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INTER-LABORATORY VARIABILITY OF SOUND ABSORPTION MEASUREMENT

by R.E. Halliwell

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RÉSUMÉ

Des mesures de l'absorption du bruit ont été effectuées en un certain nombre de laboratoires d'acoustique au Canada et aux États-Unis à l'aide des mêmes spécimens et des mêmes équipements et méthodes de mesure. Les résultats fournissent un aperçu des effets de la chambre de réverbération et de la géométrie de la source sur les coefficients d'absorption mesurés.

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Inter-laboratory variability of sound absorption measurement

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Sound absorption measurements have been made at a number of acoustical laboratories in Canada and the United States using the same specimen and the same measurement equipment and procedure. The results provide insight into the effect of reverberation room and diffuser geometry on measured absorption coefficients.

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INTRODUCTION

The question of reproducibility of sound absorption measurements among laboratories has been under study for some time, commencing with the First International Round Robin of 1959.¹ Since that time there have been several more measurement series in Japan,² Scandinavia,³ Australasia,⁴ and Europe.⁵ All have relied upon use by each laboratory of similar measurements of the same, or nominally the same specimen, the results being reported to a coordinating organization. Information gathered in this manner provides a good assessment of the reproducibility of measurements among laboratories within the variability of the test procedure permitted by the particular measurement standard. Unfortunately, in trying to determine the reasons for differences in the results from the laboratories, lack of adequate control has made it impossible to separate variations due to possible room effects from variations due to measurement procedures.

It is known,^{6,7} for example, that the measured absorption coefficient of a specimen is a function of the microphone position, loudspeaker position, and specimen position, but the effects of these variables are not explicitly considered in the North American standard for the measurement for sound absorption (ASTM C 423-77).⁸ If the measurements are to be free of these and other effects, it is apparent that a different type of round robin is required—one that will provide tighter control of measurement conditions.

The procedure adopted for this study was to take to each of the participating laboratories the entire measurement system and test specimen. In this way the analysis equipment, test specimen, and measurement procedure were kept as nearly constant as possible for all of the laboratories. Parameters relating to the room and diffuser geometry were, at least in principle, the only uncontrolled parameters. This approach permitted the room effects to be separated from procedural effects.

I. MEASUREMENT PROCEDURES

Recent studies^{6,9,10} have shown that three types of averaging are required to obtain reliable estimates of the sound absorption coefficients measured in a reverberation room. First, reverberation times must be averaged over a number of microphone positions to establish the average decay rate in the room. Second, reverberation times must be averaged over a number of source positions to ensure that, in effect, all of the room modes are properly excited and the sound field is

as close to diffuse as possible. Third, reverberation times must be averaged over a number of specimen positions, since the specimen will interact with the sound field differently in different positions in the room.

To obtain the space average of the reverberation time, eight $\frac{1}{2}$ -in. aircondenser microphones were placed in the room in such a way that each microphone was at least 1 m from any fixed reflecting surface and separated by at least 2 m from any other microphone. The microphone positions were usually restricted to the lower half of the room because of the limited height of the microphone stands. Some rooms had very large rotating vanes that further limited the microphone positions to the periphery of the room.

Previous studies⁹ have established that an average over a number of noise source positions is the equivalent of a number of independent noise sources. For this study, therefore, four loudspeakers, each driven independently, were placed in the corners facing into the room. Although driven with separate noise sources and power amplifiers, the four speakers were switched on and off simultaneously.

Measurements were made at two sample positions to provide an average over specimen positions. Although more positions would have been desirable, it was considered that this would have made the time required for an absorption measurement unreasonably long. Sound decays were collected in $\frac{1}{3}$ -octave bands from 80 to 5000 Hz using a real time analyzer interfaced to a minicomputer. This system provided simultaneous level measurements on all 19 bands every $\frac{1}{16}$ s. For each microphone the average of 20 decays was obtained for each of the 19 bands using the decay curve averaging procedure described by Chu,¹¹ and Bodlund.¹² Reverberation times and curvatures were calculated for each band from the average decay curves and then averaged over all microphone and sample positions. Absorption coefficients were calculated from these average reverberation times. As all of the average decay curves were stored, it was also possible to calculate the absorption coefficients for each microphone and sample position and thus obtain mean absorption coefficients and the standard deviations about the means. The standard deviations calculated in this manner will be referred to as the laboratory standard deviations.

The decay rate was calculated from a least-square straight line fit to the top 25 dB of decay after discarding the first four data points. Only data more than 10 dB above the background level were considered, so that for some bands, notably the very low and very high ones, there was less than 25 dB of decay available for this analysis. In this regard the

TABLE I. Participating laboratories.

Laboratory area (m ²)	Volume (m ³)	Surface area (m ²)	Floor area (m ²)	Fixed diffuser area (m ²)	Rotating diffuser area (m ²)	Total diffuser area (m ²)
A	251	246.1	51.6	53.5	4.5	58
B	251	246.1	51.6	23.3	9.1	32.4
C	303	277.4	55.2	22.9	18.2	41.1
D	267.8	255.3	50.1	~5	0	5
E	425	343.8	69.9	0	19.5	19.5
F	284.3	262	53.8	29.1	11.9	41.0
G	291.3	266.1	44.8	19.2	11.8	31
H	422.9	338.3	72.5	14.9	0	14.9
I	315.1	284.3	55.7	8.9	0	8.9
J	282	262.9	54.3	17.8	16.4	34.2

procedure differs from the requirements of ASTM C 423-77, which requires that data within 15 dB of the background be discarded. The use of 10 dB rather than 15 dB between the last data point and background will cause the last point to be high by as much as 0.4 dB. It can cause an apparent increase in curvature in cases for which there are too few data points, and thus the last point takes on an added significance. The two procedures have been tested; as they show no significant difference for the calculated reverberation times, the 10-dB rule was used to maximize the decay range. The curvature of the decays was calculated using the algorithm:

$$C = R_B/R_T - 1, \quad (1)$$

where R_B = reverberation time for bottom half of decay, R_T = reverberation time for top half of decay.

The material used for these tests comprised 600×900 mm panels of rigid glass fiber 50 mm thick with aluminum U-channel protective edging, originally developed for a current ASTM absorption round robin. The test specimen had an area of 6.69 m² and was measured on two different

mountings: flat on the floor (A mount) and mounted on a frame to provide a plenum space (E-400 mount).¹³

II. PARTICIPATING LABORATORIES

Ten laboratories in Canada and the United States participated in this round robin. Details of the reverberation rooms are given in Table I (the laboratories will be referred to by the code letters established in Table I). All the reverberation rooms except one were rectangular. The exception had five walls instead of four, although the walls were vertical and met both floor and ceiling at right angles. Three of the rooms did not have rotating diffusers and one did not have fixed diffusers.

III. DISCUSSION OF RESULTS

A. Absorption coefficients

The absorption coefficients measured at each of the ten laboratories and the overall means and inter-laboratory standard deviations are given in Table II for the A mounting

TABLE II. Absorption coefficients for A mounting.

Freq.	Laboratory designation										Mean	Sigma
	A	B	C	D	E	F	G	H	I	J		
80	0.10	0.11	0.17	0.11	0.11	0.09	0.06	0.21	0.08	0.12	0.12	0.05
100	0.21	0.16	0.25	0.21	0.16	0.13	0.12	0.18	0.15	0.14	0.17	0.04
125	0.35	0.28	0.34	0.28	0.25	0.26	0.29	0.37	0.25	0.28	0.29	0.04
160	0.46	0.43	0.47	0.47	0.36	0.44	0.35	0.52	0.43	0.42	0.43	0.05
200	0.67	0.64	0.60	0.53	0.65	0.65	0.58	0.72	0.54	0.60	0.62	0.06
250	0.83	0.83	0.81	0.75	0.84	0.82	0.69	0.87	0.71	0.74	0.79	0.06
315	0.94	0.98	0.93	0.89	0.95	0.96	0.85	0.99	0.92	0.90	0.93	0.04
400	1.07	1.10	1.06	1.03	1.11	1.08	0.99	1.15	0.98	0.99	1.06	0.06
500	1.11	1.12	1.10	1.06	1.14	1.13	1.05	1.14	1.05	1.04	1.09	0.04
630	1.08	1.11	1.07	1.07	1.12	1.14	1.03	1.13	1.09	1.03	1.09	0.04
800	1.05	1.08	1.05	1.04	1.08	1.10	1.02	1.12	1.03	1.01	1.06	0.04
1000	1.01	1.04	1.01	1.03	1.01	1.08	1.01	1.06	1.04	0.97	1.03	0.03
1250	0.99	1.02	1.00	0.99	1.00	1.05	0.99	1.01	0.97	0.96	1.00	0.02
1600	0.97	1.00	0.97	0.95	0.97	1.02	0.96	0.98	0.96	0.93	0.97	0.02
2000	0.95	0.99	0.95	0.94	0.94	1.01	0.96	0.96	0.95	0.91	0.96	0.03
2500	0.94	1.00	0.94	0.93	0.93	0.99	0.95	0.93	0.93	0.90	0.94	0.03
3150	0.95	0.98	0.93	0.88	0.91	0.97	0.93	0.88	0.90	0.89	0.92	0.04
4000	0.93	0.97	0.94	0.92	0.91	0.99	0.95	0.93	0.90	0.92	0.94	0.03
5000	0.98	0.95	0.95	0.94	0.90	0.94	0.92	0.93	0.89	0.87	0.93	0.03

TABLE III. Absorption coefficients for E-400 mounting.

Freq.	Laboratory designation										Mean	Sigma
	A	B	C	D	E	F	G	H	I	J		
80	0.78	1.04	1.03	0.67	0.26	0.66	0.70	0.60	0.39	0.73	0.69	0.24
100	0.75	0.66	1.08	0.78	0.32	0.57	0.66	0.67	0.29	0.56	0.63	0.23
125	0.65	0.66	0.70	0.72	0.69	0.69	0.60	0.80	0.68	0.65	0.68	0.05
160	0.71	0.69	0.74	0.74	0.67	0.73	0.60	0.76	0.59	0.73	0.70	0.06
200	0.79	0.82	0.76	0.79	0.83	0.79	0.69	0.80	0.74	0.74	0.78	0.04
250	0.85	0.87	0.82	0.73	0.88	0.84	0.76	0.85	0.71	0.75	0.80	0.06
315	0.84	0.88	0.84	0.80	0.86	0.88	0.82	0.86	0.85	0.81	0.84	0.03
400	0.88	0.91	0.84	0.86	0.88	0.90	0.85	0.85	0.83	0.83	0.86	0.03
500	0.98	1.02	0.95	0.96	0.98	1.01	0.96	0.92	0.97	0.94	0.97	0.03
630	1.03	1.08	1.03	1.05	1.02	1.06	1.02	1.01	1.06	1.02	1.04	0.02
800	1.06	1.08	1.05	1.05	1.03	1.09	1.06	1.04	1.05	1.04	1.05	0.02
1000	1.09	1.10	1.09	1.11	1.03	1.13	1.08	1.05	1.11	1.07	1.09	0.03
1250	1.11	1.12	1.11	1.10	1.07	1.13	1.10	1.04	1.11	1.07	1.10	0.03
1600	1.10	1.13	1.09	1.08	1.05	1.11	1.11	1.07	1.12	1.06	1.09	0.03
2000	1.05	1.12	1.06	1.05	1.01	1.10	1.10	1.03	1.09	1.03	1.07	0.04
2500	1.03	1.11	1.02	1.02	0.98	1.07	1.06	0.96	1.03	1.00	1.03	0.04
3150	1.01	1.06	1.02	0.95	0.94	1.04	1.01	0.91	1.00	0.97	0.99	0.05
4000	0.99	1.03	1.00	0.97	0.94	1.05	1.03	0.94	0.99	0.98	0.99	0.04
5000	1.00	1.01	0.99	0.97	0.93	1.00	1.00	0.96	0.97	0.95	0.98	0.03

and in Table III for the E-400 mounting. The inter-laboratory standard deviation is nearly independent of frequency or mounting, except for the two lowest frequency bands with the E-400 mounting. The large variation for the two low-frequency bands with the E-400 mounting is not clearly understood although there does appear to be some form of interaction between the frame and the room modes. The information given in Tables II and III is shown graphically in Fig. 1 for the A mounting and in Fig. 2 for the E-400 mounting. The absorption coefficients for each laboratory are plotted as a deviation from the mean of all the laboratories and demonstrate that some laboratories are consistently above the mean while others are consistently below it, a result that can only be due to differences in laboratories and

not to statistical scatter in the measurements. The same information is replotted in Figs. 3 and 4 except that the laboratory standard deviations are plotted instead of the inter-laboratory standard deviations. This illustrates the finding that variability within a laboratory and variability between laboratories are quite comparable except at low frequencies.

Three laboratories B, F, and J, showed significantly smaller standard deviations than did the others at all frequencies. It is perhaps significant that these laboratories have large rotating diffusers located centrally in the reverberation room. Laboratories C, E, and I also have large rotating diffusers, but they are located either to one side or in the upper portion of the rooms. Such configurations leave free a large volume in which the sound can decay without

FIG. 1. Deviation from the mean absorption coefficients for A mounting. The dashed lines represent the inter-laboratory standard deviations.

FIG. 2. Deviation from the mean absorption coefficients for E-400 mounting. The dashed lines represent the inter-laboratory standard deviations.

interaction with the rotating diffuser. In one of the laboratories the lower half of the room had no diffuser of any type and could be expected to act somewhat like an empty room.

The inter-laboratory standard deviations should now be compared with standard deviations obtained from measurements made in the individual laboratories, using local equipment and procedures. The solid line in Fig. 5(a) shows the inter-laboratory standard deviations of the absorption coefficients for the A mounting (Table II); the dashed line shows the standard deviations for the same laboratories calculated from data provided by the laboratories for the absorption round robin currently being undertaken by ASTM. (These are preliminary data from an ongoing measurement

FIG. 3. Deviation from the mean absorption coefficients for A mounting. The dashed lines represent the laboratory standard deviations.

program that have been published here with the permission of ASTM E 33-05, Subcommittee on Research.) There is little difference between the two curves, suggesting that there is very little extra variability in the measurements introduced by the various measurement procedures followed at the different laboratories.

A similar plot for the E-400 mounting [Fig. 5(b)], indicates that there is added variability. The only difference between measurements using an A or E-400 mounting is the frame for mounting, construction details of which are known to vary among laboratories. Measurements using different frames have shown that small changes in the frame details can have a large effect on the measured absorption

FIG. 4. Deviation from the mean absorption coefficients for E-400 mounting. The dashed lines represent the laboratory standard deviations.

coefficients.¹⁴ It is also known⁹ that there can be significant variation in the absorption coefficients for different specimen positions when an E-400 mounting is used. The measurements made for the ASTM round robin were for one specimen position only, whereas the measurements now reported are for two sample positions. The two factors are probably responsible for much of the extra variability observed.

B. Curvature

The average curvatures for each of the ten reverberation rooms without the specimen installed are shown in Fig.

FIG. 5. Inter-laboratory standard deviation of the absorption coefficients. The dashed line is the standard deviation from the ASTM absorption round robin. (a) A mounting, (b) E-400 mounting.

6. All the rooms exhibit zero or only a small curvature in the mid- to high-frequency range, increasing from 20% to 40% at low frequencies. Although these curvatures are averaged over all microphone positions, those found for individual microphones may be significantly larger. The increase in curvature at 5000 Hz is an artifact of the measurements. The short decay times and reduced source levels in this band meant that there were usually only 9 or 10 points available to fit the decay curve. This tends to increase the curvature for reasons discussed earlier.

Curvatures are essentially unchanged when the specimen is introduced on either an A or an E-400 mounting, contrary to Warnock's results.⁹ The reason for this is not understood at the present time, but it may be a result of using four independent noise sources for the measurements. Use of independent noise sources is known to reduce curvature.¹⁰

These results are, however, in agreement with those of Bodlund,¹² and of Davy *et al.*,¹⁵ who found that decay curves generally display a small positive curvature at middle and high frequencies, but quite pronounced positive curvatures at low frequencies. Using the definition of curvature given in Eq. (1), the requirements laid down in ASTM C 423-77 are equivalent to a maximum of 8% for frequencies below 250 Hz and 4% for those at 250 Hz and above. This requirement has been overlaid on Fig. 6 to demonstrate that few of the

FIG. 6. Average decay curvature for the empty reverberation rooms. The dashed line represents the requirements of ASTM C 423-77.

reverberation rooms tested were able to meet this requirement at all frequencies.

C. Effects of room and diffuser geometry

If the variability of absorption coefficients measured at different laboratories is due to variations in room or diffuser geometries, then it is useful to seek trends in the data. The two obvious parameters to consider are room volume and total diffuser area, as representative of the room and diffuser geometries. These are shown in Figs. 7 and 8, plotted against the mean absorption coefficient over the bands 500 to 4000 Hz. Other relations such as mean absorption coefficient versus diffuser area normalized to floor area, or surface area and

FIG. 7. Average absorption coefficient for 500 to 4000 Hz as a function of room volume.

absorption coefficient versus diffuser area for each $\frac{1}{3}$ -octave band were also considered. There were, however, no strong trends apparent for any of the relations. A second examination of Table I shows that there is a strong negative correlation between room volume and diffuser area for these rooms, so that the relationships are not really independent. This correlation between room size and diffuser area makes it difficult to make any statement concerning the effects of room or diffuser geometry on the absorption coefficients.

FIG. 8. Average absorption coefficient for 500 to 4000 Hz as a function of total diffuser area.

Either a much larger data set or a carefully controlled series of measurements will be needed to resolve these variables.

IV. CONCLUSIONS

From the data collected from these round robin measurements it can be concluded that:

(1) the reproducibility of sound absorption measurements that use a standard procedure is no better than that obtained when each laboratory uses its own measurement procedure for the A mounting;

(2) the larger variability observed during the ASTM round robin when the E-400 mounting was used is probably due to details in the construction of the mounting frame and to the use of only one specimen position.

There is also evidence that reverberation rooms with a large rotating vane located in the center show smaller standard deviations for the measured absorption coefficient, particularly at low frequency.

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