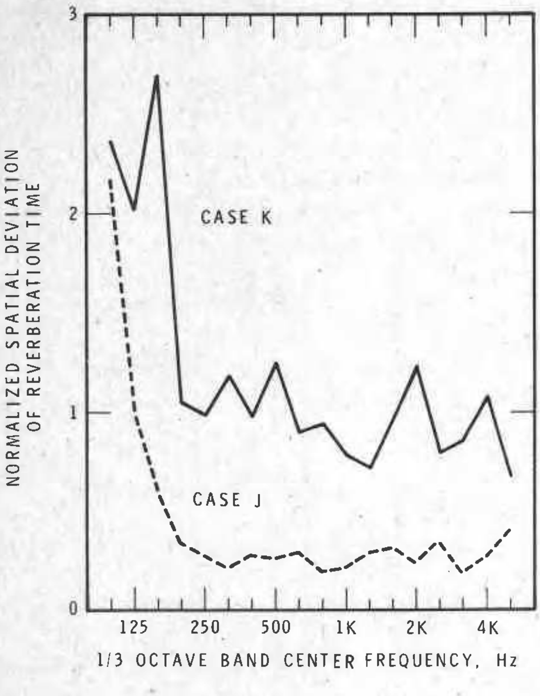

FIG. 6. Comparison of measured spatial standard deviation of reverberation time with theory; solid line—case K, 28.27 m^2 of fixed diffusers, dashed line—case J, 18.77 m^2 of fixed diffusers and 9.5 m^2 of rotating diffuser.

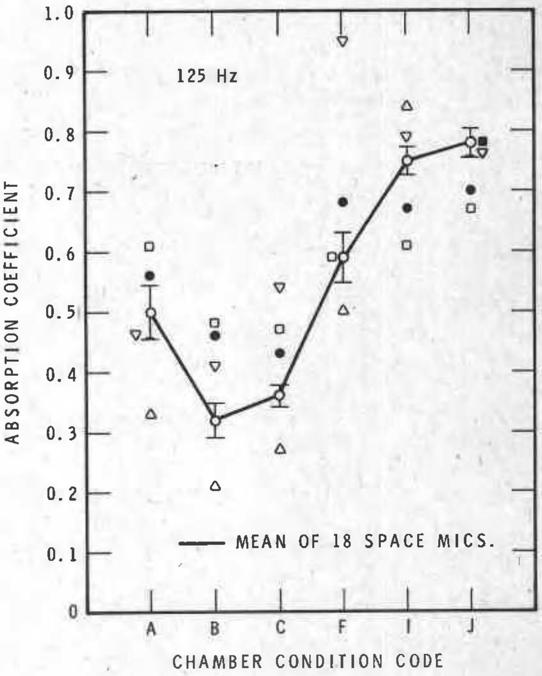

FIG. 7. Comparison of absorption coefficients measured using 18 space microphones (solid line) with those using four corner microphones (□, ●, ▽, △).

corner microphones do not agree well with each other nor with the mean of the 18 space microphones. This plot is typical of the results obtained for the corner microphones at the lower frequencies. Even the mean absorption coefficient for the four corner microphones did not agree well with the mean for the 18 space microphones at low frequencies. At the middle and high frequencies the corner microphones agreed fairly well with each other and with other microphones in the room. From all the data for the corner microphones it was concluded that they have no special advantages or disadvantages for absorption measurements in this room. They were simply four more positions in the room.

V. VARIATION OF MEASURED ABSORPTION COEFFICIENT WITH MICROPHONE POSITION

Although there are variations in measured decay rate from point to point in the room, it might have been supposed that the change caused by introducing the specimen would be constant and independent of microphone position, thus reducing the need to use multiple microphone positions.

Since the microphone positions remained fixed during the measurement series, it was possible to calculate for each microphone a set of absorption coefficients which could then be examined for spatial variations. Figure 8 shows the mean for the 18 microphones together with one standard deviation on either side of the mean for case A. The variations in measured values are substantial throughout the frequency range and are especially large at the lower frequencies. Figure 9, which is the corresponding plot for 28.27 m^2 of fixed diffusers used in case K, shows that adding fixed diffusers does not significantly affect the measured spatial variance of absorption coefficient. Setting the rotating diffuser in motion had a marked effect on this type of measurement also, as can be seen in Fig. 10 for case J. The spatial variation is greatly reduced but is still significant.

Figure 11(a) shows the average spatial standard deviation of absorption coefficient for 100–315 Hz, and 11(b), for 400–5000 Hz for all the diffuser arrangements. The rotating diffusers used were not quite as effective at the lower frequencies as at the middle and high frequencies. Thus the data show that it is essential to use several microphone positions to get acceptably precise absorption measurements at the lower frequencies and highly desirable to do so throughout the frequency range.

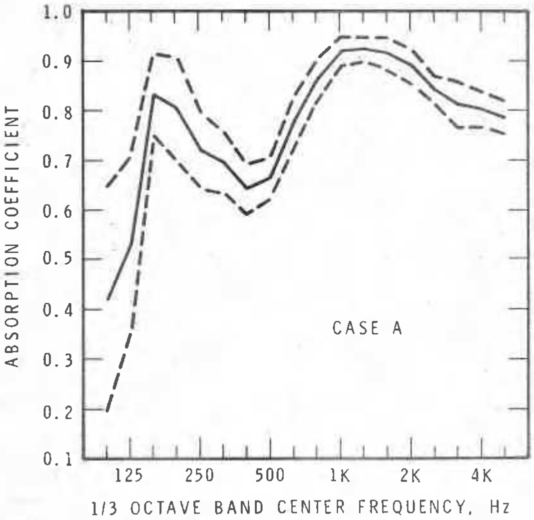

FIG. 8. Mean absorption coefficient ± one standard deviation (18 microphones) for case A—no diffusers.

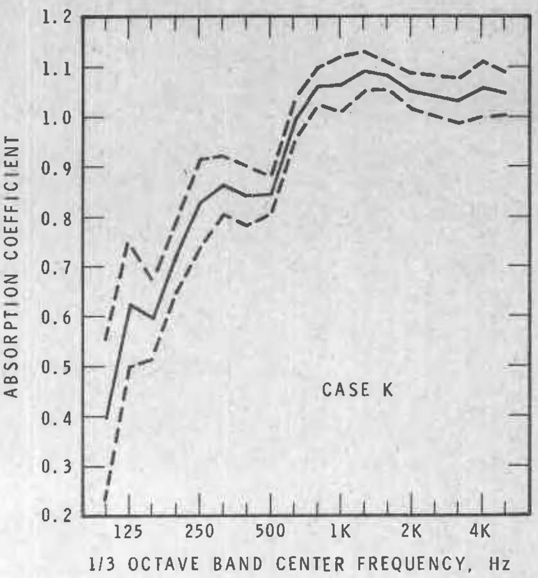

FIG. 9. Mean absorption coefficient ± one standard deviation (18 microphones) for case K—28.27 m^2 of fixed diffusers.

VI. VARIATION IN MEASURED ABSORPTION COEFFICIENT WITH SAMPLE POSITION

Neither the ISO nor the ASTM standards have much to say about the variation of the measured absorption coefficient with the specimen position in the room. C423 again assumes that the room can be adjusted so that the variations

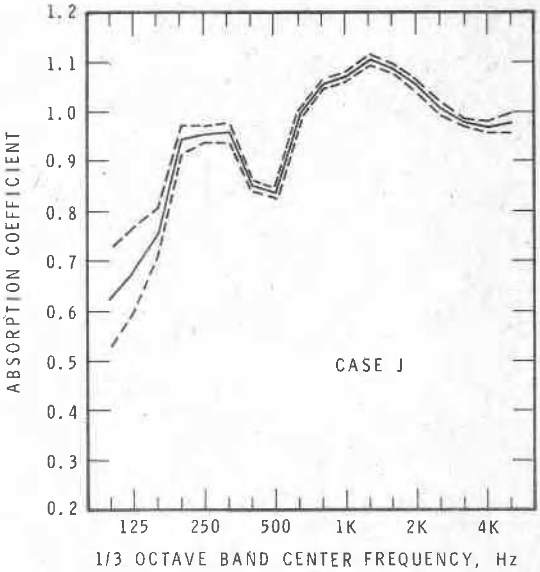

FIG. 10. Mean absorption coefficient ± one standard deviation (18 microphones) for case J—18.77 m^2 of fixed diffusers and 9.5 m^2 of rotating diffuser.

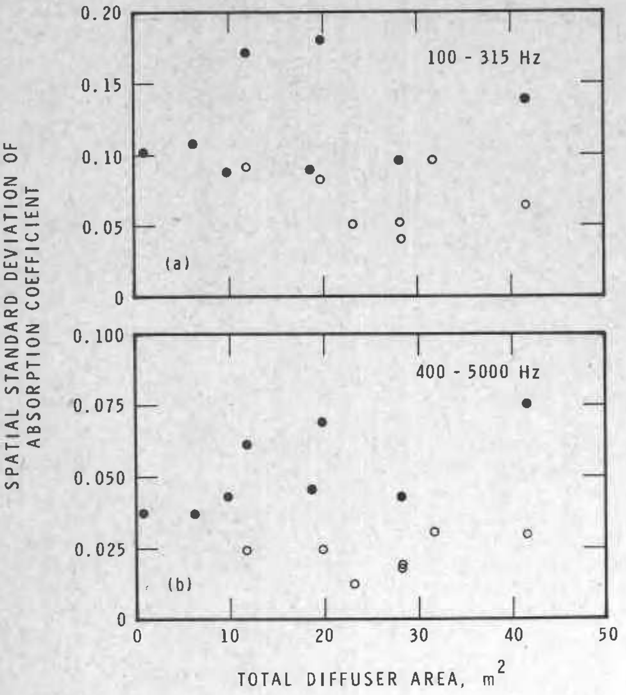

FIG. 11. Spatial standard of absorption coefficient; ●—fixed diffusers only, ○—fixed and rotating diffusers. (a) 100 to 315 Hz; (b) 400 to 5000 Hz.

with position are negligible. ISO 354 recommends that measurements be made at different positions in the room when only one discrete sound absorber is being measured. In measurements made in this laboratory, quite strong variations with position were observed, especially at low frequencies.

Figure 12 shows the mean absorption coefficients for two specimen positions for case A. The differences are considerable below 500 Hz. Some, but not all, of the high-frequency difference might be attributed to inadequate control of room temperature and humidity since the room humidity controller was not functioning properly during the case A experiments. Figure 13 is for case J with the rotating diffuser in operation. The agreement between positions is improved but there are still differences at the low frequencies. This particular specimen is quite highly absorptive throughout the frequency range and is a severe test of the stability of the room. For case J with the same absorbing panels laid directly on the floor, there are no significant differences between the two positions.

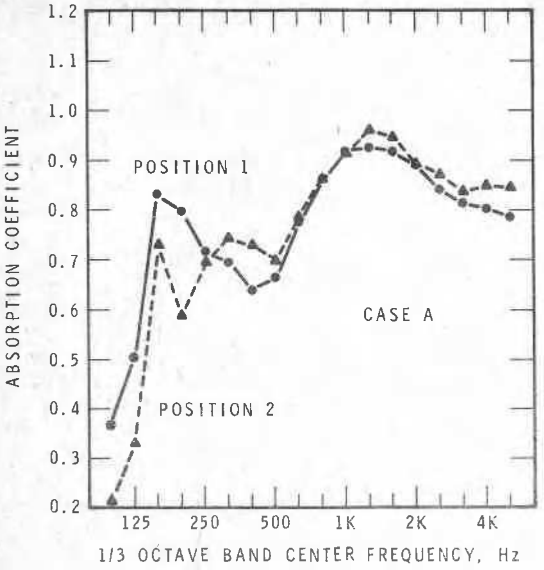

FIG. 12. Differences in mean absorption coefficient for two specimen positions—case A.

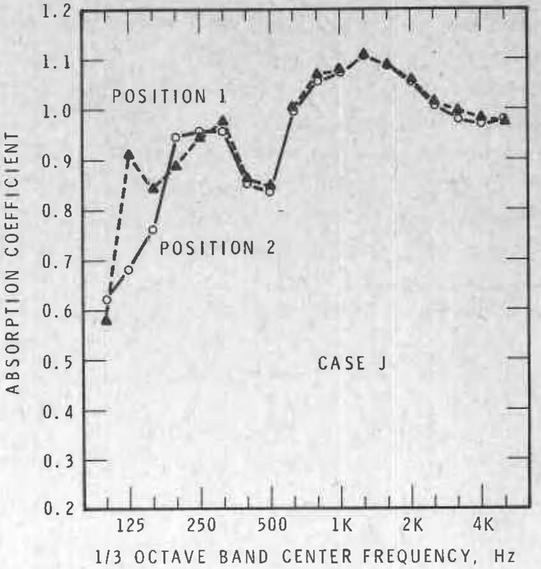

FIG. 13. Differences in mean absorption coefficient for two specimen positions—case J.

In other measurements not shown here where a large rotating vane and multiple speaker excitation were used, results at several positions in the room showed variations similar to those for cases A and J. Thus standard test methods should require measurements with different specimen positions when the low-frequency absorption is significant.

VII. VARIATION IN ABSORPTION COEFFICIENT WITH DIFFUSER SYSTEMS

In an appendix to ISO 354, instructions are given for adding diffusing elements to the reverberation room until the mean value of absorption coefficient for the bands from 500–4000 Hz first reaches a plateau.

Figure 14(a) shows the mean absorption coefficient in this range for all the different arrangements used. Arrangements incorporating rotating diffusers are again denoted by open circles. Each point represents an average over at least nine microphone positions and two specimen positions. The plateau could be said to have been reached at a total diffuser area of about 15 m^2. There is little difference between the average absorption coefficients for the fixed and rotating systems and thus no advantages or disadvantages in choosing one system over the other to get the final answer for the mean absorption coefficient.

Figure 14(b) is a similar plot for the mean values of absorption coefficient for the bands from 100–315 Hz. In contrast with Fig. 14(a), there is a tendency for arrangements with rotating diffusers to produce values of absorption coef-

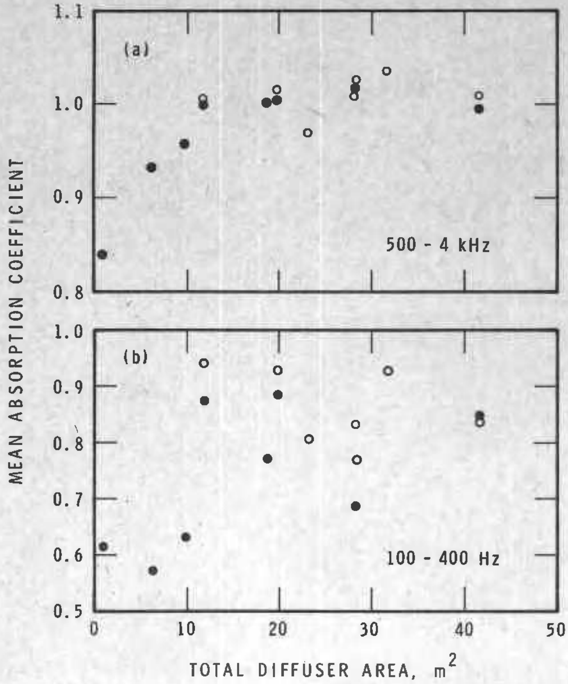

FIG. 14. Mean absorption coefficient as a function of diffuser area; ●—fixed diffusers only, ○—fixed and rotating diffusers. (a) 500–4 kHz; (b) 100–400 Hz.

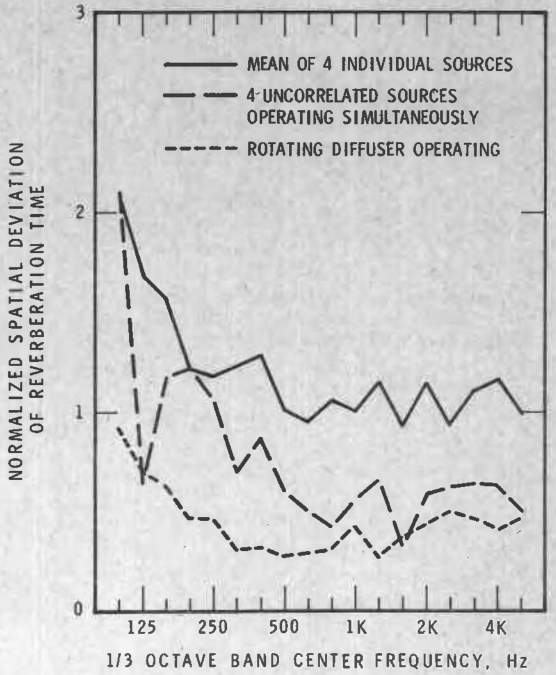

FIG. 15. Normalized spatial standard deviation for single and multiple sources with fixed diffusers and with a rotating diffuser.

ficient slightly higher than those with fixed diffusers only.

The data presented show that rotating diffusers significantly reduce spatial variations in the room and, in effect, produce a more uniform sound field. Hence, the low-frequency absorption coefficients measured in the presence of a rotating diffuser are likely to be more accurate than those from a room that uses only fixed diffusers.

VIII. MULTIPLE SOUND SOURCE EFFECTS

The effects of using multiple independent noise sources in absorption measurements have already been described elsewhere.[18,19] The main points of that work are (i) there are marked differences in measured absorption coefficient caused by using different loudspeaker positions; (ii) the use of multiple independent sources gives the same absorption coefficients as does using the sources singly in turn and then averaging the results; (iii) the use of multiple independent sources slightly reduces curvature at low frequencies.

Figure 15 shows a graph not previously presented: the average normalized spatial standard deviation of reverberation time is plotted for four individual sources and four independent, incoherent sources sounding simultaneously, first, with fixed diffusers and second, with a rotating diffuser. Multiple sources had no significant effect on the spatial standard deviation when the rotating diffuser was operating. This figure clearly shows that for a fixed number of microphones the multiple independent sources can improve the precision of measurements in rooms with fixed diffusers or reduce the number of microphone positions necessary to achieve a given precision. However, the benefits of the rotating vane are more important, especially at low- and mid-frequencies. The use of four coherent sources did not provide any reduction in spatial standard deviation of the decay rate.

IX. SUMMARY

This paper has given examples of the behavior of some of the quantities measured in reverberation rooms during absorption measurements. Many of these effects have been seen before with simpler and less precise equipment.

It is clear that

(i) Decay rates, curvature and absorption coefficients depend strongly on microphone position.

(ii) The use of fixed and rotating diffuser systems can reduce but not eliminate these variations. Systems incorporating rotating diffusers are superior to those using fixed diffusers.

(iii) Measured low-frequency absorption coefficients depend on specimen and source position.

(iv) Multiple independent sources can be used to average the effects of source position.

(v) Decay curvature cannot be measured precisely enough to warrant excluding individual decays or sets of decays. Since theory and measurement both show that there will be spatial variations of curvature, then only the room average should be considered in standards.

The new version of ISO 354 takes into account most of these factors by requiring different source and microphone positions. However, the number of positions and decays required are rather small and will lead to relatively imprecise measurements. Nor are these requirements likely to provide good reproducibility between laboratories, especially in the absence of rotating diffusers.

The present version of ASTM C423 is internally consistent since it assumes that reverberation rooms can be adjusted to be good approximations to a diffuse sound field. Unfortunately, the data presented here and elsewhere show that this assumption is not realistic.

The round robin recently carried out by Halliwell[4] used multiple microphones, speakers, and specimen positions and obtained results similar to those described here.

An adequate standard for measuring absorption should require

(i) a minimum area of fixed or moving diffusers;
(ii) a minimum number of microphone positions;
(iii) a minimum number of sources or source positions;
(iv) a minimum number of specimen positions.

Since pseudorandom noise generators, power amplifiers, and loudspeakers are relatively cheap, using multiple sources is quite practical. Also, one can obtain multiple microphone positions by physically moving one microphone instead of resorting to the more expensive but convenient multiple microphone and multiplexer used here. Computers are now comparatively inexpensive, and can easily be used to reduce the labor involved in making these measurements.

Instead of the last three requirements it is perhaps preferable to specify certain values of uncertainty for the measurement of the absorption coefficient or decay rate as is presently done in C423. The uncertainties should be calculated using the values of absorption measured at each microphone for each specimen position. Thus, laboratories with more uniform sound fields, due perhaps to a more effective diffuser system, would need to make fewer measurements to satisfy the uncertainty requirements of the standard. Conversely, laboratories with comparatively nonuniform sound fields would be required to compensate for this by taking more measurements.

No matter which approach is used, the requirements written into the standards would of course have to be compromises due to important practical considerations such as cost. However, enough is now known about absorption measurements in reverberation rooms to require better measurement procedures in the standards.

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