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**SOUND TRANSMISSION THROUGH WINDOWS II.
DOUBLE AND TRIPLE GLAZING**

by J.D. Quirt

ANALYZED

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RÉSUMÉ

Des données expérimentales concernant l'atténuation des sons par les fenêtres à double vitrage ont été comparées aux prédictions de plusieurs modèles théoriques. On a trouvé des équations simples qui permettent un ajustage empirique satisfaisant aux données. L'atténuation des sons par un vitrage double a été comparée à l'atténuation correspondante pour un vitrage triple; les résultats sont semblables lorsque le total des espaces entre les panneaux d'une fenêtre triple est égal à l'espace entre les panneaux d'une fenêtre double. Cependant, l'atténuation réalisée par un vitrage triple est toujours supérieure aux fréquences en deçà de la résonance masse-air-masse et au voisinage de la dépression de la fréquence de coïncidence.

Sound transmission through windows II. Double and triple glazing

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Experimental sound transmission loss data for double-glazed windows have been compared with the predictions of several theoretical models. Simple equations that provide a satisfactory empirical fit to the data were found. The transmission loss of double glazing was compared with that of triple glazing; the results are very similar when the combined interpane spacings of the triple window match the spacing of the double glazing. The triple glazing did, however, exhibit consistently higher transmission loss both at frequencies below the mass-air-mass resonance and in the vicinity of the coincidence dip.

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INTRODUCTION

A series of measurements of the sound transmission loss (TL) of single-, double-, and triple-glazed windows has been performed to examine the dependence of TL on glass thickness and interpane spacing. General features of the measurements and data were presented in a previous paper,¹ which concentrated primarily on trends in the data for single- and double-glazed windows. The present paper discusses the performance of double glazing more extensively, in the light of recent theoretical treatments, and compares the TL of double- and triple-glazed windows.

As noted previously,¹ the results of different studies of sound transmission through windows are not in close agreement. The discrepancies among the results are apparently due to the properties of both the samples themselves and the laboratories in which they were tested. Rather than dwell on these sources of systematic error (many of which were discussed in Ref. 1) or try to account for differences between the data from the present study and those published previously,² this paper concentrates on trends within the present data set. As many variables as possible (such as window dimensions, glass mounting, and laboratory-related details) were held as constant as was practicable. This permitted considerable confidence in comparisons of TL data for the windows tested. Although the specific characteristics of the testing laboratory and the specimens undoubtedly influenced some details of the TL data, the trends exhibited by the data are believed to be of a general nature.

This paper presents the results for double- and triple-glazed windows using data selected to illustrate trends in the sound transmission performance.

I. EXPERIMENTAL DETAILS

All the sound transmission measurements were made in accordance with ASTM standard E90-75, "Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions."³ Measurements were made for the standard 1/3-octave bands from 80 to 5000 Hz; however, 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.

Detailed features of the reverberant test chambers, the equipment used and the test frame in which the specimens were mounted are given in Ref. 1.

The test specimen consisted of three nominally identical windows mounted in wooden sashes. The exposed glass area of each was 560×1680 mm and the sash dimensions were $620 \times 1750 \times 41$ mm. The data reported here are for double and triple glazing mounted in single or double sashes, with nominal glass thicknesses of 3, 4, and 6 mm; the actual masses per unit area were 8.1 kg/m^2 (26 oz/ft^2), 10.4 kg/m^2 (34 oz/ft^2) and 14.4 kg/m^2 (47 oz/ft^2), respectively.

The window construction details are presented schematically in Fig. 1. 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). Triple glazing was tested with three panes mounted in a single sash (for combined spacings up to 19 mm) or with two panes (at 6-mm separation) mounted in one sash and the third pane in a separate sash. The sashes fitted snugly into the frame openings and were held

FIG. 1. Schematic representation of window mounting details. Caulked seals are indicated by circles and taped seals by arrows.

firmly in position by wooden strips fastened to the frame. All cracks around the perimeter were sealed using an adhesive tape (which for narrow cracks provides a seal essentially equivalent to caulking). The glass was held firmly in place by wooden strips nailed to the sash. A thin bead of caulking sealant ensured a good acoustical seal between the wood and the glass. After application of the caulking, the wood strip was pressed firmly into place and nailed so that the thickness of the resilient layer was ~ 1 mm or less.

Practical window designs usually have edge constraints somewhere between the extremes of simply supported and rigidly clamped edges,⁴ and the damping provided by edge losses tends to be substantially greater than that characteristic of the glass itself. As reported in Ref. 1, the measured damping was near the middle of the range reported in the literature^{4,5}; it is hoped that because the sealant layer was rather thin it provided little damping, so that changes associated with hardening of the sealant over the extended time period of the tests would be minimal. This study should therefore provide a reasonable estimate of the performance of "typical" windows. Of greater importance, however, was the suitability of this mounting technique for examining the dependence of TL on interpane spacing since rather similar edge constraints can be obtained reliably for a wide range of spacings. This mounting technique can, however, permit flanking transmission through the sash and the frame, as discussed later.

The data were obtained in three series of measurements with intervals of approximately 1 year between each. Although details of glass mounting and measurement procedures were consistent within each series, some modifications were made in the laboratory between series. The tests conformed in all cases to the ASTM E90-75 standard, but the modifications apparently introduced small systematic changes in the sound transmission results. Reproducibility within a series and systematic differences between the series are discussed in Ref. 1. Wherever possible, detailed comparisons of TL results to assess trends associated with variables such as glass thickness or interpane spacing are restricted to comparisons within a series. Cases where data from two or more test series are combined are specifically identified.

For ease of presentation the window glazings are identified by a simple descriptive code based on nominal glass thickness and interpane spacing, in mm. A single layer of 3-mm glass would be 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.

II. SOUND TRANSMISSION THROUGH DOUBLE GLAZING

A. General features of the data

The dependence of sound transmission through double glazing on glass thickness and on the characteristics of the interpane cavity was examined in detail in Ref. 1. The general trends are illustrated by the data in Fig. 2 showing the Sound Transmission Class (STC)⁶ as a function of interpane spacing for 3- and 6-mm glass.

The most obvious feature of the data is the steady in-

FIG. 2. Sound transmission class as a function of interpane spacing for double glazing. Open symbols denote data from the first series. Data from the second and third series are indicated by closed symbols for spacings greater than or less than 50 mm, respectively.

crease in STC with increasing spacing for separations greater than ~ 10 mm. This trend of approximately 3 dB per doubling of separation was observed for all glass thicknesses. For smaller separations this trend breaks down because of resonant coupling of the two glass layers by the stiffness of the air in the interpane cavity (commonly called the mass-air-mass resonance).¹ For the data in Fig. 2, this resonance strongly influence the STC for spacings less than ~ 20 mm.

Another clear trend in the data is the increase in TL with increasing glass thickness (or mass/unit area), which was maintained for all the data. The consistency of these rather small differences suggests that considerable success was achieved in minimizing variations in damping, edge constraints, leakage, and other such variables which have obscured the trends in previous studies. The increase with panel mass is appreciably less than one would expect from mass law predictions, but is consistent with the rather small dependence on panel mass for the sound transmission of single glazing obtained in these measurements¹ and elsewhere.^{2,7}

A full tabulation of the data is available as a separate report.⁸

B. Comparison with predictions

Numerous procedures have been proposed for calculating sound transmission loss through a double-leaf partition, but simple expressions have been derived for only certain limited cases. Some prediction models⁹⁻¹¹ assume the inter-leaf cavity to be filled with acoustically absorbing material so that the space may be treated as a simple stiffness element and cavity modes may be ignored. These models predict a

6 dB increase in TL per doubling of the interleaf spacing—a result significantly different from that exhibited by the data in the present study. This difference, which is not surprising since the interpane cavities of the windows in this study were not filled with absorptive material, indicates that the effects of cavity modes cannot reasonably be ignored.

At the other extreme is the approach of Price and Crocker¹² based on statistical energy analysis (SEA) which assumes the presence of cavity modes as a basic starting point. The fact that their model predicts no dependence on interpane spacing (in obvious disagreement with a large body of experimental data) has been ascribed by other authors¹³ to Price and Crocker's neglecting to take into account the non-resonant coupling due to stiffness of the air in the cavity.

If the cavity is not filled with absorptive material, the sound transmission appears to depend not only on interpane spacing but also on the width (w) and height (h) of the cavity relative to the wavelength.^{9,10,13} To assess the trends, it is convenient to consider separately the frequency ranges above and below the "cutoff frequency" ($f_1 = c/2d$) for which the interpane spacing (d) is one-half wavelength.

1. Above the cutoff frequency

For frequencies above $f_1 = c/2d$, standing wave patterns are possible in all three dimensions and the cavity may be considered as a reverberant space, although the sound field will obviously not approximate random incidence very well at the low-frequency end of the range. As noted in a recent paper by Brekke,¹³ in this case the transmission loss for the two-leaf partition should approach

$$TL = TL_1 + TL_2 + 10 \log (A/S), \quad (1)$$

where TL_i is the transmission loss for leaf i , A is the equivalent absorption in the cavity, and S is the area of the partition. Brekke assumes that the partition surfaces do not contribute to cavity absorption, so

$$A = \alpha d (2h + 2w), \quad (2)$$

where α is the random incidence absorption coefficient for the perimeter surfaces and d is the interpane separation. Since $S = hw$, this can be rewritten as

$$TL = TL_1 + TL_2 + 10 \log \alpha + 10 \log d + 10 \log [(h + w)/hw] + 3 \text{ dB}. \quad (3)$$

The predicted dependence on d corresponds to the 3 dB per doubling of interpane spacing observed in the present study. Figure 3(a) illustrates the agreement between this prediction and the measured TL for a 6(150)6 window. The single layer TL and the absorption coefficient α required for the calculation are also presented in Fig. 3(a) and (b), respectively. These values of α were measured in the National Research Council of Canada reverberation room for an unfinished plywood specimen (lying on the floor) and should provide a reasonable approximation for the absorption coefficient where the cavity perimeter is unfinished wood. The agreement between the measured and calculated TL values in Fig. 3(a) is quite good except below 1.6 kHz (where data are apparently affected by flanking as discussed in Sec. III).

FIG. 3. (a) Transmission loss of windows: —○— experimental data for 6(150)6, --- predicted as discussed in text, —□— data for single layer 6-mm glass. (b) Measured absorption coefficient (α) for 19-mm unfinished plywood resting on floor of reverberation room.

Similarly good agreement with Eq. (3) was observed for other values of d .

It is interesting to note that the data reported by London¹¹ appear to illustrate a dependence on cavity perimeter absorption similar to that in Eqs. (1) to (3). In that case, the two panels were attached to the concrete test walls of adjacent test chambers, but the space between the chambers around the perimeter of the specimen was left open. For interleaf spacing d smaller than the chamber separation, the observed results agree well with the predictions of Eq. (3) using $\alpha = 1$ as the absorption coefficient for the open perimeter "surface." For d much larger than the 3-in. chamber separation, London's data show very little dependence on d . This is consistent with Eq. (1) if one assumes that the additional concrete surfaces exposed when d is appreciably greater than the chamber separation do not add appreciably to the cavity absorption.

The data obtained by Sharp^{9,10} (some of which are plotted in Figs. 4 and 5) also show quite good agreement with Eq. (3) for frequencies above f_1 . The data in Figs. 4 and 5 are for three different cavity treatments of a double-panel partition of 6.4- and 3.2-mm hardboard with interpanel separation $d = 160$ mm. The dashed curve in Fig. 4 showing the prediction of Eq. (3) with $\alpha = 1$ agrees well with the experimental data for the test in which 50 mm of absorptive material was added to the perimeter surface. The data for a cavity with no

FIG. 4. Transmission loss for a double hardboard wall as discussed in text: —□— data from Ref. 9 with 50-mm glass fiber at perimeter, —○— data from Ref. 9 with no cavity treatment, — calculated with $\alpha = 1$, - - - calculated with α from Fig. 3(b) using Eq. (5).

absorptive treatment agrees rather well with the dotted curve calculated using the absorption coefficients given in Fig. 3(b). Both curves in Fig. 4 were calculated using the measured TL values for the 3.2- and 6.4-mm hardboard layers given in Ref. 9.

Considering the roughness of the estimates used for absorption coefficients and the questionable assumption of random incidence TL for the individual panels, the agree-

FIG. 5. Transmission loss for a double hardboard wall: —○— data from Ref. 9 with no cavity treatment, —□— data from Ref. 9 with 0.61×0.61 m lattice, - - - calculated with α from Fig. 3(b), — calculated with same α and $h = w = 0.61$ m using Eq. (5).

ment of Eq. (3) with the data in Figs. 3(a) and 4 seems surprisingly good.

2. Below the cutoff frequency

For frequencies below $f_1 = c/2d$, the sound field in the cavity is commonly treated theoretically as a two-dimensional standing wave system¹³; the analogy between this cavity and a reverberant room cannot be justified. Although the energy flow concepts embodied in Eq. (1) seem reasonable even for frequencies below f_1 , the radiation efficiency for energy transfer from panel vibrations to the cavity sound field is not obvious, and some allowance for the effects of air stiffness is clearly needed. Unfortunately, none of the readily tested theoretical models appear to provide an adequate treatment of all the relevant mechanisms.

Some of the basic features can be illustrated by reference to Sharp's data presented in Fig. 5. The lower set of data and calculated curves in Fig. 5 are the same as those in Fig. 4 for the cavity with no absorptive treatment. The upper curves are for the case where the 2.7×4.2 m interpanel space was partitioned into smaller cavities with a 610×610 mm wooden "lattice." This increased the TL considerably except for the band (315 Hz) where the lattice dimension of 610 mm corresponds to a half-wavelength ($\lambda/2$); lesser resonances are also evident at multiples of 315 Hz. Sharp's interpretation of this result⁹ is that the increase in TL is solely due to eliminating many lateral cavity modes; however, as shown by the upper calculated curve in Fig. 5, a rather similar increase in the TL is predicted by Eq. (3) as a result of increasing the surface area of the cavity perimeter (and hence the absorption). Presumably some combination of modal changes and cavity absorption should be considered in a thorough theoretical analysis. Unfortunately Sharp tested this effect for only one interpanel separation ($d = 160$ mm) and hence provided no information about the dependence of TL on d either with or without the lattice. The data in the present study are also for rather small lateral cavity dimensions, and should therefore resemble Sharp's results with the lattice, which were intermediate between the result with an absorption-filled cavity and that for a cavity with low perimeter absorption and high modal density (large lateral dimensions).

For frequencies below f_1 , Brekke attempted to deal with the shortcomings of previous SEA analyses by adding an empirical term $20 \log(d/d_0)$ to the SEA expressions to allow for the effect of air stiffness.¹³ Because his equations for this case include many factors such as radiation efficiencies whose values are not obvious (but are presumably discussed in his more detailed report),¹⁴ they are not reproduced here. It is worth noting, however, that his data for $f \ll f_1$ (with absorptive treatment of the cavity perimeter) show substantially less dependence on interpanel separation than is predicted by the $20 \log d$ term. Although data for the case without edge absorbers are not presented, Brekke's comments indicate that agreement with his prediction was obtained by assuming that the absorption coefficient varied from ~ 0.1 for $d \geq 0.1$ m to ~ 0.5 at $d = 0.02$ m. The net effect of this variable absorption coefficient and the $20 \log d$ term in this equation is an overall dependence on spacing of approximately $10 \log d$.

Given that two energy transmission mechanisms appear to be operating in parallel here, it would seem more reasonable to assume that the dependence of TL on d would lie somewhere between the 0 dB/doubling and 6 dB/doubling characteristic of the SEA and air stiffness approaches, respectively. A fully satisfactory treatment must allow for air stiffness, and might require specific consideration of individual cavity modes (including damping) when the lateral dimensions of the cavity are not much greater than the wavelength; this would obviously require lengthy calculations.

3. Empirical prediction

If a simple empirical expression is desired, Eq. (3) appears to fit experimental data from both this study and several previous studies.^{10,11,13} Even for frequencies far below the cutoff frequency f_1 , this equation provides a good prediction of experimental results. Another example of this is presented in Fig. 6 for two cases where the entire frequency range is below f_1 . The data are for double glazing in a single sash with an unfinished wood surface at the cavity perimeter. The absorption coefficients for unfinished wood [from Fig. 3(b)], and the measured TL data for a single layer of glass were used in Eq. (3) to calculate the corresponding predicted values. The agreement is quite good for frequencies appreciably above the mass-air-mass resonance f_0 which may be calculated from the expression

$$f_0 = F[(\mu_1 + \mu_2)/\mu_1 \mu_2 d]^{1/2}, \quad F = (1/2\pi)(\rho c^2)^{1/2}, \quad (4)$$

where d is the interpane spacing and μ_i the mass per unit area of panel i . Using appropriate constants for the density ρ and speed of sound c of air and expressing d in m and μ_i in kg/m², then $F = 60$.

This empirical use of Eq. (3) appears to have a low-

frequency limit, which may be determined by either of two conditions.

(1) In the frequency range below $\sim 2f_0$, air stiffness controls sound transmission through the cavity, resulting in a sharp dip in TL centered at f_0 . At frequencies below $\sim f_0/2$, experimental data agree with the predicted TL for a single panel with mass equal to the combined mass of the two panels, which for $TL \geq 10$ dB may be expressed as

$$TL = 20 \log[(\mu_1 + \mu_2)f] - 48 \text{ dB}. \quad (5)$$

(2) If cavity absorption is very small, then the TL predicted by Eq. (3) may fall below the value predicted by Eq. (5) even at frequencies appreciably above f_0 . In this case experimental data⁹ agree with the larger of the TL values predicted by Eqs. (3) and (5), as shown in Figs. 4 and 5.

The use of Eqs. (3) and (5) as detailed above provides a satisfactory representation of the experimental results, except in the immediate vicinity of the mass-air-mass resonance and at the coincidence dip. At the mass-air-mass resonance the TL is up to ~ 10 dB below the TL predicted by Eq. (5); the depth and sharpness of this resonance are apparently reduced by absorptive treatment of the cavity perimeter. Near the coincidence frequency (f_c) the dip in the TL shows much less dependence on interpane spacing and is substantially less pronounced than that predicted by Eq. (3). This trend is illustrated by the data in Fig. 7 for double 3-mm glazing with interpane spacings up to 19 mm; near f_c the TL is essentially independent of d . For appreciably larger spacings the TL near coincidence depends more strongly on interpane spacing as shown in Fig. 8. Because the TL near coincidence is especially sensitive to damping (and hence to mounting conditions), the trends in Fig. 8 are partially obscured by the scatter in the data. However, it appears that the TL has little dependence on spacing for $d < 20$ mm, but

FIG. 6. Transmission loss for double windows: $\square$ —data for 3(3)3 windows, --- calculated for 3(3)3 window with α from Fig. 3(b), $\circ$ —data for 3(19)3 window, — calculated for 3(19)3 window with α from Fig. 3(b).

FIG. 7. Transmission loss of double 3-mm glazing with small interpane spacing: $\triangle$ —data for 3(13)3, $\circ$ —data for 3(6)3, $\square$ —data for 3(3)3.

FIG. 8. Transmission loss in the 4-kHz third-octave band for double 3-mm glazing, as a function of interpane spacing. Data from the first and third series are denoted by open and solid circles, respectively.

increases with increasing d above this range. A similarly reduced dependence on interpane spacing is evident in Brekke's data around the coincidence dip. The apparent failure of Eq. (3) in this frequency range is not surprising, given the well-known dependence of the coincidence effect on the angle of incidence and the obvious deviation from random incidence of the sound field in the interpane cavity, especially for very small interpane spacings.

III. COMPARISON OF DOUBLE AND TRIPLE GLAZING

Because of increasing concern about thermal insulation of buildings, the use of triple glazing is becoming increasingly common. A number of measurements were included in these tests to permit a systematic assessment of how the addition of a third pane changes the TL.

A. Results for small interpane spacing

The third series of window measurements was specifically designed to provide a comparison between double and triple glazing with the panes mounted in a single sash. The depth of the wooden sashes limited the combined glass thicknesses and interpane spacings to a total of 30 mm. To maximize the range of interpane spacings, 3-mm glass was used for all tests in this series.

Very strong similarity was observed between each set of TL data for triple glazing and the corresponding data for double glazing in which the interpane spacing equalled the total of the two spaces in the triple window. A typical example is presented in Fig. 9. Three basic features of the data should be noted.

(1) Both double and triple glazing have a pronounced dip at the frequency f_0 where the mass-air-mass resonance is predicted for the double glazing (400 Hz in Fig. 9).

FIG. 9. Comparison of TL data for double- and triple-glazed windows: $\circ$ - $\circ$ data for 3(6)3, $\square$ - $\square$ data for 3(3)3(3)3.

(2) Above this resonance the TL of the double and triple glazing are virtually identical.

(3) Below this resonance the triple glazing provides slightly larger sound transmission loss.

These features are consistent with the differences between double and triple partitions predicted by Brekke¹³ for frequencies below the cutoff frequency f_1 for the cavities of the triple partition. Brekke notes that for a symmetrical mass-spring-mass-spring-mass system there are two fundamental resonances; the higher frequency is normally well

FIG. 10. Comparison of TL data for double- and triple-glazed windows: $\circ$ - $\circ$ data for 3(13)3, $\square$ - $\square$ data for 3(3)3(10)3, $\triangle$ - $\triangle$ data for 3(6)3(6)3.

FIG. 11. TL for triple 3-mm glazing minus TL for double 3-mm glazing whose interpane separation $\approx$ the combined separations of the triple glazing. The glass is mounted in single sashes (Fig. 1) and total separations range from 6 to 20 mm. Crosses and circles indicate differences in TL for specific pairs of windows in frequency bands above and below f_0 , respectively. Many symbols are superimposed due to integer rounding of TL. The bars show a range of one-standard deviation about the mean.

above the range of interest,¹⁴ and the lower resonance frequency corresponds to that predicted by Eq. (4) with d replaced by the sum of the two panel separations. This prediction is supported by the data from this study, as illustrated in Fig. 9.

Brekke also states that this expression for f_0 provides a good estimate for the lowest resonance frequency even for unsymmetrical partitions.¹³ A test of this is shown in Fig. 10. The window with identical interpane spaces has a slightly lower TL over most of the frequency range but the differences do not exceed the nominal measurement reproducibility, except in the immediate vicinity of f_0 where the minimum appears to be at a slightly higher frequency for the symmetrical window. The TL differences between the symmetric and asymmetric cases are very small, however, and comparison with the data for the corresponding double-glazed window emphasizes the similarity of its TL to that for each triple-glazed window.

A summary of the differences between the results for the four pairs of double- and triple-glazed windows in this series is presented in Fig. 11. The individual circles and crosses show the difference in TL for specific pairs of windows at frequencies below and above f_0 , respectively. The bars indicate the range of one-standard deviation about the mean. At frequencies below f_0 , the triple glazing exhibits a quite consistent small increase in TL relative to the double glazing, but there are no significant differences above 500 Hz.

B. Results for large interpane spacing

The data for larger interpane spacings are for asymmetric spacing of the three layers of the triple glazing. As shown in Fig. 1, the windows consisted of a double-glazed unit [3(6)3] in one sash and an additional pane in a separate sash with interpane spacings for the second cavity ranging from

FIG. 12. TL for triple 3(6)3(a)3 glazing minus TL for double 3(b)3 glazing where the interpane spacing $b \approx a + 6$ mm. Glass is mounted in double sashes as shown in Fig. 1. Symbols are used as in Fig. 11 with the addition that Δ is used to denote the differences for a specific pair of windows for frequency bands above the cutoff frequency f_1 for the larger interpane spacing of the triple glazing.

19 to 100 mm. This configuration was chosen because of its potential application for windows in residential buildings, for which the use of hermetically sealed double glazing (with interpane spacings < 15 mm) is common. The addition of a third pane in a separate sash is particularly attractive for retrofitting existing windows to improve noise reduction, but might also be considered in new construction to achieve both good thermal performance and noise reduction using available components.

Although the asymmetric configurations tested are of considerable practical interest, the difference in interpane spacing complicates comparison with the simple expressions proposed by Brekke.¹³ He predicts a substantial increase in TL due to the addition of a third pane for frequencies above the cutoff frequency (f_1) of both interpane spaces and presents data to support this feature of his model. This cannot be tested with data from the present study, because f_1 for the smaller interpane cavity of these windows is above the frequency range studied.

The differences between the TL results for six pairs of double- and triple-glazed windows with 3-mm glass and the same total interpane spacing are shown in Fig. 12. As in Fig. 11, the individual circles and crosses show the differences in TL below and above f_0 , respectively, and the bars indicate the range of one-standard deviation about the mean. As noted above, the larger interpane spacing for the windows ranged from 19 to 100 mm; data for frequency bands above the cutoff frequency f_1 for this cavity are indicated in Fig. 12 by triangles. There is no obvious dependence of the increase in TL on whether or not the larger cavity is above cutoff. There is, however, a very obvious increase in TL due to the

FIG. 13. TL for triple 3(6)3(a)6 glazing minus TL for double 3(b)6 glazing where the interpane spacing $b \approx a + 6$ mm. Glass is mounted in double sashes as shown in Fig. 1. Symbols are used as in Fig. 12.

addition of the third pane in the immediate vicinity of the coincidence dip at $f_c \sim 4$ kHz.

Comparable data with mismatched glass are presented in Fig. 13. Here triple glazing consisting of a 3(6)3 double-glazed unit together with a pane of 6-mm glass is compared with double 3(b)6 windows whose spacing b approximately equals the combined interpane spacing of the triple glazing. At frequencies below 1.6 kHz the differences resemble those in Fig. 12, but the improvement in TL at the higher frequen-

FIG. 14. Comparison of TL data for double- and triple-glazed windows mounted in double sashes: □—□ data for 3(35)6, ○—○ data for 3(6)3(25)6.

cies is less pronounced and spread over a broader frequency range. Since the coincidence dip for these windows is similarly broader and less pronounced (because of the combination of 3- and 6-mm glass), this suggests that the observed difference between the TL of double and triple glazing above ~ 1 kHz is associated with the coincidence effect.

Although there do appear to be some consistent changes in sound transmission loss introduced by the addition of a third pane, plots like Figs. 12 and 13 tend to overemphasize the dissimilarities. It should be stressed that for the cases studied here the TL data for double- and triple-glazed windows were very similar, as illustrated by the curves presented in Fig. 14, which exhibit differences similar to the mean result for their group given in Fig. 13.

IV. ASSESSMENT OF FLANKING

Although it is not believed that the data in this study were severely affected by flanking transmission, there are some indications that flanking may have reduced the TL in some cases.

Tests were made with heavy blocking panels inserted in the window openings to obtain an estimate of sound transmission through the filler wall in which the window frame was mounted. The resulting TL values (normalized to the window area) were sufficiently greater than any of the corresponding window TL data to permit the conclusion that flanking through the wall could not affect the results by more than 1 dB (and would be even less if the "blocked" windows transmitted a significant fraction of the sound power in this flanking test).

Subsequent considerations suggest that the absence of flanking transmission was not clearly established. For the test of flanking the blocking of the window openings consisted of a window with 6-mm glass at one extreme of the frame, and a multilayer blocking panel (~ 30 kg/m²) at the other extreme with glass fiber batts filling the intervening 150 mm cavity. Removing the blocking panels for actual window tests exposed a substantial part of the window frame. Recent tests of possible flanking through the specimen test frame at this laboratory¹⁵ and similar full-scale¹⁶ and model-scale¹⁷ tests elsewhere suggest that such an exposed surface may introduce significant flanking.

Although this possibility was overlooked at the time of the window TL measurements, the data obtained do provide some information on the flanking limit. The increase in TL due to covering the surface of the cavity perimeter with glass fiber (presented in Fig. 20 of Ref. 1) exceeds 3 dB for frequencies above 2 kHz, indicating that airborne transmission through the cavity is the dominant mechanism. The smaller improvements observed below 2 kHz were presumably due to both increased flanking transmission and the lower absorption coefficient of the glass fiber at lower frequencies. The strong dependence on interpane spacing of the 1/3-oct TL data for bands below 800 Hz suggest that the low-frequency data were not strongly affected. It appears, however, that the midfrequency (800 Hz to 2 kHz) TL data were affected by flanking. This is suggested both by the diminished dependence of the 1/3-oct TL data on interpane spacing

(especially for $d \geq 50$ mm) and by the frequency dependence of the TL data for individual windows. For large interpane spacings, the latter approach the 6 dB per frequency-doubling characteristic of flanking transmission in the 800 Hz to 2 kHz range.

Taking these apparent flanking effects into account reinforces confidence in the conclusion drawn about the general agreement of the data with the predictions of Eq. (3). Further, it should be noted that although these effects complicate comparison with theories that ignore flanking, they do not invalidate using these data to predict the performance of typical windows in buildings, because comparable flanking effects are probable in most cases.

V. SUMMARY

Experimental sound transmission loss data for double-glazed windows have been compared with the predictions of several theoretical models. Simple equations that provide a satisfactory empirical fit to the data were found. The transmission loss of double glazing was compared with that of triple glazing; the results are very similar when the combined interpane spacings of the triple window match the spacing of the double glazing. The triple glazing did, however, exhibit consistently higher transmission loss both at frequencies below the mass-air-mass resonance and in the vicinity of the coincidence dip.

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