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Warnock, A. C. C.

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by

A.C.C. Warnock

Division of Building Research, National Research Council of Canada

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INTRODUCTION

In reverberation room measurements of transmission loss and absorption coefficients, the sound source is generally one or more loudspeaker systems. Both ASTM methods dealing with these measurements (E90 and C423) (1,2) allow but do not actually recommend the use of multiple sound sources, nor do they say anything about the methods of excitation of multiple sources. In the current draft revision of ISO R354(3), the ISO equivalent of C423 which also deals with the measurement of absorption, multiple speaker positions are required. Also, measurements are to be repeated by operating each loudspeaker system consecutively or by feeding each speaker independently with uncorrelated random noise. The current version of ISO 140/III(4) actually advises against the use of multiple speakers. This Note presents some measurements made in the reverberation rooms at the Division of Building Research (DBR), National Research Council of Canada (NRCC) to examine the effects of multiple loudspeakers in transmission loss and absorption measurements.

GENERAL PROCEDURES

For all measurements, four loudspeakers were placed in the corners of the reverberation room being excited. Each speaker had its own power amplifier and independent pseudo-random noise generator. Thus it was possible to use each speaker on its own, all four together with the same and therefore correlated input, or all four together with independent, uncorrelated inputs. The speaker cones, nominally 300 mm in diameter, were mounted in horn enclosures with no separate high-frequency driver units. All measurements were made in accordance with the requirements of ASTM E90, C423 and ISO 140/III, using a computer-controlled testing apparatus which incorporated a real time analyser. Nine microphones were used in each room to measure the space-averaged sound pressure level. Decays were averaged at each microphone in the receiving room to obtain the mean room decay rate which in turn determined room absorption.

TRANSMISSION LOSS MEASUREMENTS

Transmission loss measurements were made through a wall and a floor specimen to obtain additional information. Details of the specimens used are not important for this work and are not given here. Transmission loss measurements in this laboratory have routinely been made in one direction only; that is, one room is designated as the source room and the other as the receiving room. For wall transmission loss measurements the source room is normally the smallest room with a volume of 65 m^3 and the receiving room, also used for sound absorption measurements, is the largest room with a volume of about 250 m^3. Both of these rooms, which will hereafter be called the small and large rooms respectively, are equipped with fixed and rotating diffusers. For floor transmission loss measurements the smallest room becomes the receiving room and the room above, with a volume of 158 m^3, becomes the source room. This room, which will be referred to as the upper room, did not have any diffusing elements. For these experiments, the measurements were made in both directions to observe the differences, if any. However, it was not possible to make reliable measurements in the reverse direction through the floor because of excessive noise intrusion into the upper room.

Figure 1 and Table 1 show variations in transmission loss through the wall specimen with each speaker excited in turn and measured from the small to the large room. Figure 2 and Table 2 show the corresponding data for measurements in the reverse direction. Table 3 shows the variations observed for a floor transmission loss measurement from the upper room to the lower. In all three cases there was considerable variation in the transmission loss values obtained with single speakers, indicating that a single speaker of this type does not uniformly excite the room. The tables show, however, that there was almost no effect on sound transmission class (STC)(5) for these specimens, although it is clear that for a specimen with an STC rating determined by its low-frequency transmission loss values and the 8dB rule(5), the STC could change by a few points.

Table 4 compares the transmission loss values for both correlated and uncorrelated excitation of the loudspeaker systems. The differences between these two methods of excitation are not very great and occur mainly at the lower frequencies. Figure 3, however, shows the data for transmission from the small to the large room. The increase in transmission loss values at low frequencies when correlated sources are used indicates that interference effects are causing spuriously high results. Table 4 also permits comparison of the transmission loss values for the uncorrelated sources with those obtained by averaging the values in Tables 1 to 3 for the four individual speakers. It can be seen that in all three cases the agreement is excellent.

In principle, if one accepts the need for multiple speaker systems, uncorrelated noise sources are to be preferred since interference effects are thus avoided. One also expects to produce a more random field in the source room and thus approach more closely the ideal of a diffuse sound field. Table 5 supports this idea. It shows the spatial standard deviation of the sound pressure level in the three source rooms when the four sources are uncorrelated and when they are correlated. Using uncorrelated excitation of multiple speakers clearly leads to a more uniform sound field, thereby increasing the precision of the measurements.

Figure 4 compares the measured transmission losses for the two directions of measurement through the wall. One possible reason for the large discrepancies at low frequencies shown in this graph is that the dimensions of the small room become comparable to the wavelength of sound at low frequencies. Another explanation considered is that the decay rates measured in the small room were being increased by sound transmission through the specimen from the large room, in which sound decays more slowly, thus tending to increase the adjustment for room absorption and the calculated values of transmission loss. To test this second hypothesis, all significant transmission from the large room through the specimen was eliminated by closing the auxiliary lead-cored door located between the rooms. Table 6 shows the change in measured reverberation times and the resulting correction that should be applied to the calculated transmission loss. It can be seen that the differences in reverberation time are still not sufficient to account for the differences between the transmission losses measured in the two directions.

CONCLUSIONS I

These results demonstrate that there are good reasons for using multiple speaker systems in reverberation room transmission loss measurements and that independent, uncorrelated noise generators to power the speakers are also to be preferred. The transmission loss differences observed for single loudspeakers at the lower frequencies can be explained qualitatively as inadequate excitation of the lower room modes. There are, however, some differences at the higher frequencies that can perhaps be attributed to beaming from the loudspeakers which, as has been stated, had no high-frequency driver units and were therefore poor approximations to point sources. Thus the recommendation in ISO 140/III that only a single speaker be used does not represent state-of-the-art measurement procedures, especially in view of the comparatively low cost of pseudo-random noise generators, power amplifiers and speakers.

These results have led to the decision to use multiple independent speaker systems in all future transmission loss measurements in the reverberation rooms at DBR. They have also shown the need to examine more closely the transmission in both directions through test specimens. This will require constructing a new wall in the upper room to prevent the intrusion of external noise by way of the floor hatch from the sample preparation area. Diffusing devices will also be installed in the upper room to increase the diffusivity of the sound fields.

ABSORPTION MEASUREMENTS

Using the same four loudspeakers as in the transmission loss measurements, a series of absorption measurements was carried out on a reference absorbing specimen. This specimen consisted of glass fibre batts 50 mm thick encased in an aluminum frame and faced on both sides with diamond-patterned, expanded aluminum mesh - one of a set of AMA reference specimens first introduced in 1964 under the aegis of ASTM committee C20 (now E33) and used in laboratory tests performed according to ASTM C423. The specimen was supported on a wooden frame so that its surface was 405 mm from the floor. This is known as the E400 mounting (formerly identified as the Number 7 mounting) which is described in ASTM E795 (6).

Fifty sound decays were ensemble averaged at each of the nine microphone positions. The programs calculated the decay rate and curvature for each ensemble average as well as the absorption coefficients from the mean reverberation times. Curvature is defined as (Rb/Rt-1) × 100% where Rb is the reverberation time calculated for the bottom half of the decay and Rt is that for the top half. The repeatability of this system permits one to discern quite small differences between different experimental configurations with a high degree of confidence.

The differences in the mean room decay rates were generally small when the room was excited with individual speakers or with multiple speakers. The largest differences were observed in the lower frequency bands. The mean reverberation times for all tests in the empty room are given in Table 7.

Since the room reverberation times, both with and without the specimen, are used to calculate the absorption coefficients, it is necessary to look at these coefficients to determine the final effect of the changes in procedure described above. Figure 5 and Table 8 show the mean values of the absorption coefficient obtained when the four speakers are excited individually. The differences are typically greater than the repeatability of the measurements, especially in the middle and lower frequencies.

It must be borne in mind that the use of nine microphones in the reverberation room introduces a considerable amount of averaging. Figure 6 displays the range of absorption coefficients measured for two of the loudspeakers. In this case the absorption coefficient for the specimen was calculated for each microphone in turn and stored by the computer. Figure 7 shows the absorption coefficients for a single microphone when each of the four loudspeakers was used in turn. Although these plots do not really have a direct bearing on the matter at hand, they do illustrate that averaging over all the variables in reverberation rooms is important and that microphone position is one of the most significant of these variables.

Table 9 compares the mean coefficient calculated for the specimen using the data for each of the four speakers excited individually and compares this with the correlated and the uncorrelated cases. There are no significant differences between these values.

Table 10 shows the effect of using uncorrelated noise on the measured values of spatial standard deviation of reverberation time, as well as on the percent curvature. The data in the table were obtained by averaging the results of 20 sets of data, 10 with correlated excitation of the speakers and 10 with uncorrelated excitation. It can be seen that although there are some advantages in the use of the uncorrelated multiple sources in conjunction with a rotating diffuser, they are quite small.

CONCLUSIONS II

These experiments verify that in absorption measurements one sees changes in measured coefficients when the position of any of the loudspeakers used in the measurements is changed. It is to be expected that if the loudspeakers were actually moved, the changes observed would be at least as great, if not greater, since the room would be altered by the movement. In these experiments, however, there was no physical movement of the loudspeakers. It is already known that measured absorption coefficients depend on the specimen and microphone positions. The dependence on loudspeaker position is thus simply one more effect that must be averaged to improve the precision of the measurements.

The use of multiple speakers or speaker positions as specified in the current draft of ISO 354 is thus justifiable. On the basis of the measurements in this experiment, one could perhaps argue that although multiple speaker positions are desirable, it is not really necessary to use the speakers consecutively, and that the use of uncorrelated noise excitation for multiple speakers is not really essential. However, since the effects of the multiple speakers will be most noticeable at the lower frequencies and in reverberation rooms that are substantially smaller than the 250 m^3 of the DBR room, it is likely that the requirements in ISO 354 will assume much more importance.

OVERALL CONCLUSIONS

These measurements provide a justification for the installation in the NRC reverberation rooms of new speaker systems, each provided with low-frequency and high-frequency driver units to excite the room modes effectively at all frequencies. Four speakers are currently planned for each room; however, it is not known from this experiment whether using more than four speakers would result in a significant improvement in precision. Since it is relatively simple to construct pseudo-random noise generators, each of the speakers will be provided with its own noise generator and power amplifier.

REFERENCES

(1) ASTM E90-75, "Standard method for laboratory measurement of airborne sound transmission loss of building partitions", American Society for Testing and Materials, Philadelphia, 1975.
(2) ASTM C423-81, "Standard test method for sound absorption coefficients by the reverberation room method", American Society for Testing and Materials, Philadelphia, 1981.
(3) ISO R354-1963, "Measurement of absorption coefficients in a reverberation room", International Organization for Standardization, Geneva.
(4) ISO 140/3/III-1978, "Laboratory measurements of airborne sound insulation of building elements", Geneva.
(5) E143-73, "Standard classification for determination of sound transmission class", American Society for Testing and Materials, Philadelphia, 1973.

Table 1: Transmission loss values for measurements through the wall from the small to the large room using single speakers

Frequency (Hertz)	Speaker number 1	2	3	4	MEAN
80	6.1	8.4	7.1	8.6	7.6
100	7.7	9.6	9.6	6.6	8.4
125	9.2	9.2	10.8	10.8	10.0
160	11.1	10.2	12.4	10.5	11.1
200	11.6	12.0	12.2	11.1	11.7
250	14.4	15.4	16.0	16.0	15.5
315	19.9	19.7	20.0	20.1	19.9
400	21.2	21.0	20.4	21.5	21.0
500	23.1	23.6	23.3	24.0	23.5
630	25.3	25.3	25.1	25.7	25.3
800	26.6	26.6	25.8	26.3	26.3
1000	24.9	24.8	24.7	24.4	24.7
1250	23.4	23.6	23.3	22.8	23.3
1600	23.7	23.4	23.1	23.0	23.3
2000	23.1	22.6	22.9	22.4	22.7
2500	22.1	21.8	22.0	21.5	21.8
3150	29.3	29.2	28.7	29.9	29.3
4000	32.5	31.5	32.2	31.8	32.0
5000	31.8	30.8	31.4	30.6	31.1
STC	24	24	24	24	

Table 2: Transmission loss values for measurements through the wall from the large to the small room using single speakers

Frequency (Hertz)	Speaker number 1	2	3	4	MEAN
80	19.3	16.8	15.1	16.2	16.9
100	15.5	13.9	11.9	14.1	13.8
125	14.0	12.4	12.0	12.7	12.8
160	11.1	11.1	8.6	9.9	10.2
200	13.4	14.1	12.8	13.5	13.4
250	16.7	16.9	15.4	16.5	16.4
315	21.4	21.3	20.3	20.9	21.0
400	21.3	21.7	21.4	21.5	21.5
500	23.8	24.0	23.4	23.6	23.7
630	25.3	25.6	25.1	25.4	25.4
800	26.4	26.5	26.3	26.6	26.4
1000	24.6	24.8	25.0	25.1	24.9
1250	23.1	23.6	23.4	23.6	23.4
1600	22.8	23.5	23.5	23.2	23.3
2000	22.2	22.7	22.7	22.8	22.6
2500	21.8	22.2	22.0	22.3	22.1
3150	28.6	28.7	29.5	29.0	28.9
4000	30.1	32.1	32.3	32.9	31.8
5000	30.0	32.3	31.8	32.4	31.6
STC	24	24	24	24	

Table 3: Transmission loss values for normal measurements through a floor using individual speakers

Frequency (Hertz)	Speaker number 1	2	3	4	MEAN
80	18.8	19.2	17.7	18.9	18.6
100	23.1	21.2	21.1	21.7	21.8
125	27.9	28.0	27.6	28.2	28.0
160	28.4	27.7	29.6	29.3	28.7
200	33.5	31.3	34.9	32.5	33.0
250	36.4	35.7	36.7	35.3	36.0
315	39.0	42.7	42.1	41.4	41.3
400	45.5	46.2	45.6	44.9	45.5
500	47.5	46.8	46.8	46.4	46.9
630	49.2	49.1	48.6	49.3	49.1
800	52.2	51.9	51.8	51.8	51.9
1000	54.5	55.1	55.1	54.9	54.9
1250	55.8	56.5	56.9	56.7	56.5
1600	57.3	57.8	58.4	57.6	57.8
2000	58.5	58.2	59.0	58.8	58.6
2500	56.0	57.1	57.2	55.7	56.5
3150	53.1	54.6	54.7	53.3	53.9
4000	57.3	58.8	58.4	57.7	58.1
5000	61.6	62.6	63.5	62.8	62.6
STC	48	48	49	48	

Table 4: Transmission loss values for measurements made with four loudspeakers using uncorrelated (U) and correlated (C) excitation compared with a mean of four individual speakers

Frequency	small - large			large - small			upper - small		
(Hertz)	C	U	MEAN	C	U	MEAN	C	U	MEAN
80	12.8	6.1	7.6	14.4	16.5	16.9	17.0	18.7	18.6
100	10.4	8.4	8.4	13.0	14.2	13.8	20.5	22.0	21.8
125	9.9	10.1	10.0	13.7	13.5	12.8	28.0	27.6	28.0
160	11.2	11.1	11.1	9.9	9.9	10.2	27.9	29.2	28.7
200	11.7	11.9	11.7	13.0	13.7	13.4	33.2	33.7	33.0
250	15.8	16.3	15.5	16.6	16.3	16.4	34.8	36.3	36.0
315	19.7	20.0	19.9	21.0	20.9	21.0	41.7	41.9	41.3
400	20.6	21.1	21.0	21.8	21.7	21.5	45.4	45.9	45.5
500	23.5	23.8	23.5	23.8	23.9	23.7	46.8	46.9	46.9
630	25.5	25.8	25.3	25.5	25.4	25.4	49.0	48.7	49.1
800	26.6	26.3	26.3	26.7	26.6	26.4	52.4	52.0	51.9
1000	24.6	25.0	24.7	25.0	25.0	24.9	55.1	55.2	54.9
1250	23.2	23.4	23.3	23.3	23.6	23.4	57.1	56.8	56.5
1600	23.2	23.4	23.3	23.5	23.3	23.3	58.2	58.0	57.8
2000	22.8	22.9	22.7	22.6	22.6	22.6	58.8	58.7	58.6
2500	21.8	22.0	21.8	22.2	22.0	22.1	56.2	56.5	56.5
3150	29.2	29.2	29.3	29.2	28.7	28.9	53.9	53.6	53.9
4000	31.9	32.0	32.0	31.8	31.0	31.8	58.4	57.9	58.1
5000	31.2	31.3	31.1	31.4	30.7	31.6	62.2	61.7	62.6

Table 5: Measured values of the spatial standard deviation of the sound pressure level (dB) in the three rooms for correlated (C) and uncorrelated (U) excitation of the four speakers

Frequency (Hertz)	small C	small U	large C	large U	upper C	upper U
80	4.38	2.72	2.62	1.46	3.84	2.75
100	2.78	2.07	1.85	1.31	2.08	1.54
125	2.03	1.30	1.70	1.52	1.47	1.18
160	1.77	0.79	1.03	0.58	1.80	0.97
200	1.41	0.94	0.68	0.39	1.67	1.15
250	0.86	0.48	0.65	0.46	1.24	1.08
315	0.99	0.72	0.52	0.31	1.36	0.73
400	0.71	0.66	0.52	0.18	0.66	0.94
500	0.40	0.51	0.23	0.20	0.92	0.69
630	0.45	0.64	0.34	0.25	1.06	0.64
800	0.69	0.49	0.46	0.42	0.65	0.57
1000	0.48	0.27	0.33	0.28	0.68	0.47
1250	0.55	0.48	0.40	0.28	0.57	0.62
1600	0.65	0.45	0.46	0.38	0.86	0.76
2000	0.40	0.22	0.50	0.37	1.00	0.61
2500	0.52	0.43	0.66	0.68	0.82	0.60
3150	0.47	0.52	0.61	0.73	0.85	0.84
4000	0.64	0.72	0.75	0.88	0.93	1.18
5000	0.78	0.74	0.98	0.95	0.73	0.93

Table 6: Measured reverberation times in the small room with and without transmission through the wall specimen from the large room. The effect on the measured transmission is in the third column which shows 10 log (T1-T2)

Frequency (Hertz)	T1 secs.	T2 secs.	d(TL) dB
100	2.68	2.55	.2
125	2.68	2.32	.6
160	2.00	1.70	.7
200	2.26	2.16	.2
250	2.42	2.39	.1
315	2.35	2.39	-.1
400	2.10	2.12	.0
500	2.26	2.24	.0
630	2.53	2.51	.0
800	2.53	2.54	.0
1000	2.24	2.25	.0
1250	2.10	2.11	.0
1600	2.11	2.10	.0
2000	2.10	2.10	.0
2500	2.10	2.09	.0
3150	1.95	1.95	.0
4000	1.83	1.83	.0
5000	1.63	1.63	.0

Table 7: Reverberation times (seconds) in the empty room for single speakers and for correlated (C) and uncorrelated (U) sound

Frequency (Hertz)	Speaker number 1	2	3	4	C	U
100	6.55	5.57	6.61	5.43	5.75	6.59
125	6.83	7.19	7.00	6.88	7.15	7.05
160	5.39	5.42	5.46	5.40	5.52	5.53
200	6.54	6.71	6.52	6.49	6.45	6.57
250	7.34	7.35	7.26	7.29	7.16	7.21
315	7.14	7.06	7.10	7.04	7.05	7.03
400	6.54	6.57	6.53	6.54	6.48	6.49
500	6.20	6.17	6.17	6.19	6.19	6.15
630	5.81	5.85	5.84	5.84	5.83	5.87
800	5.61	5.60	5.58	5.61	5.58	5.62
1000	5.52	5.51	5.56	5.53	5.53	5.56
1250	5.30	5.33	5.36	5.33	5.35	5.36
1600	4.83	4.97	4.83	4.97	4.94	4.91
2000	4.43	4.40	4.44	4.42	4.44	4.44
2500	3.75	3.74	3.75	3.78	3.77	3.76
3150	3.20	3.19	3.19	3.15	3.19	3.20
4000	2.72	2.70	2.71	2.72	2.72	2.72
5000	2.27	2.24	2.25	2.26	2.26	2.22

Table 8: Mean absorption coefficient for individual excitation of the loudspeakers (average of nine microphone positions)

Frequency (Hertz)	Speaker number 1	2	3	4
100	0.68	0.98	0.77	0.83
125	0.69	0.66	0.59	0.81
160	0.80	0.84	0.78	0.88
200	0.82	0.83	0.82	0.85
250	0.92	0.91	0.87	0.89
315	0.93	0.92	0.89	0.90
400	0.94	0.91	0.94	0.93
500	1.02	1.01	1.04	1.00
630	1.08	1.09	1.07	1.09
800	1.11	1.09	1.09	1.10
1000	1.14	1.14	1.14	1.15
1250	1.14	1.15	1.14	1.16
1600	1.17	1.17	1.16	1.15
2000	1.13	1.12	1.11	1.11
2500	1.09	1.08	1.08	1.08
3150	1.04	1.04	1.05	1.03
4000	1.03	1.03	1.03	1.03
5000	1.03	1.09	1.05	1.04

Table 9: Measured absorption coefficients using correlated (C) and uncorrelated (U) sound compared with the mean for the four individual speakers from Table 8

Frequency (Hertz)	C	U	MEAN
100	0.82	0.85	0.81
125	0.75	0.76	0.69
160	0.89	0.85	0.82
200	0.82	0.84	0.83
250	0.89	0.87	0.90
315	0.91	0.90	0.91
400	0.93	0.93	0.93
500	1.02	1.02	1.02
630	1.10	1.09	1.08
800	1.10	1.10	1.10
1000	1.14	1.14	1.14
1250	1.16	1.16	1.15
1600	1.16	1.16	1.16
2000	1.12	1.11	1.12
2500	1.09	1.08	1.08
3150	1.05	1.05	1.04
4000	1.02	1.03	1.03
5000	1.01	1.01	1.05

Table 10: Effect of using multiple speakers and correlated (C) and uncorrelated (U) sound on standard deviation of sound pressure level and percent curvature

Frequency (Hertz)	s.d. SPL (dB)		percent curvature	
	C	U	C	U
100	0.615	0.282	27.7	21.1
125	0.354	0.332	12.2	10.6
160	0.196	0.139	12.1	9.4
200	0.121	0.103	9.3	7.5
250	0.077	0.075	6.8	6.1
315	0.067	0.063	5.7	4.4
400	0.054	0.045	5.3	4.2
500	0.044	0.040	4.7	3.6
630	0.057	0.046	4.5	5.3
800	0.037	0.034	3.7	3.4
1000	0.027	0.029	3.1	2.7
1250	0.034	0.026	3.3	3.3
1600	0.024	0.023	2.3	2.4
2000	0.024	0.024	3.6	2.6
2500	0.020	0.018	3.0	2.3
3150	0.020	0.018	3.0	2.8
4000	0.016	0.015	2.6	2.5
5000	0.015	0.014	2.8	3.3

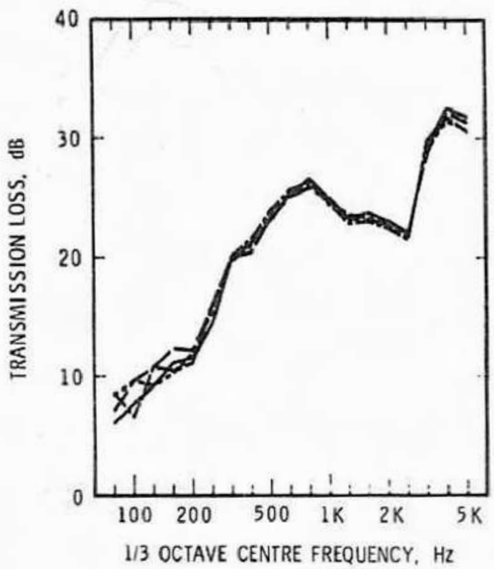

FIGURE 1
WALL TL FOR INDIVIDUAL
SPEAKERS - 65 m^3 TO 250 m^3

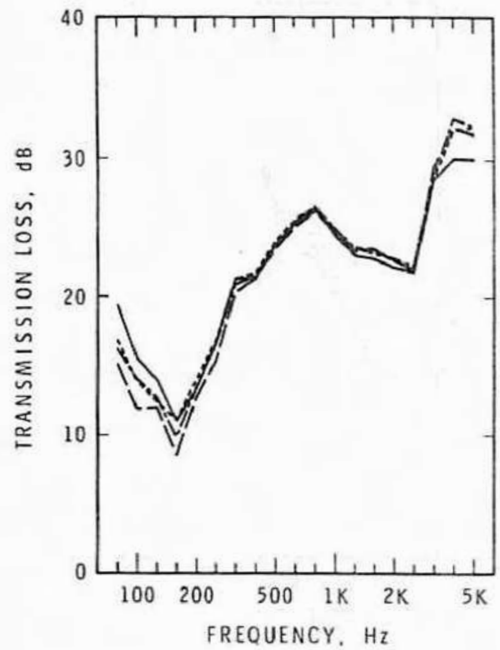

FIGURE 2
WALL TL FOR INDIVIDUAL
SPEAKERS - 250 m^3 TO 65 m^3

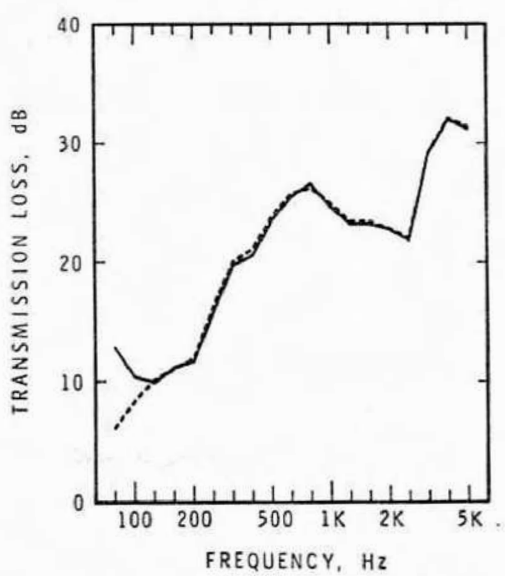

FIGURE 3
WALL TL FOR 65 m^3 TO 250 m^3
FOUR CORRELATED SPEAKERS
——— ; FOUR UNCORRELATED
SPEAKERS ----------

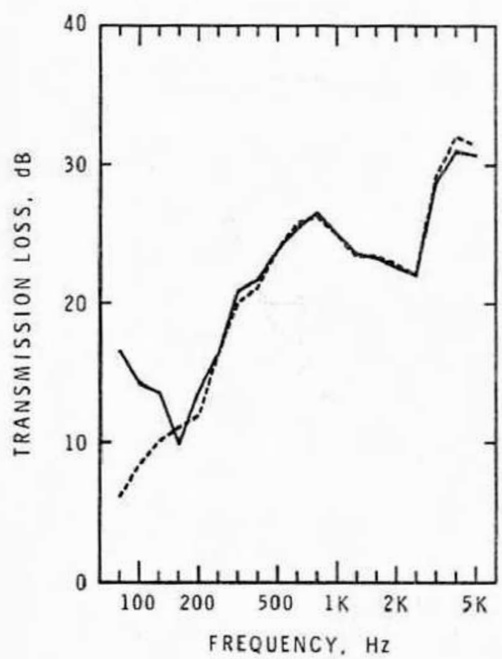

FIGURE 4
WALL TL FOR TWO DIRECTIONS OF
MEASUREMENT WITH FOUR
UNCORRELATED SOURCES (LARGE TO
SMALL ——— ; SMALL TO LARGE
---------)

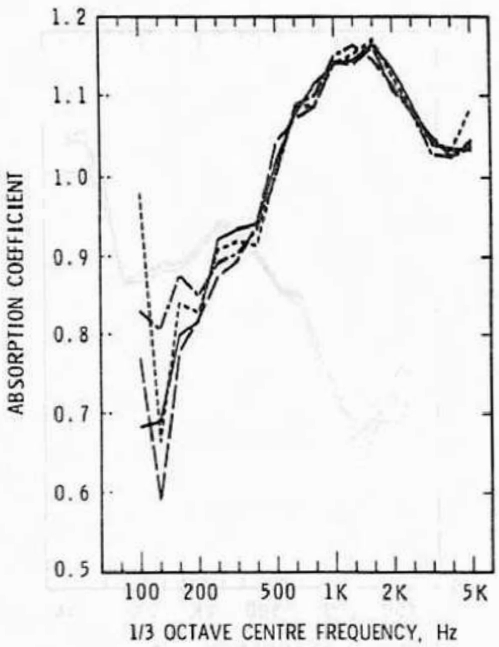

FIGURE 5

ABSORPTION COEFFICIENTS FOR INDIVIDUAL SPEAKERS (AVERAGE OF NINE MICROPHONE POSITIONS)

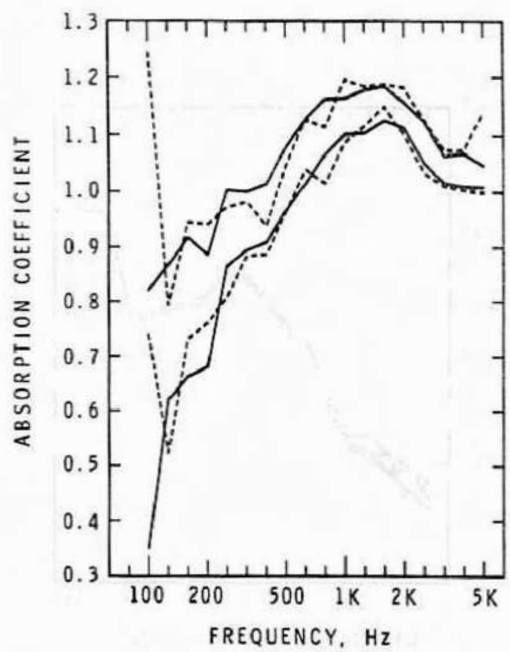

FIGURE 6

MAXIMUM AND MINIMUM VALUES OF ABSORPTION COEFFICIENT MEASURED IN THE ROOM FOR TWO LOUDSPEAKERS

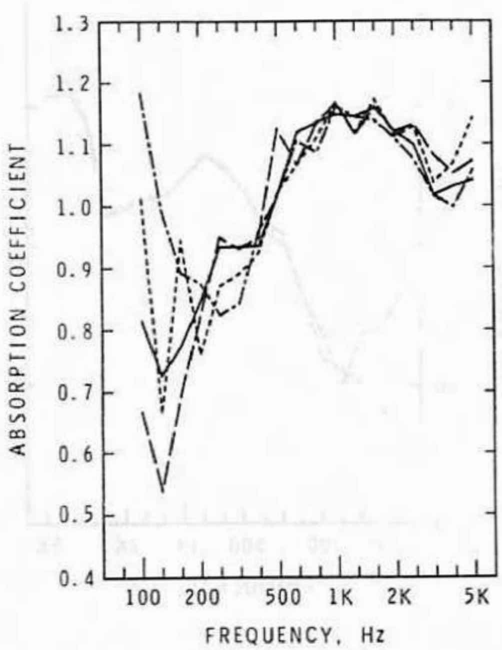

FIGURE 7

ABSORPTION COEFFICIENTS FROM A SINGLE MICROPHONE FOR EACH OF THE FOUR LOUDSPEAKERS

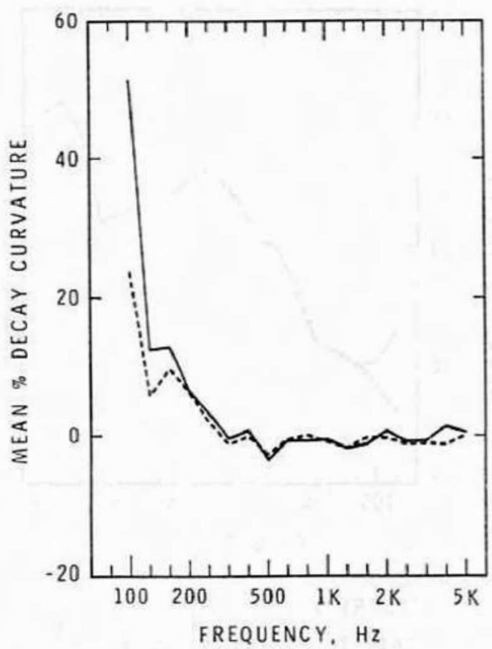

FIGURE 8

DECAY CURVATURE WITH CORRELATED (———) AND UNCORRELATED (--------) EXCITATION OF FOUR SPEAKERS