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SOUND TRANSMISSION THROUGH WINDOWS

I. SINGLE AND DOUBLE GLAZING

by J.D. Quirt

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SOMMAIRE

Dans cette note on présente une série de mesures de la transmission du son par les fenêtres relevées en laboratoire. À partir de ces informations, l'effet de perte de la transmission du son dû à l'épaisseur du vitrage et à l'espace entre les vitres est évalué pour différents cas.

Sound transmission through windows I. Single and double glazing

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The results of an extensive series of laboratory measurements of sound transmission through windows are presented. By reference to these data, the systematic dependence of the sound transmission loss on glass thickness and interpane spacing is evaluated.

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INTRODUCTION

A series of measurements of the sound transmission loss (TL) of single- and double-glazed windows has been carried out primarily to determine the dependence of TL on glass thickness and interpane spacing. Although sound transmission data for many types of window have been published, the results of different studies are not in close agreement.¹⁻⁹ Figure 1, which is based on data from a review paper by Marsh,¹ illustrates the typical variation among published results. Despite the nominal similarity of glazing and interpane spacing, the results obtained in the three sets of measurements differ appreciably. Such discrepancies are apparently due to properties of both the samples themselves and the laboratories in which they are tested.

Several window properties in addition to glass thickness and interpane spacing can appreciably affect sound transmission. At low frequencies it is affected by panel resonances whose frequencies depend on the dimensions of the panes of glass and on the edge constraints. Below the coincidence frequency both edge constraints (rigidly mounted, simply supported, etc.) and damping appear to have some effect on sound transmission, although experimental tests⁵⁻¹² are not

fully consistent with each other or with theoretical predictions.¹²⁻¹⁴ Near and above the coincidence frequency the TL is strongly dependent on damping (which depends not just on losses in the glass but on sound energy dissipated within the seals around the window or transmitted to the supporting structure). In addition to the effects that change sound transmission through the glass there is the problem of transmission around it; most of the data in the literature are for openable windows and such TL data are generally dominated by the sound transmission characteristics of the leaks around openable sections.

Variations in TL data are also introduced by the characteristics of the laboratory reverberation room suite. Problems of interlaboratory repeatability of TL measurements have been discussed in considerable detail in reports on round-robin test series.^{10,15,16} Many of the laboratory-related effects are predicted by theory, but the accuracy of prediction does not appear to justify systematic adjustment of published data (even if all relevant laboratory and test specimen details were available). Unfortunately, these systematic discrepancies are particularly pronounced for window TL data because practical constraints on pane size generally lead to the use of small windows mounted in filler walls, conditions that exaggerate some of the laboratory-related effects.

Given the large number of confounding effects, the lack of agreement among the published data, as illustrated in Fig. 1, is not particularly surprising. This large variability limits the information to be gained by combining the results of earlier studies of the change in window TL with parameters such as interpane spacing of double glazing. In an effort to obtain further information an extensive series of measurements of sound transmission through windows has now been made. As many variables as possible (such as window dimensions, glass mounting, and laboratory-related details) were held as constant as was practicable. This paper presents the results for single- and double-glazed windows, using data specifically selected to illustrate trends in the sound transmission performance. A full tabulation of the test results is available.¹⁷

I. EXPERIMENTAL CONDITIONS

A. Test environment

All the sound transmission measurements were made in accordance with ASTM standard E90-75, "Laboratory measurement of airborne sound transmission loss of build-

FIG. 1. TL data from three studies of nominally equivalent windows (double 6-mm glazing with approximately 100-mm separation).

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ing partitions."¹⁸ The source room has a volume of 62 m³ (2100 cu ft) and the receiving room a volume of 255 m³ (9000 cu ft). Test specimens are mounted in an opening 2.44 m (8 ft) high by 3.05 m (10 ft) wide between the two reverberation rooms. Following the recommendations of ASTM E90, each room is equipped with both fixed and moving diffusing panels intended to provide as good an approximation as possible to the diffuse sound field that is assumed in transmission loss theory.

The sound-pressure level in each room is sampled by a set of nine Genrad 1961 electret condenser microphones with associated preamplifiers whose outputs are observed individually. The signal from each microphone is selected via a Genrad 1566 32-channel multiplexer/amplifier and measured with a Genrad 1921 1/3-octave real-time analyzer. These instruments and the noise sources are all interfaced to a minicomputer that controls the measurements and performs all necessary calculations.

Measurements were made for the standard 1/3-octave bands with centers from 80 to 5000 Hz. The data for the 80- and 100-Hz bands should be treated with caution because the test facility does not satisfy room dimension requirements for these bands.¹⁸

Figure 2 shows the dimensions of the window frame and the associated filler wall in which the window units were mounted. The frame was sufficiently deep to permit interpane spacings up to 200 mm (8 in.). The filler wall was of double wood stud construction with multiple layers of gypsum board on each face and sound absorbing material in the cavity. Tests were made with heavy panels inserted in the window openings to make sure that flanking transmission, including sound transmitted through the filler wall and frame, was insignificant in relation to sound transmitted through the windows.

FIG. 2. Location and size of window openings in filler wall.

B. Window mounting

The window construction details are shown schematically in Fig. 3. All the windows were mounted in wooden sashes of the same size: 620 mm (24.5 in.) wide, 1750 mm (68.75 in.) high, and 41 mm (1.625 in.) thick. These had spring metal weatherstripping around their perimeter and fitted snugly into the frame openings. Each sash was butted against a wooden positioning strip and held firmly in position by a second wooden strip fastened to the frame. All cracks around the perimeter were sealed using an adhesive tape (which for narrow cracks provides a seal essentially the equivalent of caulking).

The windows tested had single or double glazing with nominal glass thicknesses of 3, 4, and 6 mm, actual mass/unit area of 8.1 kg/m² (26 oz/ft²) 10.4 kg/m² (34 oz/ft²) and 14.4 kg/m² (47 oz/ft²), respectively. The glass panes (560 mm × 1680 mm) were held in place by wooden strips nailed to the sash. A small bead of caulking sealant ensured a good acoustical seal (and a thin resilient layer) between the wood and the glass. Double glazing was tested with two panes mounted in a single sash (for interpane spacings up to 19 mm) and with each pane mounted in a separate sash (for spacings of 19 mm or greater).

The effects of edge conditions have been studied both theoretically and experimentally in several studies. Although the experimental results do not agree perfectly with theoretical predictions, the basic trends have been established at least qualitatively. As noted by Utley and Fletcher,⁹ practical window mountings usually are intermediate between rigidly clamped and simply supported edges, and the damping provided by edge losses tends to be substantially greater than that of the glass itself. In general, the lowest values of TL appear to be obtained for firmly clamped edges and minimum damping. Simply supported edges and higher

FIG. 3. Schematic representation of window mounting details. Caulked seals are indicated by circles and taped seals by arrows.

damping can provide increases of up to ~ 3 dB for frequencies below coincidence and substantially larger improvements near the critical frequency.^{6,9,12}

Although mode shapes for these windows were not measured to determine actual edge constraints, their edge conditions are probably intermediate to the simply supported and rigidly clamped cases. Measured damping (as will be discussed) appears to be in the middle of the range of results reported in the literature.^{8,9} The present study should therefore provide a reasonable estimate of the performance of "typical" windows. Of greatest concern, however, was the consideration that this mounting technique is well suited to examining the dependence of TL on interpane spacing because similar edge constraints can be obtained for a wide range of interpane spacing. It is hoped that because the sealant layer was rather thin, changes in damping associated with hardening of the sealant over the extended time period of the test series were minimal.

C. Descriptive code for windows

For ease of presentation the window glazing is identified by a simple descriptive code based on nominal glass thickness (in mm) and interpane spacing (in mm) for double glazing. A single layer of 3-mm glass is simply denoted by "3," double glazing with two panes of 4-mm glass separated by a 50-mm air space by "4(50)4," and so on. Special details related to the interpane cavity are indicated by minor variations:

(1) Nonparallel double glazing with interpane spacing at the top of the window different from that at the bottom is indicated by specifying the maximum and minimum spacing; e.g., "4(4 to 19)4."

(2) Absorptive treatment (with 25-mm thick glass-fiber) covering the surface of the cavity perimeter between the sashes is denoted by addition of the letter A to the interpane spacing code; e.g., "3(100A)3."

II. EXPERIMENTAL RESULTS

A. Precision and reproducibility of transmission loss data

Data were obtained in three series of measurements with intervals of approximately one year between each. Although details of glass mounting and measurement procedures were consistent within each series, there were some changes in the laboratory between series: alterations were made in the diffusing panels of the receiving room, in the position of the noise sources, and in the number and location of microphones in both rooms. Although the tests conform in all cases to the ASTM E90-75 standard, it was found that these modifications could introduce systematic changes in the measured TL results.

The nominal 95% confidence limits for TL measurements are ± 1 dB for the 1/3-octave bands at or above 315 Hz, ± 2 dB for the 250 and 200-Hz bands, and ± 3 dB for the lower frequencies.¹⁷ Repetition of measurements without removing the test specimen consistently gave agreement within those limits. When windows were reinstalled and tested again within a test series, the changes in TL were general-

ly larger, presumably because small changes in the mounting conditions resulted in slightly different specimens for the retests. The changes in TL were still consistently within the confidence limits, except near the coincidence dip where sensitivity to damping (and hence to mounting conditions) is expected to be greatest. In no case did the changes exceed 3 dB and no average trends were discernible.

Because of possible systematic changes in TL between test series, the second and third series of measurements included a number of window types that had been tested in the first series. Figures 4 and 5 show the changes in TL results for these tests on nominally identical windows. Not only do the differences frequently exceed the confidence limits, but rather well defined mean changes are evident for some 1/3-octave bands. Although the differences are not far outside the confidence limits (and are small when viewed in the light of interlaboratory round-robin test series),^{10,15} they do interfere with comparison of TL results from different series. Wherever possible, detailed comparison of TL results to assess trends associated with glass thickness or other variables were restricted to comparisons within a series. The window types retested were chosen primarily to facilitate this approach. Cases where data from several series are combined are specifically identified.

B. Damping measurements

The damping provided by energy dissipation in the glass and sash or by energy transfer to the surrounding structures can appreciably affect the measured sound transmission. The damping coefficient or loss factor is usually measured by means of techniques similar to those used for measuring rate of sound decay in a reverberation room.⁸ The loss factor (η) may be calculated from the expression

FIG. 4. Reproducibility of measured TL from first to second test series. Crosses indicate data for each window type (many are superimposed due to integer rounding of TL). Bars show range of one standard deviation about the mean.

FIG. 5. Reproducibility of measured TL from first to third test series. Crosses indicate data for each window type (many are superimposed due to integer rounding of TL). Bars show range of one standard deviation about the mean.

$$\eta = D(27.3 f_0)^{-1}, \quad (1)$$

where D is decay rate (in dB/s) and f_0 is resonant frequency (or band center frequency when measurements are made with 1/3-octave noise signals).

For the present study 1/3-octave bands of random noise were used to drive magnetic transducers to excite the window. The signal was obtained from one of three B and K accelerometers mounted on the glass, using a B and K 2209 sound level meter as a pre-amplifier. The ac signal from the sound level meter was input to a custom rms module (based on an Analog Device AD536A) with selectable time constants from 1 to 1000 ms and a logarithmic output of 10 dB/V. This output signal was displayed on a Tektronix 468 digital storage oscilloscope. The signal-averaging mode of the oscilloscope was used to obtain a decay curve average (typically of 32 decays), which yields a more reliable measurement of decay rate. A typical trace is shown in Fig. 6; movable cursors provided direct digital readout of time and voltage (at 10 dB/V) differences between any two points on the trace. Measurements were restricted to a range of about 5 dB below the initial signal level to 15 dB above the background level, and the rms time constant was set to less than 1/10 of the measured time constant for the decay.

Preliminary measurements were made with each of the four source transducers driven individually, and with all four driven simultaneously. Repeatability for any source position was found to be approximately $\pm 5\%$ about the mean. Similar differences were observed among values measured for individual source transducers, and much of this variation may be ascribed to measurement uncertainty. With all four transducers driven simultaneously, the data fell in the same range as those for individual sources and provided slightly higher and much more uniform signal levels at the three pickup accelerometers. Because this uniformity of signal

FIG. 6. Oscilloscope display of average decay curve for 800-Hz band. Vertical scale is 10 dB/division. Horizontal solid and dashed lines are cursors; slope of the curve segment between the cursors is the measured decay rate.

strength is desirable for decay curve averaging, the actual tests were performed with all four source transducers driven simultaneously.

Damping was measured in full detail only for the 4-mm glass, but similar results would be expected for the other thicknesses.⁹ Data for the cases with the window sash resting on a concrete floor and with it mounted in the window frame are presented in Fig. 7. Overall measurement accuracy is estimated to be approximately $\pm 10\%$. Mounting the sash in the frame significantly increases damping for frequencies below about 2 kHz.

C. Single glazing

Measured transmission loss data for the three thicknesses of glass are presented in Figs. 8 (a)–(c). For compari-

FIG. 7. Measured loss factors for single-glazed window with 4-mm glass lying on concrete floor (O) and mounted in window frame (Δ).

FIG. 8. (a) Measured and calculated TL for 3-mm glass: (●) experimental data from first series (STC = 30), ... mass law, — Sewell expression, -○- Nilsson expression; (b) Measured and calculated TL for 4-mm glass: (●) experimental data from first series (STC = 30), ... mass law, — Sewell expression, -○- Nilsson expression; (c) Measured and calculated TL for 6-mm glass: (●) experimental data from first series (STC = 32); ... mass law, — Sewell expression -○- Nilsson expression.

son with theoretical studies these were adjusted to the TL appropriate if only the exposed glass surface were transmitting sound. There is a steady increase in TL with increasing glass thickness at frequencies appreciably below the coincidence dip and a steady lowering of the critical frequency. The small change in sound transmission class (STC)¹⁹ values (from 30 for 3- and 4-mm glass to 32 for 6-mm glass) reflects the opposing effects of the two trends. The coincidence frequency may be calculated¹ from the expressions

$$f_c = \frac{c^2}{2\pi d} \left(\frac{12\rho(1-\sigma^2)}{E} \right)^{1/2} = \frac{c^2}{2\pi\mu} \left(\frac{12\rho^3(1-\sigma^2)}{E} \right)^{1/2}, \quad (2)$$

where c is the speed of sound, E is Young's modulus of elasticity, σ is Poisson's ratio, ρ is the density of the panel material, and d and μ are its thickness and mass/unit area. Using appropriate constants for glass, these become approximately

$$f_c \approx 12/d \approx 3.4 \times 10^4/\mu, \quad (3)$$

where d is expressed in meters and μ in kg/m^2 . The observed

coincidence frequencies in this study are in good agreement with Eq. (3).

In calculating sound transmission at frequencies appreciably below coincidence, it is common to use the "mass law" expression. Actually, numerous mass law expressions have been proposed¹⁵; that used in the present study is

$$TL = 20 \log(f\mu) - 48, \quad (4)$$

where f is the 1/3-octave band center frequency. As shown in Figs. 8 (a)–(c), this equation does not accurately predict the dependence of the TL data on frequency. The so-called "baffle effect" and "niche effect" are presumably responsible for much of this deviation from Eq. (4).

The baffle effect arises when the sound transmitting element constitutes only part of the partition separating the source and receiving rooms (the remainder of the partition being the baffle, which transmits negligible sound power). Expressions for sound transmission through a panel in a baffle have been derived by Nilsson¹² and by Sewell¹³; resulting calculated TL values are presented in Figs. 8 (a)–(c). For comparison with measured data 1/3-octave band TL values were calculated using transmission coefficients evaluated at 1/30-octave frequency intervals and weighting their contribution to each band in accordance with the response characteristic of an ANSI class III 1/3-octave filter.²⁰

Sewell's evaluation of forced sound transmission through a panel in an infinite baffle¹³ yielded a correction of the mass law that should be applicable for frequencies below $f_c/2$. As is evident from Figs. 8 (a)–(c), this correction appreciably improves the prediction relative to the mass law. It should be noted, however, that this curve represents only the contribution from forced transmission; the effect of including resonant transmission (which depends on damping and edge constraints of the panel) would be to lower the calculated TL, changing the apparent agreement with experiment.

Nilsson's treatment of the problem^{11,12} includes the contribution of resonant transmission and takes specific account of the effect of room and panel modes. The curves in Figs. 8 (a)–(c) were calculated following Eqs. (6.5) to (6.7) of Ref. 12, with $b = 3.05$ m and $c = 2.44$ m (the test opening dimensions) to allow for the effect of the deep niches on either side of the test frame in the DBR/NRC reverberation rooms. The experimentally determined loss factors were used in the calculation and edge effects were assumed to be midway between the clamped and simply supported cases. For frequencies above f_c the expression developed by Cremer²¹ (which has been validated in many studies) was substituted for that of Nilsson because it provides markedly better agreement with the experimental data. The calculated TL values do not agree perfectly with the measured ones, but do exhibit many qualitative similarities such as the local minimum in TL at 160 Hz and the general shape of the curve near f_c .

The fairly consistent discrepancy ~ 1 to 3 dB between experiment and Nilsson's expression at frequencies below f_c may be due to a "niche effect." The windows were mounted at one extreme of the 25-cm thick filler wall, with the window frame creating a deep niche on the source room side. A similar increase in TL associated with a deep niche at one

side of the specimen has been reported elsewhere.¹⁰ An appreciable niche was present for all the tests reported here; because of the low sensitivity of this effect to the depth of the niche¹⁶ it should not appreciably affect the trends observed in TL as a function of interpane spacing.

The measured sound transmission class of the single-glazed windows showed much less dependence on mass/unit area (μ) of the glass than one would expect from the $20 \log(\mu)$ dependence of the mass law expression. Similar results have been presented in previous studies.^{2,5} In part, this may be explained by the decrease in the critical frequency (f_c) with increasing μ , so that for heavier glass the coincidence dip has a greater effect within the frequency range affecting the STC or the mean sound insulation. Even at frequencies appreciably below f_c , however, the change in TL was less than 6 dB/doubling of μ . It is interesting that for small panels Nilsson's theory predicts a very similar reduced dependence of TL on μ , as is evident from the changing relation between the curves for mass law and Nilsson's expression in Figs. 8 (a)–(c).

D. Simple double glazing

The basic results of the main series of tests on simple double-glazed windows are presented in Fig. 9 in terms of the sound transmission class (STC). Here "simple double glazing" is taken to mean two parallel sheets of glass with the same mass per unit area, having no special treatment of the interpane cavity. The most obvious feature of the data in Fig. 9 is the steady increase in STC with increasing spacing, a quite consistent trend of approximately 3 dB per doubling of separation.

This obviously differs from the 6 dB per doubling of interleaf spacing predicted by London²² and widely accepted

FIG. 9. STC as a function of interpane spacing for double glazing; open and closed symbols denote data from first and third test series, respectively.

as characteristic of double-leaf partitions.²³ One feature of these approaches to calculating the TL of two-leaf partitions is their limitation to the case with acoustically absorbing material filling the interleaf cavity, so that the space may be treated as a simple stiffness element and cavity modes may be ignored. The obvious requirement for transparency of a window precludes the presence of absorptive material except around the perimeter, and most windows lack even that limited absorption treatment. Thus the available simple expressions for calculating the TL of a two-leaf wall²³ are not properly applicable to windows, and deviations from their prediction of dependence on interleaf spacing are not unduly startling. Unfortunately, more appropriate analytical treatments²⁴ have not yielded readily usable expressions for the TL.

A second obvious feature of the data in Fig. 9 is the consistent improvement in STC with thicker (or heavier) glass, and this is maintained for all the data. The consistency of these rather small differences gives reason to believe that considerable success was achieved in minimizing variations in damping, edge constraints, leakage, and other such variables. The STC does not increase so much for the heavier glass as one would expect from mass law predictions, as discussed for single glazing.

Because of the widespread use of factory-sealed double glazing with less than 20-mm airspace, sound insulation with small interpane spacing is a common concern. Some tests on double 3-mm glazing with very small interpane spacing were included to investigate the relevant systematic trends; the resulting STC data are presented in Fig. 10. For spacing of 10, 13, and 19 mm there are two STC values; in each case the higher value is from the first measurement series and the lower values from the third series. These differences are presumably associated with changes in the test environment, as discussed in the section on precision and

FIG. 10. Sound transmission class as a function of interpane spacing for double 3-mm glazing. Data from first series (O), data from third series (●).

repeatability. Despite the scatter introduced by interseries disparities, the basic trend is quite clear: the STC has a minimum for interpane separation ~ 5 mm, but is appreciably higher for much larger or smaller spacings.

The cause of this minimum in STC is readily identified from an examination of the transmission loss data, for example, the result for 6-mm interpane spacing presented in Fig. 11. The STC is limited by the sharp dip in the TL curve around 400 Hz. This is commonly called the “mass-air-mass resonance” and results from the elastic coupling provided by the entrapped gas in the cavity between the masses of the two panels of glass.²² The approximate resonant frequency f_0 may be calculated from the expression

$$f_0 = F \left(\frac{\mu_1 + \mu_2}{\mu_1 \mu_2 d} \right)^{1/2}, \quad F = \frac{1}{2\pi} (\rho c^2)^{1/2}, \quad (5)$$

where d is interpane spacing and μ_i is mass/unit area of each panel. Using the appropriate constants for air (with d expressed in m and μ_i in kg/m^2), then $F \approx 60$. For the curve shown in Fig. 11 this predicts $f_0 = 385$, in good agreement with the measured result; similar agreement was observed in other cases. For very large interpane spaces this resonance moves to frequencies below the range of interest; conversely for very small spacing the resonance should be at very high frequency.

In evaluating the effect of interpane spacing on TL it seemed desirable to establish the performance with zero spacing, as a reference case. Figure 12 presents the data for single 3-mm glazing and two layers of 3-mm glass nominally in direct contact. The change in TL is very similar to that reported elsewhere for gypsum board partitions,²³ with three obvious features: (1) the coincidence dip at 4 kHz remains clearly defined, indicating that the two layers are not acting

FIG. 11. Sound transmission loss data for 3(6)3 glazing; the dashed line is the corresponding STC contour.

FIG. 12. Sound transmission loss data from the third series for single 3-mm glass (●), double 3-mm glass with the panes touching (△), and double 3-mm glass with a very thin oil film between (○).

as a single layer of 6-mm glass; (2) for most frequencies the TL of the double layer is 5 or 6 dB higher, as one would expect because of the increased mass; (3) around 2 kHz the increase in TL is much smaller.

Two simple hypotheses may be advanced to explain the smaller increase near 2 kHz: one or more of the three windows may have sufficient contact between layers to make it act like a single layer of 6-mm glass (with $f_c \approx 2$ kHz). Alternatively, there may be a small air gap between the panes; the resonance frequency of 2 kHz would occur for an airspace ~ 0.4 mm (which could readily exist, considering the observed presence of minute glass chips). To investigate these possibilities further, an additional test was run with a very thin film of oil between the two layers of glass; the data are included in Fig. 12. The resulting TL curve matches very closely the shape of that for a single layer of 3-mm glass, but it is higher by an average of 5.4 dB (with a standard deviation of 0.9 dB). Because the oil would both reduce interpane friction and move the mass-spring-mass resonance to much higher frequencies, this test does not discriminate between the two hypotheses about the origin of the dip at 2 kHz. On the other hand, it does give a result that can reasonably be interpreted as the TL of double glazing in the limit as interpane spacing goes to zero.

Figure 13 compares this result with the TL curves for 3- and 6-mm interpane spacings. At frequencies well below the mass-air-mass resonance the change in TL with spacing is insignificant. For the two-octave range centered on the mass-air-mass resonance the TL is lower than that for zero interpane spacing. Above the resonance the TL increases steadily with increasing interpane space. For the cases shown in Fig. 13 the STC decreases with increasing spacing; this trend is reversed for large interpane spacing, with the minimum STC values occurring for the range from 6 to 13 mm. It is unfortunate that most hermetically sealed double glazing is fairly close to the worst case condition.

FIG. 13. Comparison of TL data for small interpane spacings: ○ for 3(6)3, ● for 3(3)3, and △ for 3(oil film)3 data.

Trends in the TL as a function of interpane spacing are also clearly evident in the data for individual frequency bands. For lower frequency bands the effect of the mass-air-mass resonance is clearly evident. Figure 14 presents data for the 250-Hz band; for double 3-mm glass the data exhibit a pronounced minimum apparently centered between 13 and 19 mm, in good agreement with the values predicted by Eq. (5). For much smaller spacing the TL becomes almost independent of spacing; the arrows at the left of Fig. 14 show the TL for the limiting cases with nominally touching panes (with and without an oil film).

For frequencies and spacings appreciably above the mass-air-mass resonance the TL data exhibit a steady rise

FIG. 14. TL for 250-Hz band as a function of interpane spacing for double 3-mm glazing: symbols ○, △, and ● denote data from the first, second, and third test series, respectively.

with increasing spacing, as illustrated by the 800-Hz data in Fig. 15. For frequencies near coincidence (where variations in damping and edge conditions would be expected to have their strongest effect) the scatter increases, but the data still exhibit the same trend of slightly less than 3-dB increase per doubling of the spacing. This dependence on spacing is slightly less than that exhibited by the STC, because the latter is also affected by the shifting of the mass-air-mass resonance. In neither case is there a clear indication that a limiting value is being approached at very large spacing.

E. Special double glazing

In the preceding section the effect of changing interpane spacing on the sound transmission loss of double glazing has been examined in some detail. Sometimes other constraints may limit the acceptable total thickness of the window. In such cases changing the thickness of the two panes of glass does alter the TL, as shown in Fig. 9, but simply increasing the thickness of both panes of glass is not the only (and seldom the best) way to improve the TL. This section examines the effectiveness of special window treatments, including the use of two different thicknesses of glass, nonparallel orientation of the two layers of glass, and special treatment of the interpane cavity.

Figure 16 compares the STC results for the heaviest glass tested (two layers of 6-mm glass) with the corresponding results obtained when one of the layers is 6-mm glass and the other 3-mm glass. In most cases the lighter glass gave the same STC or higher. In part, this is possible because of the small change in STC with glass thickness of typical single or double glazing, as noted in the preceding sections. The positive reason for the effectiveness of mismatched glass is illustrated by the TL curves in Fig. 17. The different mass/unit area gives different panel resonances and coincidence frequencies for the mismatched glass layers, so that the combined system exhibits much smaller deviations from a steady

FIG. 15. TL for the 800-Hz band as a function of interpane spacing: symbols $\circ$, Δ , and $\square$ denote double 3-mm, 4-mm, and 6-mm glazing, respectively. The dashed line indicates a slope of 3 dB/distance doubling.

FIG. 16. STC as a function of interpane spacing for double glazing; open and closed symbols denote data from first and second test series, respectively.

increase with increasing frequency. Because the STC (like the corresponding ISO rating, I_a) tends to be controlled mainly by dips in the TL curve, this smoothing of the curve more than offsets the effect of reducing the mass. Thus the traditional ^{1,7} recommendation for use of glass of different thicknesses is supported by these results.

Following London's theoretical analysis of sound transmission through double walls,²² many papers have postulated the presence of significant dips in TL owing to standing waves within the interpane cavity. To suppress such resonances, and for various other reasons, the use of nonparallel glass has been recommended in innumerable review and tutorial papers. The present series of measurements

FIG. 17. TL curves for 3(63)6 glazing (∇) and for 6(63)6 glazing ($\square$).

FIG. 18. (a) TL for slanted double glazing (separation d to $3d$) minus TL for parallel double glazing with separation $3d$. (b) TL for slanted double glazing (separation d to $3d$) minus TL for corresponding parallel glazing with separation $2d$. (c) TL for slanted double glazing (separation d to $3d$) minus TL for corresponding parallel glazing with separation d . Crosses indicate data for each window type (many are superimposed due to integer rounding of TL). Bars show range of one standard deviation about the mean.

included tests with each of the four glass thicknesses for three cases with interpane separation at one end of the sash three times greater than that at the other end. Interpane spacings of 6 to 19 mm, 25 to 75 mm, and 50 to 150 mm were chosen. These not only spanned the range of typical interpane separation but also permitted comparison with the corresponding TL data for parallel windows with spacing equal to the minimum, mean, or maximum spacing of the slanted windows.

Figure 18(a) shows the difference between the TL for 12 slanted windows and that obtained with parallel glazing whose interpane spacing matches the maximum spacing for the nonparallel glass. The negative values observed in almost all cases (including all the STC values) indicate the consistent superiority of parallel glass. Thus, if the thickness of a wall permits a maximum interpane spacing of, for example, 100 mm, better noise reduction can be obtained with parallel glass at 100-mm separation than with slanted glass with 100 mm as the largest separation. This agrees with the conclusion of several review papers^{1,7} based on the limited data previously available.²

The difference between TL for slanted double glazing and that for parallel windows having the same mean interpane spacing is shown in Fig. 18(b). Neither the STC nor the TL for individual 1/3-octave bands shows much evidence of appreciable change introduced by slanting the glass except possibly a slight improvement near coincidence. The form of data presentation in Fig. 18(b) tends to put undue stress on the differences between the results for parallel and nonparallel glass. A typical example of the similarity of the pairs of TL curves is presented in Fig. 19. The dips and peaks occur at the same frequencies and do not exhibit great differences in the strength of resonance. Most of the differences could reasonably be ascribed to measurement uncertainty and slight changes in damping and edge constraints.

The third case (where the parallel glass spacing equals

FIG. 19. TL curves for 4(12.5)4 glazing ($\circ$) and for 4(6 to 19)4 glazing (Δ).

FIG. 20. TL with fiberglass lining around perimeter minus TL for same glazing without absorptive material, for 100-mm interpane space. Crosses indicate data for each window type (many are superimposed due to integer rounding of TL). Bars show range of one standard deviation about the mean.

the minimum interpane spacing for nonparallel orientation) is presented in Fig. 18(c). Here the slanted glass is clearly superior, by about 3 dB on average, but this improvement is essentially what one would expect from the doubling of the mean interpane spacing. Thus nonparallel glazing does not appear to offer any significant benefits.

The effect of special treatment of the interpane cavity was examined only briefly in this study as it has already been fully examined.^{1,23} Figure 20 illustrates the effect of adding a 25-mm layer of glass fiber around the perimeter of the window openings. Clearly, the glass fiber substantially increased TL at the high frequencies, but had little effect at lower frequencies, as one might expect from the absorption coefficient of the material used. By using a thicker layer of absorptive material with suitable surface treatment it should be possible to tailor this effect to offset dips in TL over most of the frequency range.

III. SUMMARY

Experimental sound transmission loss (TL) data for single-glazed windows have been compared with theoretical predictions. Changes in the STC with increasing glass thickness are smaller than predicted by "mass-law."

A systematic study of the TL of double-glazed windows has shown clear trends as a function of glass thickness, interpane spacing, and cavity treatment. Changes in STC of double glazing with glass thickness are ~6 dB/doubling of thickness. For typical spacing of the two panes the STC of double-glazed windows increases at 3 dB/doubling of the separation. The data do not indicate any significant improvement in TL for nonparallel glass relative to that for parallel glass of the same mean spacing. Absorptive treat-

ment of the cavity perimeter and use of different thicknesses of glass in the two layers give noticeable improvements.

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