Kirk-Othmer Encyclopedia of Chemical Technology.

INSULATION, ACOUSTIC

Acoustic insulation may be defined as a material or construction that reduces the passage or transmission of sound into or out of a medium such as air, water, or a solid structure. For the purpose of this article, sound is a vibratory disturbance in the air consisting of alternating compressions and rarefactions transmitted through the air in waves. The term acoustic insulation covers a broad range of materials and mechanisms for the control of sound: sound-absorbing materials that reduce the reflections of impinging sounds; sound-blocking materials that reduce sound transmission from one location to another; vibration isolating materials and devices that reduce transmission of vibrations from a vibrating source to potential sound-radiating structures; and vibration damping materials that reduce vibrations and sound radiation in and from materials and structures.

1. Sound Absorption

When a sound wave strikes a material a fraction of its energy is reflected and a fraction is dissipated, or absorbed, by the material. The fraction of sound energy absorbed by a material is designated by its sound-absorption coefficient (α). The sound-absorption coefficient of a given material is between zero and one; if it is zero all the impinging energy is reflected and none absorbed; if it is one all the energy is absorbed and none reflected.

1.1. Units

The unit of sound absorption is the metric sabin, which is equivalent to one square meter of "perfect" absorption, eg, one square meter of a material with $\alpha = 1.0$. The English unit of sound absorption is the sabin, which is equivalent to one square foot of perfect absorption. In order to avoid confusion, the designation metric should always be used when referring to metric sabins. The number of metric sabins of absorption provided by an area of material is calculated by multiplying its area by its sound-absorption coefficient. For example, 10 m^2 of material having a sound-absorption coefficient of 0.75 provides 7.5 metric sabins of absorption.

The sound absorption of materials is frequency dependent; most materials absorb more or less sound at some frequencies than at others. Sound absorption is usually measured in laboratories in 18 one-third octave frequency bands with center frequencies ranging from 100 to 5000 Hz, but it is common practice to publish only the data for the six octave band center frequencies from 125 to 4000 Hz. Suppliers of acoustical products frequently report the noise reduction coefficient (NRC) for their materials. The NRC is the arithmetic mean of the absorption coefficients in the 250, 500, 1000, and 2000 Hz bands, rounded to the nearest multiple of 0.05.

All materials, even those considered to be sound-reflecting, absorb some small fraction of the sound energy impinging on them. Table 1 provides sound-absorption coefficients for some common building materials.

Table 1. Sound-Absorption Coefficients (α) for Some Common Building Materials

Material	Octave band center frequency, Hz 125	250	500	1000	2000	4000	NRC
brick	0.03	0.03	0.03	0.04	0.05	0.07	0.05
concrete block							
coarse	0.36	0.44	0.31	0.29	0.39	0.25	0.35
painted	0.10	0.05	0.06	0.07	0.09	0.08	0.05
concrete, smooth	0.01	0.01	0.02	0.02	0.02	0.03	0.05
gypsum board on wood studs	0.29	0.10	0.05	0.04	0.07	0.09	0.05
heavy plate glass	0.18	0.06	0.04	0.03	0.02	0.02	0.05
wood floor	0.15	0.11	0.10	0.07	0.06	0.07	0.10

1.2. Test Methods

Two basic types of test methods are commonly used to measure sound-absorption in test laboratories: the reverberation room method and the impedance tube method.

1.2.1. Reverberation Room Test Method

The more widely used test method is the reverberation room method, defined in the United States by the American Society for Testing and Materials (ASTM) C423-90a (1). The basis for this test is the relationship that the rate of decay of an instantaneously stopped sound in a room is proportional to the amount of sound absorption in the room. The material is tested in a reverberation room where all other surfaces are hard and sound-reflecting. The rate of decay in each frequency band is measured with and without the sample, the number of metric sabins contributed by the sample is calculated, and the sound-absorption coefficients are determined based on the size of the sample and the amount of absorption provided. Because of edge effects the calculated absorption coefficients for a small sample are larger than for a large sample of the same material. To minimize this problem the standard recommends a sample size of 6.69 m^2 (72 ft^2) and requires that it not be less than 4.46 m^2 (48 ft^2). Even for the recommended sample size the measured sound absorption is influenced by edge effects, and for very efficient sound-absorbing materials the result can be calculated absorption coefficients greater than 1.0. These high coefficients, which are sometimes reported by manufacturers of acoustical products, are artifacts of the test procedure. Sound-absorption coefficients greater than one should never be used for acoustical analysis purposes.

The sound-absorbing properties of acoustical materials also are influenced by the manner in which the materials are mounted. Standard mounting methods for use in laboratory testing are specified in ASTM E795-92 (2). Unless noted otherwise, published data for acoustic ceiling materials are for Mounting Type E-400, for which the material being tested is suspended 400 mm below a hard surface.

For reverberation room tests of some irregularly shaped items, such as items of furniture, the number of sabins of absorption per item is commonly reported, rather than the absorption coefficient. It is important that the number and arrangement of the items also be reported because both of these factors can affect the results of the test.

Because the reverberation room test method approximates many real-world conditions, it is used to derive sound-absorption coefficients for evaluating the effect of most actual applications of sound-absorbing treatments. Sound-absorption coefficients published in acoustical textbooks and by manufacturers of acoustical materials are almost exclusively from reverberation room tests, and this may be assumed unless specified otherwise.

1.2.2. Impedance Tube Test Methods

There are two impedance tube test methods: ASTM C384-90a (3) and ASTM E1050-90 (4). Test method C384-90a makes use of a tube with a test specimen at one end, a loudspeaker at the other, and a probe microphone that can be moved inside the tube. Sound emitted from the loudspeaker propagates down the tube and is reflected back by the specimen. A standing wave pattern develops inside the tube, and the probe microphone determines the nature of the pattern. The normal incidence sound-absorption coefficient (α_n) is then calculated by means of a formula based on the ratio of the maximum to minimum pressure of the standing wave.

ASTM E1050-90 also makes use of a tube with a test specimen at one end and a loudspeaker at the other end, but instead of a single movable microphone there are two microphones at fixed locations in the tube. The signals from these microphones are processed by a digital frequency analysis system which calculates the standing wave pattern and the normal incidence sound-absorption coefficients.

One advantage of the impedance tube test methods is the small (usually <10 cm (4 in.) dia) size of the test samples. For these tests sound impinges on the test sample only at normal incidence to the surface, and the sound-absorption coefficients derived in this manner are valid only at this angle. Because of this limitation the tube methods are used primarily for research and for applications where sound is incident only normal to the surface of a material.

1.3. Materials

1.3.1. Fibrous and Foamed Materials

Most sound-absorbing materials are fibrous or porous and are easily penetrated by sound waves. Air particles excited by sound energy move rapidly to and fro within the material and rub against the fibers or porous material. The frictional forces developed dissipate some of the sound energy by converting it into heat.

The fibrous materials most often used for sound-absorbing purposes are composed of either glass fibers or mineral fibers. Fibrous glass, commonly known as fiber glass, is manufactured by forcing molten glass through a series of nozzles to form liquid fibers that are then split into smaller fibers with diameters of 1 to 10 μm (see Glass). The fibers are formed into unfinished blankets, batts, and boards of various densities, using a variety of binders to hold the fibers together. Glass fibers tend to shred or settle on contact or in the presence of vibration or high velocity air flow, so unfinished fiber glass products are often used for acoustical purposes behind protective sound-transparent facings. Fiber glass used for acoustical purposes should not be confused with fiber glass-reinforced plastic materials, also commonly referred to as fiber glass, which are used in boat construction and other products.

Rock wool, frequently referred to as mineral fiber, is made from nonvirgin siliceous materials and is formed in a similar manner to that of fiber glass. Refractory fibers(qv), also formed in a similar manner, are available for high temperature applications.

Foamed plastic acoustical materials are manufactured by two different processes. Both processes involve combining reactants that simultaneously produce a polymer, typically polyurethane, and generate a gas. Bubbles of gas expand the reacting mass and eventually form contiguous polyhedrons. If the contact planes between the polyhedrons rupture and establish openings between the cells, allowing air to penetrate, the material will have useful sound-absorbing properties. On the other hand, if the cells remain closed so air cannot penetrate, the foamed material will be ineffective as a sound-absorbing treatment. In one process a reacting mass is batch-formulated by allowing it to form a large bun about 1 meter thick that is then cut into sheets. Pressure-sensitive adhesives, mass-loaded backings or septums, or thin impervious plastic film facings are sometimes applied to the sheets. In another process the foam product is continuously cast and formed into a final thickness, and various substrates are applied as the foam is formed (see Foamed plastics).

Other fibrous and porous materials used for sound-absorbing treatments include wood, cellulose, and metal fibers; foamed gypsum or Portland cement combined with other materials; and sintered metals. Wood fibers can be combined with binders and flame-retardent chemicals. Metal fibers and sintered metals can be manufactured with finely controlled physical properties. They usually are made for applications involving severe chemical or physical environments, although some sintered metal materials have found their way into architectural applications. Prior to concerns regarding its carcinogenic properties, asbestos fiber had been used extensively in spray-on acoustical treatments.

1.4. Resonant Sound Absorbers

Two other types of sound-absorbing treatments, resonant panel absorbers and resonant cavity absorbers (Helmholtz resonators), are used in special applications, usually to absorb low frequency sounds in a narrow range of frequencies. Resonant panel absorbers consist of thin plywood or other membrane-like materials installed over a sealed airspace. These absorbers are tuned to specific frequencies, which are a function of the mass of the membrane and the depth of the airspace behind it. Resonant cavity absorbers consist of a volume of air with a restricted aperture to the sound field. They are tuned to specific frequencies, which are a function of the volume of the cavity and the size and geometry of the aperture.

1.5. Uses

Sound-absorbing materials are frequently used to reduce reverberation, or the persistence of sound in a space after generation of the sound ceases; to reduce focused reflections from concave surfaces; to prevent echoes, or delayed sound reflections from distant surfaces; and to prevent the buildup of sound by multiple reflections within rooms and other enclosures. Sound-absorbing materials also are used to reduce the transmission of noise from one location to another by multiple reflections from sound-reflecting surfaces.

1.5.1. Reverberation Control

Reverberation time (T_{60}) is defined as the length of time in seconds for the sound of an instantaneously stopped source in a room to decay by 60 decibels (dB). Reverberation time is one important factor in determining the acoustical character of a space and its suitability for specific activities. For lectures and other speech activities a relatively short reverberation time is desirable so that syllables do not persist and overlap one another, causing difficulty with intelligibility; conversely, for music activities, a relatively long reverberation time is desirable to allow blending of the sound and a sense of being surrounded by the music. Without reverberation music usually sounds dull and lifeless.

The reverberation time in a room is directly proportional to the volume and inversely proportional to the amount of sound absorption in the room. For most practical purposes the reverberation time is determined by the Sabine equation:

$$T_{60} = \frac{0.161\ V}{A}$$

where V is the volume of the room in m^3 and A is the total absorption in the room in metric sabins (5). Thus the reverberation time in an existing room can be decreased by adding sound absorption, or increased by removing sound absorption; if the amount of sound absorption is doubled, the reverberation time is cut in half, and vice versa. More sophisticated equations are sometimes used to take into account air absorption and other acoustical effects not accounted for in the Sabine equation, but for many applications the Sabine equation provides a satisfactory degree of accuracy.

1.5.1.1. Noise Reduction in Rooms. Sound from a source in an enclosed room can be divided into two parts: the direct field, dominated by sound radiated directly from a source to a receiver without reflections; and the reverberant field, dominated by sound that has been reflected many times by surfaces in the room before

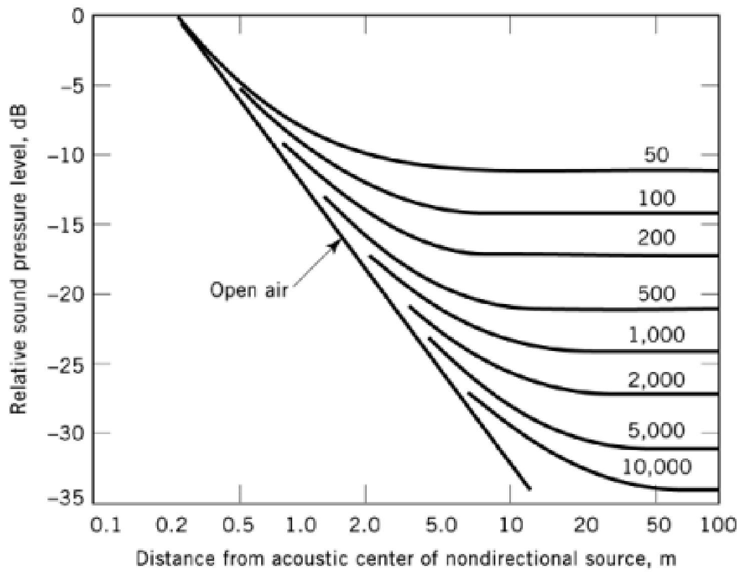

Fig. 1. Approximate relationship between sound pressure level and distance as a function of room absorption. Numbers on the curves are metric sabins.

it reaches a receiver (5). This relationship is defined by the following equation:

$$L_p(r) = L_w + 10\log_{10}\left(\frac{Q_\phi}{4\ \pi r^2} + \frac{4}{R}\right)$$

where $L_p(r)$ is the sound pressure level (dB at 20 μPa) at a distance r from the sound source and away from the immediate vicinity of any reflecting surfaces; L_w is the sound power level emitted by the source into the space (dB at 10^{-12} W); $Q_\varphi$is the directivity factor of the source in the direction φ, R is the room constant, m^2; $Q_\phi/4\ \pi r^2$ represents the direct field; and $4/R$, represents the reverberant field. The room constant, *R,* is difficult to determine, and for practical purposes the total absorption, *A,* may be substituted for *R*. Sound in the direct field is a function of distance from the source and drops off at approximately 6 dB per doubling of distance. Sound in the reverberant field is primarily a function of the amount of absorption in the room; each doubling of the amount of absorption reduces the reverberant sound pressure level by 3 dB. For most existing untreated rooms the practical upper limit of reduction that can be achieved for remedial purposes is about 10 dB. Figure 1 is a plot of the relative sound pressure level vs distance for spaces with total sound absorption ranging from 50 to 10,000 metric sabins. The sloped portions of the curves represent the sound in the near field of the source, while the flat portions represent the sound in the reverberant field.

1.5.2. Noise Transmission Reduction in HVAC Systems

One common use of sound-absorbing treatment is to reduce noise transmission in heating, ventilating, and air-conditioning (HVAC) systems (6). The treatments are used to reduce the transmission of fan noise and air turbulence noise through ducts into occupied spaces. Noise transmission reduction in duct systems is described in terms of insertion loss, the difference in sound power level or sound pressure level measured at a given location before and after installation of the treatment; or sound attenuation, the reduction in sound power between two locations affected by a sound source. The units are decibels.

Table 2. Sound-Absorption Coefficients (α) for Some Sound-Absorbing Treatments

	Octave band center frequency, Hz						
Treatment	125	250	500	1000	2000	4000	NRC
1.9-cm thick mineral fiber acoustic tiles[a]							
low absorption	0.40	0.30	0.54	0.78	0.67	0.48	0.55
high absorption	0.67	0.62	0.66	0.88	0.99	0.99	0.80
2.5-cm nubby fiber glass ceiling panels	0.70	0.95	0.75	0.99	0.99	0.99	0.90
fabric-wrapped fiber glass panels							
2.5-cm thick	0.07	0.37	0.73	0.97	0.99	0.99	0.75
5.1-cm thick	0.23	0.81	0.99	0.99	0.99	0.99	0.95
heavy velour draperies[b]	0.15	0.35	0.55	0.70	0.70	0.70	0.60
thin carpet on concrete	0.02	0.05	0.10	0.15	0.25	0.50	0.15
heavy carpet on pad on concrete	0.05	0.10	0.30	0.50	0.70	0.80	0.40
7.6-cm acoustical steel deck[c]	0.73	0.99	0.99	0.89	0.52	0.31	0.85
2.5-cm sprayed cellulose fiber	0.08	0.29	0.75	0.98	0.93	0.76	0.75

[a]Mounting E-400 (Ref. 2).
[b]50% fullness spaced 15 cm from hard surface.
[c]Ribbed deck with ribs filled with fiber glass and sides perforated (Fig. 2).

1.5.3. Sound Blocking

Most sound-absorbing materials by themselves are not effective as sound barriers for blocking sound transmission; air can penetrate these materials and so can sound. As a result, wrapping or enclosing noisy equipment in fiber glass or porous foam materials does little to reduce the noise radiated to the surrounding areas. Although sound-absorbing materials by themselves are ineffective as sound barriers, they can improve the sound-isolating performance of impervious materials when combined with them.

1.6. Products

There is a large number of commercially available sound-absorbing products for use on ceilings, walls, and for other special applications. Sound absorption coefficients and NRC values for some sound-absorbing products and treatments are indicated in Table 2.

1.6.1. Unfinished Products

Unfinished fiber glass products are available in the form of boards, blankets, and batts in various thicknesses and densities. These products are used by fabricators who apply finishes to make products suitable for ceilings, walls, open-plan office screens, etc. They also are used for sound absorption behind decorative and protective facings such as perforated or expanded metal and wood grilles. Thicker materials have better low frequency performance than thinner materials. Low frequency performance can be improved by spacing the material away from a sound-reflecting surface rather than applying the material directly to the surface.

1.6.2. Ceiling Tiles and Panels

Acoustical ceiling tiles and lay-in panels are the most commonly used acoustical products for noise and reverberation control in architectural applications. The majority of ceiling tiles and panels are manufactured using mineral fibers and a gypsum binder, although fiber glass panels also are common. The units are factory painted using nonbridging paints. Repainting, which can bridge the openings that allow sound to penetrate and be absorbed, should be done carefully and only with nonbridging paints. Typical tiles are 30.5 cm (12 in.) by 30.5 cm and range in thickness from 1.3 cm ($\frac{1}{2}$ in.) to 1.9 cm ($\frac{1}{3}$ in.). They are installed most frequently as suspended ceilings below the structural members and ventilating ducts in commercial buildings, although they

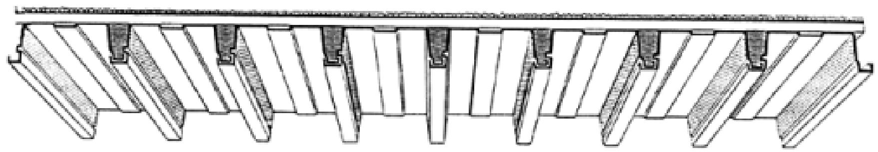

Fig. 2. Typical ribbed acoustical metal deck.(Courtesy of Inryco.)

also can be adhesive-applied to gypsum board or plaster ceilings. Most acoustical ceiling panels are 61 cm (24 in.) by 61 cm or 61 cm (24 in.) by 122 cm (48 in.), although other sizes are sometimes available. Thicknesses range from 1.3 cm ($\frac{1}{2}$ in.) to 3.8 cm (1–$\frac{1}{2}$ in.). The panels usually are laid into a grid of horizontal members having an inverted T-shaped section, allowing the panels to be lifted for access to the plenum space above the ceiling. Ceiling tiles and panels are generally soft and friable and are not suitable for use on surfaces that are subject to abuse.

1.6.3. Metal Pan Assemblies

These units consist of tiles and panels formed from perforated aluminum or steel with pads of fiber glass or mineral wool inserted into the pans to provide the sound absorption. They are used primarily for ceilings in a similar manner to acoustical tiles and panels. The pads are sometimes sealed in plastic film to prevent absorption of moisture, dirt, and odors. The perforated metal is relatively sound transparent and functions as the finished ceiling and the support for the sound-absorbing material. The perforated metal by itself has no acoustical value.

1.6.4. Spray-On Treatments

Several types of sound-absorbing treatments are available for spray-on application to a backup surface of concrete, gypsum board, plaster, or other hard and reflective material. Gypsum, Portland cement, and cellulose-based materials are used in these applications, which employ a spray process that generates a rigid foam-like structure with interconnecting pores. The procedure, equipment, and some of the products are similar to those employed in spray-on fireproofing of building structures. They are commonly sprayed to thicknesses ranging from about 1.3 cm ($\frac{1}{2}$ in.) to 5 cm (2 in.), with the thicker treatments typically providing greater sound absorption. Some of these treatments are known as acoustical plasters and their surfaces are sometimes modified by troweling or screeding. A problem with spray-on treatments is that the acoustical performance depends on careful control of the application procedure and thickness, so the desired acoustical performance may not always be achieved. Sprayed asbestos was a popular and effective sound-absorbing treatment prior to concerns regarding its carcinogenic properties.

1.6.5. Acoustical Roof Decks

Acoustical roof decks are frequently used in gymnasiums, one-story commercial buildings, and similar utilitarian rooms and buildings. They comprise part of the roof structure, taking the place of nonacoustical roof decking materials. Acoustical metal roof decks consist of structural panels that are hollow or ribbed and are filled with fiber glass or mineral wool sound-absorbing material; the bottom faces of the deck or the sides of the ribs are perforated metal. One common type of acoustical metal deck is illustrated in Figure 2. Another type of acoustical roof deck is made with shredded wood fibers with a gypsum or Portland cement binder. Conventional insulation and roofing are installed on top of the acoustical roof decks.

1.6.6. Acoustical Wall Treatments

Sound-absorbing wall treatments are sometimes required to prevent echoes (long-delayed reflections) or flutter echoes (repeated reflections between hard parallel surfaces). Prefabricated fiber glass boards 2.5 cm (1 in.) to 5.1 cm (2 in.) thick wrapped in fabric or thin perforated vinyl are widely used. Mineral fiber boards with integral facings of fabric-like material also are available. Open-cell foam products represent another type of acoustical treatment used on walls. The foam products are available in several thicknesses and with sculptured surfaces, some of which have a sawtooth shape and others a textured appearance similar to egg cartons. They can be applied to wall surfaces by means of a self-adhesive backing and are popular in sound studios because of their appearance as well as their properties. Porous concrete blocks with carefully designed slots and cavities, which act as resonant cavity absorbers, also are used for sound-absorbing walls. The resonant cavities provide a significant amount of low frequency absorption, and the porous concrete provides some middle and high frequency absorption.

Custom decorative sound-absorbing treatments for wall surfaces are frequently used in auditoriums and theaters, especially for control of echoes from rear walls. Typical treatments consist of prefabricated or custom-built wood grilles over fiber glass or mineral wool blankets or batts.

1.6.7. Carpeting

Carpeting may be used for noise and reverberation control, but because of its limited thickness it is only effective at relatively high frequencies. Thick pile carpeting is more effective than thin carpeting, and installation over foam pads further improves the sound-absorbing properties. When installed over a foam pad, carpeting should not have an impermeable backing, eg, latex, but should have an open back to allow sound to penetrate into the pad. In addition to providing sound absorption at higher frequencies, carpeting provides a resilient surface that reduces the noise of heel clicks, footfalls, and other sounds originating on the floor.

1.6.8. Draperies

Draperies of light weight or open-weave fabrics are ineffective for sound-absorbing purposes. Heavy draperies, such as flannel and velour, can provide useful sound absorption if properly installed. For best results they should be hung with 100% fullness, ie, 2 m^2 for every m^2 of wall or window surface covered. The sound-absorbing properties also are affected by the amount of space between the draperies and the surface behind them.

1.6.9. Unit Absorbers

Sound-absorbing baffles are the most common type of unit absorber. Typical baffles are 61 cm (24 in.) by 122 cm (48 in.) and consist of a 5.1 cm (2 in.) fiber glass core wrapped in thin plastic film, fabric, or perforated vinyl. The baffles usually are suspended from the ceiling by one of the long sides in rows or in the form of a grid. Baffles wrapped in thin plastic film are frequently used to provide sound absorption in factories and other industrial applications where suspended ceilings are impractical because of the large amount of suspended ductwork, conduits, and other mechanical and electrical equipment requiring periodic access. Fabric-wrapped baffles are used in open-plan offices, cafeterias, and other nonindustrial applications where appearance is an important factor. Cylindrical unit absorbers also are available with fabric or plastic film finishes, and units having a triangular or diamond-shaped cross section are sometimes fabricated from acoustical ceiling panels. Acoustical performance of unit absorbers is usually described in terms of sabins per unit rather than absorption coefficients.

1.6.10. Acoustical Duct Lining

Acoustical duct lining is used to reduce transmission of fan and air turbulence noise through heating and air-conditioning duct systems (6). Most duct lining products are made of low density fiber glass with special facings or treatment to resist erosion and moisture in the air stream. The most useful thickness is 2.5 cm (1 in.),

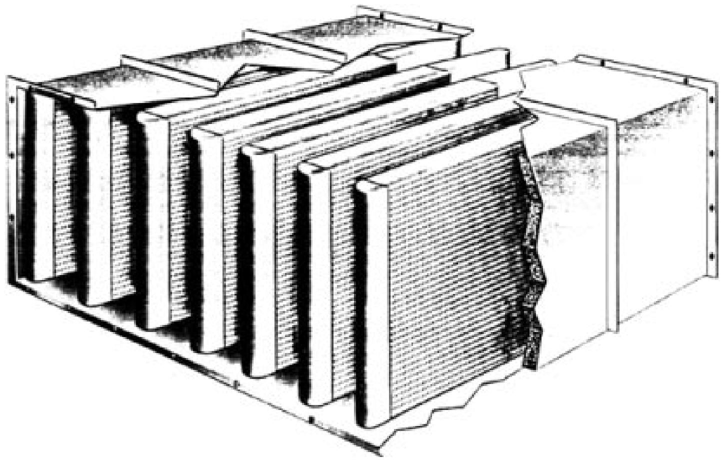

Fig. 3. Parallel baffle duct silencer; see Table 3.(Courtesy of Industrial Acoustics Co., Inc.)

although 1.3 cm ($\frac{1}{2}$ in.) and 5 cm (2 in.) thicknesses also are available. The performance of the 1.3 cm lining is restricted to higher frequencies and is not suitable for most applications. The 5 cm material provides better low frequency performance than the 2.5 cm material, but its use is generally limited because of the large duct sizes required. Two types of ducts with integral sound-absorbing treatment also are available. One type is formed of fiber glass boards with an outer facing of aluminum foil. Another type consists of double-wall round or oval ducts having fiber glass sound-absorbing material between a solid sheet metal outer wall and a perforated metal inner wall. These double-wall ducts can be used in high velocity systems where standard acoustical duct lining or fiber glass ducts would not withstand the high velocity air flow. The acoustical performance of duct systems is measured in decibels of sound attenuation per unit length.

1.6.11. Duct Silencers

Duct silencers, which make use of sound-absorbing materials and restrictive air passages to dissipate sound energy, are known as dissipative mufflers. Reactive mufflers, widely used in motor vehicles, do not use sound-absorbing materials. The most common type of duct silencer consists of a rectangular section of duct containing a number of perforated metal baffles filled with sound-absorbing material, usually fiber glass or mineral wool. Air and sound flow between the parallel baffles and sound is absorbed by the acoustical material. In applications where contamination of the air stream by the fibrous material is a concern, the fill material can be bagged in thin plastic film. In some critical “clean” installations, where even bagged fill is inappropriate, “packless” silencers using only resonant cavity absorption principles are available. Duct silencers are available in standard lengths of 0.9 m (3 ft), 1.5 m (5 ft), 2.1 m (7 ft), and 3.0 m (10 ft). Custom sizes also are available from some manufacturers. Acoustical performance varies with frequency and air flow, and is described in terms of insertion loss as a function of frequency for various forward and reverse air flow velocities. Silencers induce pressure drop in duct systems, and because this is an important parameter in HVAC system design, various silencer configurations are available that result in varying amounts of pressure drop and insertion loss. Higher performance silencers generally produce higher pressure drops. A typical duct silencer is illustrated in Figure 3 and its rated acoustical performance is represented in Table 3.

1.6.12. Acoustical Louvers

Acoustical louvers are used in building mechanical systems when exterior walls are penetrated for fresh air intake, exhaust, or relief air, in situations where the impact of HVAC noise is of concern in the surrounding

Table 3. Performance of a Typical Duct Silencer[a]

	Octave band center frequency, Hz[b]							
Face velocity,[c] m/min	63	125	250	500	1000	2000	4000	8000
−1220	9	12	21	34	43	33	22	9
−610	8	11	18	32	42	33	22	11
+610	6	10	18	30	42	34	23	14
+1220	4	9	17	29	38	34	23	14

[a] Length = 1.5 m.
[b] Having dynamic insertion loss in dB.
[c] Forward (+) and reverse (−) flow.

environment. The louvers consist of a series of hollow sheet metal blades. The bottom faces of the louver blades are perforated and the blades are filled with fibrous sound-absorbing material. Typical acoustical louvers are 20 cm (8 in.) to 30 cm (12 in.) in depth. The amount of insertion loss they provide is limited.

1.6.13. Acoustical Lagging

Sound-absorbing materials are frequently used in combination with sound-blocking materials to reduce noise radiated from pipes, ducts, gearboxes, and other noise sources. This procedure, known as lagging (7), usually consists of 2.5 cm (1 in.) or more of acoustical insulation wrapped around the offending source, with a covering of sheet lead, mass-loaded vinyl, or some other heavy impervious material. A heavy outer covering is an essential part of the treatment, because sound easily passes through porous sound-absorbing materials. The sound-absorbing material provides some sound absorption as well as decoupling between the source and the outer jacket.

2. Sound Isolation

When a sound wave comes in contact with a solid structure, such as a wall between two spaces, some of the sound energy is transmitted from the vibrating air particles into the structure causing it to vibrate. The vibrating structure, in turn, transmits some of its vibrational energy into the air particles immediately adjacent on the opposite side, thereby radiating sound to the adjacent space. For an incomplete barrier, such as a fence or open-plan office screen, sound also diffracts over the top and around the ends of the barrier. The subject of this section is confined to complete barriers that provide complete physical separation of two adjacent spaces. Procedures for estimating the acoustical performance of partial barriers can be found in References 5 and 7.

Two useful measures of the performance of a sound-isolating construction are sound transmission loss (TL) and noise reduction (NR). Sound transmission loss is defined as follows, where W_{i} is the incident sound power (Watts) on the source side of the specimen, and W_{t} is the transmitted sound power on the receiving side (7).

$$TL = 10\log_{10}(W_i/W_t)$$

Noise reduction (NR) is the difference in the average sound pressure level between the source room and the receiving room. When the receiving room is relatively reverberant and the measurements are made in the reverberant fields of the two rooms the relationship between TL and NR is as follows, where S is the surface area of the sound barrier between the two rooms and A is the amount of sound absorption in the receiving room (7).

$$TL = NR + 10\log_{10}(S/A)$$

2.1. Units and Rating Procedures

The unit of sound pressure level is the decibel (dB), defined as follows where L_p is the sound pressure level, p is the measured sound pressure, and p_{ref} is the reference sound pressure of 20 μPa. TL and NR also are expressed in decibels.

$$L_p = 10\log_{10}(p/p_{ref})$$

The sound-isolating performance of materials and structures vary with frequency. Sound-transmission loss is measured in one-third octave frequency bands with center frequencies ranging from 100 to 5000 Hz. In the past, the arithmetic mean of the one-third octave TL values (the average sound-transmission loss) was used to provide a single-number rating, but this number can be misleading and is now rarely used. A widely used single-number rating for laboratory measurements of sound-transmission loss is the sound-transmission class (STC). This rating is determined by comparing the measured sound-transmission loss curve with a reference curve that is moved up and down in level relative to the measured curve until certain criteria are met. The STC rating is then established by the level of the reference curve at 500 Hz. The procedure is described in ASTM E413-87 (8). Although the STC was developed for rating the performance of constructions for isolating speech, it is also frequently used for rating the overall performance of sound-isolating constructions. STC rating curves are illustrated in Figure 4.

Two single-number ratings are used for field measurements of sound isolation: noise isolation class (NIC) and field sound-transmission class (FSTC). For NIC ratings the measured noise reduction between two rooms is rated using the procedure just described for STC ratings, with no corrections for receiving room absorption or other field irregularities. FSTC ratings, on the other hand, take into account the amount of absorption in the receiving room, and require complex procedures to ensure that there are no flanking paths around the sound-isolating element being measured and rated. Because of its simplicity, NIC is the more widely used of the two rating procedures for field measurements of sound isolation between rooms.

These procedures are used only for rating airborne sound isolation. A related procedure is used for rating the effectiveness of floor/ceiling constructions in reducing impact noise transmission, such as footsteps, from upper floors to rooms below. The noise produced by a standard “tapping machine” is measured in the room below, and is rated using a standard curve in a similar manner to the STC rating procedure. This procedure is described in ASTM E492-90 (9). The result is a single-number rating called the impact isolation class (IIC). A great deal of controversy exists over impact rating procedures and criteria. An older impact rating procedure, which is now obsolete, is the impact noise rating (INR). When INR was developed a rating of zero was considered to provide adequate impact isolation. An IIC rating of 51 is approximately equal to an INR of zero. Impact isolation criteria for multifamily dwellings were established in the 1960s by the U.S. Department of Housing and Urban Development (10). These remain the most comprehensive criteria of this type in the United States.

2.2. Test Methods

2.2.1. Laboratory Methods

The laboratory test method for determining the sound-transmission loss performance of constructions is defined in ASTM E90-90 (11). The sample is installed in an opening between two highly reverberant rooms that are acoustically well isolated from each other. Rotating vanes are provided in the rooms to ensure diffuse sound fields. Sound is introduced into the source room, the average sound pressure level is measured in one-third

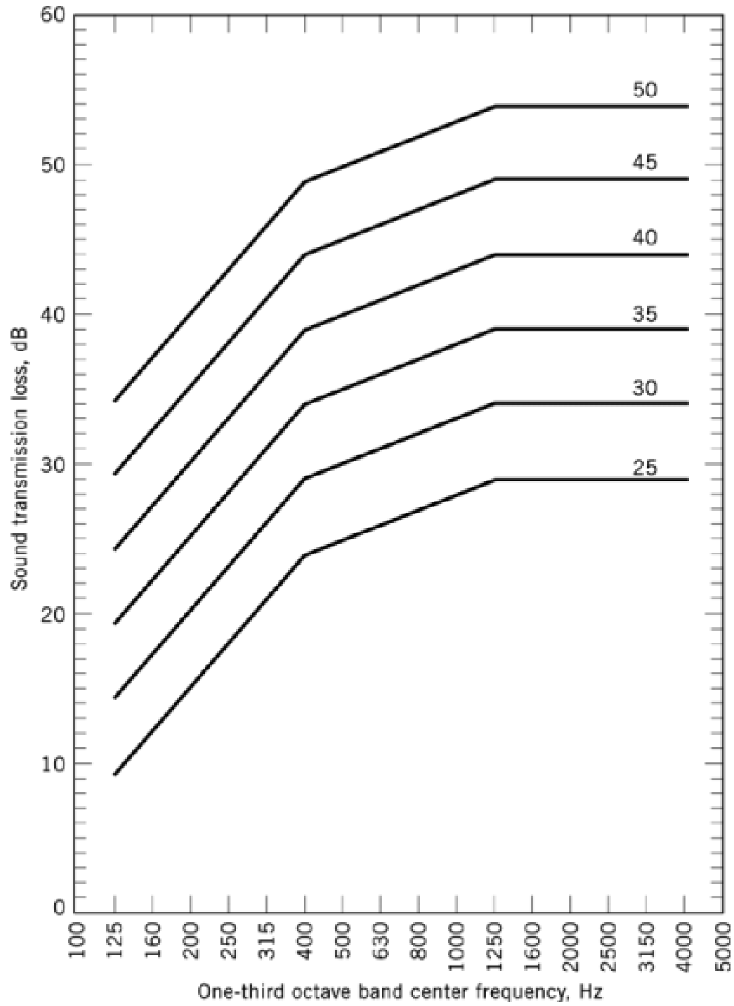

Fig. 4. Typical STC rating curves. Numbers on curves designate sound-transmission class (STC).

octave bands in both rooms, and the sound-transmission loss is calculated as follows, where $\overline{L}_1$ and $\overline{L}_2$ are the average sound pressure levels in the source and receiving rooms; S is the area of the test sample, m^2; and A_2 is the absorption in the receiving room, metric sabins.

$$TL = \overline{L}_1 - \overline{L}_2 + 10\log S - 10\log A_2$$

2.2.2. Field Methods

The purpose of noise reduction measurements in buildings is to determine the overall sound-isolating performance of the construction. Random noise is introduced into a source room. The space-averaged noise is then measured in the source room and the receiving room in one-third octave or octave frequency bands. The noise reduction is determined by subtracting the measured sound pressure levels in the receiving room from those in the source room. The noise isolation class (NIC) is determined using the STC rating procedure. Measurement of field sound-transmission loss is similar to noise reduction, except that it is used to determine the

Table 4. Sound-Transmission Loss of Some Common Materials

	Octave band center frequency, Hz						
Material	125	250	500	1000	2000	4000	STC
22 ga steel	13	17	23	28	34	39	27
1.3-cm gypsum board	15	20	24	30	31	27	28
6.3-mm acrylic plastic	15	18	22	28	32	35	27
1.0-cm plywood	14	18	22	20	21	26	22
1.6-mm lead foil	9	15	21	27	33	39	24

sound-isolating performance of a single element of the construction and can be compared directly to laboratory measurements. It may be necessary to construct barriers to shield other elements of the construction to ensure that they do not contribute to the measured sound levels in the receiving room. In addition, the amount of sound absorption must be determined in the receiving room in order to convert the measured noise reduction to transmission loss. The STC rating procedure is used to determine the field sound-transmission class (FSTC). The field test method is defined in ASTM E336-90 (12).

2.3. Materials

All common building materials provide some degree of sound isolation when used to separate adjacent spaces. The sound-isolating performance depends on a number of factors including mass, stiffness, size, and complexity of construction. In general, materials used for sound-isolating purposes must be impervious to air penetration; therefore porous materials like fiber glass and rock wool, which air can penetrate, are not effective for sound-isolating purposes unless combined with impervious materials. Heavy materials, such as concrete or lead, provide more sound isolation than lighter ones, such as wood or gypsum board. For a single-layer construction, transmission loss at lower frequencies varies as 20 $\log_{10} W$, where W is the surface mass per unit area. In general, doubling the thickness, and thus the mass, of a given material increases the low frequency *TL* by 6 decibels. At higher frequencies other factors relating to stiffness and damping come into play, and the relationship is no longer valid. For most practical purposes, the low frequency performance of a simple homogenous material is determined by mass or limp wall law, and the *TL* is determined by

$$TL_f\ 20\log_{10}(W/17)+20\log_{10}(f/63)$$

where W is the surface mass in $kg/m2$ and f is the frequency in Hz. At some higher frequency the stiffness of the material causes the speed of flexural waves to match the speed of sound waves in air (5). In this frequency region the sound-isolating performance falls below the mass law *TL*. Above this region it increases but does not reach mass law performance again. The extent of the reduction depends on the internal damping of the material. Limp materials, such as lead, have better sound-isolating performance for the same mass than stiffer materials, such as plaster. Table 4 provides the sound-transmission loss and STC ratings of some common materials.

2.4. Uses

Sound-isolating constructions are needed around many types of rooms in buildings to reduce transmission of intrusive noise from exterior and interior noise sources and to provide acoustical privacy between rooms. Frequently the required degree of isolation can be provided using standard construction techniques. Music buildings, studios, performance facilities, and other acoustically critical spaces usually require special sound-isolating constructions to provide high degrees of sound isolation from exterior noises and between rooms.

Table 5. STC Ratings of Some Common Building Constructions

Construction	STC
wood stud	
with 1.6-cm gypsum board both sides	35
with fiber glass insulation	38
double row of wood studs	
with 1.6-cm gypsum board on outside faces	45
with fiber glass insulation	56
9.1-cm steel stud	
with 1.6-cm gypsum board both sides	39
with fiber glass insulation	47
29-cm lightweight concrete block	47
29-cm dense concrete block	52
29-cm poured concrete	58
6.3-cm plate glass	31
solid wood door	
normally hung	15
fully gasketed	29

Increases in road and air traffic mean higher levels of environmental noise in many areas, and sound-proofing of residential properties and schools in the vicinity of highways and airports is being carried out in many locations in the United States. Within buildings sound-isolating constructions also are used to enclose noise-producing air-handling units and other mechanical equipment.

2.5. Sound-Isolating Constructions

Although some materials are used alone in single-layer constructions for sound-isolating purposes, most sound-isolating constructions contain two or more parts, frequently separated by an airspace.

2.5.1. Double-Wall Constructions

Significant improvements in *TL* can be achieved by using constructions consisting of two independent parts separated by an airspace (5, 7). Double-glazed windows are one example of double-wall construction. Other common constructions of this type are steel stud partitions with gypsum board on both sides. Although the two sides are connected by the studs, the studs are relatively flexible and transmit a smaller amount of energy between the gypsum board faces than would be transmitted by a rigid connection; thus the acoustical performance of steel stud and gypsum board constructions approximates double-wall performance. Standard wood stud construction does not behave as a double wall because the stiffness of the studs provides rigid bridging between the gypsum board faces. Double-wall constructions have relatively poor performance at a specific low frequency, where a resonance of the two faces on the intervening air spring occurs, but above this frequency the *TL* increases rapidly. This double-wall resonance varies as the square root of the mass of the faces and the airspace separating them, so heavier constructions with large airspaces are more effective than lightweight ones with small airspaces, as illustrated in Figure 5 by the two double windows with different airspaces and glass thicknesses. The acoustical performance of many double-wall constructions can be improved by adding sound-absorbing material, such as fiber glass or mineral wool, in the cavity between the two faces. The increase in *TL* caused by the addition of fiber glass between the studs in a typical steel stud and gypsum board partition is shown in Figure 6 .

STC ratings for wall constructions vary from about STC-15 for simple lightweight constructions to as high as STC-80 for heavy complex constructions. Ratings for some wall constructions are indicated in Table 5.

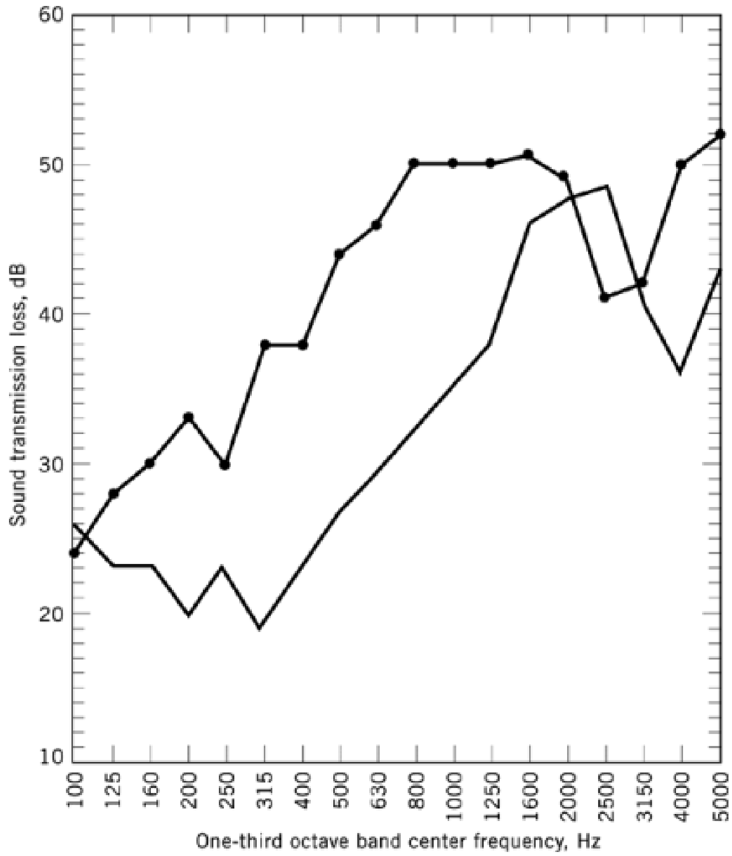

Fig. 5. Transmission loss of two types of double glass where (—) is 0.32 cm ($\frac{1}{8}$ in.) double glass and 0.95 cm ($\frac{3}{8}$ in.) air, and (—●—) is 0.48 cm ($\frac{3}{16}$ in.) double glass and 10 cm (4 in.) air.

2.6. Impact-Isolating Constructions

Adequate impact sound isolation is difficult to achieve when hard materials, such as terrazzo, quarry tile, vinyl tile, hardwood, etc, are used on floors in multistory buildings. Complex constructions incorporating resiliently supported floors and/or ceilings are required to reduce impact noise transmission when hard flooring materials are used. Carpeting can significantly reduce impact noise transmission, especially when installed over resilient padding. Because of the effectiveness of carpets and pads, many condominium associations require the owners to carpet significant portions of the floors in upper story units. Impact isolating class (IIC) and STC ratings of some floor/ceiling constructions are provided in Table 6.

3. Vibration Isolation

Reciprocating, rotating, and rolling equipment not only generate noise, they also can transmit vibrational energy into supporting structures. These structures can transmit vibrations and/or radiate unwanted sound into rooms or other occupied spaces where it can interfere with activities or cause annoyance. Vibration isolation

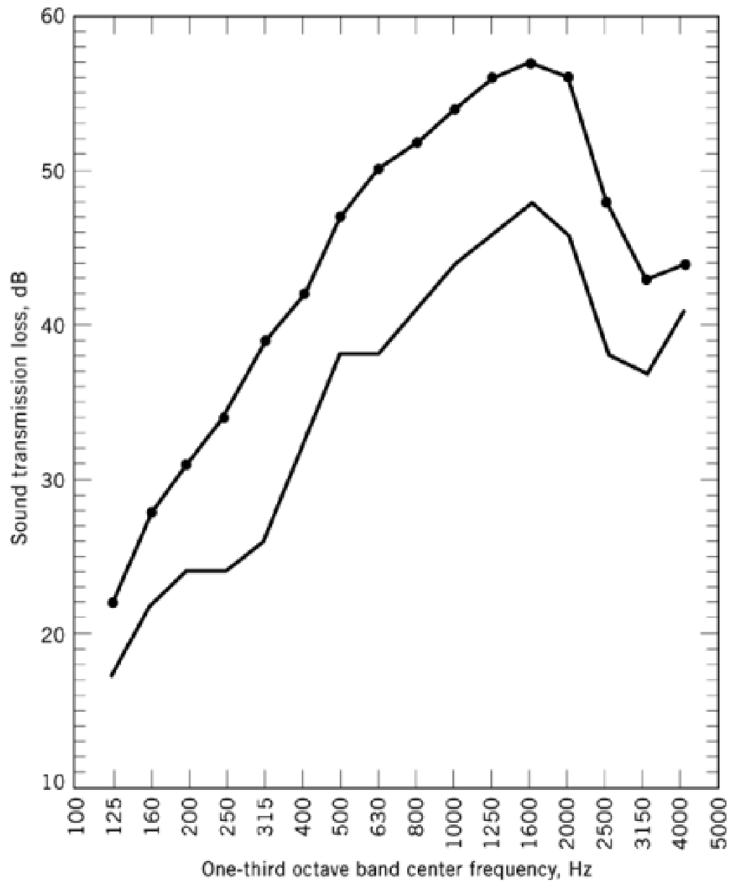

Fig. 6. Effect of fiber glass on transmission loss of steel stud partition where (—) is 6.35 cm ($2\frac{1}{2}$ in.) steel stud and 1.27 cm ($\frac{1}{2}$ in.) gypsum board, and (-•-) is 6.35 cm ($2\frac{1}{2}$ in.) steel stud with 5 cm (2 in.) fiber glass.

Table 6. Acoustical Performance of Floor/Ceiling Constructions

Construction	IIC	STC
20-cm reinforced concrete slab		
with marble floor	40	40
with hardwood floor on wood sleepers	45	44
with carpet and pad	70	40
5×25−cm wood joists, 41 cm on centers		
with oak flooring on plywood subfloor, gypsum board ceiling	35	39
with gypsum board on resilient channels	50	50
with carpet and pad	60	40

devices reduce the transmission of vibrational energy between a supported vibrating object and the supporting structure.

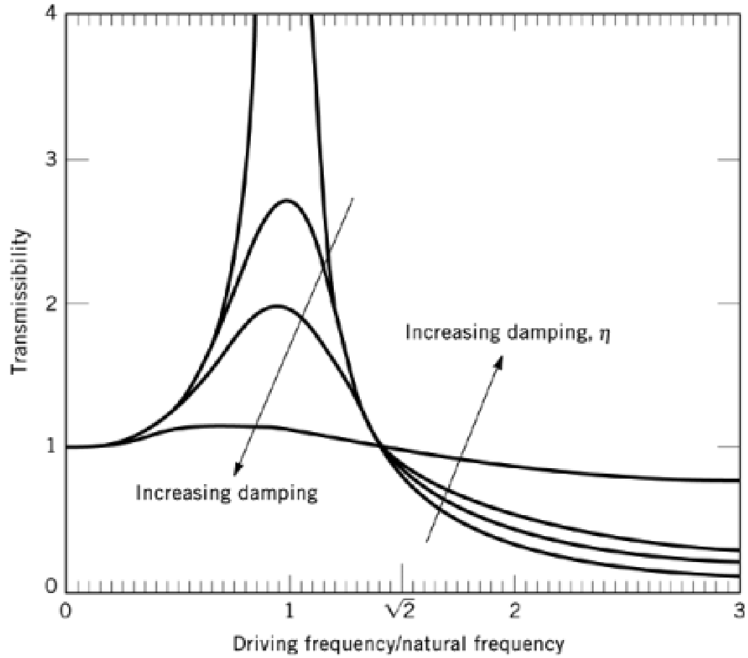

Fig. 7. Transmissibility as a function of frequency ratio for single-degree-of-freedom isolators with different degrees of internal damping.

3.1. Units

The performance of a vibration isolator is characterized by its transmissibility, defined as the ratio of the force transmitted to the supporting side of the isolator compared with the driving force acting on the vibrating side of the isolator (5, 6):

$$\text{transmissibility} = \text{output force}/\text{input force}$$

The transmissibility of an isolator varies with frequency and is a function of the natural frequency (f_n) of the isolator and its internal damping. Figure 7 shows the transmissibility for a family of simple isolators whose fundamental frequency can be represented as follows, where k is the stiffness of the isolator, N/m; and m is the supported mass, kg. Figure 7 shows that an isolator acts as an amplifier at its natural frequency, with the output force being greater than the input force. Vibration isolation only occurs above a frequency of about $\sqrt{2}$ times the natural frequency of the isolator.

$$f_n = 1/2\pi\sqrt{\frac{k}{m}}$$

Damping reduces the transmissibility at the natural frequency, but increases the transmissibility at higher frequencies. The natural frequency of isolators made from most materials also can be expressed as a function of the static deflection of the isolator due to the load imposed by the supported equipment; that is, $f_n = 5/\sqrt{\delta}$ where δ is the static deflection of the isolator, cm (5) .

Another measure of vibration isolation is isolation efficiency, which is one minus transmissibility and is usually defined as the percent of force transmitted through the isolator. Thus an isolator with a transmissibility of 0.75 has an isolation efficiency of 25%. A third measure of vibration isolation is insertion loss, which is the difference between the transmitted vibration with the isolators in place and with no isolators.

3.2. Test Methods

There is no standard test method for measuring transmissibility or isolation efficiency of vibration isolation devices. The most common procedure is to measure the vibration transmitted to the supporting structure with the isolators in place and with the equipment supported on rigid blocking. From these measurements the insertion loss in dB is determined by the following where L_{i} is the transmitted vibration with isolators in place and L_{ni} is the transmitted vibration with rigid supports.

$$IL = 10\ \log_{10} (L_i/L_{ni})$$

3.3. Materials

Materials commonly used in vibration isolators include steel in the form of springs, and elastomers (neoprene, natural rubber, glass fiber, cork, and felt) in the form of cubes and pads. The low frequency performance of steel spring isolators is superior to that of elastomeric isolators. They can be readily and repeatedly manufactured with predictable characteristics, and with the proper preparation they can be used in severe chemical and physical environments. A disadvantage of steel springs is that they tend to transmit high frequency vibrational energy. For this reason they are frequently used in combination with elastomeric elements, which are more effective in reducing high frequency vibrational energy.

Elastomeric materials, which provide relatively low practical static deflections and have relatively high natural frequencies, are used only to isolate higher frequencies. The volume compressibility of elastomeric materials is relatively low, therefore the shape of the elastomeric isolator must be taken into account, and space must be provided for lateral expansion. Because of their inherent resistance to chemical and environmental deterioration, neoprene and other synthetic materials often can be used in severe environments where natural materials would deteriorate.

3.4. Uses

In architectural and industrial applications vibrational isolators are used to reduce transmission of vibration into building structures from rotating or reciprocating machinery, such as ventilating fans, pumps, chillers, industrial machinery, and the piping and ductwork connected to this equipment (6). Vibration isolators also can be used to isolate vibration-sensitive equipment or noise-sensitive areas from sources of vibration. Examples are special pneumatic isolators to protect electron microscopes, and isolators used to support floating concrete floors in recording studios. Transportation-related applications include isolators used to reduce transmission of vibration from automobile and truck motors and exhaust systems into vehicle frames and bodies; from rapid transit and railroad steel rails into concrete inverts, bridges, and other supporting structures; and numerous other applications. Isolators also are used to minimize the vibration generated by fans and motors in various appliances. In many cases reducing transmission of vibration from the vibration-producing elements into structures having greater radiating efficiency can significantly reduce radiated noise.

3.5. Products

Vibration isolators typically are selected to have a static deflection, under load, that yields a natural frequency no more than one-third the lowest driving frequency that must be isolated (see Fig. 7). The supporting structure must have sufficient stiffness so it does not deflect under the load of the supported equipment by more than one-tenth the deflection of the isolator itself (6). In addition to static deflection requirements, vibration isolators are selected for a particular application according to their ability to carry an imposed load, and to withstand the environment in which they are used (extreme temperatures, chemical exposure, etc).

Commercially available vibration isolators include single and multiple coil springs with mounting bases and connectors for HVAC fans and other equipment. Frequently the springs are in series with neoprene or rubber elements. Spring hangers, neoprene hangers, and combinations of the two also are available for suspending vibrating equipment. Ribbed or waffled neoprene isolators typically are used to isolate equipment such as electrical transformers, which produce vibrational energy only at higher frequencies. At the other end of the spectrum are pneumatic isolators (air springs) consisting of inflated air bladders of neoprene or rubber with one or more tuned air chambers. They are used to isolate very low frequency vibrations. Several types of commercially available spring and neoprene vibration isolators are illustrated in Figure 8 .

Effective vibration isolation requires that there be no rigid connections between the isolated object and the supporting structure and other surrounding objects, because such connections short-circuit the isolators and reduce their effectiveness. An example of a short circuit that frequently is encountered in buildings is rigid electrical conduit connecting an isolated machine to the building structure from which it is being isolated. Such connections should be made with slack loops of flexible conduit or with special flexible electrical connectors. In some critical installations the conduits also should be vibration isolated.

4. Vibration Damping

Vibration damping is a process that reduces the vibrational energy in a system by converting some of the energy into heat. All materials and systems have some inherent damping, just as all materials absorb some sound, although in both cases the amounts can be very small. Damping is a highly complex phenomenon and there are many damping mechanisms, including interface friction, fluid viscosity, turbulence, acoustic radiation, eddy currents, and magnetic and mechanical hysteresis. Mechanical hysteresis is the only damping process that depends on internal friction within a material and is, therefore, also known as material damping.

4.1. Units

Two measures that are commonly used to define material damping are the loss factor (η) and amplification at resonance (Q), both of which are dimensionless: $\eta = D/2\pi W = 1/Q$ where D is the energy dissipated per cycle of vibration and W is the average total energy of the vibrating system. These relationships become more complex and less useful for highly damped systems. See References 5 and 7 for more extensive treatment ofdamping measures and treatments.

4.2. Test Methods

There are no national standards for the measurement of vibration damping. The most useful and convenient technique is to measure the reverberation time or decay rate of a panel or bar. The sample is vibrated by noise from a transducer, the noise is abruptly terminated, and the decaying vibrations are measured using an accelerometer to determine the decay rate Δ_t. The loss factor η is computed by $\eta = \Delta_t/27.3f_n$ where Δ_t is the decay rate, $\mathrm{dB/s}$; and f_n is the natural frequency of the sample, Hz (5). One significant difficulty encountered in making these measurements is how to prevent excessive energy dissipation by the supporting system, the transducer, the accelerometer, and related cables. The sample may be suspended from long strings; the transducer should not contact the panel; the accelerometer should be as low in mass as possible; and the cables should be thin and flexible.

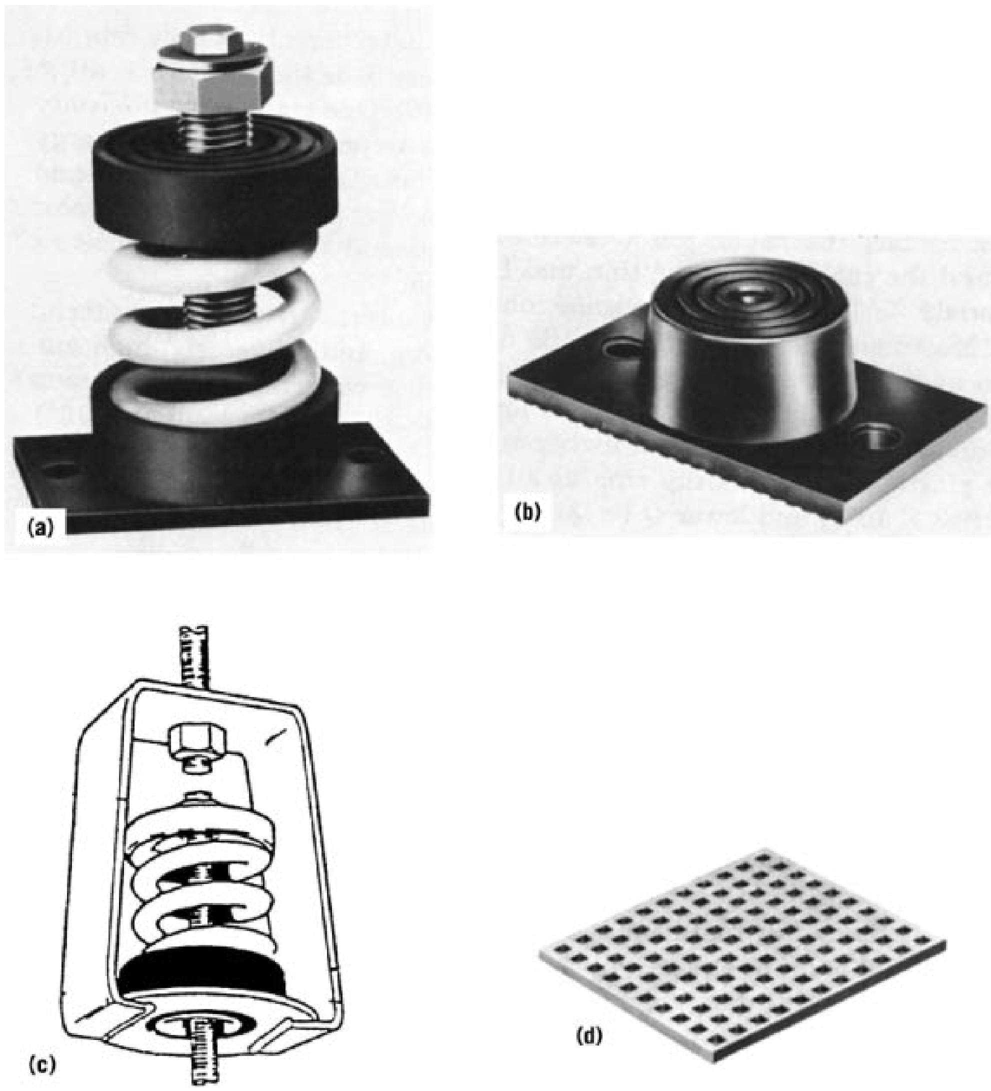

Fig. 8. Vibration isolators: (**a**) single-spring mount with base plate; (**b**) neoprene mount; (**c**) spring and neoprene hanger; and (**d**) neoprene waffle pad. Courtesy of Mason Industries, Inc.

4.3. Materials

All materials have some inherent internal friction, or material damping. Most metals have relatively little damping, and conversely, high amplification at resonance. Strike a bronze bell and it will ring at its resonant frequency for an extended period. It has a low η ($<10^{-3}$) and a high Q ($>10^3$). Rubbery and soft materials have a higher η and lower Q. If a bell were made of acrylic plastic it would hardly ring at all when struck. Acrylic has a much higher η (3×10^{-3}) and lower Q (33) than that of bronze.

The loss factor (η) for most rigid materials such as metals, concrete, plywood, glass, etc, ranges from about 10^{-4} to slightly more than 10^{-2}. The loss factors for these materials do not vary much with frequency or temperature, and they are not high enough for these materials to be used for damping purposes. The loss factors for viscoelastic materials are orders of magnitude higher than for rigid materials; as a result, these materials are widely used for damping treatments. The maximum loss factors for these materials at room temperatures range from about 0.2 to about 5.0, but they vary widely with temperature and frequency. Because of these variations, viscoelastic materials intended for use as damping treatments must be selected to suit the frequency and temperature ranges of concern.

4.4. Uses

A damping treatment is a material or combination of materials applied to a metal panel or other structural element to increase its damping. The purpose of increasing the damping may be to reduce the vibration of the element at its resonant frequency, or it may be to attenuate flexural wave propagation along an extended structure, thereby increasing the sound-transmission loss of the structure. In both cases effective noise control is achieved only in very narrow frequency ranges; therefore caution should be exercised when using damping as a means of noise control.

4.4.1. Reduce Resonant Vibration

Metal structures are induced to vibrate at their natural frequencies when driven mechanically by attachment to some other vibrating structure, by impact of solid objects, or by turbulent impingement of a fluid (including air). Examples are stainless steel sinks driven by garbage disposals; dishwasher cabinets impacted by water sprays; trash chutes and bins impacted by cans and bottles; tumbling bins, conveyors, and vibratory feeders impacted by small parts; and other devices that are periodically or continuously impacted by hard objects or attached to vibrating machinery. Damping treatments often can provide a considerable amount of noise reduction at the natural frequency of this type of sheet metal structure when applied to its radiating surfaces, but the treatment has no significant effect at nonresonant frequencies.

4.4.2. Increase Sound-Transmission Loss

The only significant increases in sound-transmission loss that can be achieved by the application of damping treatments to a panel occur at and above the critical frequency, which is the frequency at which the speed of bending wave propagation in the panel matches the speed of sound in air. Application of damping treatment to 16 ga metal panel can improve the *TL* at frequencies of about 2000 Hz and above. This may or may not be helpful, depending on the application of the panel.

Another practical application of damping to increase sound-transmission loss is the fabrication of acoustical glass by laminating a soft vinyl interlayer between two sheets of glass. This lamination improves the *TL* in two ways: first, by raising the critical frequency above that of the same thickness of monolithic glass; and second, by providing damping, which reduces flexural wave propagation in the glass.

4.5. Products

Damping treatments are available from many manufacturers in sheet form, as tapes for adhering to a surface, and in bulk form for spraying or troweling onto a surface. Laminated glass is available from many glass suppliers (see Laminated materials, glass).

4.5.1. Extensional or Free-Layer Treatments

These are viscoelastic damping treatments that are applied directly to a surface in a variety of ways. A free viscoelastic layer stores and dissipates energy primarily as a result of the stretching and compression of the layer caused by bending. The damping provided by this type of treatment increases roughly as the square of the layer's thickness until it reaches a thickness about three times that of the surface to which it is applied. Above this thickness the increase is less rapid. Free-layer damping treatments tend to use viscoelastic layers that are between one-half and two times as thick as the underlying structure. They must be continuous and well-bonded to the structure. Some sheet damping products are available with a self-adhesive backing and others are applied using a thin layer of epoxy or some other rigid adhesive.

4.5.2. Constrained-Layer Treatments

Constrained-layer damping treatments consist of a thin layer (μm) of viscoelastic material sandwiched between a base material and an outer constraining layer of sheet metal or other structural material. Some of these treatments are available with self-adhesives on both sides of the viscoelastic material and act as a bonding agent between the base and constraining layers; others have the constraining layer already bonded to the inner layer so they need only be applied to the base material.

4.5.3. Sound-Absorptive Blankets

Sound-absorptive blankets of fiber glass or mineral wool are not usually considered damping materials, but when fastened to sheet metal machine enclosures they can provide some useful damping in addition to sound absorption.

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