9 SOUND TRANSMISSION LOSS

9.1 TRANSMISSION LOSS

Sound Transmission Between Reverberant Spaces

The transmission of sound from one space to another through a partition is a subject of some complexity. In the simplest case, there are two rooms separated by a common wall having area S_w, as in Fig. 9.1. If we have a diffuse sound field in the source room that produces a sound pressure p_s and a corresponding intensity

$$I_s = \frac{p_s^2}{4\,\rho_0\,c_0} \tag{9.1}$$

which is incident on the transmitting surface, a fraction τ of the incident power is transmitted into the receiving room through the wall

$$W_r = I_s\,S_w\,\tau = \frac{p_s^2\,S_w\,\tau}{4\,\rho_0\,c_0} \tag{9.2}$$

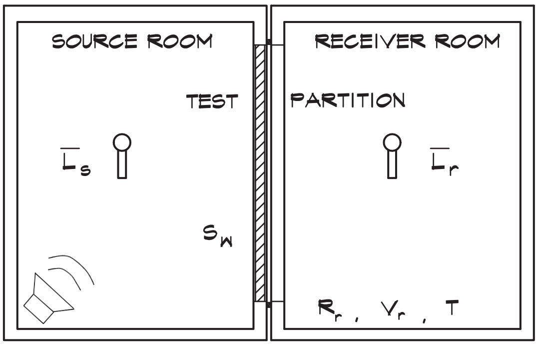
where it generates a sound pressure level. If the receiving room is highly reverberant, the sound field there also will be dominated by the diffuse field component. We use Eq. 8.83 for the reverberant-field contribution to the energy and obtain the mean square pressure in the receiving room

$$\frac{p_r^2}{\rho_0\,c_0} = \frac{p_s^2\,S_w\,\tau}{R_r\,\rho_0\,c_0} \tag{9.3}$$

We can express this as a level by taking 10 log of each side and using the definition of the *transmission loss*

$$\Delta L_{TL} = -10\ \log\ \tau \tag{9.4}$$

FIGURE 9.1 Laboratory Measurements of the Transmission Loss



we obtain the equation for the transmission of sound between two reverberant spaces

$$\overline{L}_r = \overline{L}_s - \Delta L_{TL} + 10 \log \left(\frac{S_w}{R_r} \right) \tag{9.5}$$

where $\overline{L}_r$ = spatial average sound pressure level in the receiver room (dB)
$\overline{L}_s$ = spatial average sound pressure level in the source room (dB)
ΔL_{TL} = reverberant field transmission loss (dB)
S_w = area of the transmitting surface (m^2 or ft^2)
R_r = room constant in the receiving room (m^2 or ft^2 sabins)

Measurement of the Transmission Loss

Under laboratory conditions, both the source and receiving rooms are highly reverberant and the transmission loss of the common partition is given by

$$\Delta L_{TL} = \overline{L}_s - \overline{L}_r + 10 \log S_w - 10 \log R_r \tag{9.6}$$

where the bars over the source and receiver room levels indicate a spatial average in the reverberant-field portion of the rooms. Formal procedures have been established for laboratory (ASTM E90 and ISO 140/III) and field (ASTM E336 and ISO 140/IV) measurements of the transmission loss of partitions, which establish the partition size, the minimum room volume, the method of determining of the room constant, and the appropriate measurement techniques. Loudspeakers are used to generate a sound field in the source room and are positioned in the corners of the room far enough from the transmitting partition that a diffuse field is produced. Sound levels are measured at least a distance $r \geq 0.63 \sqrt{R}$ from the source and 1 m (3 ft) from large reflecting surfaces.

Two methods are used for the determination of the room constant. The reverberation time method measures the value of R_r using the Sabine equation (Eq. 8.72). A second method, called the source substitution method, uses a calibrated noise source having a known sound power level to determine R_r by means of Eq. 8.83. The standard source is usually an unhoused centrifugal fan, which produces a relatively flat noise spectrum.

Transmission loss measurements are done in third-octave bands over a standard range of frequencies, from 125 Hz to 4000 Hz. Below 125 Hz, the size of the test room necessary to achieve the diffuse-field condition becomes large and many labs do not meet this requirement. Data are sometimes taken below the 125 Hz third-octave band for research or other specialized purposes. When measured low-frequency data are unavailable, they can be calculated based on theoretical models. When the room size does not meet the minimum volume requirements for a diffuse field, the noise reduction is used instead of the transmission loss in standard tests and a notation to that effect is included in the test report.

Sound Transmission Class (STC)

Although transmission loss data in third-octave or full-octave bands are used for the calculation of sound transmission between adjacent spaces, it is convenient to have a single-number rating system to characterize the properties of a construction element. The *Sound Transmission Class* is such a system and is calculated in accordance with ASTM E413 and ISO/R 717. It begins with a plot of the third-octave transmission loss data versus frequency. The three-segment STC curve, shown in Fig. 9.2, is compared to the measured data by sliding it vertically until certain criteria are met: 1) no single transmission loss may fall below the curve by more than 8 dB and 2) the sum of all deficiencies (the difference between the curve value and the transmission loss falling below it) may not exceed 32 dB. When the curve is positioned at its highest point consistent with these criteria, as in Fig. 9.3, the STC rating is the transmission loss value at the point where the curve crosses the 500 Hz frequency line. The shape of the STC curve is based on a speech spectrum on the source-room side so this rating system is most useful for evaluating the audibility of conversations, television, and radio receivers. It is less accurate for low-frequency sounds such as music or industrial noise, where energy in the bass frequencies may predominate.

FIGURE 9.2 Reference Contour for Calculating Sound Transmission Class and Other Ratings

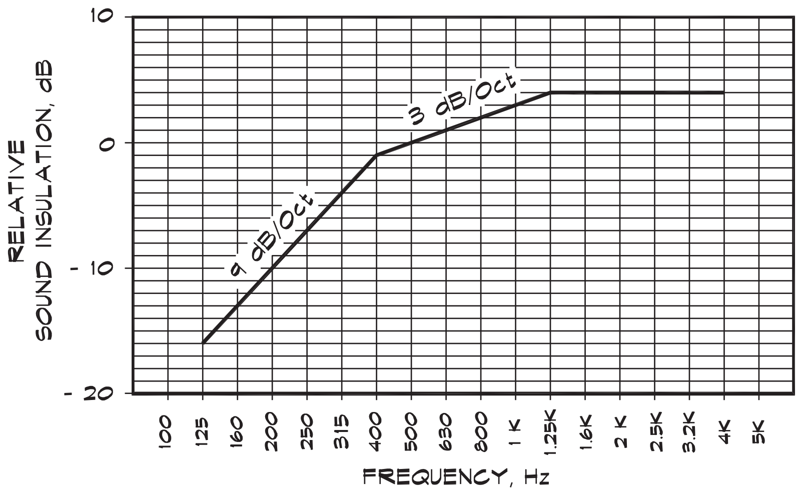
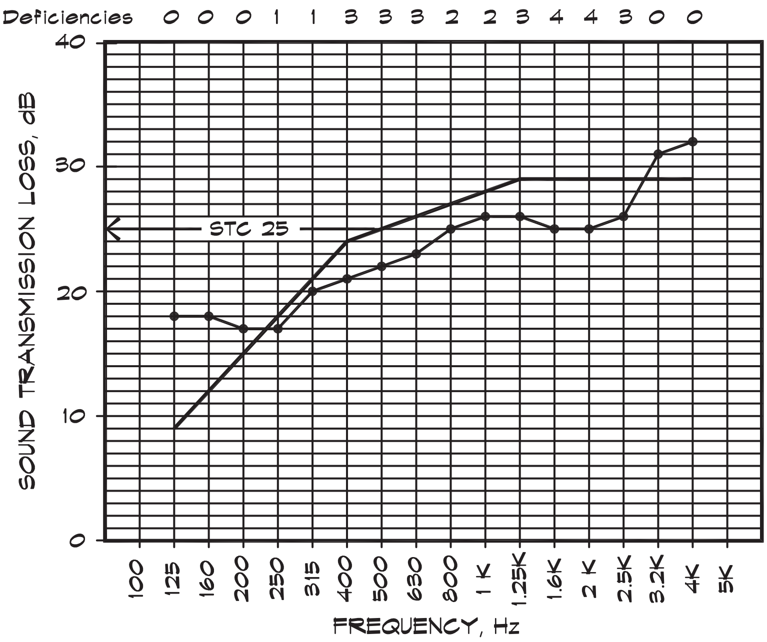


FIGURE 9.3 Example of the Reference Contour Fitted to Transmission Loss Data (STC 25)



Field Sound Transmission Class (FSTC)

Field measurements of the STC can be made in existing buildings and are designated FSTC. Care must be exercised to minimize flanking, where sound is transmitted by paths other than directly through the test partition. The FSTC rating is about five points lower than the STC rating for a given partition, due to flanking and direct-field contributions. It applies only to the partition on which it is measured, but it can serve as an example of the rating of other partitions in a group of similarly constructed structures. It is not generally applicable to a construction type as a laboratory test would be. In building codes, if a given STC rating is required, an FSTC test that is five points lower is sufficient to demonstrate compliance.

Noise Reduction and Noise Isolation Class (NIC)

The arithmetic difference between the sound pressure levels in adjacent spaces is called the *noise reduction*.

$$\Delta L_{NR} = \overline{L}_s - \overline{L}_r \tag{9.7}$$

At frequencies where rooms do not meet the minimum volume requirements necessary to establish the required modal density for a diffuse field, the noise reduction is used instead of the transmission loss to calculate the Sound Transmission Class.

A *Noise Isolation Class* (NIC) can be calculated from noise reduction values by comparing the measured data to the standard reference contour, using the STC calculation criteria (ASTM E413). The NIC is measured in the field, since a laboratory measurement would require knowledge of the transmitting area and the absorption in the receiving room to be useful. A field NIC rating is not applicable to a type of partition since it relates only to the unique combination of partition type, partition area, and the amount of absorption present in the receiving room at the time of the measurement. Thus, it is not appropriate to assign an NIC rating to a specific construction element or to use it in place of an FSTC value.

9.2 SINGLE PANEL TRANSMISSION LOSS THEORY

Free Single Panels

When a sound wave strikes a freely suspended solid panel, there is a movement imparted, which in turn transmits its motion to the air on the opposite side. Figure 9.4 shows the geometry. The total pressure acting on the panel along its normal is

$$\Delta \mathbf{p} = \mathbf{p}_i + \mathbf{p}_r - \mathbf{p}_t \tag{9.8}$$

The velocity of a normally reacting panel can be calculated using Newton's law

$$\Delta \mathbf{p} = m_s \frac{d\,\mathbf{u}_p}{d\,t} = m_s\,(j\,\omega\,\mathbf{u}_p) \tag{9.9}$$

Note that the normal panel impedance in this model, $j\,\omega\,m_s$, is only due to the panel mass.

If a plane wave approaches at an angle θ to the surface normal and is specularly reflected,

$$\mathbf{u}_i = \frac{j\,k\,\cos\theta}{j\,\omega\,\rho_0}\,\mathbf{p}_i = \frac{\cos\theta}{\rho_0\,c_0}\,\mathbf{p}_i \tag{9.10}$$

and

$$\mathbf{u}_r = -\frac{\cos\theta}{\rho_0\,c_0}\,\mathbf{p}_r \quad \text{and} \quad \mathbf{u}_t = \frac{\cos\theta}{\rho_0\,c_0}\,\mathbf{p}_t \tag{9.11}$$

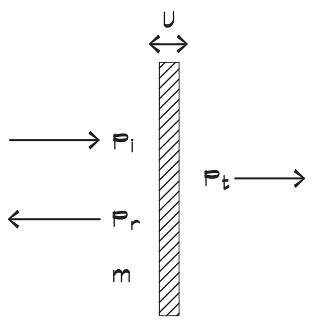
Substituting Eq. 9.10 and 9.11 into 9.9, we obtain the force balance equation along the normal

$$\frac{\rho_0\,c_0\,\mathbf{u}_i}{\cos\theta} - \frac{\rho_0\,c_0\,\mathbf{u}_r}{\cos\theta} = \frac{\rho_0\,c_0\,\mathbf{u}_t}{\cos\theta} + m_s\,(j\,\omega\,\mathbf{u}_t) \tag{9.12}$$

At the surface, the particle velocities on both sides of the plate are the same as the plate velocity, so

$$\mathbf{u}_i + \mathbf{u}_r = \mathbf{u}_t = \mathbf{u}_p \tag{9.13}$$

FIGURE 9.4 Pressure on a Plate Having a Mass, m, Per Unit Area



Substituting these into Eq. 9.9 to eliminate the $\mathbf{u}_r$ term we get the ratio of the transmitted to incident pressures, which is

$$\frac{\mathbf{p_t}}{\mathbf{p_i}} = \frac{1}{1 + \dfrac{j\,\omega\,m_s\,\cos\theta}{2\,\rho_0\,c_0}} = \frac{1}{1 + \dfrac{\mathbf{z_n}\,\cos\theta}{2\rho_0\,c_0}} \tag{9.14}$$

If we use $\zeta_n = \dfrac{\mathbf{z_n}}{\rho_0\,c_0}$ for the normalized impedance, and define the transmissivity as the ratio of the transmitted to the incident power, the square of Eq. 9.14

$$\boldsymbol{\tau}_\theta = \left[\frac{\mathbf{p_t}}{\mathbf{p_i}}\right]^2 = \frac{1}{\left|1 + \dfrac{\zeta_n\,\cos\theta}{2}\right|^2} \tag{9.15}$$

The generalized transmission loss is

$$\Delta\,L_{TL}(\theta) = 10\,\log\left|1 + \frac{\zeta_n\,\cos\theta}{2}\right|^2 \tag{9.16}$$

Mass Law

The limp mass approximation for the normalized panel impedance $\zeta_n = \dfrac{\mathbf{z_n}}{\rho_0 c_0} \cong \dfrac{j\,\omega\,m_s}{\rho_0\,c_0}$ holds for thin walls or heavy membranes in the low-frequency limit, where the panel acts as one mass, moving along its normal, and bending stiffness is not a significant contributor. Using this impedance and recalling that the square of an imaginary number is the sum of the squares of its real and imaginary parts, we can write the *transmissivity* as

$$\tau_\theta = \left[1 + \left(\frac{\omega\,m_s\,\cos\theta}{2\,\rho_0\,c_0}\right)^2\right]^{-1} \tag{9.17}$$

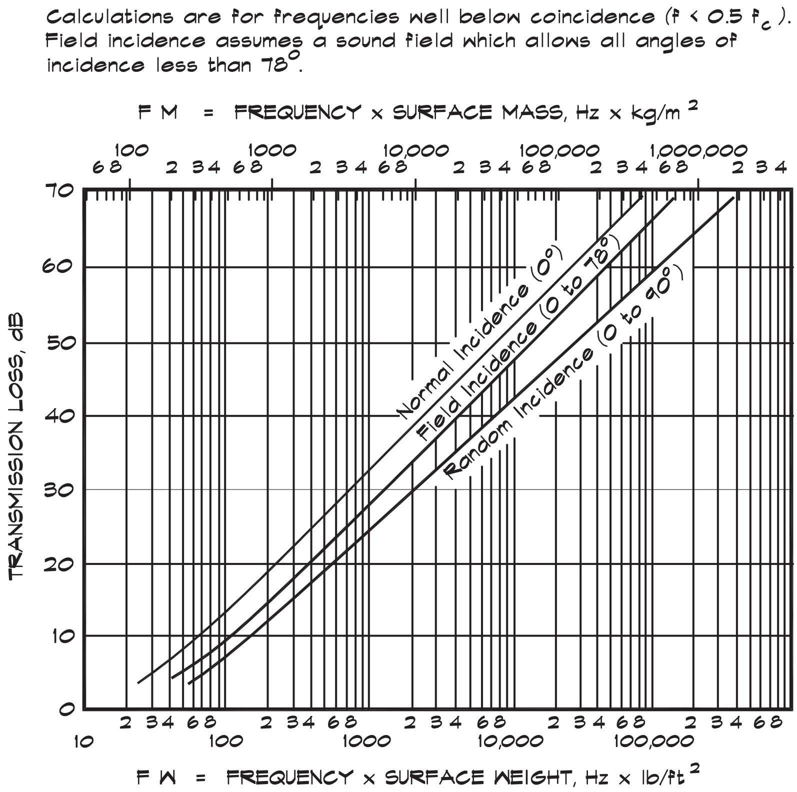
where τ_θ = transmissivity or the fraction of the incident energy transmitted through the panel as a function of incident angle θ
ω = radial frequency (rad / s)
m_s = surface mass density (kg / m^2 or lbs / ft^2)
ρ_0 = density of air (1.18 kg / m^3 or 0.0745 lbs / ft^3)
c_0 = speed of sound in air (344 m / s or 1128 ft / s)

By taking 10 log of Eq. 9.17, we obtain the transmission loss of a panel for a plane wave incident at an angle θ to the normal. A graph of the behavior of the mass law transmission loss as a function of the angle of incidence of the sound wave is given in Fig. 9.5.

$$\Delta L_{TL}(\theta) = 10\,\log\left[1 + \left(\frac{\omega\,m_s\,\cos\theta}{2\,\rho_0 c_0}\right)^2\right] \tag{9.18}$$

For most architectural materials, the normalized mass impedance is much greater than one so that the term on the right-hand side of the bracket dominates.

FIGURE 9.5 Theoretical Sound Transmission Loss of Panels (Beranek, 1971)



When the incident sound field is diffuse, there is an equal probability that sound will come from any direction. The diffuse incidence transmissivity is obtained by integrating Eq. 9.17 over all angles of incidence up to a limiting value of θ_{Max}.

$$\tau = \frac{\int_0^{\theta_{Max}} \tau_\theta \cos\theta \sin\theta \, d\theta}{\int_0^{\theta_{Max}} \cos\theta \sin\theta \, d\theta} \tag{9.19}$$

The reason for this approach is that the elementary theory of Eq. 9.18 predicts a transmission loss of zero for grazing incidence, so if the limiting angle is 90°, we obtain a result that does not occur in practice. It has become standard procedure to select a maximum angle that yields the best fit to the measured data. This turns out to be about 78°, and gives what is known as the field-incidence transmission loss

$$\Delta L_{TL} = 10 \log \left[1 + \left(\frac{\omega \, m_s}{3.6 \, \rho_0 c_0} \right)^2 \right] \tag{9.20}$$

or

$$\Delta L_{TL} = 20 \log \left(f \, m_s \right) - K_{TL} \tag{9.21}$$

where ΔL_{TL} = diffuse field transmission loss (dB)
f = frequency (Hz)
m_s = surface mass density of the panel material (kg / m^2 or lbs / ft^2)
K_{TL} = numerical constant
= 47.3 dB in metric units and 33.5 dB in FP units

Equation 9.21 is known as the mass law since the transmission loss at a given frequency is only dependent on the surface mass of the panel. The transmission loss increases six dB for each doubling of surface mass or frequency. Under field-incidence conditions, the integration over the angle of incidence results in an effective mass that is lower by a factor 1.8 than the actual mass. Comparing Eq. 9.18 with Eq. 9.20, we see that this is the same as a difference between the field and normal incidence transmission losses of 5 dB.

$$\Delta L_{TL} \cong \Delta L_{TL} (\theta = 0) - 5 \tag{9.22}$$

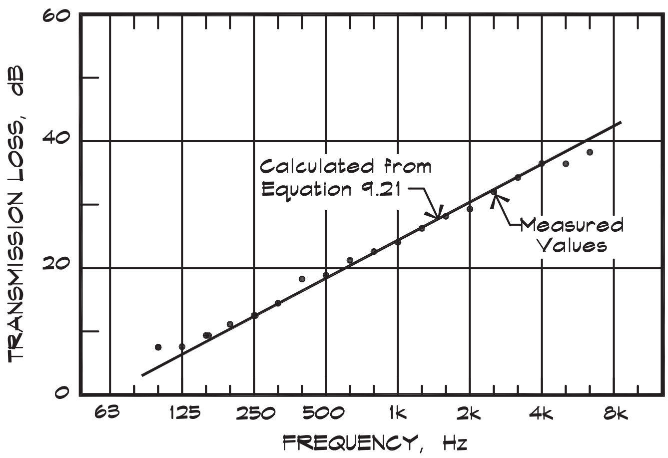
Figure 9.6 shows a graph of the diffuse field transmission loss measured for a 3-mm (1/8”) hardboard panel compared with the calculated value. In this frequency range, the agreement with measured data for thin panels is quite good.

Large Panels—Bending and Shear

Panels that are large compared to a wavelength, react to an applied pressure not only as a limp mass but also as a plate, which can bend or shear. As such, they have an impedance that is more complicated than that previously assumed. When the possibility of bending or shear is present, the two transmission mechanisms act much like resistors in an electric circuit. The composite panel impedance is treated mathematically like two resistors in parallel, which are in series with the mass impedance

$$\mathbf{z} \cong j\,\omega\, m_s + \frac{\mathbf{z}_B\, \mathbf{z}_s}{\mathbf{z}_B + \mathbf{z}_s} \tag{9.23}$$

FIGURE 9.6 Transmission Loss of 3 mm (1/8”) Hardboard (Sharp, 1973)



For an isotropic plate, the bending impedance (Sharp, 1973; Cremer, Heckel, and Ungar, 1973; or Fahy, 1985) is given by

$$\mathbf{z}_B \cong -\frac{j\,\omega^3\,B}{c_0^4}\,\sin^4\theta \tag{9.24}$$

and the shear impedance (Mindlin, 1951; Cremer, Heckel, and Ungar, 1973; or Beranek and Ver, 1992) is

$$\mathbf{z}_s = -j\,\frac{G\,h\,\omega\,\sin^2\theta}{c_0^2} \tag{9.25}$$

where ω = radial frequency = $2\,\pi\,f$ (rad/s)
m_s = surface mass density of the panel (kg / m² or lbs / ft²)
$j = \sqrt{-1}$
E = Young's modulus of elasticity (N / m² or lb / ft²)
$B = \dfrac{E\,h^3}{12\,(1-\sigma^2)}$ = bending stiffness (N m or ft lbs)
$G = \dfrac{E}{2\,(1+\sigma)}$ = shear modulus (N / m² or lbs / ft²)
c_0 = speed of sound in air (m / s or ft / s)
σ = Poisson's ratio
h = panel thickness (m or ft)

Thin Panels—Bending Waves and the Coincidence Effect

In Eq. 9.23, the impedance is composed of three imaginary terms: the inertial mass, the bending stiffness, and the shear impedance. At low frequencies, the mass term predominates; at high frequencies it is the combination of bending and shear that determines the composite impedance. Thin panels are easier to bend than to shear, so more of the energy will flow into this mode. The resulting plate impedance becomes

$$\mathbf{z} \cong j\,\omega\,m_s - \frac{j\,\omega^3\,B}{c_0^4}\,\sin^4\theta \tag{9.26}$$

At one frequency, called the *coincidence frequency*, the mass and bending impedance terms are equal and, since they have opposite signs, the composite impedance is zero. Figure 9.7 illustrates the crossover point for this condition.

Coincidence can be understood by realizing that the velocity of bending waves in a panel is a function of frequency. At the coincidence frequency, the bending wave velocity is the same as the trace velocity of the airborne sound moving along the panel. Since the pressure maxima and minima are spatially matched, as in Fig. 9.8, energy is easily transmitted from the air into the panel and vice versa. The frequency at which coincidence occurs varies with the angle of incidence and is obtained by setting Eq. 9.26 to zero

$$f_{co}\,(\theta) = \frac{c_0^2}{2\,\pi\,\sin^2\theta}\sqrt{\frac{m_s}{B}} \tag{9.27}$$

FIGURE 9.7 Imaginary Part of the Thin Panel Impedance (Sharp, 1973)

The imaginary part of the transmission impedance of a thin panel for grazing incidence ($\theta = \pi / 2$) showing the effect of coincidence.

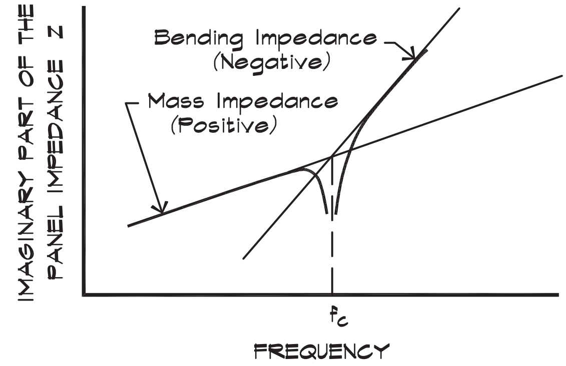
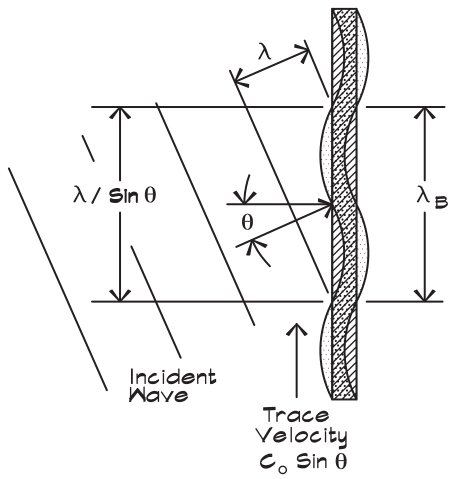


FIGURE 9.8 Coincidence Effect

The coincidence effect matches the trace of the airborne wavelength and the bending wavelength in the panel.



For normal incidence, the coincidence frequency is infinite, so there is no effect. The minimum value of the matching frequency occurs at grazing incidence and is called the *critical frequency*.

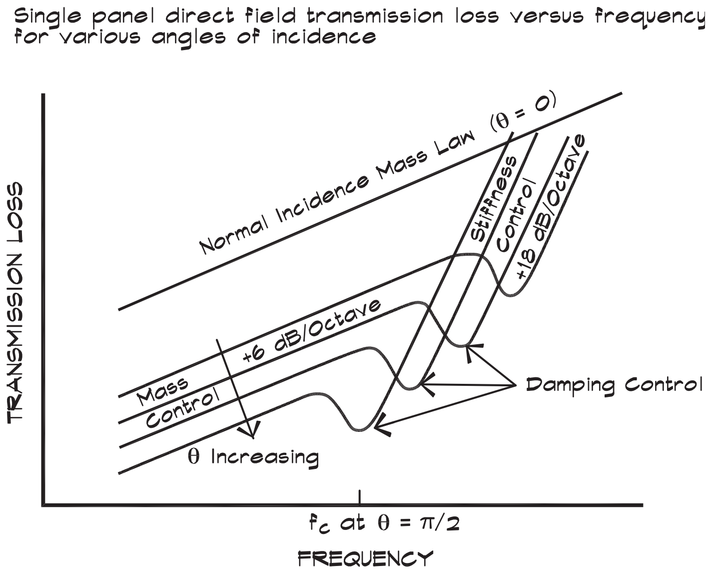
$$f_c = \frac{c_0^2}{2\pi}\sqrt{\frac{m_s}{B}} = \frac{c_0^2}{2\pi h}\sqrt{\frac{12\,(1-\sigma^2)\,\rho_m}{E}} \tag{9.28}$$

where ρ_m = bulk density of the panel material (kg/m^3 or lbs/ft^3).

The two frequencies are related by means of

$$f_{co}(\theta) = \frac{f_c}{\sin^2\theta} \tag{9.29}$$

FIGURE 9.9 Single Panel Direct Field Transmission Loss (Fahy, 1985)



which implies that the *coincidence effect* always occurs at or above the critical frequency. Figure 9.9 gives examples in which the position of the coincidence dip varies with the angle of incidence.

Above coincidence the bending impedance term increasingly dominates and the transmission loss becomes (Fahy, 1985)

$$\Delta L_{TL}(\theta) \cong 10 \log \left[1 + \left(\frac{B k^4 \sin^4 \theta \cos \theta}{2 \rho_0 c_0 \omega} \right)^2 \right] \tag{9.30}$$

The bending transmission loss is stiffness controlled in this region and has an 18 dB per octave slope as well as a strong angular dependence.

At the critical frequency, the transmission loss does not fall to zero because internal damping prevents it. To treat this theoretically, a complex bending stiffness $\mathbf{B} = B(1 + j\eta)$ is introduced with a damping term η having a value less than one. Since the mass term and the bending term cancel out at coincidence, damping is left. Using Eq. 9.27, Eq. 9.30 can be written as an inertial term with a damping coefficient (Fahy, 1985)

$$\Delta L_{TL}(\theta) \cong 10 \log \left(1 + \frac{\eta\, \omega_{co}\, m_s \cos \theta}{2 \rho_0 c_0} \right)^2 \tag{9.31}$$

At coincidence, the transmission loss is expressed as the direct-field mass law plus a damping term $20 \log \eta$. Figure 9.9 also shows where internal damping becomes important.

The diffuse-field transmission loss is normally calculated by integrating the direct-field transmission loss expression over all relevant angles of incidence. The integration in the coincidence region is difficult because different equations apply, depending on the angle and the frequency. Although the coincidence frequency varies with angle of incidence, the diffuse-field transmission loss still has a minimum at the critical frequency, since the dominant path is that having the lowest loss.

Several authors have developed approximate relations to use in this region. Fahy (1985) gives an equation for the transmission loss at the diffuse-field coincidence point, which is written in terms of a combination of the normal-incidence mass law and a damping term, dependent on the bandwidth

$$\Delta L_{TL}\ (f = f_c) \cong 20\ \log \left(\frac{\omega_c\, m_s}{2\, \rho_0\, c_0} \right) + 10\ \log \left\{ \frac{2\, \eta}{\pi} \left(\frac{\Delta f}{f_c} \right) \right\} \tag{9.32}$$

where Δf = bandwidth (Hz) - - typically one - third octave or one octave wide
f_c = critical frequency (Hz)
η = damping coefficient ($\eta < 1$)

When the transmission loss is calculated just below coincidence, a line is drawn between the field-incidence mass law value at $f_c/2$ and the critical-frequency transmission loss from Eq. 9.32. Above the coincidence frequency, Eq. 9.30 predicts an 18 dB per octave increase in transmission loss for a given angle of incidence. Measured diffuse-field data yield a slope that is about half that (Sharp, 1973), due to the shifting location of the coincidence dip with angle. Cremer (1942) has derived an approximate diffuse-field equation for use above the coincidence frequency that combines the normal-incidence mass law and a frequency-dependent damping term.

$$\Delta\, L_{TL}\ (f > f_c) \cong 20\ \log \left(\frac{\omega\, m_s}{2\, \rho_0\, c_0} \right) + 10\ \log \left\{ \frac{2\eta}{\pi} \left(\frac{f}{f_c} - 1 \right) \right\} \tag{9.33}$$

Above coincidence, Eq. 9.33 yields a transmission loss that increases 9 dB per octave for a single panel, which agrees with measured values.

Table 9.1 and Fig. 9.10 give a compilation of material properties: the product of the critical frequency and the panel thickness along with the damping coefficients for use in these equations. Figure 9.11 plots the measured transmission loss for a sheet of 5/8" drywall, which exhibits a coincidence dip around 2500 Hz. Data calculated from Eqs. 9.32 and 9.33 are also shown.

Thick Panels

As panel thickness increases, the composite panel impedance utilized in thin panel theory is no longer accurate. At high frequencies a shear wave can develop and propagate in a thick panel. When shear presents a lower impedance than bending, it will become the predominant transmission mode. The composite impedance is given by Eq. 9.25.

The crossover point between bending and shear occurs where the thickness of the plate is equal to a bending wavelength in the plate material. When the panel is thicker than a wavelength, shear predominates, as illustrated in Fig. 9.12. The shear limiting frequency is (Sharp, 1973)

$$f_s = \frac{c_0^2\, (1 - \sigma)}{59\, h^2\, f_c} \tag{9.34}$$

TABLE 9.1 Product of Plate Thickness and Critical Frequency in Air (20° C) (Beranek, 1971; Cremer et al., 1973; Fahy, 1985)

Material	f_c (m sec^{-1})	h f_c (ft sec^{-1})
Steel	12.4	41
Aluminum	12.0	39
Brass	17.8	58
Copper	16.3	54
Glass or Sand	12.7	42
Plaster		
Gypsum Board	38	125
Chipboard	23	75
Plywood or Brick	20	66
Asbestos Cement	17	56
Concrete		
Dense	19	62
Porous	33	108
Light	34	112
Lead	55	180

Note that variations of 10% are not uncommon.

FIGURE 9.10 Values of Material Loss Factors (Beranek and Ver 1992)

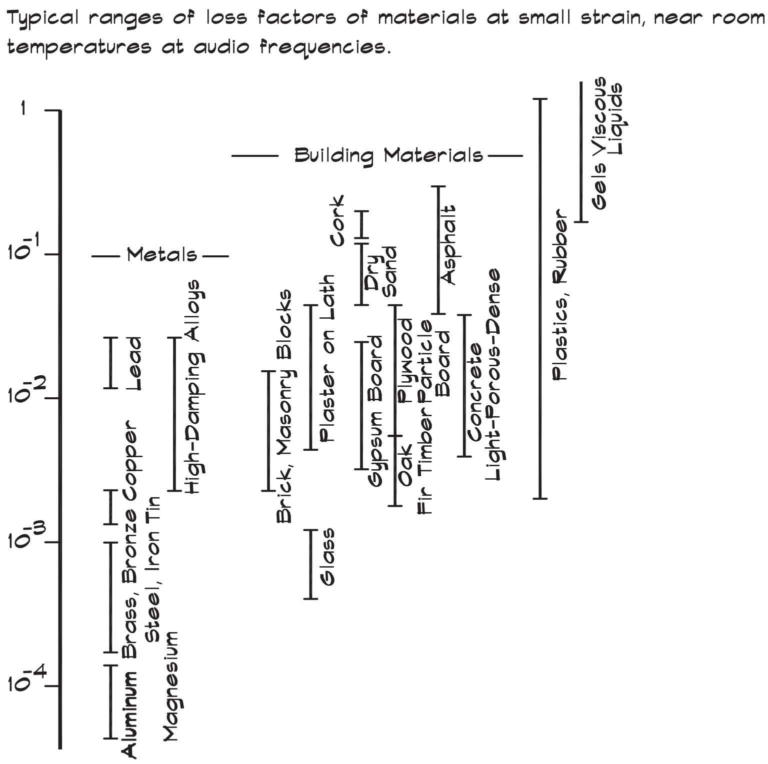


FIGURE 9.11 Transmission Loss of 16 mm (5/8") Gypboard (Sharp, 1973)

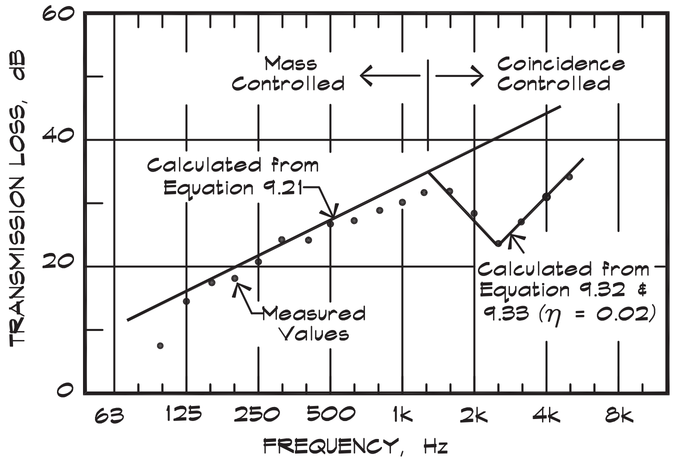
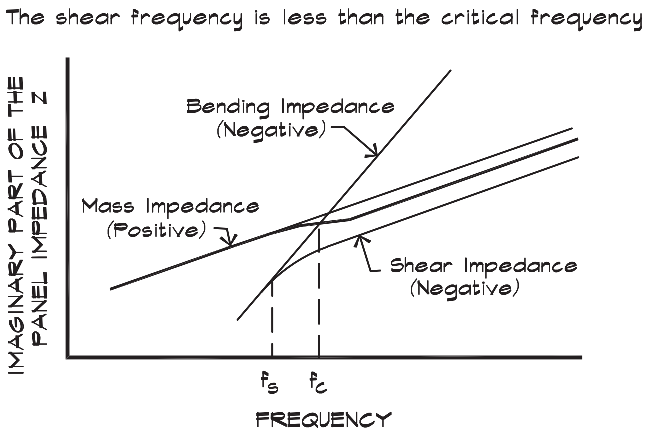


FIGURE 9.12 Transmission Impedance of Thick Panels (Sharp, 1973)



When the shear frequency falls below the critical frequency, as it can with thick panels such as concrete slabs and brick or masonry walls, there is no coincidence dip and the shear mechanism lowers the transmission loss even below that which might be expected from purely mass law considerations. This can be very important since in Fig. 9.13, it occurs in the frequency range around 200 Hz for a 15 cm (6") concrete slab. A good estimate of the transmission loss can be made above this point by using 6 dB less than the diffuse field mass law. For concrete or solid brick structures this is equivalent to assuming that there is half the actual mass.

If the shear frequency is greater than the coincidence frequency, the shear wave impedance eventually becomes lower than the bending impedance. All materials appear thick at a high enough frequency. The shear-wave impedance limits the slope of the transmission loss line above the shear-bending frequency to 6 dB per octave. Figure 9.14 gives

FIGURE 9.13 Transmission Loss of a 6" Concrete Panel (Sharp, 1973)

The measured values of transmission loss for a 6-inch (150 mm) concrete panel compared to values predicted by means of the thin and thick panel theories.

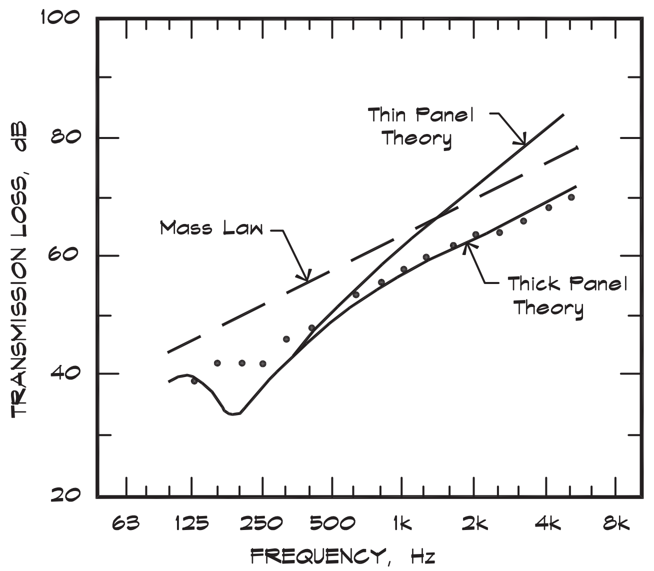
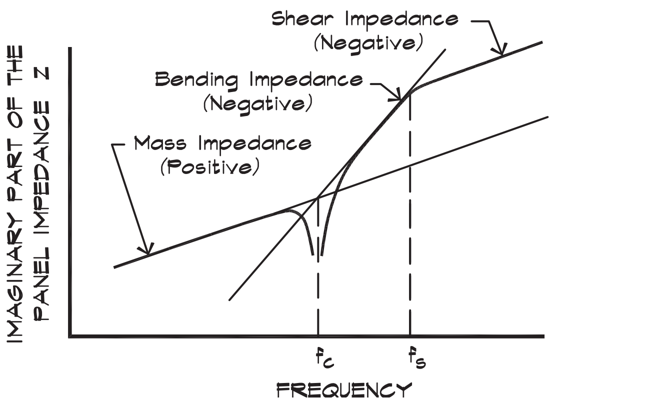


FIGURE 9.14 Imaginary Part of the Transmission Impedance (Sharp, 1973)

The imaginary part of the transmission impedance of a thin panel for grazing incidence ($\theta = \pi/2$) showing the effect of coincidence. The shear frequency is greater than the critical frequency.



an example. Since coincidence in lightweight construction materials such as sheet metal, gypsum board, or thin wood panels occurs at a relatively high frequency (e.g., above 2000 Hz), there is little practical impact from shearing effects since there is little sound transmission in this region.

Finite Panels—Resonance and Stiffness Considerations

For a finite-sized panel, an additional term must be added to the impedance at very low frequencies, to account for panel bending resonances. This term is given by (Leissa, 1969; Sharp, 1973)

$$\mathbf{z}_P = -j\,\frac{K_P}{\omega} \tag{9.35}$$

where

$$K_P = \pi^4\, B \left[\frac{1}{a^2} + \frac{1}{b^2}\right]^2 \tag{9.36}$$

and a and b are the dimensions of the panel. In this frequency range, the overall impedance is the sum of the panel impedance and the mass impedance. When the two terms are equal, a panel resonant frequency is produced

$$f_P = \frac{\pi}{2}\sqrt{\frac{B}{m_s}}\left[\frac{1}{a^2} + \frac{1}{b^2}\right] \tag{9.37}$$

Typically, the dimensions of a panel such as a wall are large enough that the panel resonance is quite low, on the order of 10 Hz or less. A 2 m × 3 m sheet of gypboard, for example, has a panel resonance of about 5 Hz. Note that Eq. 9.37 is based on the fundamental resonant frequency of the panel. There are also higher panel modes; however, due to damping these rarely contribute to the transmission loss. The frequency appears in the denominator in Eq. 9.35, so below the panel resonance the transmission loss increases with decreasing frequency at 6 dB per octave. Sharp (1973) has given an approximate relationship for this region.

$$\Delta L_{TL} \cong 20\,\log\,(f\,m_s) - K_{TL} + 40\,\log\left(\frac{f_P}{f}\right) \tag{9.38}$$

for $f < f_P$ the lowest panel resonance frequency.

Design of Single Panels

For single panels the transmission loss is influenced by four factors: 1) size, 2) stiffness, 3) mass, and 4) damping. Josse and Lamure (1964) have developed a comprehensive, albeit somewhat more complex, formulation for the region below the critical frequency that includes all four components

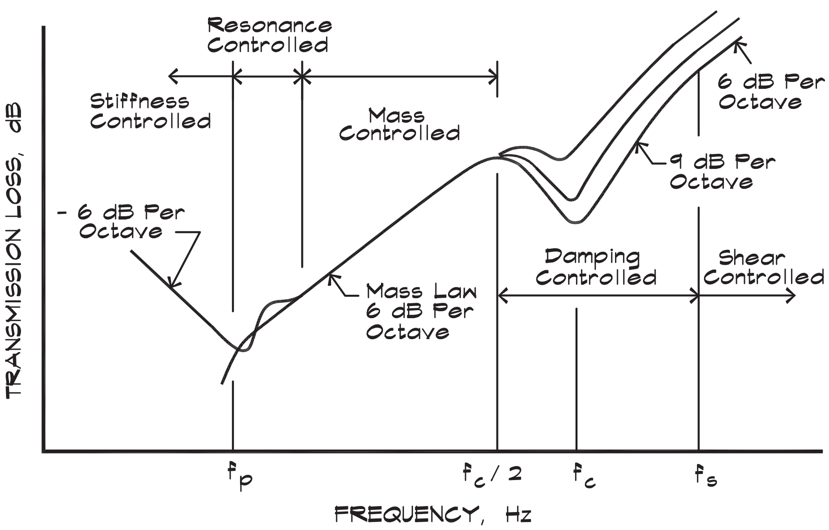
$$\Delta L_{TL} = 20 \log \left(\frac{\omega\, m_s}{2\, \rho_0\, c_0} \right) - 10 \log \left\{ \left[\frac{3}{2} + \ln \left(\frac{2\, \omega}{\Delta\, \omega} \right) \right] \right. \\ \left. + \frac{16\, c_0^2}{\eta\, \omega_c} \frac{1}{\left(\omega\, \omega_c\right)^{1/2}} \left(\frac{a^2 + b^2}{a^2\, b^2} \right) \left[1 + \frac{2\, \omega}{\omega_c} + 3 \left(\frac{\omega}{\omega_c} \right)^2 \right] \right\} \tag{9.39}$$

For typical panel sizes, in the mass-law region Eq. 9.39 gives about the same result as Eq. 9.21. Above the critical frequency, Eq. 9.32 or Eq. 9.33 can be used to predict the transmission loss. For thick panels, the mass law holds up to the point where shear predominates. Above this point, mass law less 6 dB gives a good estimate.

The transmission loss of a thin panel falls into five frequency regions illustrated in Fig. 9.15. At very low frequencies the transmission loss is stiffness controlled. The greater the bending stiffness and the shorter the span, the higher the transmission loss. These considerations become important in low-frequency sound transmission problems in long-span floor structures, particularly in lightweight wood construction, where the bending stiffness of the structure is not great. Although floors are a composite structure, they can be thought of as a single bending element at these low frequencies.

Above the fundamental panel mode, the transmission loss of a thin single panel is primarily a function of its mass. Techniques such as mass loading can be used to increase the intrinsic panel mass, by adding asphalt roofing paper, built-up roofing, sand, gravel, lightweight concrete, gypboard, or discrete masses. Lead-loaded gypsum board panels are available for critical applications. Mass loading increases the weight of the panel without increasing the panel stiffness. Loading materials need not cover the entire panel but can be located at regular intervals over the surface. In existing wooden floor structures mass can be added by screwing sheets of gypboard to the underside of wood subfloors between the

FIGURE 9.15 General Form of the Diffuse Field Transmission Loss vs Frequency Curve for a Thin Panel



joists, a technique that also helps close off any cracks in the subflooring. Although a high mass is desirable, a high thickness is not, due to its effect on the coincidence frequency. For example, 9 mm (3/8") glass has a higher STC rating (STC 34) than a normal 44 mm (1 3/4") solid core door (STC 30) even though it weighs less per unit area, due to the fact that its coincidence frequency is much higher.

In the region around coincidence, damping controls the depth of the notch. Several techniques can be used to increase the transmission loss. In windows and glazed doors, a resin interlayer of 0.7 to 1.4 mm (30 to 60 mils) thickness can be introduced between two layers of glass to increase damping. Products of this type are called laminated glass or sometimes acoustical glass. Sheets of 6 mm (1/4 in) laminated glass make good acoustical windows and can achieve an STC rating of 34 in fixed stops or high-quality frames.

Damping compounds are also commercially available. Products come in sheet or paste form and add both mass and damping. They are primarily used to treat thin materials such as sheet-metal panels on vibrating equipment. Asphalt materials such as undercoat on car bodies serve the same function and reduce the vibration amplitudes of these surfaces.

Spot Laminating

Spot laminating is a technique used to increase transmission loss near coincidence. In this region, it is important not to thicken the panel, which decreases the critical frequency. If the mass is increased through the addition of an extra layer, it may decrease the transmission loss in the frequency range of interest. One way to achieve a combination of high mass and low stiffness is to laminate panels together using dabs (spots) of panel adhesive at regular intervals. At low frequencies, the panels act as one and their composite bending stiffness is greatly increased. At high frequencies the shearing effect of the adhesive acts to reduce the bending stiffness to that of an individual panel. The panels act individually and the critical frequency remains high, since it is that of a single panel in bending.

When using the spot laminating technique the spacing of the adhesive dots determines the frequency at which the two panels begin to decouple. Decoupling begins when the dot spacing is equal to the wavelength of bending waves. The bending wavelength of a single panel at a frequency f is given by (Sharp, 1973) as

$$\lambda_B = \frac{c_0}{\sqrt{f\, f_c}} \tag{9.40}$$

At low frequencies, the critical frequency is that of the composite panel since the bending wavelength is much greater than the spacing of the adhesive. If two panels of identical materials are joined together, the coincidence frequency of each sheet is about twice that of the composite. The decoupling frequency can be written as

$$f_d = \frac{2\, c_0^2}{a^2\, f_c} \tag{9.41}$$

where a is the adhesive spacing and f_c is the critical frequency of a single sheet of material. If the two panels are 1/2" gypboard, which has a coincidence frequency of about 3000 Hz, and the adhesive dot spacing is 24", then the decoupling frequency is 210 Hz. This is well below the composite panel's coincidence frequency, which would be about 1500 Hz.

9.3 DOUBLE-PANEL TRANSMISSION LOSS THEORY

Free Double Panels

The transmission loss of a double panel system is based on a theory that first considers panels of infinite extent, not structurally connected, and subsequently addresses the effects of various types of attachments. The treatment here follows that first developed by London (1950) and later by Sharp (1973). It is assumed that the air cavity is filled with batt insulation, which damps the wave motion parallel to the wall, so we are mainly concerned with internal wave motion normal to the surface. The airspace separating the panels acts as a spring and at a given frequency, a mass-air-mass resonance occurs. The resonance is the same as that given in Eq. 7.103, which was developed in the discussion of air-backed panel absorbers, but the mass has been modified to account for the diffuse field and for the fact that both panels can move

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{3.6\,\rho_0\,c_0^2}{m'\,d}} \tag{9.42}$$

where $m' = \dfrac{2\,m_1\,m_2}{m_1 + m_2}$ = effective mass per unit area of the construction (kg/m^2 or lbs/ft^2)

d = panel spacing (m or ft)

For a double panel wall, consisting of 16 mm (5/8") gypboard separated by a stud space of 9 cm (3.5"), the mass-air-mass resonance occurs at about 66 Hz. At low frequencies, below the resonant frequency, the two panels act as one mass. If the individual panels are mass controlled then the transmission loss follows the mass law of the composite structure.

At frequencies above the mass-air-mass resonance, the effect of the air cavity is to increase the transmission loss significantly. In fact for N separate panels, the ideal theoretical transmission loss increases 6(2N-1) dB per octave. At high frequencies, constructions having multiple panels with intervening air spaces can provide significant increases in transmission loss over that achieved by a single panel. Since it is rarely practical to construct walls or floors with more than about three panels, consideration of large numbers of panels is generally not useful.

A plane wave encountering a double-panel system sees the impedance of the nearest panel, the impedance of the airspace, the impedance of the second panel, and finally the impedance of the air beyond. The transmissivity has been given by London (1950) as

$$\boldsymbol{\tau}_\theta = \left[1 + (\boldsymbol{X}_1 + \boldsymbol{X}_2) + \boldsymbol{X}_1\,\boldsymbol{X}_2\left(1 - e^{-j\sigma}\right)\right]^{-2} \tag{9.43}$$

where $\boldsymbol{X} = \dfrac{\mathbf{z}_n\,\cos\theta}{2\,\rho_0\,c_0}$

$\mathbf{z}_n$ = normal impedance of a panel (rayls)

$\sigma = 2\,k\,d\,\cos\theta$

$k = \dfrac{2\,\pi\,f}{c_0}$ = wave number (m^{-1})

Below the critical frequency the panel impedance is equal to its mass reactance and, for a diffuse field, the transmission loss of an ideal double panel system of infinite extent, attached only through the air spring coupling, is

$$\Delta L_{TL} \cong 10 \log \left\{ 1 + \left[\frac{\omega M}{3.6 \rho_0 c_0} - \frac{\omega^2 m_1 m_2}{(3.6 \rho_0 c_0)^2} \left(1 - e^{-2jkd}\right) \right]^2 \right\} \tag{9.44}$$

where m = mass per unit area of an individual panel (kg/m^2)
M = total mass per unit area of the construction (kg/m^2)

At low frequencies, below the mass-air-mass resonance, the panel spacing is small compared with a wavelength so the rightmost term in Eq. 9.44 approaches zero and the transmission loss can be approximated by

$$\Delta L_{TL} \cong 10 \log \left\{ 1 + \left[\frac{\omega M}{3.6 \rho_0 c_0} \right]^2 \right\} \tag{9.45}$$

which is just the mass law for the composite panel.

$$\Delta L_{TL} \cong 20 \log (f M) - K_{TL} \qquad f < f_0 \tag{9.46}$$

At frequencies above f_0, but still below the point where the wavelength is comparable to the panel separation, the rightmost term in Eq. 9.44 begins to dominate. In this region the wavelength is still larger than the panel spacing, so (2 k d) is small and $e^{-2jkd} \cong 1 - 2jkd$. The transmission loss can be approximated by

$$\Delta L_{TL} \cong 20 \log \left[\frac{\omega^2 m_1 m_2}{(3.6 \rho_0 c_0)^2} 2kd \right] \tag{9.47}$$

which can be written as

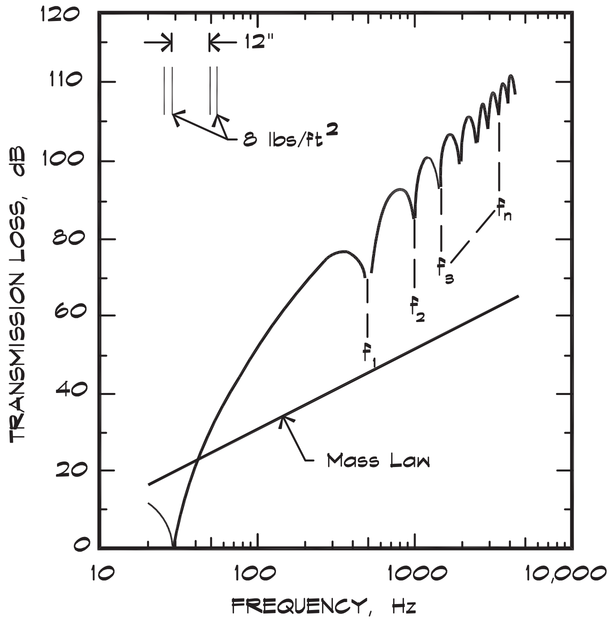
$$\Delta L_{TL} \cong \Delta L_{TL1} + \Delta L_{TL2} + 20 \log (2kd) \qquad f_0 > f > f_\ell \tag{9.48}$$

where ΔL_{TL1} and ΔL_{TL2} are the mass law transmission losses for each panel. Each term in Eq. 9.48 increases 6 dB per octave so the overall transmission loss rises 18 dB per octave in this frequency range. It also increases 6 dB for each doubling of the separation distance between the panels. At still higher frequencies resonant modes can be sustained in the airspace between the panels and there arises a series of closed tube resonances, normal to the surfaces, having frequencies

$$f_n = \frac{n c_0}{2d} \quad \text{for } n = 1, 2, 3 \ldots \tag{9.49}$$

These aid in the transfer of sound energy between the panels and result in a series of dips in the double-panel transmission loss, shown in Fig. 9.16. Due to the damping provided by batt insulation, we usually do not see this pattern in actual transmission loss measurements, which are carried out in third-octave bands. Batt flattens out the slope of the transmission

FIGURE 9.16 Theoretical Transmission Loss of an Ideal Double Panel (Sharp, 1973)



loss curve from 18 dB/octave down to 12 dB/octave in this region. The transmission loss behavior above a limiting frequency is given by

$$\Delta L_{TL} \cong \Delta L_{TL1} + \Delta L_{TL2} + 6 \qquad f_{\ell} < f \tag{9.50}$$

The crossover frequency, which can be obtained by setting Eq. 9.48 equal to Eq. 9.50, is equal to the first cavity resonance frequency divided by π.

$$f_l = \frac{c_0}{2\pi d} = \frac{f_1}{\pi} \tag{9.51}$$

Equations 9.46, 9.48, and 9.50 give the transmission loss of an ideal double panel system in three frequency ranges separated by the frequencies in Eqs. 9.42 and 9.51. Measurements by Sharp (1973) have shown that there is good agreement between theoretical and measured data for both the mass-reactance region (Fig. 9.17) and the critical region (Fig. 9.18). The panel transmission loss values in the critical region were used instead of simple mass law predictions.

Cavity Insulation

The theory that has been developed here has assumed that the air cavity is well damped. When there is no absorptive material between the panels, cavity resonances contribute to the transmission of sound from one side to the other in much the same way as a mechanical coupling would. The addition of damping material such as fiberglass batt insulation attenuates these modes. Figure 9.19 (Sharp, 1973) shows the effects of a fully isolated double-panel system, with and without batt insulation. The panels used were 1/4” and 1/8” hardboard so that the coincidence frequencies were above the frequency range of interest. Below the first

FIGURE 9.17 Measured and Calculated Transmission Loss Values for a Separated Double Panel (Sharp, 1973)

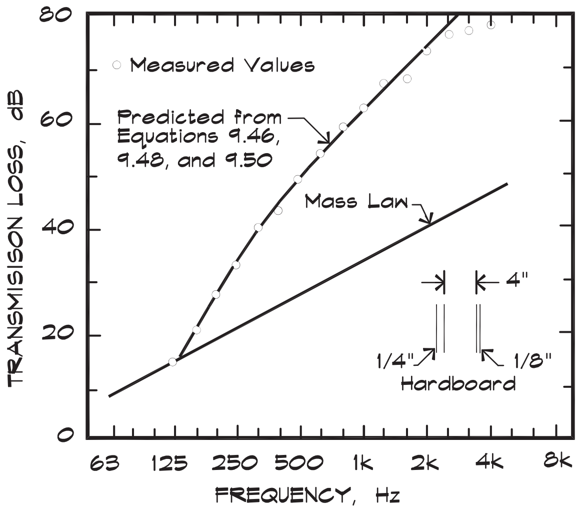


FIGURE 9.18 Transmission Loss Values for a Separated Double Panel Including Coincidence (Sharp, 1973)

Measured and calculated values of the transmission loss of 5/8-inch gypsum board wall including the coincidence region.

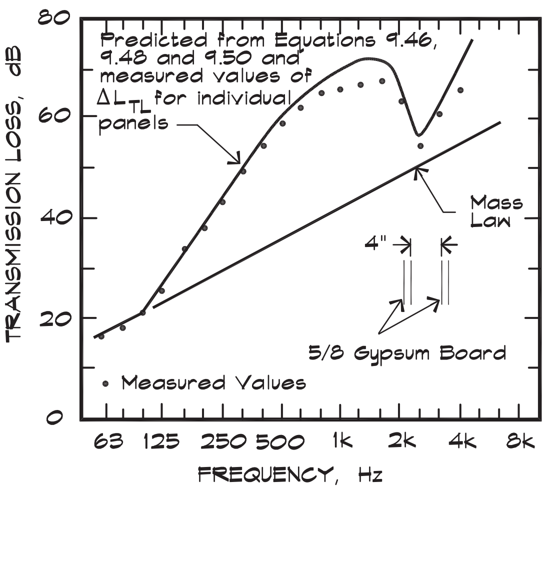
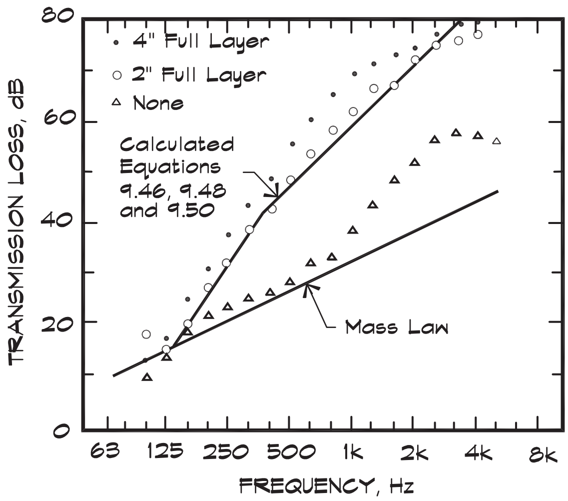


FIGURE 9.19 Transmission Loss of an Isolated Double Panel Construction with and without Insulation (Sharp, 1973)

The construction consists of 1/4" and 1/8" hardboard with a spacing of 6-1/4 inches.



cavity resonance (1100 Hz), the panels are so coupled by the cavity resonances that the transmission loss follows the mass law. Above the first resonance, the phase varies over the depth of the cavity and the coupling is weaker. When 2” insulation is introduced into the cavity the wall begins to act like a double-panel system. With 4” of insulation, the mass of the insulation is comparable to that of the panel and transmission losses are greater than those predicted using simple theory.

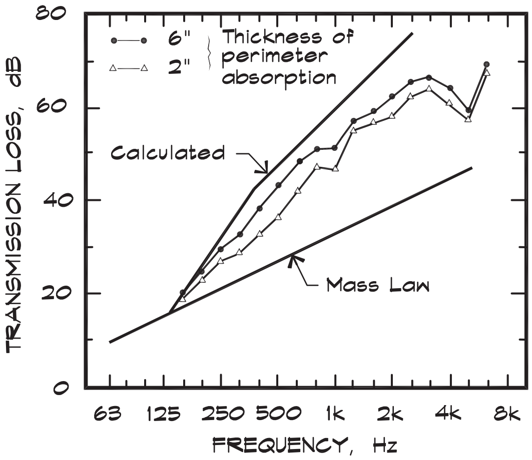
Table 9.2 shows measured increases in STC values for various thicknesses of insulation between separately supported 16-mm (5/8”) gypboard wall panels. The effectiveness of batt insulation in a wall cavity is almost entirely dependent on its thickness. The density of the fill for a given thickness makes only a small difference at relatively high frequencies, above 1000 Hz. The presence of paper backing on the fiberglass makes no difference for gypboard partitions, nor does the position of the partial thickness within the cavity, including contact with either side. Weaving a blanket of insulation around staggered studs is no more effective than the simpler method of placing the batt vertically between the studs. The

TABLE 9.2 Measured Effects of Fiberglass Batt in Completely Separated Double Panel Walls (Owens Corning Fiberglass, 1970)

Thickness of Cavity Fill	Average Increase in STC (dB)
1 1/2”	10
2”	11
3”	12
4”	13
6”	15
8”	16

FIGURE 9.20 **Transmission Loss of an Isolated Double Panel Construction with Perimeter Insulation (Sharp, 1973)**

The construction is 1/4" and 1/8" hardboard panels with a 6 1/4" airspace.



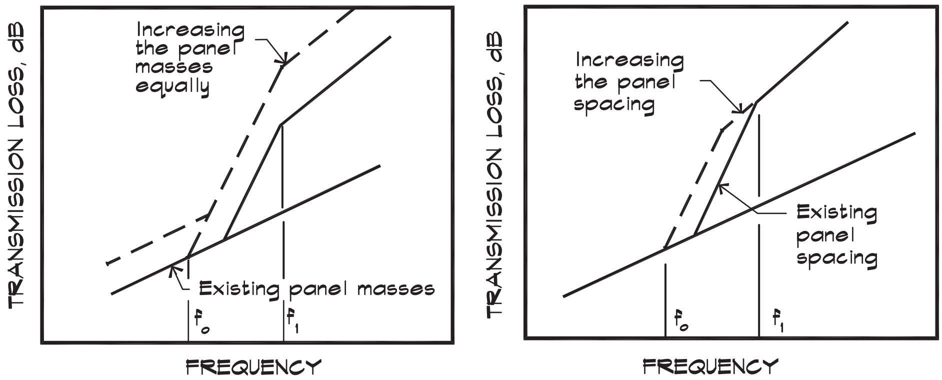
effectiveness of insulation in staggered stud and single stud walls is much less than in ideal walls due to the high degree of mechanical coupling between the two sides. Improvements in real (with studs, etc.) walls of from 3 to 7 dB were obtained, with insulation thicknesses of 2 to 6 inches. For most walls and floor-ceilings, where the two sides are mechanically coupled together in some way, the addition of batt insulation increases the STC from 3 to 5 dB for the first three inches of material and about a dB per inch above that point. Thicknesses of batt insulation beyond the stud spacing are not helpful since the compressed batt can form a structural bridge between the panels.

Higher order cavity modes, which are not necessarily perpendicular to the panels, can contribute to the sound transmission in the mid and high frequencies. Therefore, absorptive material is quite effective even if it is placed only around the perimeter of the cavity. This is a common technique used in the construction of double-glazed sound-rated windows for studios. Figure 9.20 illustrates the effect of insulation placed only around the perimeter of the cavity. At low frequencies, the transmission loss increases with the thickness of the insulation. In studio window construction it is helpful to leave an opening into the wall cavity, which acts as a Helmholtz resonator absorber, tuned to the mass-air-mass resonance frequency.

Double-Panel Design Techniques

At frequencies below the mass-air-mass (m-a-m) resonance, a double-panel wall acts as a single unit and the stiffness and mass are the most important contributors to transmission loss. Above the m-a-m resonance, both mass and panel spacing are important as shown in Fig. 9.21. Equation 9.47 holds that, for a given total mass, the transmission loss is greatest if the mass is distributed equally on both sides of the wall. This is generally true although it is a commonly held belief that unbalanced construction is preferred because of the desirability of mismatching the critical frequencies of the panels. Recent studies (Uris et al., 2000) have

FIGURE 9.21 Effect of Mass and Spacing on Transmission Loss Ideal Double Panel Construction (Sharp, 1973)



shown that, for a given mass, there is little difference between balanced and unbalanced gypsum board wall constructions, even at coincidence. The coincidence effect can be controlled by adding damping or by using different thicknesses of gypboard, while maintaining an overall equality of mass on each side (Green and Sherry, 1982).

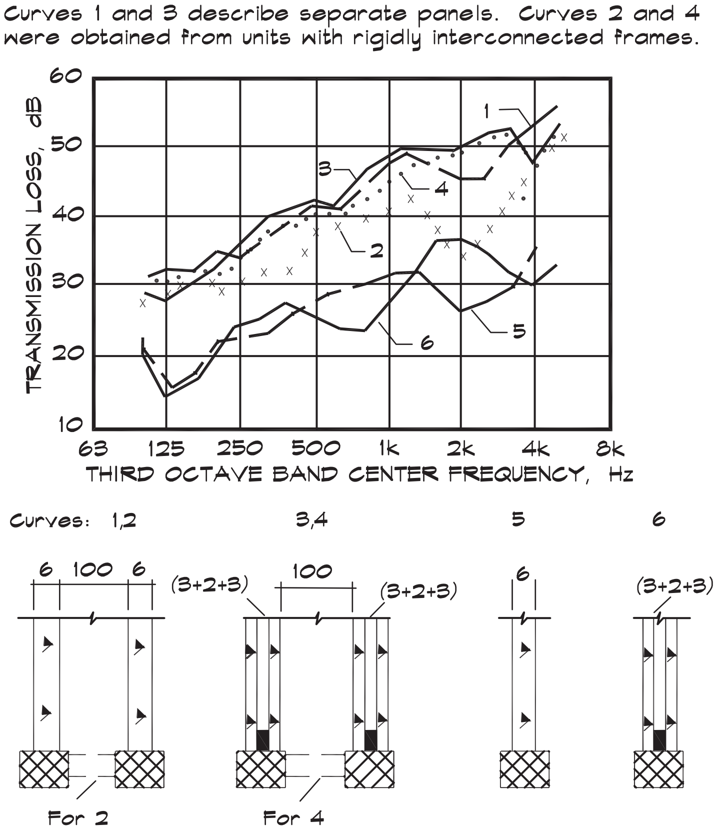
Because of the m-a-m resonance, a certain minimum air space is necessary before double-panel construction becomes significantly better than a single panel. Figure 9.22 shows a series of transmission loss tests (Vinokur, 1996) for single-glazed and various configurations of dual-glazed windows. The large dip at about 700 Hz for curve 6 corresponds to the m-a-m resonant frequency. Curves 2 and 4 illustrate the effects of mechanical coupling through direct connection between the window frames. Bridging provides a short circuit across the main air gap and magnifies the importance of the coincidence effects.

Additional tests by Vinokur using 3 mm (1/8”) laminated and plate glass are summarized in Fig. 9.23. An STC of 34 was achieved with the two sheets of glass laminated together, and this result was not bettered for double-glazed windows until the airspace exceeded 25 mm (1”). The lesson here is that not all double-glazed windows are better than single-glazed even when the total overall thickness of glass is the same. When the spacing between panels is small, it is not uncommon to find that a double-panel construction has a lower transmission loss than that of the two individual single panels sandwiched together. This accounts for the failure of thin double-panel windows, sometimes referred to as thermopane windows, to provide appreciable noise reduction.

In the region around coincidence, panels may be deadened using a sandwiched damping compound. In the Vinokur tests, glass panels were laminated together using 0.7 or 1.4 mm thick polyvinylbutyral. The coincidence dip for a laminated panel (curve 6) is significantly smaller than for single (curve 5) or double (curve 2) plate glass, where there is structural bridging. Harris (1992) reports that a sandwiched viscoelastic layer contained between two layers of 5/8” plywood can improve the transmission loss of lightweight wood floor systems. Gluing plywood floor sheathing can also be helpful.

Increasing the spacing between the partitions drives down the m-a-m resonance frequency and increases the transmission loss above that point. Measured window data show that above a spacing of about 20 mm the improvement is about 3.5 STC points per doubling

FIGURE 9.22 Transmission Loss of Various Glazing Configurations (Vinokur, 1996)

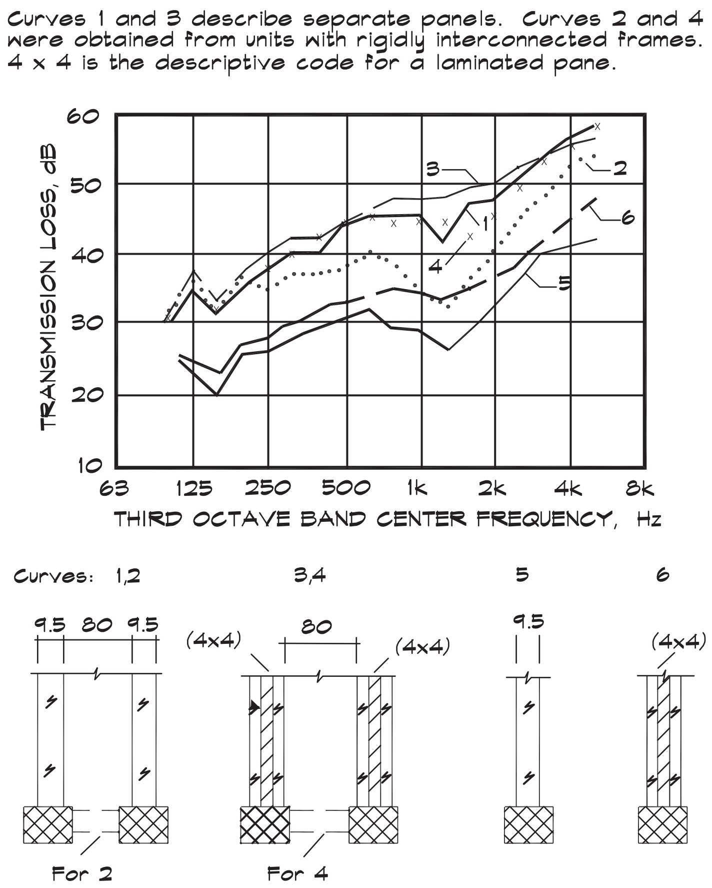


of distance between the panes and about the same increase per doubling of mass. Figure 9.24 gives laboratory data taken by Quirt (1982) for various thicknesses and spacings of window glazing. The upward trend for both mass and spacing is clear.

In the case of gypboard panels, the coincidence frequency can be kept high by using multiple sheets of differing thicknesses that are spot laminated together. In other cases, panels can be designed so that the coincidence frequency is greater than the frequency range of interest. Where thick panels such as concrete slabs or grouted concrete masonry units are used, an additional separately supported panel of gypsum board can be used to offset the low shear frequency of the concrete with a high coincidence frequency in the gypboard. In the coincidence region, the ideal mismatch is on the order of a factor of two; however, more modest ratios can provide several dB of benefit.

The coincidence effect is emphasized, perhaps overemphasized, by the STC test procedure since the knee in the standard STC curve falls at about half the critical frequency of 16-mm (5/8") drywall. Due to this fact double walls with single 13 mm (1/2") gypboard often test higher than 16 mm (5/8") gypboard and 10 mm (3/8") higher than 13 mm (1/2") (California Office of Noise Control, 1981). For a given mass of panel the thinner material is more effective due to the higher critical frequency. A higher STC value in these cases does not necessarily mean that a given construction is more effective at reducing noise, since

FIGURE 9.23 Transmission Loss Tests on Laminated and Double Glazed Windows (Vinokur, 1996)

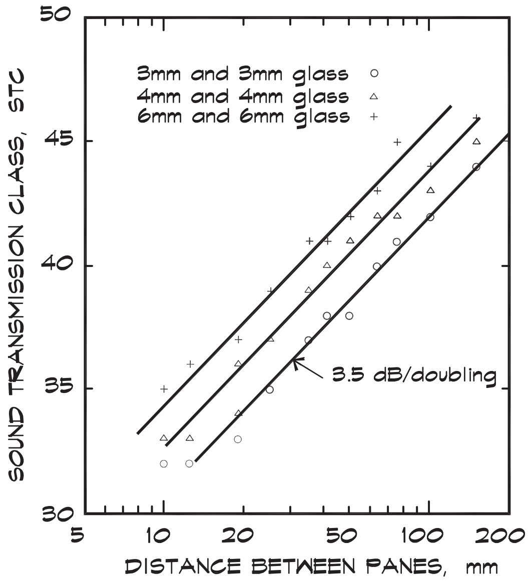


noise reduction depends on the source spectrum. At low frequencies, the heavier panels are more effective regardless of their STC rating.

There is a common misunderstanding, particularly in the design of windows in sound studios, that the slanting of one of the panes of glass with respect to the other provides some acoustical benefit. The mass-air-mass resonance is a bulk effect and is shifted only slightly by the use of a slanted panel. A careful study of window design effects, undertaken by Quirt (1982), showed that slanting had no appreciable effect on the transmission loss of double pane windows. However the technique of slanting one sheet of glass in studio control room windows is useful in reducing the ghost images from light reflections between the panes.

The introduction into the airspace of a gas such as argon, carbon dioxide, or SF_6, which have a sound velocity lower than that of air, has much the same effect as batt insulation in the cavity. Gasses that have a higher velocity than air, such as helium, can also be effective. These gasses are used in hermetically sealed dual-paned windows. The mismatch in velocity reduces the coincidence effect since, when the interior wave matches the bending velocity, the exterior wave does not.

FIGURE 9.24 STC vs Interpane Spacing for Separately Supported Double Glazing (Quirt, 1982)



9.4 TRIPLE-PANEL TRANSMISSION LOSS THEORY

Free Triple Panels

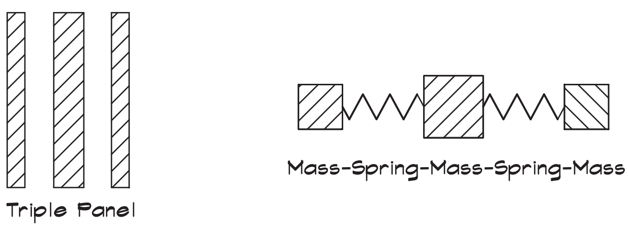
The impedance of ideal triple panels, with no mechanical connections, can be calculated in a similar fashion to that used to obtain the double panel result. The system is pictured in Fig. 9.25. It consists of three masses and two air springs and is a two-degree of freedom system. As such it has two resonant frequencies given by the equation (Vinokur, 1996)

$$f_{\alpha,\beta} = \frac{1}{2\pi}\sqrt{3.6\,\rho_0\,c_0^2}\,\sqrt{a \pm \sqrt{a^2 - b}} \qquad \left(f_\beta > f_\alpha\right) \tag{9.52}$$

where $a = \dfrac{1}{2\,m_2}\left(\dfrac{m_1 + m_2}{m_1\,d_1} + \dfrac{m_2 + m_3}{m_3\,d_2}\right)$

$$b = \frac{M}{m_1\,m_2\,m_3\,d_1\,d_2}$$

FIGURE 9.25 General Model of a Triple Panel System



m_i = mass of the i th panel (kg / m^2 or lbs / ft^2)
d_j = spacing of the j th air gap between the layers (m or ft)
$M = m_1 + m_2 + m_3$

The resulting transmission loss can be simplified (Sharp,1973) to provide approximations, which fall into three frequency ranges

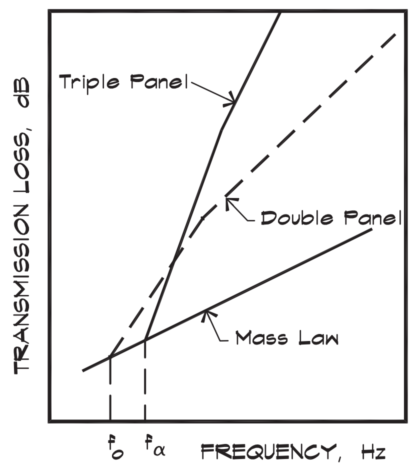
$$\Delta L_{TL} \cong \begin{Bmatrix} 20 \log (M f) - K_{TL} & f < f_\alpha \\ \Delta L_{TL1} + \Delta L_{TL2} + \Delta L_{TL3} + 20 \log (2 k d_1) + 20 \log (2 k d_2) & \\ & f_\beta < f < f_l \\ \Delta L_{TL1} + \Delta L_{TL2} + \Delta L_{TL3} + 12 & f_l > f \end{Bmatrix} \quad (9.53)$$

Below the lower mass-air-mass resonance, the triple-panel construction reverts to mass-law behavior. Above the higher mass-air-mass resonance, but lower than the lowest cavity resonance divided by π (as defined by Eq. 9.51), the transmission loss increases at a rate of 30 dB per octave compared with 18 dB per octave for the double panel. In this frequency range the transmission loss is increased 18 dB per doubling of mass.

Comparison of Double and Triple-Panel Partitions

It is useful to compare the behavior of double- and triple-panel walls, which are available for the construction of critical separations such as those found in sound studios and high-quality residential construction. At low frequencies, below f_0, the mass law applies to both types of construction, so for a given mass and thickness the performance is the same. Figure 9.26 shows a graph of the transmission loss achieved by the two types. Here the triple panel has a symmetric construction with the center panel having twice the mass of the outer panels and equal air spaces on either side. For this configuration, the lowest mass-air-mass resonant frequency, f_α, is twice that of the double construction frequency f_0. The two transmission

FIGURE 9.26 Double and Triple Panel ΔL_{TL} Comparison (Sharp, 1973)

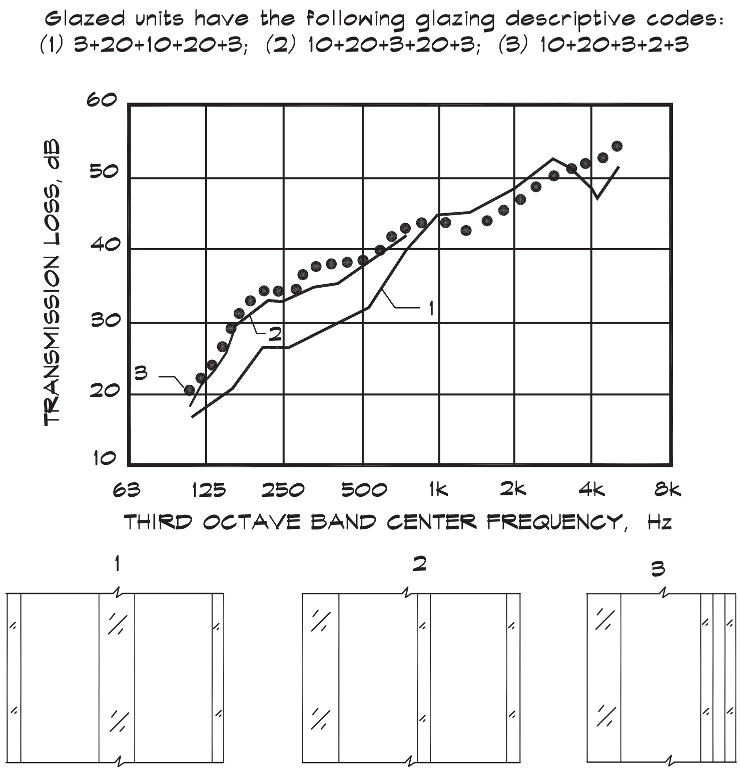


loss curves cross at a frequency that is four times f_0. Thus, assuming no connections between the panels, the double panel system is better below $4f_0$ and the triple panel is better above $4f_0$. For a wall consisting of one layer of 16 mm (5/8") gypboard on the outer panels and two layers on the inside, separated by two 90 mm (3.5") airspaces, the crossover point $4f_0$ is about 260 Hz.

In general, walls with double panels are more efficient for the isolation of music, where bass is the main concern, and triple panels for the isolation of speech. Triple panels, however, are more forgiving of poor construction practice, such as improperly isolated electrical boxes and noisy plumbing, since they provide an additional layer in the middle of the wall or floor. These practical effects in many cases may be more important than a theoretically higher transmission loss.

For a given total mass and thickness, triple-glazed windows are not as effective as double glazing, since the separation between panes in triple-glazed windows is not large. They are most effective when the heaviest sheet of glass is an outer layer and not in the center, and when the airspace dimensions are not the same. Figure 9.27 illustrates this point through a series of tests carried out by Vinokur (1996). Example 2 shows the effect of the transposition of position of the heavy and light sheets of glass. Example 3 shows that it is effective to closely space the two light panes of glass even when the larger airspace does not increase. This configuration acts more like a double-glazed unit. At the higher frequencies, the primary transmission path in windows is from pane to pane through the edge connections at the frame.

FIGURE 9.27 Measurements of Triple Panel Glass Units (Vinokur, 1996)



9.5 STRUCTURAL CONNECTIONS

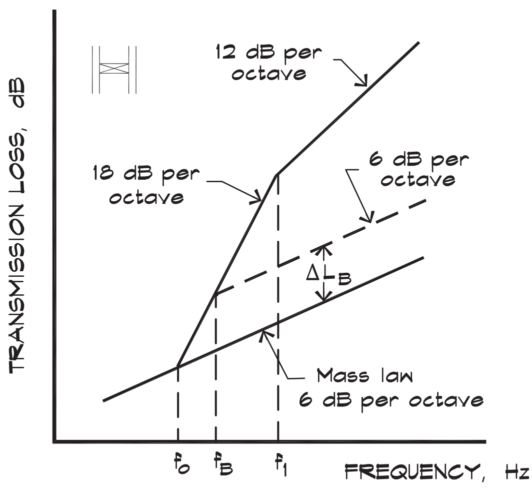
Point and Line Connections

In the previous theoretical analysis, it has been assumed that there were no structural connections linking the panels, in either the double or the triple constructions. The only means of connection between the panels was through the coupling provided by the air space. In actual building construction, there are studs, joists, and other elements that provide the structural support system and physically connect panels together. These produce a parallel means of sound transmission, by way of mechanical connections from one panel to another. In general there are two types of connections: a line connection, such as that provided by wood or metal studs, which touch the panels continuously along their length; and a point connection, in which the contact is made over a relatively small area that approximates a point.

The theory published by Sharp (1973) for the transmission of sound through mechanical connections assumes that the power transmitted by the panel on the receiving side is proportional to the square of the velocity of the panel and to its radiating area. It further assumes that, in the local area around the connection, the panel velocity on the receiving side is the same as on the sending side, and that the sending side panel is unaffected by the presence of the receiving side panel. He develops the equivalent radiating area for point and line connections, since these areas act as localized sources, which transmit energy in addition to that transmitted by the air-gap transmission path. The bridging energy transmitted is proportional to the transmitting area, which decreases with frequency since its effective radius is about one-quarter of the bending wavelength. The power radiated by this area, however, increases with frequency so that the total bridging energy transmitted stays constant.

The effect of sound bridges in double-panel construction is shown in Fig. 9.28. The normal double-panel transmission loss is truncated by the extra energy transmitted through the solid connections above the bridging frequency. The limiting value of the transmission

FIGURE 9.28 Transmission Loss of a Double Panel with Structural Bridges (Sharp, 1973)



loss above the composite mass law is given for point connections (Sharp, 1973)

$$\Delta L_{BP} = 20 \log \left(e\, f_c\right) + 20 \log \left(\frac{m_1}{m_1 + m_2}\right) - K_{BP} \tag{9.54}$$

and for line connections

$$\Delta L_{BL} = 20 \log \left(b\, f_c\right) + 20 \log \left(\frac{m_1}{m_1 + m_2}\right) - K_{BL} \tag{9.55}$$

where e = point lattice spacing (m or ft)
b = line stud separation (m or ft)
m_1 = mass per unit area of the panel (kg/m^2 or lb/ft^2)
m_2 = mass per unit area on the side supported by point or line connections (kg/m^2 or lb/ft^2)
f_c = critical frequency of the panel supported by point connections or, in the case of line connections, the higher critical frequency of the two panels (Hz)
K_{BP} = constant for point connections
= − 44.7 for metric units
= − 55 for FP units
K_{BL} = constant for line connections
= − 22.8 for metric units
= − 28 for FP units

The bridging frequency for point connections is

$$f_{BP} = f_0 \left(\frac{e}{\lambda_c}\right)^{1/2} \tag{9.56}$$

and for line connections

$$f_{BL} = f_0 \left(\frac{\pi\, b}{8\, \lambda_c}\right)^{1/4} \tag{9.57}$$

Note that e^2 = the area associated with each point connection (m^2 or ft^2)
f_0 = fundamental resonance of the double panel (Hz)

The overall transmission loss for a bridged double panel is given by

$$\Delta L_{TL} \cong \begin{Bmatrix} 20 \log (M\, f) - K_{TL} & f < f_0 \\ \Delta L_{TL1} + \Delta L_{TL2} + 20 \log (2\, k\, d) & f_0 < f < f_B \\ 20 \log (M\, f) - K_{TL} + \Delta L_B & f_B < f < 0.5 f_c \end{Bmatrix} \tag{9.58}$$

FIGURE 9.29 ΔL_{TL} for a Point Mounted Double Panel Sharp (1973)

Measured values of transmission loss for a double panel with one and both panels mounted with point connections.

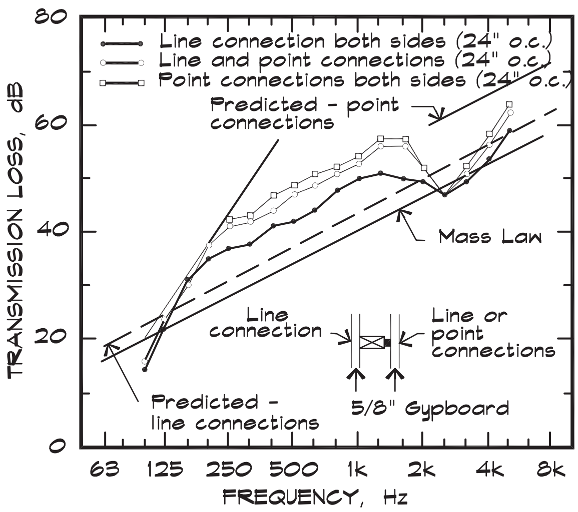


Figure 9.29 shows the results of measurements of bridged double panels done by Sharp (1973). The figure illustrates that there is little advantage to mounting both sides on point connections. Note that Eq. 9.58 does not account for the behavior at the critical frequency where the energy is transmitted by an airborne path. At the critical frequency, the various connection methods yield the same results.

When making a comparison between theoretical and laboratory transmission loss data, calculated data yield a higher result. Better agreement is obtained by assuming line bridging at a spacing based on edge connections for the panel area specified in the test standard.

Transmission Loss of Apertures

The sound transmission through apertures has been treated in some detail. Wilson and Soroka (1965) utilize an approach that analyzes a normally incident plane wave falling on a circular opening of radius a and depth h. They assume massless rigid pistons of negligible thickness at the entrance and exit of the aperture, which simulate the air motion. The radiation impedance is assumed to be that of a rigid piston in a baffle discussed in Chapt. 6. The transmission coefficient is

$$\tau = 4\, w_r \begin{Bmatrix} 4\, w_r^2 (\cos k\, h - x_r\ \sin k\, h)^2 + \\ \left[(w_r^2 - x_r^2 + 1)\ \sin k\, h + 2\, x_r\ \cos k\, h \right]^2 \end{Bmatrix}^{-1} \tag{9.59}$$

where w_r and x_r are the resistive and reactive components of the mechanical radiation impedance of the piston radiator from Eq. 6.65. The real and imaginary parts are given in Eqs. 6.66 and 6.68.

FIGURE 9.30 Transmission Loss through a 1" (25 mm) Diameter 4"(100 mm) Long Hole (Gibbs and Balilah, 1989)

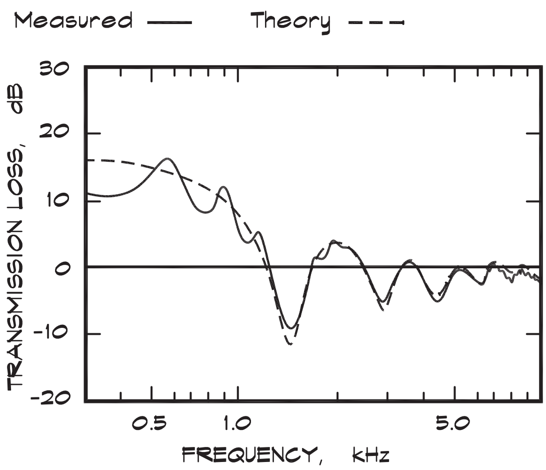
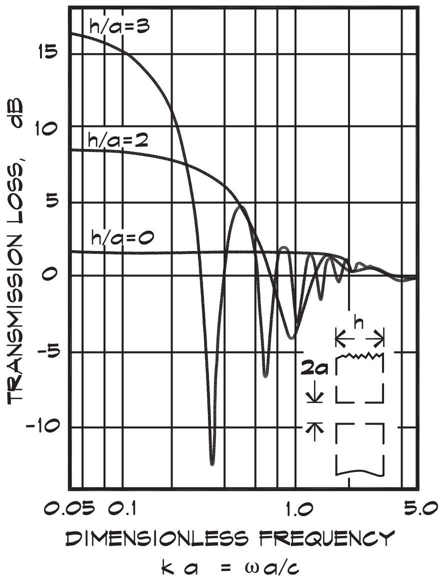


FIGURE 9.31 Transmission Loss through a Circular Aperture vs Frequency for Various h/a Ratios (Wilson and Soroka, 1965)



Apertures in enclosures can create Helmholtz resonator cavities, which increase the noise emitted from a source housed within them in much the same way that bass-reflex enclosures are used with cone loudspeakers to augment the low-frequency response. Figure 9.30 (Gibbs and Balilah, 1989) plots the theoretical and measured transmission loss of a 1" (25 mm) diameter hole having a 4" (100 mm) length. At low frequencies there is about a 16 dB (theoretical) loss in this example, which drops sharply at the first open-open tube resonance. The transmission loss is negative in the vicinity of the tube resonant frequencies and gradually goes to zero as the wavelength approaches the hole diameter. Similar results were obtained by Sauter and Soroka (1970) for rectangular apertures. The loss at low frequencies depends on the ratio of the depth, h, to the hole radius, a. Figure 9.31 illustrates this effect.

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