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Publisher's version / Version de l'éditeur:

Journal of the Acoustical Society of America, 77, 6, pp. 2094-2103, 1985-06

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Sound Transmission Loss: Comparison of Conventional Techniques with Sound Intensity Techniques

by R.E. Halliwell and A.C.C. Warnock

Reprinted from
Journal of Acoustical Society of America
Volume 77, No. 6, June 1985
p. 2094-2103

ANALYZED

DBR Paper No. 1299

Price \$1.00

NRCC 24689

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RÉSUMÉ

Les pertes de transmission du son dans un mur à simple paroi ont été mesurées dans une chambre réverbérante, au moyen de méthodes conventionnelles (ASTM E90) et de la méthode basée sur l'intensité sonore, introduite récemment. L'échantillon est placé dans cinq positions différentes à l'intérieur d'un tunnel reliant les deux chambres réverbérantes et des mesures sont effectuées dans la plus petite des salles pour quatre conditions d'absorption différentes. Des différences importantes ont été enregistrées entre les deux méthodes, à basses et à hautes fréquences. Les différences constatées à basses fréquences sont attribuables à l'augmentation de l'énergie acoustique à proximité des surfaces de la chambre de réception (effet Waterhouse) et au fait que les méthodes d'essai normalisées ne tiennent pas compte de ce phénomène. Lorsque l'effet Waterhouse est intégré à la formule conventionnelle de perte de transmission, on en arrive à une meilleure concordance, à basses fréquences, des résultats obtenus par la technique de mesure conventionnelle avec ceux obtenus par la technique basée sur l'intensité sonore. Les différences constatées à hautes fréquences ne sont pas expliquées.

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Sound transmission loss: Comparison of conventional techniques with sound intensity techniques

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(Received 19 December 1984; accepted for publication 20 February 1985)

Sound transmission losses for a single layer wall are measured in a reverberation room facility using conventional methods (ASTM E90) and the more recently introduced sound intensity method. The specimen is placed in five positions in the tunnel between the two reverberation rooms and measurements are made for four different absorptive conditions in the smaller room. Significant differences between the two measurement techniques are found at low frequencies and at high frequencies. Low-frequency differences are attributed partly to the increase in sound energy close to the surfaces of the receiving room (the Waterhouse effect) and the lack of any consideration of this in standard test methods. Inclusion of the Waterhouse term in the conventional transmission loss formula improves the agreement between the conventional and the sound intensity measurement technique at low frequencies. High-frequency differences are not explained.

PACS numbers: 43.55.Rg

INTRODUCTION

This paper compares transmission loss (TL) data for different room conditions and two measurement techniques: the conventional level difference method (CTL)^{1,2} and the newer technique based on measurements of sound intensity on the receiving room side of the partition (ITL).³ It is now comparatively simple to measure sound intensity thanks to advances in instrumentation and technology. Superficially the advantages of a direct measurement of sound intensity are many. In laboratories one can, in principle, measure sound transmission loss of complete partitions or only parts of them. The receiving room need only be a small nonreverberant space instead of a large reverberant room with specific acoustical properties. In buildings, the effects of different methods of construction might be studied with ease by measuring sound transmission through the various parts of a partition or the surfaces of a room. Before these benefits can be enjoyed, however, it is important to be aware of any disadvantages of the sound intensity technique or of any differences that might exist between the results it provides and those of the conventional method.

I. TEST SPECIMEN

Comparison measurements were made on a wall test specimen constructed from 3-mm hardboard weighing 3.7 kg/m². Two 2.44 × 1.22-m panels and one 2.44 × 0.61-m panel were attached using self-tapping screws to a lightweight steel stud frame around the periphery of the test opening, which measures 2.44 × 3.05 m, and the edges of the panels were connected together using screws. The whole assembly rested on 6-mm foam tape to reduce the solid contact between the specimen and the walls of the rooms; it was caulked and taped around the edges and at the joints to prevent leaks. Damping for the panel was not measured.

II. REVERBERATION ROOM DESCRIPTION

For wall TL measurements the two rooms used at the National Research Council of Canada have volumes of 65 and 250 m³. Both rooms are rectangular parallelepipeds with perturbations for test openings and have surface areas of about 100 and 245 m², respectively. Volumes and surface areas vary with specimen thickness and position. Four loud-speaker systems mounted in corners of each room have independent random noise generators and power amplifiers. Nine GenRad 25-mm electret condenser microphones in each room are connected through a multiplexer to an amplifier controlled by computer. The larger room is equipped with rotating as well as fixed diffusers with panels measuring 2.4 × 1.2 m. Although the small room is similarly fitted, its rotating diffuser was not operated during these experiments. (Previous experiments in this laboratory have shown that having the rotating diffuser stationary during a transmission loss measurement increases the variance of the measured sound pressure levels but does not change the mean.) (Unpublished data.) The test specimen normally sits on a wheeled frame in a fairly pronounced tunnel between the rooms (Fig. 1) and does not form a complete wall of either

FIG. 1. Cross section through the wall specimen test opening showing the five test positions in the tunnel. The specimen mounting frame in the middle of the opening is not rigidly connected to either test chamber.

reverberation room. For these measurements, the test specimen was placed in five different positions, $W1-W5$, in the tunnel between the two rooms. For each position the small room absorption was changed using glass fiber batts to give four different absorptive conditions, $A0-A3$. The $A0$ condition corresponded to the room in its normal condition; i.e., reverberation times around 2 s, while the other three conditions had gradually increasing amounts of absorption added until the reverberation times were below 0.5 s in almost all bands. Table I gives some representative reverberation times for one wall position and four absorptive conditions. In each absorptive condition the TL was measured using the sound intensity technique as well as the conventional method.

III. MICROPHONE CALIBRATION

The use of multiple microphones in reverberation rooms enforces their calibration to eliminate errors due to differences in microphone sensitivity. For this the microphone response curves supplied by the manufacturer (GenRad) were digitized and stored in the computer as levels relative to the 1-kHz level. The response of each channel of the multiplexer amplifier was then obtained by measuring its response to several constant amplitude sine waves in each of the third octave bands. This step was necessary because high-pass filters, only nominally identical, had been inserted in some channels of the multiplexer. These responses were combined with the microphone response curves to provide an overall frequency response for each channel. System calibration for absolute level at all frequencies could then be obtained by applying a Bruel and Kjaer (B & K) 4340 calibrator to each microphone in turn and reading the 1-kHz level on the real-time analyzer described in the next section.

TABLE I. Reverberation times in a small room.

Absorption condition:	$A0$	$A1$	$A2$	$A3$
Frequency (Hz)	Reverberation time (s) in 65-m ³ room			
63	3.5	2.2	1.6	1.1
80	1.9	1.2	1.0	0.8
100	1.7	0.9	0.6	0.5
125	1.8	1.0	0.6	0.5
160	1.8	0.8	0.6	0.5
200	2.4	0.8	0.5	0.5
250	1.8	0.6	0.4	0.3
315	2.1	0.6	0.4	0.3
400	2.1	0.6	0.3	0.2
500	2.3	0.5	0.3	0.2
630	2.5	0.6	0.3	0.2
800	2.4	0.5	0.3	0.2
1000	2.5	0.6	0.3	0.2
1250	2.5	0.6	0.3	0.2
1600	2.3	0.6	0.3	0.2
2000	2.1	0.6	0.3	0.2
2500	1.4	0.6	0.3	0.2
3150	1.7	0.6	0.3	0.3
4000	1.5	0.6	0.3	0.3
5000	1.2	0.5	0.3	0.2
6300	1.0	0.5	0.3	0.2

IV. CTL MEASUREMENTS

CTL measurements were made using a GenRad GR1921 real-time analyzer (RTA) and a computer controlled system. This instrumentation has a minimum integration time of 0.1 s and a maximum sample rate of 10 Hz. For very absorptive rooms this is too slow to measure rapid decays accurately. To circumvent this difficulty the 1/3-oct band multifilter section of the GR1921 was connected to a bank of analog rms detectors with RC time constants of 10 ms. An analog-digital converter sampled the detector outputs at 128 Hz and samples were added together to give an effective integration time of 1/32 s. This system was fast enough to follow the decay rates produced in the rooms. It was used to measure only decay rates in those instances where the commercial instrumentation was too slow. Sound pressure levels or decay rates were measured in the third-octave frequency bands from 63 to 6300 Hz. The spectrum in the source room was approximately white with some increased levels at high frequencies to overcome difficulties met during sound intensity measurements (see Appendix A). The CTL measurements were made in both directions, that is, with each room serving in turn as the source room. Normally the 65-m³ room is the source room and this is called the "forward" CTL. The "reverse" CTL measurement has the 250-m³ room as the source room and the 65-m³ room as the receiving room. The measurement procedures were in accord with ASTM E90¹ except that the smaller of the two rooms does not meet the current minimum volume requirements of that standard. Appendix B discusses the origins of the room volume criterion in ASTM E90 and shows that it is somewhat arbitrary. The conventional measurement techniques used in these rooms appear to give reasonable results down to 125 Hz, the lowest frequency required by ASTM E90, and perhaps even below that.

V. SOUND INTENSITY PROCEDURES

For the ITL measurements, the larger room was used as the source room to give a better approximation to a diffuse incident sound field throughout the frequency range. Sound intensity measurements were made with a B & K 3360 sound intensity analyzing system. Each of the two microphones were pressure calibrated with the B & K 4340 calibrator. Two probe spacings were used to cover the frequency range of the measurements, 12 mm spacing for 63–400 Hz and 50 mm for 500–6300 Hz, with the midpoint of the probe kept at 5 cm from the wall surface. Both sound pressure and intensity were measured on the receiving side of the wall. Because of microphone phase mismatch and instrument noise, a limit must be placed on the permissible difference between sound pressure and intensity to ensure that sound intensity measurements are reliable. This limit, which depends on frequency, sets the usable range of the instrument. The nominal minimum range of the instrument is given in Ref. 4 and it was decreased for this work by 8 dB to ensure reliable measurements. If the difference between pressure and intensity exceeded this limit, then the measurement was flagged as unreliable. Initially 100 uniformly distributed probe positions were used to sample the intensity at the surface of the

wall but comparisons showed that 25 positions gave practically identical results with a negligible decrease in precision. This was not surprising since the specimen was an essentially uniform sheet of material. Even at the lowest frequencies measured, the intensity variations on the receiving room side were rather small. Spectra from the B & K 3360 were transferred to a larger computer for processing.

It has been reported that sweeping the intensity probe manually over the surface of the specimen is equivalent to making measurements at fixed positions. Nevertheless, for this study it was decided to use the fixed point sampling method rather than the sweep technique to ensure the highest repeatability.

VI. THEORETICAL BACKGROUND TO TRANSMISSION LOSS MEASUREMENTS

A. Conventional measurements

The equations for the conventional method of measuring transmission loss originate with workers such as Davis⁵ and Buckingham.⁶ The analysis that follows is similar to that of Buckingham but has been changed slightly to emphasize certain points. If we begin with the assumption that the sound field in the room containing the source is perfectly diffuse, then the intensity per unit area incident on the partition $I_1 = \langle p^2 \rangle_1 / 4 \rho_0 c_0$, where ρ_0 and c_0 are the density of air and sound speed in air, respectively, and $\langle p^2 \rangle_1$ is the mean square sound pressure level in the source room. Thus the rate of transfer of sound energy through the partition separating the two rooms is $\tau S \langle p^2 \rangle_1 / 4 \rho_0 c_0$, where τ is the transmission coefficient of the partition of area S . τ is defined as the ratio of transmitted to incident intensity. The rate of energy loss in the receiving room is given by $(d/dt) \int_{V_2} \rho_2 dV$, where ρ_2 is the energy density in the receiving room with volume V_2 , and is a function of position in the room. In the steady state these two rates will be equal giving rise to the equation

$$\frac{\tau S \langle p^2 \rangle_1}{4 \rho_0 c_0} = \frac{d}{dt} \int_{V_2} \rho_2 dV. \quad (1)$$

If we assume an exponential decay of energy in the receiving room with a time constant b , then the right-hand side of Eq. (1) becomes $b \int_{V_2} \rho_2 dV$. With the further assumption that the integral can be replaced by $V_2 \langle p^2 \rangle_2 / \rho_0 c_0^2$ one has

$$\tau S \langle p^2 \rangle_1 / 4 \rho_0 c_0 = b \langle p^2 \rangle_2 V_2 / \rho_0 c_0^2. \quad (2)$$

Setting:

$$A = 4bV_2/c_0 \quad (3)$$

and taking logarithms, one gets the familiar equation

$$TL = L_1 - L_2 + 10 \log(S/A), \quad (4)$$

where TL = transmission loss = $10 \log_{10}(I/\tau)$; L_1 = mean sound pressure level in the source room; L_2 = mean sound pressure level in the receiving room. A is identified as the room absorption and represents energy loss at all room surfaces and throughout its volume.

Note that for Eq. (4) to be valid, the sound field in the source room should be diffuse so that the expression used to calculate the energy incident on the partition is correct. The sound field in the receiving room must also be such that the

average sound pressure level there is a good measure of the mean energy in the room. It is not likely that the sound field in a reverberation room will be approximately diffuse at all frequencies, especially at low frequencies where the specimen dimensions become comparable to the wavelength of sound. Note however that in laboratory measurements of transmission loss, one actually measures sound decay rate in the receiving room, not room absorption. Measurements show that the spatial variance of decay rate in rooms is relatively small⁷ and, since any uncertainty in the magnitude of the mean decay rate is further reduced by taking the logarithm, it is unlikely that this term causes any serious error because of spatial variance. On the other hand, one obvious indicator of nonideal conditions is the observation of nonlinear decays, which occur most often at low frequencies. In such cases it is better to estimate decay rate from the early part of the curve, since it includes the effects of short lived modes that would not be significant later in the decay. This measure would be more consistent with the energy loss rate during the steady-state excitation when the noise reduction is measured.

Valid CTL measurements thus require that both the receiving room and the source room be diffuse, a condition which does not hold true at all frequencies in the smaller of the two rooms used in this work, especially for absorption conditions A 1-A 3.

B. Intensity measurements

If the sound field in the source room is diffuse, then the intensity incident on the partition is again $I_1 = \langle p^2 \rangle_1 / 4 \rho_0 c_0$ as for CTL measurements. Thus by measuring the mean sound pressure level in the central part of the source room, exactly as for conventional measurements, one can calculate the level of intensity incident on the partition. The direct measurement of sound intensity on the receiving side of the partition then provides enough information to calculate transmission loss without any consideration of the properties of the receiving room, other than the requirement that the reverberant field level there does not invalidate the measurement. Thus, valid ITL measurements require that only the source room, the 250-m³ room, be "diffuse," a condition that is more likely to be satisfied over most of the frequency range because of the room size the diffusing elements, and the multiple loudspeakers.

VII. RESULTS

A. Intensity measurements

Possible errors associated with sound intensity measurements have been studied by several authors and can be found easily in recent literature.⁸ In this application, one must ensure that errors due to the reverberant sound field in the receiving room are negligible. This can be achieved by using an anechoic chamber as the receiving room or by adding sound absorbing material to the room to reduce the level of the reactive field. Since the absorptive material was added in four stages in this work it is of interest to see what effects there are, if any, on the ITL values. Figure 2 shows, for wall position W 3, the four ITL curves obtained for the different

FIG. 2. Sound transmission loss data obtained using the intensity technique for four absorptive conditions in the 65-m³ room and for wall position *W3*.

absorption conditions. In this figure, the results appear to agree very well with each other. The range in measured ITL values was about 45 dB and, since the main reason for this work was to compare CTL and ITL measurements, a reference contour was created to reduce the range of the data displayed on plots and to facilitate comparisons. This reference contour has a TL of 10 dB at 250 Hz and an ideal mass-law slope of 6 dB/oct up to 6.3 kHz. Above 6.3 kHz the effects of coincidence begin to appear. All subsequent plots, unless otherwise noted, are shown relative to this reference mass-law contour. Figure 3 shows the same data as Fig. 2 but drawn relative to the reference contour. It is now clear that there are differences between measurements in the *A0* condition and in the *A1*, *A2*, and *A3* conditions, but they are small. Similar plots were obtained for each of the other four wall positions and one can conclude in general that any of the three conditions *A2* to *A3* are adequate for making ITL measurements. Under the *A0* condition the ITL values varied randomly with respect to the other conditions and the mea-

FIG. 3. Same sound transmission loss data as in Fig. 2 but drawn relative to an ideal contour with a slope of 6 dB/oct. Differences between the *A0* condition and the more absorptive conditions, *A2* to *A3*, are more apparent.

surement conditions were apparently less acceptable. For the *A0* condition where the receiving room is fairly reverberant, it was expected that ITL would be in error since the reactive part of the field would contaminate the measurements. However, since the measurement is made close to the wall surface the nearfield dominates and the errors are not as large as might have been expected. The difference between sound pressure level and intensity level was larger than the other three conditions by about 1 to 2 dB, but the difference was still within the acceptable range. Nevertheless, measurements made in condition *A0* are considered to be less reliable. From a practical point of view, it is encouraging to note that one does not have to convert a reverberant receiving room into an anechoic chamber to make ITL measurements.

B. Comparison between ITL and CTL

The above results confirmed what has already been found by other authors^{3,9,10}: the ITL technique gives apparently reasonable results and good repeatability. The next point to consider is how well the results it gives for sound transmission loss agree with those from CTL measurements. Figures 4–6 compare ITL with forward and reverse CTL measurements for three of the five wall positions. For these comparisons the “best” measurement conditions have been shown; i.e., ITL measured in condition *A3*, the most absorptive receiving room, and CTL in condition *A0*, the most reverberant condition in the 65-m³ room.

These figures represent some of the more interesting data from this work. Recalling that the reference contour would be a horizontal straight line through zero on these plots, it can be seen that in general the ITL results are closer to this ideal case, particularly in wall position *W3*. It is only in the lowest two bands that there are significant departures from the reference contour. In contrast, CTL measurements show a different slope from the ideal 6 dB/oct case, approximately 5 dB/oct. Alternatively, the ITL technique gives lower transmission loss values at low frequencies and higher values at high frequencies than does the conventional level

FIG. 4. Comparison of CTL and ITL data for wall position *W1*. The curve labeled ITL is with absorptive condition *A3*. The FORWARD and REVERSE CTL were obtained with absorptive condition *A0*.

FIG. 5. Comparison of CTL and ITL data for wall position *W3*. The curve labeled ITL is with absorptive condition *A3*. The FORward and REVerse CTL were obtained with absorptive condition *A0*.

difference technique. This behavior is quite consistent for all sets of measurements and for both directions for CTL. The same kind of result can be seen in the work of Cops⁹ and others.^{10,11}

The other effect that is clear in these three figures is that the reverse CTL is consistently about 1 dB less in all bands than the forward CTL. The data we have on this point are somewhat confusing. In all of the five positions used with this test specimen this difference existed. Other specimens in other positions do not show any differences between forward and reverse CTL except at low frequencies.¹² A similar result was noted by Michelson¹³ for the case of rooms with markedly different reverberation times and a loosely coupled wall specimen, suggesting that this effect is related to the edge conditions. Further work is planned to sort out this problem.

FIG. 6. Comparison of CTL and ITL data for wall position *W5*. The curve labeled ITL is with absorptive condition *A3*. The FORward and REVerse CTL were obtained with absorptive condition *A0*.

FIG. 7. Changes in forward CTL measurements caused by moving specimen to different positions. Low frequencies only.

C. Tunnel effect

Changing the position of the specimen in the test opening of a reverberation room suite such as this has been reported to cause changes in the measured CTL.¹⁴ This effect has been studied experimentally and is attributed to the presence of a niche or tunnel on one or both sides of the specimen. Some studies investigated the effects of an artificially created niche but, in this case, the niche is an unalterable part of the room design. Generally it has been found that the measured transmission losses show minima when the specimen is in the middle position of the test opening and maxima at either end. Figure 7 shows the effect for forward CTL measurements in this facility, and Fig. 8 for ITL measurements. The reverse CTL measurements show the same effect. In both figures the "tunnel" effect is quite obvious at the lower frequencies. Figures 9 and 10 show the same data as in the previous two figures but in this case the center wall position, *W3*, is the

FIG. 8. Changes in ITL measurements caused by moving specimen to different positions. Low frequencies only.

FIG. 9. Changes in forward CTL measurements caused by moving specimen to different positions. Reference transmission loss curve is CTL data for wall position *W*3, the center position.

reference contour and high-frequency data are shown. These figures show that, as well as low-frequency differences, there are also differences in the transmission losses at the high frequencies. In particular, as the specimen moves deeper into the niche, the ITL values become significantly higher. In conventional transmission loss measurements one is actually measuring the properties of the combination of the specimen and the two niches on either side. The modal properties of the niches and the coupling through the specimen influence the results. In ITL measurements, the effect of the niche on the source room side will still be the same so it is to be expected that there will still be some tunnel effect. As measurements on the receiving room side are to some extent free of the influence of the tunnel on that side, it is not surprising that the tunnel effects are somewhat different for the two measurement techniques. During measurements the tunnel surfaces were never covered with sound absorbing materials so that any resonance effects in the tunnel were not disturbed.

FIG. 10. Changes in ITL measurements caused by moving specimen to different positions. Reference transmission loss curve is ITL data for wall position *W*3, the center position.

VIII. DISCUSSION

The differences between ITL and CTL results present a problem for laboratories wishing to make standard measurements on a commercial basis for comparison of systems and for standard writing groups. There seems little doubt from the results presented here and seen in other laboratories that in general ITL measurements give lower transmission loss values at low frequencies and higher ITL values at the higher frequencies. In this case it results in a transmission loss curve that has a slope closer to the ideal predicted by the mass law. In cases where the sound transmission class (STC)¹⁵ is governed by the transmission loss at low frequencies it is quite probable that an ITL measurement would give an STC value significantly lower than the conventional technique, especially if the 8-dB rule applied in the lowest test bands.

In considering explanations for the difference between the ITL and the CTL technique, it is worth noting that one has to make fewer assumptions when using the intensity technique. The incident sound field is assumed to be approximately diffuse in both techniques and, for these measurements, is the same field. No assumptions need be made about the sound field in the receiving room; one must only ensure that the residual reverberant part of the field does not invalidate the measurement of intensity. The measurements show that this apparently was not a serious problem even in the most reverberant condition of the 65-m³ room, *A* 0. If the specimen transmission loss is very small and the receiving room is too reverberant, then the intensity measured at the specimen surface will be reduced because of the fraction of the reverberant sound energy being transmitted back into the source room. This results in a small error component in the measured intensity which will be approximately $(TL - 10 \log S/A)$ dB below that being transmitted from the source room directly. When this term is about 6 dB, then the error in the measurement of TL will be about 1 dB. Obviously this effect is part of the low-frequency discrepancy but it is not the major cause. In the *A* 3 condition the error in the measured TL is about 1 dB in only the bottom few bands. Some calculated correction for this effect might have been introduced but this was not done because there are too many underlying assumptions about the sound field in the receiving room for it to be accurate, especially in the cases where the room is very absorptive.

On further examination, Sec. VI A provides some insight into the reasons for the discrepancies among ITL and CTL measurements in both directions. The fundamental principle for the analysis presented there is that, in the steady state, the energy flow through the partition is balanced by the energy loss in the receiving room. Waterhouse¹⁶ pointed out that in a reverberation room there is an increase in the energy density at the surfaces, at the junction of surfaces, and in the corners because of the interference between the incident and reflected waves. Thus, estimates of total room sound energy based on measurements of sound pressure level in the central portions of the room will be too low. As a result of his work, sound power measurement standards now include a correction for this effect.^{17,18} The mean sound level in the room is corrected by the addition of a term $10 \log_{10} (1 + S\lambda/8V)$, where λ is the wavelength of sound at

the center frequency of the band. In the case of conventional sound transmission loss measurements one is also interested in measuring the total energy in the receiving room, so the Waterhouse correction should be applied to the sound pressure level measurements made there. It is not correct to apply the correction to the measurements in the source room for in that case one wants to know the incident sound intensity or incident sound power. The normal derivation of the analytical expression for sound transmission loss includes both incident and reflected waves in the analysis so that the increased sound energy due to interference at the surface is automatically accounted for.

In principle, the Waterhouse correction can account for some of the differences between forward and reverse CTL measurements at low frequencies in these rooms as well as the difference between ITL and CTL results. When the correction term is applied in the receiving room to each of the CTL measurements, the data presented in Figs. 4-6 become altered to those in Figs. 11-13. The agreement between the three types of measurement has been improved significantly at low frequencies, although there are still differences between them probably partly due to intensity transmitted back into the source room. Present sound transmission loss standards^{1,2} do not include any correction term to be applied to sound pressure levels in the receiving room. If a correction is applied in sound transmission loss standards, then it follows that it should also be applied in other standards such as ASTM E492,¹⁹ ISO 140/VI,²⁰ and the field versions of these standards. While it seems evident that some kind of correction for increased energy close to the room surfaces should be included in the standard formula, Eq. (4), it is not certain that the Waterhouse correction will be adequate in all cases. At those low frequencies where the correction becomes significant, many reverberation rooms will not have a uniform sound field in their central portions because of interference between room modes and possible influence of the nearfield of the specimen. Calculations for the ideal case of a point source in a rectangular parallelepiped are straightforward

FIG. 12. Comparison of CTL and ITL data for wall position W3. The curve labeled ITL is with absorptive condition A 3. The FORward and REVerse CTL were obtained with absorptive condition A 0 and are corrected in each case for the Waterhouse effect.

and interesting but will probably not apply to real rooms with their large specimens, tunnels, rotating and fixed diffusers, nonparallel walls, and other geometrical perturbations. More research is needed to find out how best to sample the sound field in a room to estimate the total sound energy in it. Present reverberation room standards require users to avoid the room surfaces and corners. It might ultimately prove better to include such regions in a complete survey of the room so that the total energy is known more precisely. On the other hand, until such research is done, the Waterhouse correction is better than no correction at all.

Considering only the practical aspects of making standardized sound transmission loss measurements in a laboratory, ITL procedures offer no advantage over CTL procedures where a fully automated system is in operation. In the latter case almost no operator intervention is necessary once the test has been initiated. In contrast with this, the ITL

FIG. 11. Comparison of CTL and ITL data for wall position W1. The curve labeled ITL is with absorptive condition A 3. The FORward and REVerse CTL were obtained with absorptive condition A 0 and are corrected in each case for the Waterhouse effect.

FIG. 13. Comparison of CTL and ITL data for wall position W5. The curve labeled ITL is with absorptive condition A 3. The FORward and REVerse CTL were obtained with absorptive condition A 0 and are corrected in each case for the Waterhouse effect.

procedures require an operator to place the microphone in many positions or sweep it over the surface of the specimen. Although the sweep could be automated, it would still usually be done for at least two microphone separations to ensure accurate measurements over the entire frequency range. Sampling the surface of a test specimen can obviously be a valuable diagnostic procedure but in a laboratory situation where the transmission loss for a system is required for comparison with other systems, one has to be sure that the entire surface has been sampled uniformly and that no weak spots or leaks have been overlooked. It is conceivable that an outwardly uniform specimen could have areas that transmit much more strongly than others and that these areas could be sampled incorrectly leading to an erroneous transmission loss value. A carefully written standard measurement procedure could perhaps deal with this problem. However, the reverberant receiving room in conventional test procedures automatically performs integration of the sound energy coming from the test partition so that many of these problems disappear. In addition, the calibration procedures in ITL measurements are more difficult than in CTL measurements.

The situation is different when one considers the design and construction of a new reverberation room facility for making sound transmission loss and other acoustical measurements. Conceptually, instead of a three room suite to deal with wall and floor specimens, one needs only a single large reverberant room with two or more openings for the insertion of wall or floor specimens. The room could be large enough to be used for sound power and sound absorption measurements and the vertical walls could provide at least two or three wall test openings. The ceiling could provide enough space for perhaps two floor test openings. Because the ITL procedures do not require large, reverberant receiving rooms but only a relatively absorbent and quiet space, the receiving spaces could be quite small. This work shows, however, the importance of the depth of the specimen mounting fixture even when transmission loss measurements are made using sound intensity techniques, because ITL is still markedly influenced by wall position. A comparison of the economics of such a scheme with those for a traditional three room suite may be interesting but is beyond the subject area of this paper.

Note added in proof. No explanation was given for the discrepancy between the ITL and CTL at high frequencies. It was realized in retrospect that much of this difference could be due to the finite difference error which results when the microphone spacing used for ITL is large compared to the wavelength. The expected error at 6.3 kHz would be 1.6 dB for the case of a plane wave. This is a reasonable estimate for the $A3$ case when the receiving room is essentially anechoic but would not be true for a more general case. This additional source of error serves to highlight the difficulties encountered when trying to use Sound Intensity Techniques for Transmission Loss measurements. To adequately cover the frequency range used here, keeping the errors below 0.5 dB, requires that three different microphone spacings be used. If the B & K 3360 sound intensity analyzing system is used, it also means that the highest frequency bands must be

measured using 1/4-in. microphones. Thus, at the frequencies where the signal is weakest because of a high transmission loss, it is necessary to use microphones which reduce sensitivity. This can hardly be considered to be an optimum solution.

ACKNOWLEDGMENTS

We are grateful to J. Kopec, Riverbank Acoustical Laboratories, and T. J. Schultz who supplied the references for the material in Appendix B. Discussion of the results of this work with J. Roland, CSTB, France, were very useful and he reminded us of the importance of the Waterhouse effect. We thank also our colleagues in the Noise and Vibration Section for numerous stimulating arguments. This paper is a contribution from the Division of Building Research, National Research Council Canada and is published with the approval of the Director of the Division.

APPENDIX A: SOURCE SPECTRUM EFFECTS ON TRANSMISSION LOSS

Some practical difficulties were encountered with the instrumentation when measuring sound intensity on the receiving room side of the wall. The combination of source room spectrum, approximately white, and the wall transfer function produced an intensity spectrum that decreased rapidly as frequency increased. This, together with the fundamental limitations of the digital processing in the B & K 3360, meant that it was not possible to measure all bands simultaneously since some of the high-frequency intensity levels fell below the measuring range of the instrument. One simple remedy for this is to shape the spectrum in the source room so that the received intensity spectrum is approximately flat or at least does not exceed the limits of the instrument. For this specimen it was only necessary to increase the high-frequency levels in the source room, but more shaping would be necessary for a test specimen with a more complicated transmission loss spectrum. An alternative procedure that is perhaps more convenient, since two microphone separations would often be used, is to excite the source room with sound that is limited to the bands being measured. Even with this limitation, however, there still exists a possibility of exceeding the limits of the instrumentation and it is necessary to consider the possible bias introduced by using source spectra that are "whiter than white."

The use of $1/f$ or pink noise as a source signal is common in acoustics when a system response is to be obtained in 1/3-oct bands. It can be argued however that it is incorrect to use pink noise as the source spectrum in transmission loss because this will introduce some bias in the measurements. The definitions given in ASTM C634²¹ for sound transmission coefficient and sound transmission loss make no mention of the bandwidth of the signal being considered and, in practice, TL is obtained for different bandwidths. It is reasonable to assume that the definitions apply at single frequencies and that single frequency values should be integrated over the required bandwidth to get the final value. Thus at a given frequency f the transmission coefficient may be defined as

$$\tau(f) = I_{tr}(f)/I_{inc}(f),$$

where I_{tr} and I_{inc} are transmitted and incident intensity, respectively, and τ is the transmission coefficient. It follows that:

$$\int_{f_1}^{f_2} \tau(f) df = \int_{f_1}^{f_2} I_{tr}(f)/I_{inc}(f) df,$$

where f_1 and f_2 are the lower and upper passband frequencies for the filter. In practice with 1/3-oct band instrumentation one usually measures $\int I_{tr} df$ and $\int I_{inc} df$ and calls the ratio of these two quantities the transmission coefficient for the band. This is only strictly correct if $I_{inc}(f)$ is constant for all f , i.e., white noise. The difference between a white noise source and pink noise source might be expected to be negligible for 1/3-oct bands since the difference in level at the two extremes of the filter bandwidth is only 1 dB in theory, and in practice the convolution of source spectrum with speaker and room response would make it difficult to distinguish between them. If it becomes necessary to use source spectra that increase in level with frequency, however, then possible bias errors introduced by the different noise source spectra, wall transmission loss spectra, and the non-negligible energy transmission outside the passband of a real filter should be investigated. These possible errors are most easily investigated numerically.

Three types of 1/3-oct band filters were simulated numerically: a perfect filter with infinite attenuation outside of the passband, a minimum ANSI class III filter, and a minimum ANSI class II filter. To model the transmission loss of the wall the TL characteristic was assumed to vary as f^t . The spectrum of the source was assumed to vary as f^s . (A source exponent of -1 corresponds to pink noise, 0 to white noise, and the higher values of s to spectra that increase in energy with frequency. Similarly, a wall exponent of -2 corresponds to an ideal mass-law characteristic.) A center frequency of 100 Hz was chosen for the filter for convenience and the wall was assumed to have a TL of 30 dB at the band center. Integration was carried out from three octaves below the band center to three octaves above the band center. Although specific values were chosen to simplify the calculations, because of the functions chosen and the fact that one is dealing with a logarithmic frequency scale, the results will have general application.

The data showed that for filters with performance equal to Class III or better there were no differences from the ideal case greater than ± 0.6 dB. For the class II filter, the error became greater than 1 dB when $t + s \leq -7$. The same calculations applied to walls with transmission coefficients that increased with frequency (t positive) showed errors greater than 1 dB when $t + s \geq 6$ with class III filters, and when $t + s \geq 4$ with class II filters. Positive values of t correspond to wall transmission loss characteristics that decrease very rapidly with frequency, a most unusual occurrence except in the region of resonant dips in the curve. Thus, for most practical purposes the use of spectra with enhanced high-frequency content is not likely to introduce any serious bias errors to the measurements.

APPENDIX B: MINIMUM ROOM VOLUME REQUIREMENTS

Current versions of ASTM standards dealing with reverberation room measurements require that the minimum room volume be greater than $4\lambda^3$, where λ is the wavelength of sound at the center of the lowest third-octave band, where measurements are to be made. It is instructive to examine the source of this criterion, especially considering the fact that comparable ISO standards^{2,20} do not make use of this criterion and allow lower room volumes.

The $4\lambda^3$ criterion is a development of the requirement that the reverberation room should be large enough to contain at least 20 eigenmodes in the lowest measurement band. This statement appears in Chap. 8 of Ref. 22. An expression for the approximate number of modes in a frequency band Δf wide is quoted that is essentially the same as those given in other references.²³ An approximate expression for an octave band is then derived and attributed in a footnote to R. J. Wells. Because the bandwidth is one octave, the criterion becomes $V \geq 4\lambda^3/3$ rather than $V \geq 4\lambda^3$.

The same criterion was then published in ANSI S1.2 — 1962²⁴ in virtually the same form. Again the requirement was stated for an octave band and no reference was given to justify the choice of 20 modes and not some other number. A footnote says, however, that for narrower bandwidths, larger room volumes are required. Thus for 1/3-oct bands the requirement becomes $V \geq 4\lambda^3$. The idea that the minimum required room volume depends on measurement bandwidth was actually used in ASTM E336 — 77²⁵ which allowed measurements in smaller rooms if the analysis bandwidth was one octave wide instead of one-third of an octave. For example, a room could have 20 modes in the 100-Hz-oct band and would thus be acceptable for measurements in octave bands down to this frequency. The same room would not be acceptable for measurements in 1/3-oct bands. Obviously three 1/3-oct band measurements could be added together to form the same octave band result, so the criterion suggests that three unsatisfactory measurements can be combined to form a single satisfactory one, yet nothing physical has changed.

The application of the 20-mode requirement gives smaller minimum room volumes than the approach used by Schroeder²⁶ and Schroeder and Kuttruff²⁷ which considered the statistical separation between modes and the modal overlap due to room absorption to arrive at a criterion for a reverberation room to which statistical theories could be applied, in other words a good approximation to a diffuse sound field. It should also be noted that ANSI S1.2 is now obsolete, and ANSI S1.311¹⁷ simply provides a table of preferred minimum room volumes. A volume of 200 m³ is recommended for measurements down to 100 or 125 Hz.

The 20-mode criterion is more stringent in the low-frequency bands than it is in the higher bands because the bandwidth of 1/3-oct band filters decreases with decreasing frequency. Thus at low frequencies the criterion imposes a smaller mean separation between modes and the room response is required to be smoother at low frequencies than at high frequencies—an inconsistency.

Low-frequency measurements in rooms are difficult to

interpret and have doubtful validity. It is not clear, however, just what the acceptable minimum volume for a particular type of measurement should be. The equations used to derive the $4\lambda^3$ requirement are derived from eigenmode theory for a rectangular room. In real rooms the situation is complicated by the use of such devices as rotating diffusers which mean that the simple eigenmode theory does not apply provided the rotating diffuser is large enough and heavy enough to perturb the sound field. More work is needed to settle this point.

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