Evaluating Sound-Transmission Effects in Multi-Layer Partitions

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The most important sound-transmission phenomena in partitions include mass law, coincidence, and mass-spring resonances. Other important effects also exist that significantly affect airborne sound insulation by multi-layer partitions (windows, walls, and floors). This article briefly describes such effects and illustrates them with experimental results. Mass-spring resonances (in triple window glazings) and "linear sound bridge" transmission have been given main consideration.

In spite of the interest in active control of noise, traditional "passive" techniques prevail. The sound insulation provided by partitions such as walls, windows, and floors is of great importance. High-frequency noise can be controlled easily by partitions. Their sound insulation abilities at low frequencies is more difficult to accomplish, however. Sound transmission effects are peculiar in that they are not always obvious. An improperly designed partition may appear reliable. When such a partition is built and tested, however, its acoustical deficiencies are often perceived by ear without additional measurements. It should be noted that trustworthy calculation methods have been developed to determine the sound insulation of comparatively simple partitions. Lesser known phenomena that regularly occur in actual practice are discussed here.

The author has tested a rich variety of experimental and commercial windows, walls, and floors, and has evaluated a number of effects which significantly affect sound transmission. This article will expose readers to several important phenomena occurring in multi-layer partitions. It is illustrated with experimental results obtained by the author at the Laboratory of Building Acoustics, Moscow, Russia.

Resonances in Double Partitions

In 1950, A. London evaluated the sound insulation of double partitions consisting of two thin layers with an air gap between them as shown in Figure 1a.[1] He concluded that double partitions may be less effective than each of the layers individually at low frequencies. It should be noted that London considered the layers to be identical and of infinite extent. Nevertheless, his results advanced understanding of sound insulation techniques. He determined that the main reason for the reduced sound insulation of double partitions at low frequencies is that a double partition acts as if it were a single-degree-of-freedom resonant system. In such a system, the masses and the spring simulate the layers and the air gap, respectively, as shown in Figure 1b.

The resonance frequency is given by the equation:

$$f_0 \quad \frac{1}{2}\sqrt{\frac{c^2 M_1 M_2}{(M_1 \quad M_2)d}} \qquad (1)$$

M_1, M_2 = surface densities (mass/unit area) of the layers
d = thickness of air gap
ρ = air density, 1.29 kg/m^3
C = speed of sound in air, 340 m/s

One should be aware of the fact that the mass-spring-mass model is just an approximation. It is correct at frequencies which are well below both the critical coincidence frequencies of the layers (otherwise, we can't neglect the springiness of the leaves) and the resonance frequency of the air gap $f_a = C/(2d)$. In the opposite case, the air between the leaves could not be considered inertia free.

Mass-spring-mass resonances have a dramatic impact on the sound insulation of window glazings. In a single-space multiple glass unit, the pane edges are cemented along the perimeter to a plastic or aluminum profile functioning as a rigid frame, and sealed with rubber as shown in Figure 2a. Such a rigid boundary becomes an extensive "sound bridge" and is considered unfavorable from an acoustical point of view. Nevertheless, detrimental effects produced by the mass-spring-mass resonance prove to be more significant, at least at low frequencies. As seen in Figure 3, the single gap multiple glass unit with the glazing descriptive code 8+12+5 (glass layer + air gap + glass layer in mm), has a lesser sound insulating ability at low frequencies compared to a single pane that is 8 mm thick. In this case, the mass-spring-mass resonance frequency is approximately 200 Hz as calculated by Equation 1 provided the density of the glass equals 2500 kg/m^3. After eliminating the cement layer connecting the 5 mm pane to the aluminum frame, the edge "sound bridge" was reduced, but sound transmission loss went up at relatively high frequencies (above 800 Hz). The low-frequency region affected by the mass-spring-mass resonance remained the same.

What needs to be done to lessen the unfavorable effect of the resonance on sound insulation of double partitions? Sound-absorptive materials can be installed in the air gap between the leaves and the resonance frequency can be decreased by increasing the thickness of the air gap and/or the surface densities of the layers. A question may be raised as to whether lowering the resonance frequency is always beneficial. Similarly, what value of resonance frequency is the most adverse? The author statistically processed experimental data for about 40 different glazings. Using various criterions (single numbers derived from the measured frequency characteristics of sound transmission loss), it was found that the "worst" mass-spring-mass resonant frequency lies between 200 and 250 Hz. That means, for example, that a double glazing of 3+18+3 is less effective in acoustical performance than one with a descriptive code of 3+9+3. This is because the resonance frequencies of the glazings are 230 and 327 Hz, respectively, and the lowest frequency is the worst case if the total surface densities of the glazings are the same. It should be noted that such a phenomenon is not important, for example, for multiple gypsum board partitions because their air gaps are wide enough, and, hence, the resonance frequencies are usally well below 200 Hz. Sound insulation by a double partition tends to be higher than that of a single partition of the same total surface density if the mass-spring-mass resonance frequency is below the frequency range tested (the lowest test frequency is usually 100 Hz).

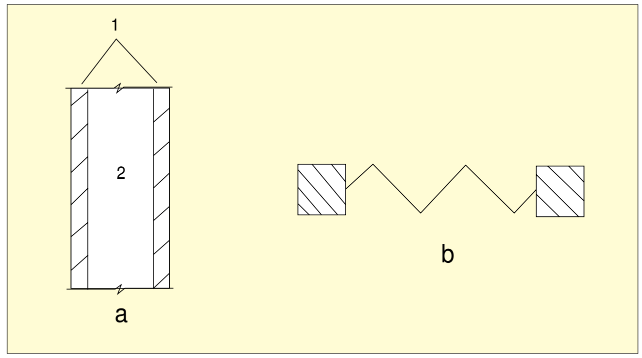

Figure 1. A typical double partition: (a) general view; (b) mass-spring-mass analogy at low frequencies; 1 – layers; 2 – air gap.

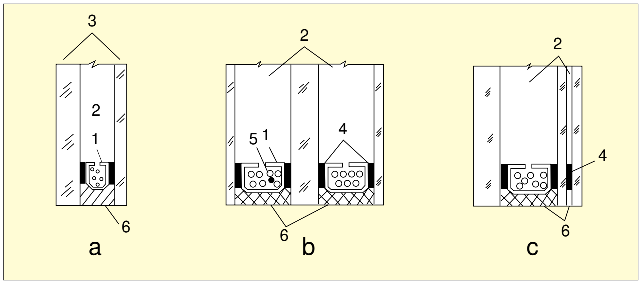

Figure 2. Multi-layer glass units: (a) single-space; (b) symmetrical double-space; (c) asymmetrical double-space; 1 – separating frame; 2 – air cavity; 3 – glass panes; 4 – mastic; 5 – silica gel granules to absorb moisture; 6 – rubber seals.

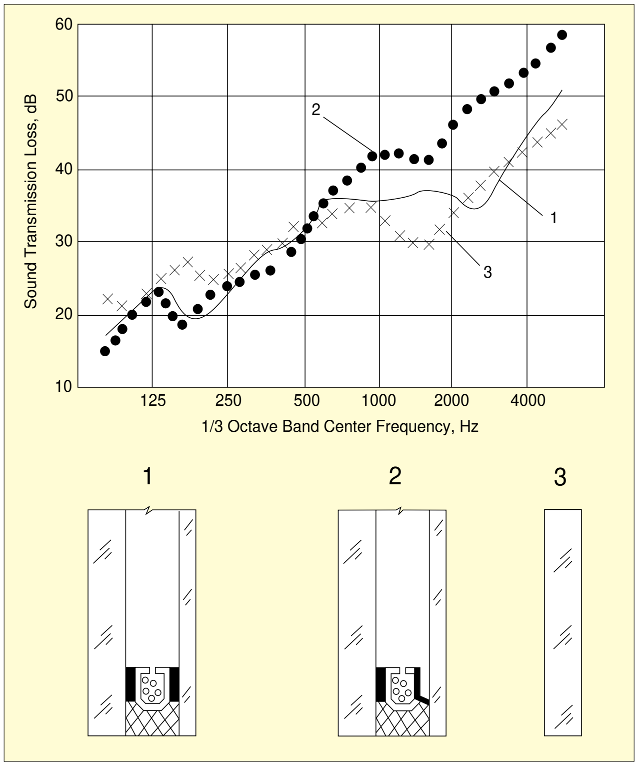

Figure 3. Measured transmission loss as a function of frequency. Curves 1 and 2 are associated with a single-space glass unit of 8+12+5 mm; In case 2, the mastic layer between the frame and 5 mm pane has been removed to minimize the rigid structural link between the panes. All the partitions tested measured 1.1 m long and 0.9 m wide. Curve 3 is the transmission loss of an 8 mm pane.

Resonances in Triple Partitions

The "paradox" of low sound insulation in symmetrical configurations. Triple partitions with three layers and two air gaps as shown in Figure 4 are much more "enigmatic" than double-layer partitions. Sound-transmission effects unique to triple-layer partitions are not well-known although they might be considered quite important. Triple glazings have been used to improve thermal insulation by windows in areas with extremely cold winters. At first, it was believed that triple windows would provide excellent sound insulation as well. Such an opinion was based upon erroneous assumptions that materials and methods, which are effective for thermal insulation, are also effective for sound insulation. Actually, two separate problems need to be considered even though certain types of structures are effective for both. If the total width of the air gaps is large enough, the unit should be effective for both thermal and sound insulation. Otherwise, a triple unit may be approximated by a simple mechanical resonant system consisting of masses and springs. as shown in Figure 4b. However, this system is more complicated than the analogy for a double partition. It includes three masses and two springs, and is therefore a two degree-of-freedom system. The masses and the springs simulate the layers and the air gaps, respectively. Such

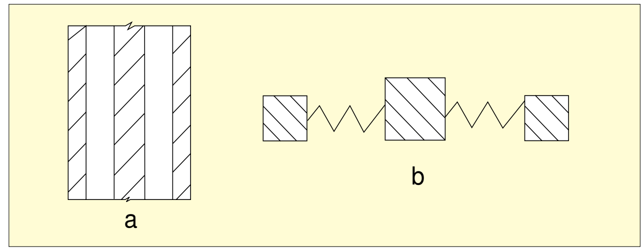

Figure 4. Triple partition: (a) general view; (b) mass-spring-mass-spring-mass analogy at low frequencies.

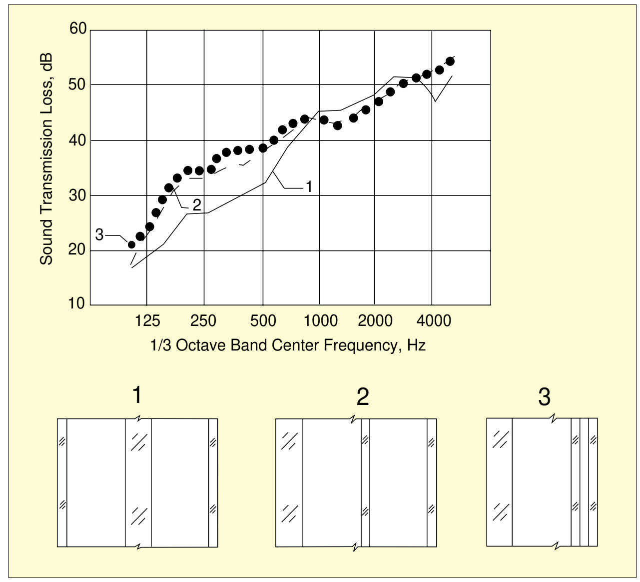

Figure 5. Measured transmission loss of double-space glass units with the following glazing descriptive codes: (1) 3+20+10+20+3; (2) 10+20+3+20+3; (3) 10+20+3+2+3.

a system has two resonance frequencies which are given by the equation:

$$f_{1,2} \quad Q\sqrt{a \quad \sqrt{a^2 \quad b}} \qquad (f_2 \quad f_1)$$

with the values $Q \quad \sqrt{\quad c^2} \,/\, 2$

$$a \quad \frac{1}{2M_2}\left(\frac{M_1 \quad M_2}{M_1 d_1} \quad \frac{M_2 \quad M_3}{M_3 d_2}\right)$$

$$b \quad M \,/\, (M_1 M_2 M_3 d_1 d_2)$$

M_i = surface density of the ith layer
d_j = thickness of the jth air gap between the layers
$M = M_1 + M_2 + M_3$

The transmission loss by a triple partition at low frequencies primarily depends on the location of the internal layer.[2] Usually the external layers are similar and the internal layer is evenly spaced between them. This is the worst case from an acoustical standpoint. The explanation is simple. In a symmetrical unit, the ratio of the first resonance frequency f_1 to the second f_2 approaches 1, provided the internal layer's surface density approaches infinity. Even if the layers are the same, such a ratio equals about 0.6. However, the closer the resonance frequencies, the more significant the reduction in transmission loss. That is why a symmetrical configuration is undesirable if sound insulation is of importance. It should be noted that all the results mentioned above are correct if the sum of the air gaps widths is comparatively small. To illustrate the phenomenon, sound insulation by three double-space glazing units was measured. All the units consisted of two 3 mm and one 10 mm panes. Their descriptive codes were as follows: (1) 3+20+10+20+3; (2) 10+20+3+20+3; and (3) 10+20+3+2+3. As seen from Figure 5, the symmetrical case is the worst. In the asymmetrical case, produced by simple transposition of the massive internal pane and the light external pane, the trans-

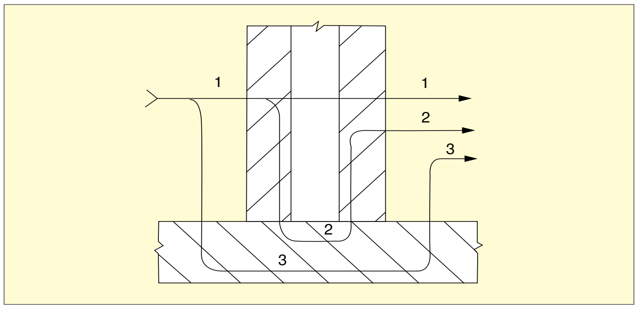

Figure 6. Direct (1), "linear sound bridge" (2), and flanking sound transmissions (3) through a double partition.

mission loss is much higher. Moreover, it's effective to closely space one external pane and the internal pane, even though the total width of the air gaps is nearly halved. The phenomenon discussed is revealed at frequencies where the resonances of the glazings (as with systems of masses and springs) take place. At higher frequencies, the transmission loss depends primarily on the sound transmission from pane to pane through their edge connections (see Figure 6, path 2).

Sound Transmission From Layer to Layer

Even lightweight double partitions can provide high airborne sound insulation. This can be achieved by increasing the air gap provided the airborne insulation is controlled only by direct sound transmission via the layers and air gap (see path 1 in Figure 6). In practice, direct transmission plays no significant role at high and, in many cases, middle frequencies. Direct transmission is usually prevalent at comparatively low frequencies especially, in the vicinity of the mass-spring-mass resonance frequency. At higher frequencies, transmission via sound bridges becomes dominant. Linear sound bridges are known to be of much greater consequence than point sound bridges. For example, in multiple glass units, the edge structural link creates a linear bridge distributed along the perimeter. In multi-layer gypsum panels, linear sound bridges are formed by the wooden or metal joists. In massive double walls, "sound bridge" transmission goes through the layers and adjacent parts of flanking partitions. Although, flanking sound transmission (path 3, Figure 6) occurs around one or both panels, in this discussion, we will mainly consider "linear sound bridge" transmission (path 2, Figure 6).

To gain greater insight into the peculiarities of "sound bridge" transmission, measurements were made of the airborne sound transmission losses of partitions consisting of two wood frames with a glazing specimen mounted in each of them as either an ordinary pane, a single space multiple glass unit with a rather thin air gap, or a laminated pane. For the first specimen, the frames were vibrationally isolated from one another. In the second case, the frames were firmly interconnected all around their perimeter. This enabled us to compare the airborne sound insulation of the same partition in the case of direct transmission only and where both direct and "sound bridge" transmission existed. The measured transmission loss by the partitions with either 6 mm panes or glazing units (3+2+3) are presented in Figure 7.

One finds that if "bridge" transmission is absent, there is no significant difference between the sound transmission losses of both double partitions. Sound bridge transmission decreases airborne sound insulation of the partitions (with identical 6 mm panes) about 10 dB at a frequency of 2,000 Hz which is the coincidence frequency of a 6 mm pane. The coincidence frequency of a 3 mm pane is 4,000 Hz. Curve 2 (6+100+6) looks much different from curve 4 (3+2+3+100+3+2+3) despite the fact that total surface densities and air gaps are the same. It should be noted that the width of the narrow air gaps in the glass units is not important. Similar results were obtained using single-space glazing units (3+0.5+3). The reason for this is as follows: replacing each layer of a double partition with a system consisting of two thin leaves increases the coincidence

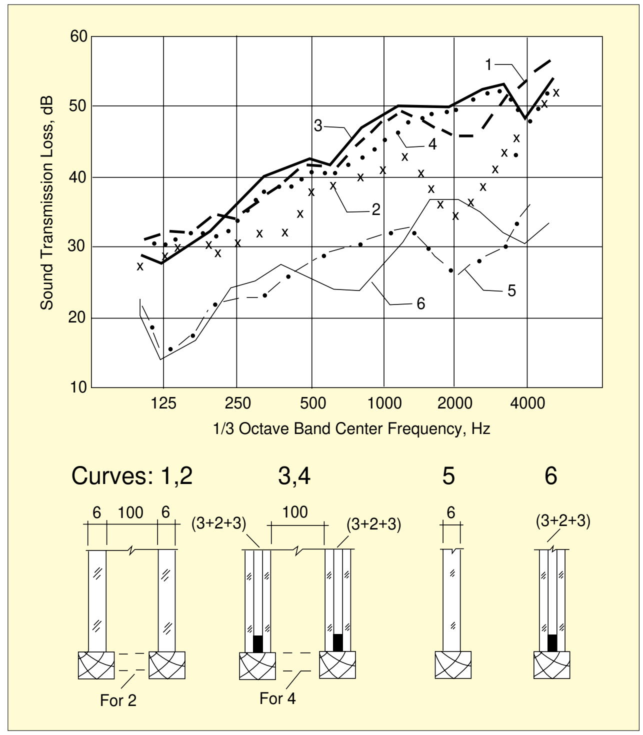

Figure 7. Measured transmission loss of various glazing configurations. Curves 1 and 3 describe "direct sound transmission." Curves 2 and 4 were obtained from units with rigidly interconnected frames.

frequency of the partition elements. If this frequency is rather high, the coincidence dip has little effect on the sound insulation. That is why gypsum board partitions are often built of several thin layers. Such a structure may have a comparatively large surface density provided that the coincidence frequency remains high enough to reduce the linear bridge effect. It is important to mention that such an obvious result is not trivial. For example, similar double glazing partitions also were investigated.[4] The results were comparable to those described above but the explanation was different: the double partition with "thin" glass units was more effective due to sound energy dissipation in the narrow air gaps. This evaluation did not even consider edge conditions.

The other way to reduce unfavorable "sound bridge" transmission is to increase the total loss factors of the layers. Laminated panes as shown in Figure 8 provide this function. They consist of two or more glass panes coupled with a transparent polyvinylbutyral film (typically 0.7 or 1.4 mm thick). Such a structure, compared to "ordinary" panes, has the ability to dissipate substantial vibration energy. The coincidence frequency of a laminated pane may be identical to that of an "ordinary" pane of the same surface density. A laminated pane consisting of two 4 mm "ordinary" panes coupled with a polyvinylbutyral film 1.44 mm thick has a surface density of 24 kg/m^2 and coincidence frequency of 1250 Hz. This is close to those of an "ordinary" glass pane 9.5 mm thick. Let's denote such a laminated pane with a descriptive code of 4×4. As shown in Figure 8, if "bridge" transmission is absent, then the transmission loss of both double partitions tested is nearly the same. Bridge transmission essentially decreases airborne sound insulation by the partitions, with identical 9.5 mm thick panes, about 10 dB at the coincidence frequency. Note that bridge transmission affects the transmission loss of a double partition with ordinary panes having substantially different thicknesses of 9.5 and 3.5 mm to a lesser extent as shown in Figure 9.

Practical Examples

How do lightweight multiple gypsum board partitions produce high sound insulation? Their surface density is not large compared to that of massive concrete or brick walls. Besides, they contain many structural links (metal or wood joists) which

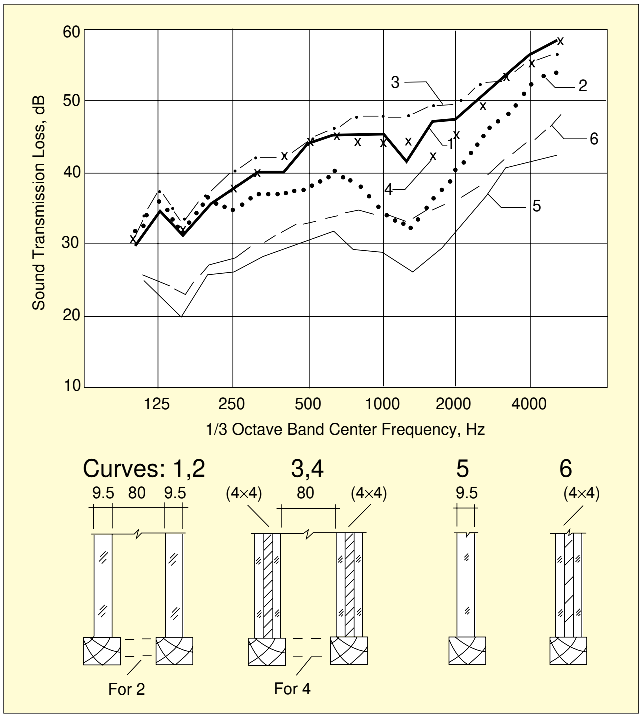

Figure 8. Measured transmission loss of various glazing configurations. Curves 1 and 3 describe “direct sound transmission.” Curves 2 and 4 were obtained from units with rigidly interconnected frames. 4 × 4 is the descriptive code for a laminated pane.

form linear sound bridges. If the air gap and surface densities of the layers are increased, the mass-spring-mass resonance frequency is reduced to well below 100 Hz. Direct sound transmission is reduced. Sound absorption material placed inside the air gap achieves the same objective. If direct transmission is low enough, “bridge” transmission must be considered. The problem isn’t simple because structural links remain intact. Nevertheless, this problem may be also be solved adequately. Each layer may consist of comparatively thin gypsum board sheets. The coincidence frequency of each layer exceeds 3500 Hz (above the 3150 Hz upper limit of the frequency range used to characterize sound insulation). One can reduce “bridge” transmission significantly during assembly of a partition even though the structural links are still present. This is due to the same phenomenon which takes place in “thin” glass units with ordinary panes of the same surface density.

Another example is related to lightweight floor systems. The damped plywood material shown in Figure 10 is designed to be applied as a subfloor over wood and metal joists and consists of two plywood layers coupled with a viscoelastic core.[5] Such a structure proved to have higher sound insulation than a plywood layer of equivalent thickness. There are two reasons for this: 1) two thin layers are used instead of one thick layer; and 2) the loss factor of the multi-layer material is higher due to the viscoelastic core than for a single-layer plywood material.

Summary

Sound-transmission phenomena that affect sound insulation include the resonances of the partition modeled as a system of masses (layers) and springs (air gaps) and effects produced by linear “sound bridges.” Resonances affect low frequencies while sound bridges affect higher frequency regions.

Mass-spring-mass-spring-mass resonances control sound insulation of triple windows in particular. The worst situation takes place in a “symmetrical case” (the external panes are similar, and air gaps are equally thick). In this case, the sound insulation remains low even with a massive internal pane. Resonances are of lessor concern if the fundamental frequency is low enough.

“Linear sound bridge” transmission is of great concern in the

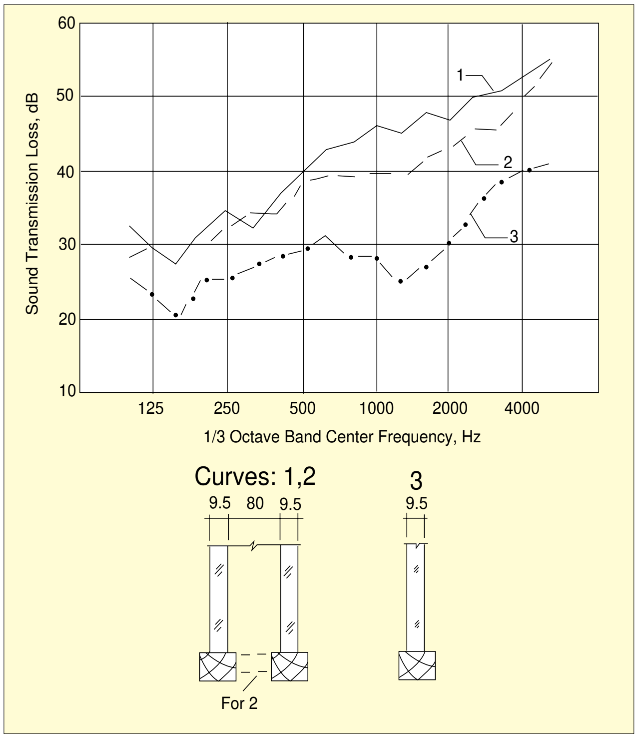

Figure 9. Measured transmission loss characteristics. Curve 1 describes "direct transmission." Curve 2 is associated with rigidly interconnected frames.

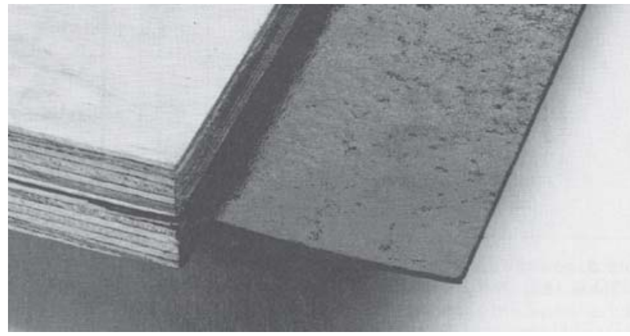

Figure 10. A closeup view of a plywood subfloor material with a viscoelastic core which is located at the center and adhered to both faces. The product has proven to be acoustically effective in thicknesses from 5/8 to 1-1/8 in.[5]

sound insulation of almost all partitions, especially in the vicinity of the coincidence frequencies of the layers if they are similar. Advantageous ways to reduce the "bridge" transmission are: 1) substantially increase the coincidence frequency by making up each layer with multiple layers of material; 2) increase loss factors of the layers by using "laminated" plates having a viscoelastic layer; and 3) use layers with different coincidence frequencies. All these techniques are effective providing the linear "sound bridges" remain rigid to maintain the structural integrity of the partitions.

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