12 NOISE TRANSMISSION IN FLOOR SYSTEMS

12.1 TYPES OF NOISE TRANSMISSION

The noise and vibration problems encountered in real floor-ceilings generally fall into four categories: airborne, footfall, structural deflection, and floor squeak. Each is a distinct class of problem with unique solutions.

Airborne Noise Isolation

Airborne noise isolation in floors follows the same principles and is tested in the same manner as airborne noise isolation in walls. STC tests are done by placing the noise source in the downstairs room to insure vibrational decoupling between the loudspeakers and the floor-ceiling system being tested.

As was the case with wall transmission, the isolation of airborne noise such as speech is well characterized by the STC rating. The best floor systems combine a high-mass floor slab with a large separation between the floor and ceiling. The two panels should be vibrationally decoupled either by means of a separate structure or by a resilient support. At low frequencies a high structural stiffness is desirable, to minimize the floor deflection. In all cases at least 3" (75mm) of batt insulation should be placed in the air cavity and openings and joints must be sealed air tight.

Footfall

The act of walking across a floor generates noise due to two mechanisms: footfall and structural deflection. Footfall noise is created by the impact of a hard object, such as a heel, striking the surface of a floor. The heel is relatively lightweight and the noise associated with its fall is considered separately from the transfer of weight due to walking. Impact noise can be measured using a standard tapping machine as a source, which leads to an Impact Insulation Class (IIC) rating. The IIC test measures the reaction of a floor system to a series of small hammers dropped from a standard height. Although this may accurately characterize the noise of a heel tap against the floor surface, it does not measure the effect of loading and unloading under the full weight of a walker. Thus the achievement of a particular IIC rating in a given floor-ceiling system does not guarantee that footfall noise will not be a problem, or that the sound of walking will not be audible in the spaces below. The level of impact noise in the receiving space is primarily dependent on the softness of the floor covering, and is best attenuated using a thick carpet and pad.

Structural Deflection

When a person walks or bounces up and down, a floor will deflect under the static and dynamic load of his weight. Under these conditions the floor acts like a large spring mass system, which responds to a periodic or impulsive force. If the underside of the moving structure is exposed to the room below, the low-frequency sound generated by the movement will radiate directly into the receiving space. Noise created by structural deflection sounds like low-frequency thumps similar to the sound of a very large bass drum, whereas footfall sounds like a high-frequency click. Noise associated with floor deflection is more difficult to correct than footfall noise since the joist system must be stiffened and damped and the ceiling must be physically decoupled from it. Where resilient ceiling supports are used to provide effective vibration isolation, their static deflection must be much greater than the potential structural deflection under the excitation force.

Squeak

Floor squeak is a phenomenon found in wood structures, which is most often caused by the rubbing of nails against wood framing members or metal hangers. It is high pitched and localized to the area around the point of contact. It can occur when there are gaps between the floor diaphragm and the supporting joists and when no glue has been used, or when joists are supported by metal hangers. It can also be exacerbated by the use of wood products having a high glue content, which do not allow the nail to grip the wood.

To control squeak all nonbedded nails (sometimes called shiners) that can rub against a joist or other wood or metal members should be removed and wood diaphragms should be glued to their supporting joists. Shiners must be removed before any concrete topping is poured. When the squeak originates at a joist hanger, it can be caused by inconsistencies in the joist size, and can be treated with small wood shims inserted between the joist and the hanger.

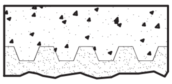
12.2 AIRBORNE NOISE TRANSMISSION

Concrete Floor Slabs

The transmission loss in thick, monolithic concrete floor slabs can be modeled by subtracting 6 dB from the mass law relationship previously developed. In thick panels the shear wave impedance is below the bending impedance so there is no coincidence effect. Typical examples of measured transmission loss data are given in Fig. 10.10. Because of the mass law, we quickly reach a point of diminishing returns if we wish to increase the transmission loss by thickening the slab. A thickness of 8 to 10 inches, which rates around an STC 58, is usually the practical limit for multistory buildings.

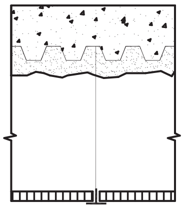
In order to achieve significantly higher STC ratings we must use double panel or other compound construction techniques. In many situations, a concrete floor slab is an excellent choice. Although it may not by itself provide an extremely high STC rating, it has many other advantages. Its low-frequency performance is excellent. If the spans are controlled it can be relatively stiff, and there are no squeak problems.

FIGURE 12.1 Transmission Loss of Metal Deck Floor-Ceilings (National Research Council Canada, 1966)



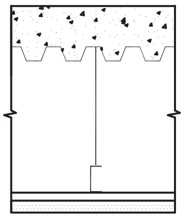
5" Thick Concrete Slab on Metal Decking (42 lbs/sq ft)
3/4" Fireproofing

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
34	37	38	38	39	41	42	50	54	55	54	54	54	56	60	65	50



5" Thick Concrete Slab on Metal Decking (42 lbs/sq ft)
3/4" Fireproofing
16" Airspace
5/8" Mineral Tile in T-Bar

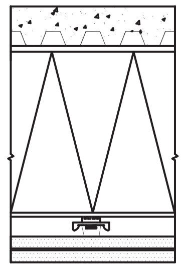
125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
41	47	50	52	53	53	52	62	67	71	72	75	75	76	77	78	60



5" Thick Concrete Slab on Metal Decking (42 lbs/sq ft)
16" Airspace
5/8" Gypsum Board on Resilient Channel
NIOSH, 1980

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
35	37	39	44	48	50	53	55	58	60	63	62	59	61	65	67	55

(PAC International, 2001)



3.5" Thick Concrete Slab on Metal Decking (39 lbs/sq ft)
9.6" Steel Joists at 24" O.C.
RSIC-1 Neoprene Clips Screwed to Joists at 24" O.C.
2 X 5/8" Gypsum Board on 7/8" Hat Channel
Riverbank, TL01-220

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
42	42	44	48	52	57	59	61	66	70	73	76	76	78	82	84	60

Concrete on Metal Pans

Concrete poured into a sheet metal pan supported on metal joists can deliver reasonable sound isolation if it is combined with a suspended drywall ceiling. Figure 12.1 gives several examples. The ceiling is supported from hanger wires at 4'-0" (1.2 m) on center that are tied to a 1.5" (38 mm) carrying channel (called black iron). A 7/8" (22 mm) thick hat channel is wire tied or clipped to the black iron and the gypsum board is screwed to it. STC ratings for this construction vary with the airspace depth and the softness of the ceiling support system. Since the slab is relatively stiff, good transmission loss values can be achieved using a neoprene mount, or a neoprene or spring hanger in the ceiling support wires.

Wood Floor Construction

Wood floor construction consists of separate floor and ceiling panels, which may be supported from the same joists or supported separately. Wood construction is lightweight and, if limited to short spans, relatively stiff, compared to long span concrete and steel floors. There is considerable damping in wood structures, so that vibrations do not propagate laterally as easily as in steel framing. Being lightweight, high transmission loss values are achieved only in compound, vibrationally isolated structures. The advantage of isolated construction is that it can approach ideal double panel performance if the floor and ceiling are sufficiently decoupled. Examples of lightweight wood and gypsum board floor-ceiling systems are shown in Fig. 12.2. In several of these the ceiling is attached directly to the underside of the wood joists, so the sound isolation ratings are relatively poor. In others the ceiling is mounted on resilient channels, which results in a modest improvement in STC rating. Resilient channel helps to provide a degree of vibration isolation between the joist system and the ceiling. The preferred type of channel is z-shaped rather than hat-shaped and can be attached only on one side. In order for a hat-shaped channel to be effective, one side of the flange and then the other must be alternately screwed to each joist. Both sides must never be screwed to the same joist. This is an important installation detail, which is rarely implemented correctly in the field, and renders the channel ineffective if not properly done. With all resilient channel, the length of the drywall screws must be controlled so that when the gypsum board is attached to the channel, the screws do not penetrate the joist and short out the isolation.

The third floor in Fig. 12.2 shows an example of adding mass to the underside of the diaphragm. This technique can be used to make improvements to existing construction. It has the advantage of adding mass without adding thickness to the diaphragm and consequently the coincidence frequency of the floor panel is not lowered. The addition of an extra layer of gypsum board on resilient channel over an existing layer is not effective due to the coupling through the air spring between the layers. Improvements of 1 dB or less are the usual result. In cases where there is an existing ceiling and substantial improvement is desired it is most effective to remove the ceiling drywall and add mass, batt insulation, and stepped blocking between the joists before resiliently supporting a double layer gypsum board ceiling.

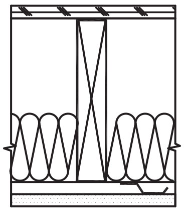
Resiliently Supported Ceilings

Supporting ceilings on resilient mounts can increase the sound transmission class. Resilient channels are one such support system. Working as a spring isolator they rarely achieve a deflection of more than about 1/8" (3 mm). Thus they do not have the softness required to isolate noise due to structural deflection. They are, however, helpful in providing a degree of decoupling of airborne or footfall vibrations transmitted through the structure. In Fig. 12.2 we can see an example in the difference between constructions B and D in the second example.

Where a moderate degree of decoupling is desired, the ceiling can be suspended from neoprene mounts. These can be cut into the hanger wire or screwed directly to the support framing. Test ratings are included in Fig. 12.1 in the last example. This system has the advantage of being able to support multiple layers of drywall in critical applications.

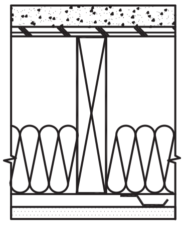
If high STC ratings are desired the ceiling must be independently supported on a separate joist system or suspended from springs, having a deflection of one-inch (25 mm)

FIGURE 12.2 Transmission Loss of Floor-Ceilings (California Office of Noise Control, 1981)



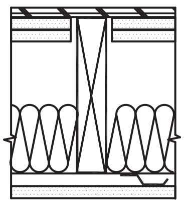
Double Layer Plywood - 1" Thick
2 x 10 Wood Joists
1 Layer 1/2" Gypsum Board
A - No Batt Insulation - No Resilient Channel
B - R-11 Batt Insulation - No Resilient Channel
C - No Insulation - With Resilient Channel
D - R-11 Batt Insulation - With Resilient Channel

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	23	23	21	27	31	31	31	35	37	41	42	45	44	41	42	45	37
B	20	23	29	32	38	41	44	41	43	45	47	50	51	50	51	54	43
C	27	29	31	33	38	41	43	45	47	48	49	52	54	52	51	54	45
D	27	33	36	35	38	41	44	47	51	51	54	57	59	61	57	60	47



1 1/2" Lightweight Concrete (110 lbs/cu ft)
1 Layer 5/8" Plywood
2 x 10 Wood Joists
1 Layer 1/2" Gypsum Board
A - No R-11 Batt Insulation - No Resilient Channel
B - R-11 Batt Insulation - No Resilient Channel
C - No Insulation - With Resilient Channel
D - R-11 Batt Insulation - With Resilient Channel

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	26	30	35	36	41	43	46	43	43	47	52	55	57	57	57	60	46
B	28	32	34	37	41	46	50	50	50	51	54	55	57	55	55	58	49
C	36	38	34	38	41	44	51	53	54	57	61	63	64	63	60	62	52
D	40	40	37	41	45	49	51	51	52	54	59	61	63	62	60	63	53

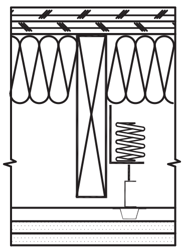


1 Layer 5/8" Plywood
2 x 5/8" Gypsum Board Screwed to the Subfloor
2 x 10 Wood Joists
1 Layer 5/8" Gypsum Board
A - R-11 Batt Insulation - With Resilient Channel

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	37	40	44	46	51	51	54	56	57	58	63	63	62	58	59	61	56

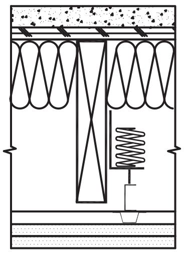
or greater. In these cases the floor and ceiling panels begin to act separately and we gain the advantages of double panel construction, which were discussed in Chapt. 9. With a spring-supported ceiling the transmission loss behavior approaches, but does not reach, the ideal double panel values. In practice, with one-inch deflection isolators, transmission losses are approximately the simple sum of the mass law values above the mass-air-mass resonance or about 6 dB below the ideal behavior. Several examples are given in Fig. 12.3 for suspended gypsum ceilings.

FIGURE 12.3 Transmission Loss of Floors and Spring Supported Ceilings (Kinetics Corporation Test Data)



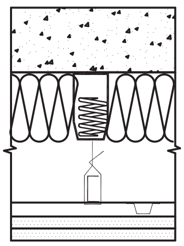
3/4" Thick Hardwood Flooring
3/4" Plywood
2 x 10 Wood Joists
R-11 Batt Insulation
1" Deflection Spring Isolators
2 Layers 5/8" Gypsum Board

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	FSTC
42	39	38	40	44	42	47	48	51	53	55	54	56	59	67	66	51



1 1/2" Lightweight Concrete (110 lbs/cu ft)
1 Layer 5/8" Plywood
2 x 10 Wood Joists
R-11 Batt Insulation
1" Deflection Spring Isolators
2 Layers 5/8" Gypsum Board

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
50	56	58	59	62	70	74	79	84	86	90	94	97	100	100	95	73



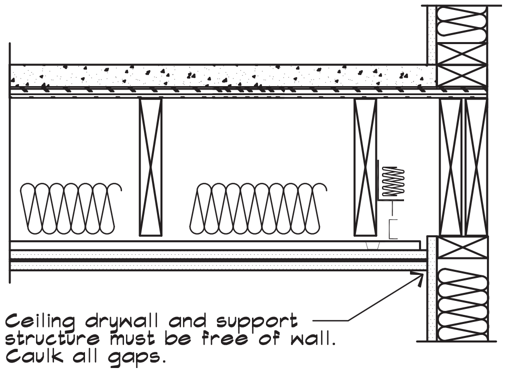
6" Concrete Slab
R-11 Batt Insulation
1" Deflection Spring Isolators
2 Layers 5/8" Gypsum Board

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
63	64	66	72	73	83	84	86	91	92	96	104	104	105	105	105	84

A number of details are important to the successful installation of hanger-supported ceilings. When sheets of drywall are applied to a ceiling, supported from a series of springs, the weight due to each additional layer will cause the ceiling to drop. As it drops it is important that neither the drywall nor the hat or carrying channel above it rests on the side wall structure or gypsum board. If it does an uneven load distribution will result and the ceiling will bow. The ceiling should be free to move so that the isolators can work effectively. This is accomplished most easily by building the ceiling within the confines of the side wall finish material as in Fig. 12.4. Joints between the two may then be caulked and molding can be applied slightly below the finish ceiling.

The second detail has to do with the load carried by each spring hanger. Typically hangers are located at 4'-0" (1.2 m) on center so that each spring supports 16 sq. ft. (1.5 sq m) of ceiling material. For a ceiling constructed of double 5/8" (16 mm) drywall the total weight along with the support framing works out to be about 100 lbs (45 kg) per isolator. When a spring is located near a wall it may support as little as half the load of a center

FIGURE 12.4 Resiliently Suspended Ceiling Detail



spring and when it is in a corner, as little as one-quarter. If a hanger supports a vertical portion of a soffit and therefore more than its normal load, the stiffness of each spring must be matched to the load it carries so that the deflection across the ceiling is uniform. This is done by calculating the load on each hanger and by having springs of varying stiffness (usually color-coded) available at the construction site to insert into a hanger. The deflection can also be adjusted by means of a threaded cap screw on top of each spring. This is often required in corner springs supporting more than a quarter load.

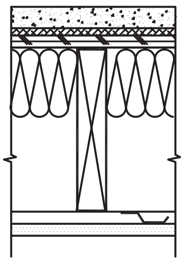
Floating Floors

Floating floors, which are resiliently supported panels located above the structural system, can be used to attenuate vertical as well as lateral noise and vibration transmission. They are usually heavier than resiliently hung ceilings and thus have the attendant advantages of mass. This is offset somewhat by the narrow air gap and low deflections inherent in the neoprene or pressed fiberglass isolators that normally are employed. Where low-deflection (< 0.1” or 3 mm) continuous support systems such as sheets of neoprene, pressed fiberglass board, pressed paper, or wire mesh materials are used, the degree of decoupling is much less, due to the low deflection as well as the additional stiffness attributable to the trapped air. Some of these materials can become overloaded and crush over time, further reducing their effectiveness. Any concrete, which flows into the space beneath the floating floor and shorts out the resilient support, also severely reduces its effectiveness.

Since the floating floor supports are acting as vibration isolators it is desirable to reduce their natural frequency by maximizing the static deflection under load. Consequently a grid of regularly spaced individual mounts is much more effective than a continuous material since the loading on each isolator is much greater.

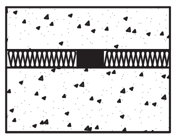
Where very high transmission loss values are required, such as in the construction of sound studios, floating floors in combination with resiliently supported ceilings can yield very good results. Figure 12.5 shows an example of a continuous floor support system and two point-mounted floor systems. Note that the floating floor is most effective if it is heavy and point mounted. The weight is important for several reasons. First, it provides the additional mass for sound attenuation. Second, it yields good isolator deflection without softening the floating floor. A high stiffness in the floating floor is important since it should not deflect appreciably between the mounts. Lightweight floating floors, such as those used

FIGURE 12.5 Transmission Loss of Floating Floors (Kinetics Corporation Test Data)



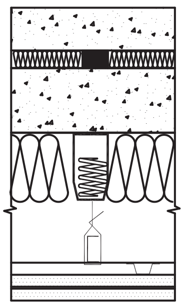
1 1/2" Lightweight Concrete (110 lbs/cu ft)
5/8" Continuous Resilient Underlayerment
1 Layer 3/4" Wood Subfloor
2 x 10 Wood Joists
R-11 Batt Insulation
Resilient Channel
1 Layer 5/8" Gypsum Board

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	FSTC
37	35	42	45	47	49	52	52	54	55	59	60	61	60	64	68	54



4" Concrete Slab (144 lbs/cu ft)
2" Thick Pressed Fiberglass Isolators at 16" on Center
R-11 Batt Insulation
6" Concrete Structural Slab (144 lbs/cu ft)

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
53	54	55	57	63	70	72	78	83	86	91	93	98	101	101	100	72



4" Concrete Slab (144 lbs/cu ft)
2" Thick Pressed Fiberglass Isolators at 16" on Center
R-11 Batt Insulation
6" Concrete Structural Slab (144 lbs/cu ft)
R-11 Batt Insulation
1" Deflection Spring Isolators
2 Layers 5/8" Gypsum Board

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
71	74	81	84	86	96	99	101	101	106	105	106	106	106	107	107	94

as gymnasium floors, tend to be springy and walkers can perceive a noticeable movement. Thus concrete floating floors are preferred for residential and studio applications.

12.3 FOOTFALL NOISE

Impact Insulation Class—IIC

The Impact Insulation Class (IIC) is a laboratory rating much like the Sound Transmission Class; however, it represents the isolation provided by a floor system subjected to a controlled impulsive load. Since there is no standard footstep, the impulsive loads are generated by a tapping machine pictured in Fig. 12.6. The machine consists of a frame supporting a row of five cylindrical hammers, each weighing a half-kilogram (1.1 lbs), which are raised by a cam mechanism and dropped sequentially from a height of 4 cm (1.6 in) onto the surface of the floor. The cam is driven by an electric motor that is set to deliver 10 impacts per second at equal intervals.

There are test standards in the United States and Europe that regulate the laboratory (ASTM E 492 and ISO 140/6) as well as field (ASTM E 1007 and ISO 140/7) test methodologies. The test is performed by placing the tapping machine near the center of the

FIGURE 12.6 Tapping Machine Showing Inner Workings

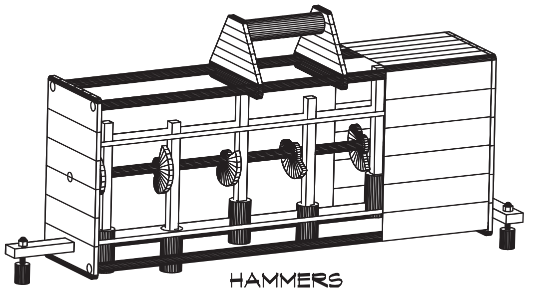
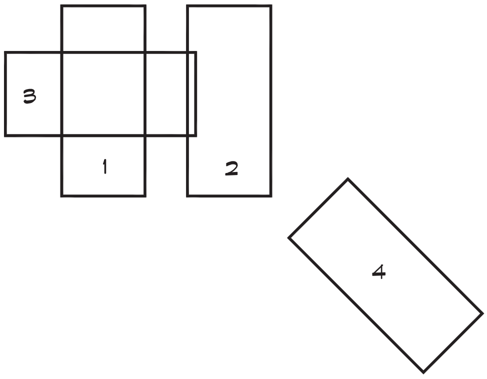


FIGURE 12.7 IIC Tapping Machine Positions



floor under test. Spatially averaged sound pressure levels are then measured in the room below in third-octave bands ranging from 100 through 3150 Hz. The readings are done for four specified tapping machine positions illustrated in Fig. 12.7. A normalized impact sound pressure level in the receiving room is then obtained from the spatial average sound pressure levels

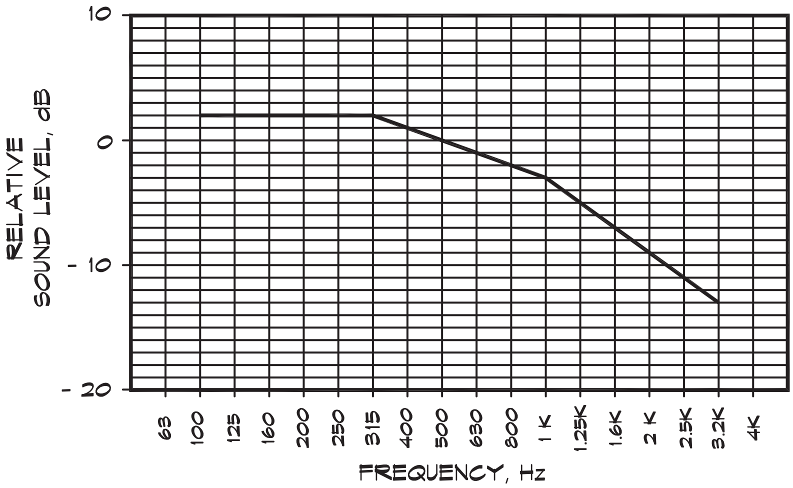
$$L_n = \overline{L}_p - 10 \log (A_0 / R) \tag{12.1}$$

The absorption in the receiving room is measured either by using the reverberant field approximation (Eq. 12.2) and a source of known sound power, or by measuring the reverberation time, from which the total absorption is obtained using the Sabine equation.

$$\overline{L}_p \cong L_w + 10 \log (4 / R) + K \tag{12.2}$$

where $\overline{L}_p$ = average one - third octave sound pressure level measured in the receiving room (dB)
L_w = one - third octave sound power level of the reference source (dB)
R = sound absorption in the receiving room (m^2 or ft^2)
A_0 = reference absorption in the same units as R (either 10 metric sabins or 108 sabins)
K = 0.1 for SI units or 10.5 for FP units

FIGURE 12.8 Reference Contour for Calculating Impact Insulation Class and Other Ratings (ASTM E989, 1989)



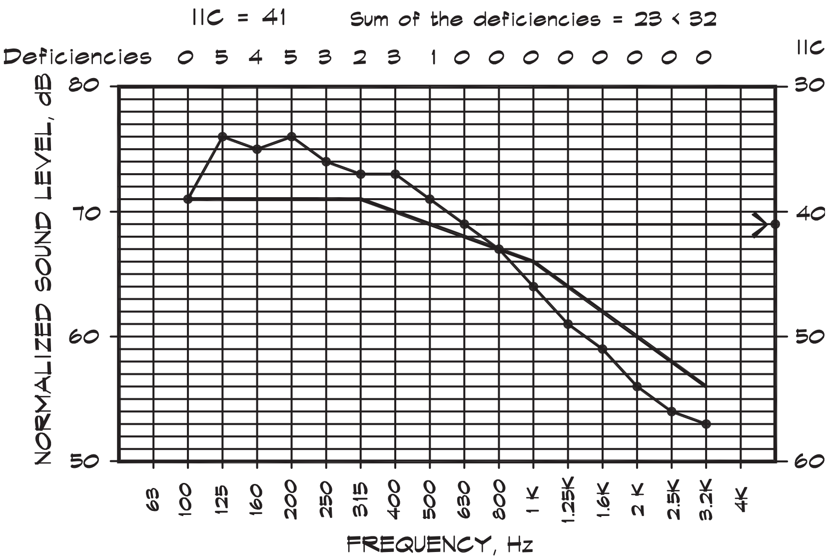
Note that $\overline{L}_p$ in Eq. 12.1 is measured using the tapping machine as the noise source, whereas in Eq. 12.2 a standard reference noise source such as a calibrated fan or loudspeaker is used.

Once the normalized levels have been obtained, they are compared to the standard IIC curve (ASTM E 989) in Fig. 12.8 by taking the deficiencies (differences) at each third-octave frequency band. The standard curve is shifted vertically relative to the test data until two conditions are fulfilled: 1) the sum of the deficiencies above the contour does not exceed 32 dB, and 2) the maximum deficiency at a single frequency band does not exceed 8 dB. Once these criteria are satisfied, the normalized sound pressure level at the intersection of the standard curve and the 500 Hz ordinate is subtracted from 110 to obtain the Impact Insulation Class. A typical example is given in Fig. 12.9.

Field tests of the IIC rating also may be carried out after a building has been constructed. These are designated FIIC, and like the FSTC tests fall about five points below the laboratory test for the same construction. They apply only to the room in which they are measured and are not generally applicable to a type of construction. Test standards set minimum limits on the volume of the receiving space at each third-octave frequency. Receiving rooms are required to meet minimum volume requirements such that there are at least 10 room modes at 125 Hz and the same modal spacing at 100 and 160 Hz. Minimum room volumes are 2100 cu ft (60 cu m) at 100 Hz, 1400 cu ft (40 cu m) at 125 Hz, and 800 cu ft (25 cu m) at 160 Hz. If room volumes fall below these limits the field report must include a notation to that effect.

The State of California has modified the standard FSTC and FIIC procedures to make them less strict by dropping the room constant term. In the revised code only the raw receiving levels are used to compute $L_n \cong \overline{L}_p$. Nonnormalized field tests generally produce ratings that are 3 to 5 dB higher than tests properly done, in accordance with the accepted ASTM standards. They yield an FIIC rating that is not normalized to the absorption in the receiving room and thus may vary from room to room or for the same room if the receiving space contains different amounts of furniture or other absorptive materials. Field tests made under these requirements are representative only of the rooms and conditions under which they

FIGURE 12.9 Calculation of an IIC Rating



were measured and are not generally applicable to other rooms, even those having the same nominal construction.

Impact Insulation Class Ratings

The IIC rating reflects the softness of the floor covering including any resilient support system. IIC ratings are shown for various floor coverings in Fig. 12.10 for a concrete slab and in Figs. 12.11 and 12.12 for wood floor-ceiling systems. The Uniform Building Code (UBC) and the State of California set minimum standards of 50 IIC (laboratory) and 45 FIIC (field) ratings in multifamily dwellings. At this rating footfall noise from a person walking on a floor above is clearly audible, and it is possible to follow the progress of the walker around the room. Thus these building code standards do not represent good building practice. Rather they represent minimums below which it is illegal to build. It is only when the ratings are above an IIC 65 that heel clicks begin to become inaudible (Kopec, 1990).

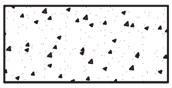
Vibrationally Induced Noise

To construct a theoretical model of vibration transmitted through floor systems we can assume that a mechanical force is applied to one or more points on the floor, which induces a motion in the ceiling below. Clearly if the ceiling vibrates, an airborne sound will be radiated. Assuming that the ceiling is a flat plate moving vertically, the intensity near its surface is the same as that radiated by a plane wave.

$$W_{rad} = I\,S = \frac{p^2}{\rho_0\,c_0} S \tag{12.3}$$

The radiated acoustic power can be written in terms of the surface velocity and a radiation efficiency, which is an empirical constant expressing the ratio of the actual power emitted

FIGURE 12.10 Impact Insulation Class of Concrete Floors (Kinetics Corporation Test Data)

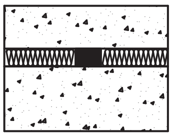


6" Concrete Slab (144 lbs/cu ft)

A 1/2" Wood Fiber Board glued to Concrete
44 oz Carpet on 40 oz Pad

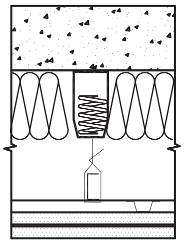
B No Floor Covering

	100	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	IIC
A	39	36	34	28	29	29	25	18	14	11	0	0	0	0	0	0	81
B	62	63	67	73	71	74	73	74	74	75	74	74	73	73	73	72	28



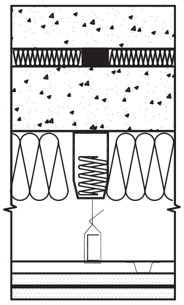
4" Concrete Slab (144 lbs/cu ft)
2" Thick Pressed Fiberglass Isolators at 16" on Center
R-11 Batt Insulation
6" Concrete Structural Slab (144 lbs/cu ft)
R-11 Batt Insulation
No Floor Covering

100	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	IIC
50	52	53	60	58	52	48	47	46	45	45	41	40	41	34	36	60



6" Concrete Structural Slab (144 lbs/cu ft)
R-11 Batt Insulation
1" Deflection Spring Isolators
2 Layers 5/8" Gypsum Board
No Floor Covering

100	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	IIC
42	42	43	44	41	45	37	39	38	39	41	36	29	29	32	30	70



4" Concrete Slab (144 lbs/cu ft)
2" Thick Pressed Fiberglass Isolators at 16" on Center
R-11 Batt Insulation
6" Concrete Structural Slab (144 lbs/cu ft)
R-11 Batt Insulation
1" Deflection Spring Isolators
2 Layers 5/8" Gypsum Board
No Floor Covering

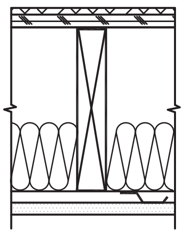
100	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	IIC
38	37	27	27	27	26	24	16	15	13	12	13	7	4	4	4	82

by a source compared with that emitted by an ideal radiating surface.

$$W_{rad} = \sigma\, u^2\, \rho_0\, c_0\, S \qquad (12.4)$$

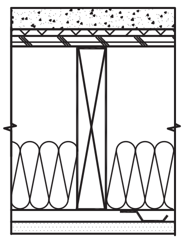
where W_{rad} = radiated sound power, (W)
σ = radiation efficiency (usually ≤ 1)
u = rms velocity of the radiating surface, (m / s)

FIGURE 12.11 Impact Insulation Class of Wood Framed Floors (California Office of Noise Control, 1981)



1/4" Particle Board Glued
5/8" Plywood Glued and Nailed
2 x 10 Wood Joists
R-11 Batt Insulation
1 Layer 1/2" Gypsum Board on Resilient Channel
A - 76 oz Carpet on 50 oz Hair Pad
B - 65 oz Carpet on 30 oz Foam Rubber Pad
C - 50 oz Carpet on 24 oz Hair Pad
D - Cushioned Vinyl Tile
E - 1/16" Vinyl Asbestos Tile
F - 1/2" Wood Parquet Flooring
G - No Floor Covering

	100	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	IIC
A	50	43	42	37	34	34	33	30	31	31	32	29	0	0	0	0	70
B	49	42	39	35	34	32	32	28	28	29	29	0	0	0	0	0	71
C	62	57	56	52	47	42	38	33	34	34	34	32	0	0	0	0	58
D	68	66	68	67	65	61	53	47	45	44	41	37	33	34	0	0	51
E	69	65	69	69	69	69	67	65	64	64	60	56	50	48	48	48	47
F	65	64	64	65	64	63	63	60	60	59	57	55	49	45	45	49	50
G	66	64	68	67	66	67	65	62	62	61	58	54	49	47	46	47	49



1 5/8" Lightweight Concrete (110 lbs/cu ft)
1/4" Particle Board Glued to Plywood
5/8" Plywood Glued and Nailed to Joists
2 x 10 Wood Joists
R-11 Batt Insulation
1 Layer 1/2" Gypsum Board on Resilient Channel
A - 76 oz Carpet on 50 oz Hair Pad
B - 65 oz Carpet on 30 oz Foam Rubber Pad
C - 50 oz Carpet on 24 oz Hair Pad
D - Cushioned Vinyl Tile
E - 1/16" Vinyl Asbestos Tile
F - 1/2" Wood Parquet Flooring
G - No Floor Covering

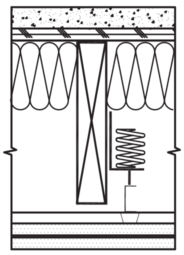
	100	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	IIC
A	47	42	39	34	34	29	30	26	25	27	28	23	22	21	0	0	73
B	44	38	35	31	32	27	28	24	24	25	27	22	19	19	0	0	76
C	56	54	50	46	43	37	35	31	30	31	32	29	0	0	0	0	64
D	64	61	62	60	58	52	48	40	36	37	39	34	33	34	0	0	56
E	62	59	60	60	61	60	62	62	62	65	66	64	62	60	60	55	43
F	64	61	63	63	63	60	61	60	59	58	55	50	46	42	40	40	52
G	62	61	60	60	61	59	62	63	63	65	66	65	62	61	61	62	38

ρ_0 = density of air, (kg/m^3)
c_0 = speed of sound in air, (m/s)
S = area of the radiating surface, (m^2)

Radiation efficiencies are helpful in describing the process since real sources do not move in a perfectly planar manner and are not infinite. Sound radiation by heavy thick materials such as brick or concrete, where shear waves predominate at high frequencies, usually can be

FIGURE 12.12 Impact Insulation Class of Floors with Resiliently Supported Ceilings

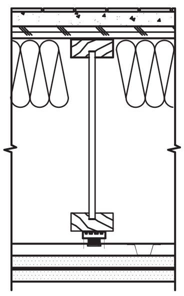
(Kinetics Corporation Test Data)



1 1/2" (40 mm) Lightweight Concrete
(12.8 lbs/sq ft or 63.4 kg/sq m)
1 Layer 5/8" (16 mm) Plywood
2 x 10 (240 mm) Wood Joists
R-11 Batt Insulation
1" (25 mm) Deflection Spring Isolators
2 Layers 5/8" (16 mm) Gypsum Board
A - Carpet on 3/8" (10 mm) Hair Pad
B - 5/16" (8 mm) Parquet Flooring

	100	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	IIC
A	31	29	27	22	19	16	14	10	10	6	6	5	6	7	7	9	89
B	56	56	53	53	55	54	50	48	46	44	43	40	36	34	31	24	62

(PAC International Test Data)



1/4" (13 mm) Ceramic Tile
1" (25 mm) Lightweight Concrete
(130 lb/cu ft or 2,083 kg/cu m)
1 Layer 3/4" (18 mm) Plywood
18" (457 mm) Truss Wood Joist
R-11 Batt Insulation
RSIC-1 Isolation Clips with 7/8" (22 mm) Hat Channel
2 Layers 5/8" (16 mm) Gypsum Board
A - As Shown
B - 3/8" (10 mm) Carpet on 3/8" (10 mm) Pad on Tile
with 1 x 5/8" (16 mm) Gypsum Board Ceiling

	100	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	IIC
A	64	55	57	57	54	52	53	54	57	55	53	51	50	52	50	45	53
B	46	32	32	28	28	29	22	13	9	8	8	5	5	5	4	4	74

assumed to have a radiation efficiency of one. If bending waves are part of the transmission mechanism they result in a pronounced increase in the radiation efficiency around the critical frequency and a decrease below it, as shown in Fig. 12.13. For finite-sized panels there are also contributions due to edge effects, so that there are additional terms contributing to Eq. 12.4.

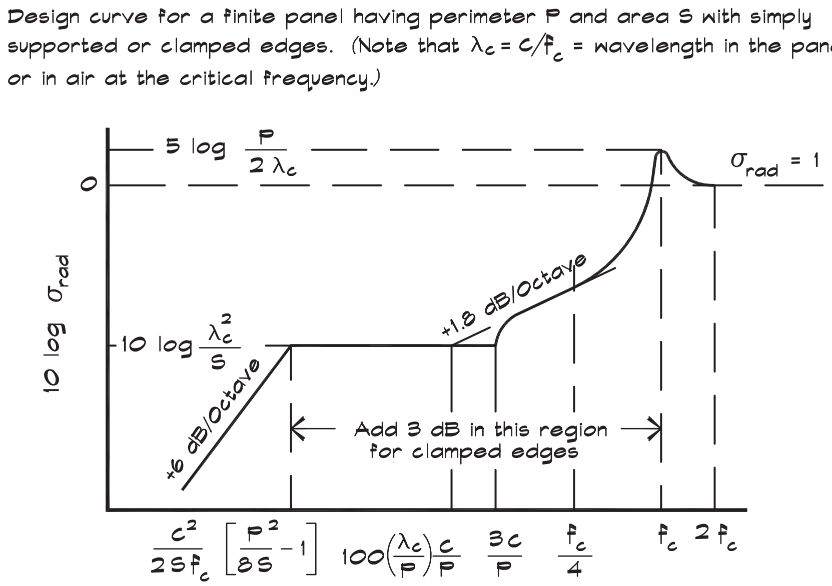
Mechanical Impedance of a Spring Mass System

A vibrationally driven system such as a floor can be analyzed in terms of its mechanical impedance, which is the ratio of an applied force to the induced velocity. This is somewhat different from the specific acoustic impedance in which the force was expressed as a pressure. The mechanical or driving point impedance is given by

$$\mathbf{z}_{\mathrm{m}} = \frac{\mathbf{F}}{\mathbf{u}} \tag{12.5}$$

The model of vibrational point excitation of structures is analogous to the use of point sources in the study of sound propagation. They allow us to deal with complex force distributions by integrating (summing) over a distribution of point forces. Point impedances can be measured

FIGURE 12.13 Design Curve for Approximating the Radiation Efficiency (Beranek, 1971)



in the laboratory under controlled conditions and are a useful tool in characterizing complex systems.

If a force is applied to a simple spring mass system the mechanical impedance is the sum of the impedances of the individual components, namely the mass, spring, and damping.

$$\mathbf{z}_{\mathrm{m}} = c + \mathrm{j}\,\omega\,\mathrm{m} + \frac{k}{\mathrm{j}\,\omega} \tag{12.6}$$

Note that at resonance the mechanical impedance is zero, since a large velocity is produced by a very small force. If we set the impedance to zero and solve Eq. 12.6 for the resonant frequency, we get Eq. 6.4 for zero damping.

For a sinusoidal force $\mathbf{F} = \mathrm{F}_0\, \mathrm{e}^{\mathrm{j}\,\omega\,\mathrm{t}}$ applied to a spring-mass system, the induced velocity is

$$\mathbf{u} = \frac{\mathrm{F}_0\,\mathrm{e}^{\mathrm{j}\,\omega\,\mathrm{t}}}{\mathbf{z}_{\mathrm{m}}} = \frac{\mathrm{F}_0\,\mathrm{e}^{\mathrm{j}\,\omega\,\mathrm{t}}}{c + \mathrm{j}\,\omega\,\mathrm{m} + \dfrac{k}{\mathrm{j}\,\omega}} \tag{12.7}$$

It is clear that for low induced velocities we want high mass, high stiffness, and high damping. Although floors are not pure spring-mass systems, the model is a helpful analogy. An examination of Eq. 12.7 reveals that at high frequencies the mass and damping terms predominate, while at very low frequencies the stiffness and damping terms are more important.

In a generalized system having a complex impedance the power is

$$W = \frac{\omega}{2\pi} \int_{0}^{2\pi/\omega} \mathbf{F}(t)\, \mathbf{u}(t)\, dt = \frac{1}{2} \left|F_0\right| \left|u_0\right| \cos\phi \tag{12.8}$$

so

$$W = \frac{1}{2} \left|F_0\right|^2 \mathrm{Re}\left\{\frac{1}{\mathbf{z}_m}\right\} = \frac{1}{2} \left|u_0\right|^2 \mathrm{Re}\left\{\mathbf{z}_m\right\} \tag{12.9}$$

where F_0 is the peak force amplitude, u_0 is the peak velocity amplitude, and ϕ is the relative phase between the force and the velocity. The bracketed terms are the real parts of the complex impedance or its reciprocal. If a sinusoidal force is applied to a spring mass system the steady state energy is dissipated in the dashpot. The dashpot impedance c is real and the velocity of the mass is in phase with the resistance force. The power expended is

$$W = \frac{\left|F_0^2\right|}{2\,c} \tag{12.10}$$

Spring mass models are useful abstractions when the structural wavelengths are large compared to the dimensions of the system (Ver, 1992). When the wavelengths are small compared to the dimensions of the floor, we use another approximation, the driving point impedance. In this model we assume that the panel is infinite so we can ignore the reflection of structural waves from the plate boundaries. We then use the infinite plate model to approximate the result for a finite structure.

Driving Point Impedance

The driving point impedance of a structural system can be measured directly or calculated from its mass and bending stiffness. This exercise has been carried out by a number of authors. Results have been published by Cremer (1973), Pinnington (1988), and Beranek and Ver (1992). The structural configuration that is generally of the greatest interest in architectural acoustics is a flat plate. The point impedance of an infinite thin plate in bending is

$$z_m = 8\sqrt{D\,\rho_m\,h} \cong 2.3\, c_L\, \rho_m\, h^2 \tag{12.11}$$

where D = flexural rigidity per unit length = $\dfrac{E\,h^3}{12\,(1-\mu^2)}$ (N m)

ρ_m = density of the plate (kg / m^3)

c_L = longitudinal sound velocity in the plate = $\sqrt{\dfrac{E}{\rho_m}}$ (m / s)

h = plate thickness (m)

μ = Poisson's ratio $\cong 0.3$

E = Young's modulus (N / m^2)

Cremer (1973, pp. 260–264) gives the derivation of this relationship.

Power Transmitted through a Plate

For vibrational energy transmitted into and out of a plate, there is an energy balance whereby the energy entering the plate is either dissipated within the plate or radiated away as sound.

$$W_{in} = W_{dis} + W_{rad} \tag{12.12}$$

There are several possible energy dissipation mechanisms. The energy may be transmitted away as a bending wave in an infinite plate, or in a finite plate it may end up exciting the normal modes of vibration, which decay out due to internal losses. In both cases we can assume there is internal damping, which attenuates energy by some amount over time.

$$E_{dis}(t) = E_0 \left(1 - e^{-\eta\,\omega\,t}\right) \tag{12.13}$$

where $E_{dis}(t)$ = energy dissipated as a function of time (W)
E_0 = initial vibrational energy (W)
η = damping constant
ω = radial frequency (s^{-1})
t = time (s)

We can calculate the energy lost in one period ($T = 2\,\pi\,/\,\omega$) assuming a damping constant much less than one

$$E_{dis} \cong 2\,\pi\,\eta\,E_0 \tag{12.14}$$

Now we examine a small element of plate, which is vibrating. The initial energy in that element is

$$E_0 = \frac{1}{2}\rho_s\,u_0^2\,dx\,dz \tag{12.15}$$

where $\rho_s = \rho_m\,h$ is the surface density of the plate. Dividing the energy by the period $T = 1\,/\,f$, we obtain the energy dissipated per unit time

$$E_{dis} = \frac{1}{2}\,\omega\,\eta\,\rho_s\,u_0^2\,dx\,dz \tag{12.16}$$

so the power converted to heat for a total plate area S is

$$W_{dis} = \frac{1}{2}\,\omega\,\eta \int_s \rho_s\,u_0^2\,dx\,dz = \frac{1}{2}\,\omega\,\eta\,\rho_s\,S\,u_0^2 \tag{12.17}$$

Therefore the power balance equation can be written as

$$\frac{1}{2}\,F_0^2\,Re\left\{\frac{1}{\mathbf{z}_m}\right\} = u^2\,S\left[\omega\,\eta\,\rho_s + 2\,\rho_0\,c_0\,\sigma\right] \tag{12.18}$$

and using the mechanical impedance given in Eq. 12.11, the mean square velocity in a thin infinite plate that results from an imposed force having an amplitude F_0 is

$$u^2 = \frac{F_0^2}{4.6\,\rho_S^2\,c_L\,h\,\omega\,\eta\,S\,(1 + 2\,\rho_0\,c_0\,\sigma/\omega\,\eta\,\rho_s)} \tag{12.19}$$

When $\omega\,\eta\,\rho_s >> 2\,\rho_0\,c_0\,\sigma$, Eq. 12.19 simplifies to

$$u^2 \cong \frac{F_0^2}{4.6\,\rho_S^2\,c_L\,h\,\omega\,\eta\,S} \tag{12.20}$$

Thus the transmission mechanism for impact noise in a thin plate is primarily due to bending waves.

Impact Generated Noise

When a standard tapping machine is used to test the Impact Insulation Class of a floor, a series of blows is created by releasing hammers timed to fall on the floor 10 times per second. This generates a train of force pulses that can be analyzed in terms of a Fourier series (Ver, 1971). The reason we use this methodology is that we wish to be able to calculate noise generated in each frequency band and thus we must determine the vibrational frequency spectrum of the exciting force. The Fourier series describes any repeated wave form using an infinite sum having the form

$$F\,(t) = \sum_{n=1}^{\infty} F_n \cos\,(n\,\omega\,t) \tag{12.21}$$

where the amplitudes are given by

$$F_n = \frac{2}{T_r} \int_0^{T_r} f\,(t)\,\cos\left(\frac{2\,\pi\,n}{T_r}\,t\right) dt \tag{12.22}$$

and f (t) is the shape of a typical force pulse, T_r is the time period between hammer blows, and $n = 1, 2, 3 \ldots$ The duration of the force impulse for a hard concrete slab is small compared to the period of the highest frequency of interest. Thus the term

$$\cos\left(\frac{2\,\pi\,n}{T_r}\,t\right) \cong 1 \tag{12.23}$$

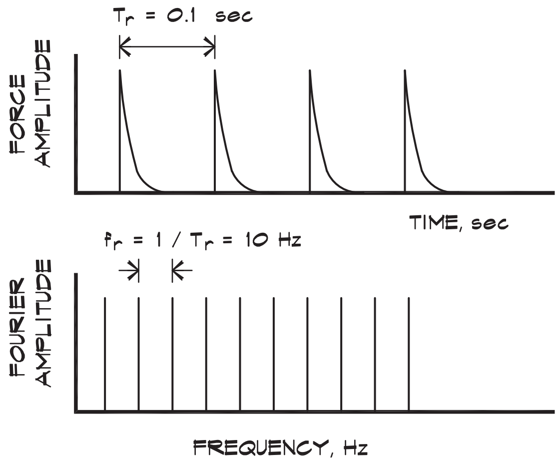
and the Fourier amplitude of the pulse train can be simplified to

$$F_n \cong \frac{2}{T_r} \int_0^{T_r} f\,(t)\,dt = 2\,f_r\,m\,v_0 = 2\,f_r\,m\,\sqrt{2\,g\,d} \tag{12.24}$$

where f_r = repetition frequency, (Hz)
m = mass of the hammer, (kg)
v_0 = velocity of the hammer at impact, (m / s)
d = drop distance, (m)
g = gravitational acceleration (9.8 m / s^2)

Figure 12.14 shows a pulse train and its spectrum. The frequency spectrum is a series of lines of the same length that are separated by the frequency interval f_r.

FIGURE 12.14 Time Dependence and Frequency Spectrum of Tapping Machine Noise (Cremer and Heckl, 1973)



This relationship holds for ideal impacts. For real impacts, which have a finite duration, the length of the lines decreases slowly at high frequencies (Lange, 1953).

To determine the force spectrum at a given frequency, we define a mean square force spectrum density, S_f, which when multiplied by the bandwidth yields the mean square force in the same bandwidth (Ver, 1971 and Cremer, 1973)

$$S_f = \frac{1}{2} T_r F_n^2 = 4 f_r m^2 g d \quad (N^2 / Hz) \tag{12.25}$$

For a standard tapping machine the value of S_f can be calculated from the fixed mass, the drop frequency, and the drop distance to be 4 N^2 / Hz. The mean square force in a standard octave band is the spectrum density times the octave bandwidth or

$$F_{rms}^2 (oct) = 4 \frac{f}{\sqrt{2}} \quad (N^2) \tag{12.26}$$

Using Eqs. 12.3 and 12.18 we can calculate the sound power level generated by a tapping machine in a given frequency range

$$L_w (oct) = 10 \log \left(\frac{\rho_0 \, c_0 \, \sigma_{rad}}{5.1 \, \rho_m^2 \, c_L \, \eta \, h^3} \right) + 120 \tag{12.27}$$

and using Eqs. 12.1 and 8.83, the normalized impact sound level in each octave band is

$$L_n (oct) = 10 \log \left(\frac{4}{5.1} \frac{(\rho_0 \, c_0)^2 \, \sigma_{rad}}{p_{ref}^2 \, A_0 \, \rho_m^2 \, c_L \, \eta \, h^3} \right) \tag{12.28}$$

where $p_{ref} = 2 \times 10^{-5}$ $(N / m^2) = 0.0002 \, \mu$ bar. Note that in Eq. 12.28, the transmitted sound level follows the normal mass law, increasing 6 dB per doubling of density; however, it decreases 9 dB per doubling of slab thickness. The normalized level, L_n, decreases with increasing damping and is independent of the frequency, as long as the radiation efficiency and damping are frequency independent. To calculate the spatial average diffuse field sound level in the room below the tapping machine we use

$$\overline{L}_p = L_n\,(\text{oct}) + 10\log\frac{A_o}{S\,\overline{\alpha}} \tag{12.29}$$

To estimate the sound levels radiated by structural concrete or lightweight concrete floors we can use the material constants for the propagation speed of longitudinal waves and the characteristic density, which are: 1) for dense concrete $\rho_m = 2.3 \times 10^3$ (kg / m^3) and $c_L = 3.4 \times 10^3$ (m/s), and 2) for lightweight concrete $\rho_m = 6 \times 10^2$ (kg/m^3) and $c_L = 1.7 \times 10^3$ (m/s). Using these constants the expected levels for dense concrete are

$$L_n\,(\text{oct}) = 32.5 - 30\log h_m + 10\log(\sigma_{rad} / \eta) \tag{12.30}$$

or

$$L_n\,(\text{oct}) = 80.5 - 30\log h_{in} + 10\log(\sigma_{rad} / \eta) \tag{12.31}$$

and for lightweight concrete

$$L_n\,(\text{oct}) = 47 - 30\log h_m + 10\log(\sigma_{rad} / \eta) \tag{12.32}$$

or

$$L_n\,(\text{oct}) = 95 - 30\log h_{in} + 10\log(\sigma_{rad} / \eta) \tag{12.33}$$

where h_m is the thickness of the floor slab in meters and h_{in} is the thickness in inches.

Ver (1971) published a plot of the calculated levels, which is reproduced as Fig. 12.15. The quantity L_n (oct) + $10\log(\eta/\sigma_{rad})$ is shown on the left-hand scale as a function of slab thickness. On the right-hand scale L_n (oct) is given for the typical values, $\eta = 0.01$

FIGURE 12.15 Normalized Impact Sound Level as a Function of Slab Thickness for Lightweight and Dense Concrete Floor Slabs (Ver, 1971)

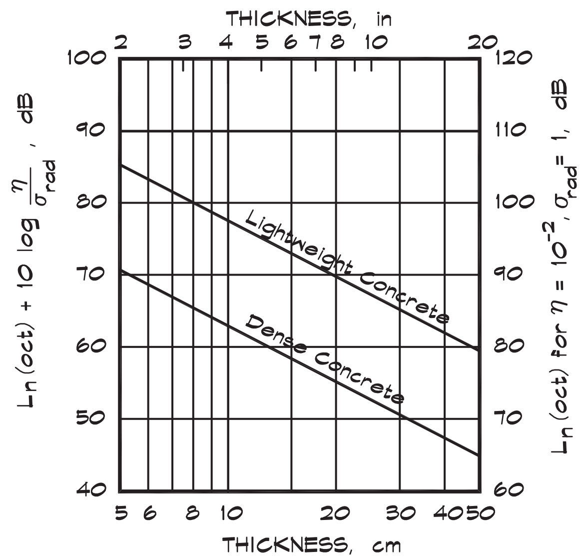
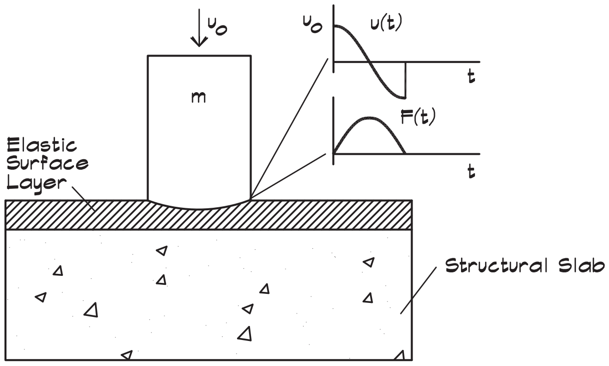


FIGURE 12.16 Forces and Velocities for Soft Floor Covering (Ver, 1971)



and $\sigma_{rad} = 1$. If we assume a 15 cm (6 in) dense concrete slab and use the figure, we get about 78 dB, and for a lightweight concrete structure of the same thickness we get about 92 dB with no surface covering. Human heel drops are not this loud, but the numbers are close to the measured levels for a tapping machine test (Fig. 12.18). Since it is usually impractical to increase the slab thickness and density enough to make a significant change, we turn to the floor surface covering for improvement.

Improvement Due to Soft Surfaces

Ver (1971) and Cremer (1973) have analyzed the impact of a carpet or other similar elastic surfaces on tapping machine noise transmitted through a floor. An illustration of Ver's model is given in Fig. 12.16.

The falling weight strikes a surface, whose stiffness is the elasticity of the carpet. In this model damping is ignored and the weight is assumed to strike the surface and recoil elastically once without multiple bounces. The equation of motion of the spring mass system is

$$m \frac{d^2 x}{d t^2} - k x = 0 \tag{12.34}$$

and

$$m \frac{d u}{d t} + \frac{k}{j \omega_0} u = 0 \tag{12.35}$$

where the natural frequency of the spring mass system is

$$\omega_n = \sqrt{\frac{k}{m}} \tag{12.36}$$

The spring constant is given by

$$k = \frac{E_d \, S_h}{h} \tag{12.37}$$

where E_d = dynamic Young's modulus of elasticity (N/m^2) which is about twice the static modulus
S_h = area of the striking surface of the hammer = 0.0007 m^2
h = thickness of the elastic layer (m)
m = mass of the hammer = 0.5 kg

When the hammer is dropped it strikes the elastic layer with a velocity u_0 at time t = 0 and its subsequent motion can be calculated from Eq. 12.34 to be

$$u(t) = u_0 \cos(\omega_n t) \qquad \text{for } 0 < t < \pi/\omega_n \tag{12.38}$$

and

$$u(t) = 0 \qquad \text{for } t < 0 \text{ and } t > \pi/\omega_n \tag{12.39}$$

Figure 12.16 also shows this velocity function. The force is given by

$$F(t) = m \frac{du}{dt} = u_0\, \omega_n\, m \sin(\omega_n t) \quad \text{for } 0 < t < \pi/\omega_n \tag{12.40}$$

$$F(t) = 0 \qquad \text{for } t < 0 \text{ and } t > \pi/\omega_n \tag{12.41}$$

Now the Fourier amplitude of the tapping machine pulse train as given in Eq. 12.22

$$F'_n = 2 f_r \int_0^{1/(2 f_0)} u_0\, 2\pi f_0\, m \sin(2\pi f_0 t) \cos(2\pi n f_r t)\, dt \tag{12.42}$$

where n = 1, 2, 3, ... This yields the force coefficients of the Fourier series

$$F'_n = F_n \frac{\pi}{4} \left(\frac{\sin\alpha}{\alpha} + \frac{\sin\beta}{\beta} \right) \tag{12.43}$$

in terms of the coefficients given in Eq. 12.43 and

$$\alpha = \frac{\pi}{2}\left(1 - n\frac{f_r}{f_0}\right) \quad \text{and} \quad \beta = \frac{\pi}{2}\left(1 + n\frac{f_r}{f_0}\right) \tag{12.44}$$

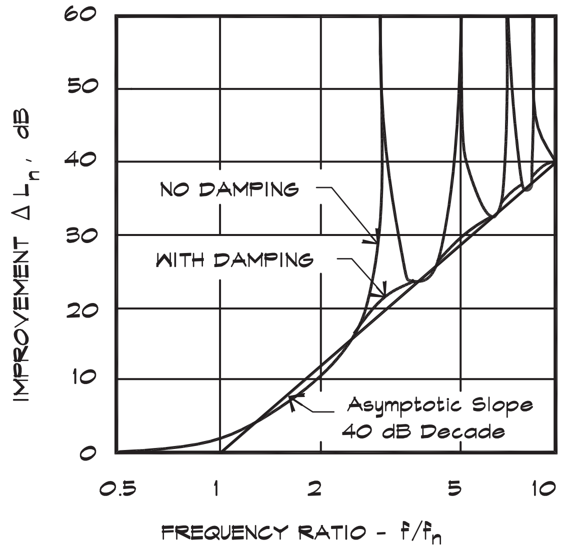
The improvement due to the elastic surface in the impact noise isolation is given in terms of a level

$$\Delta L_n = 20 \log \frac{F_n}{F'_n} = 20 \log \left(\frac{4/\pi}{\sin\alpha/\alpha + \sin\beta/\beta} \right) \tag{12.45}$$

which is shown graphically in Fig. 12.17.

Note that in this model we have ignored the contribution of the floor impedance and have assumed that it is very stiff compared with the elastic covering. At very low frequencies—that is, below the spring mass resonance—the improvement due the covering is zero. Above this frequency the surface covering becomes quite effective, giving a 12 dB per

FIGURE 12.17 Improvement in Impact Noise Isolation by an Elastic Surface (Ver, 1971)



octave attenuation. The resonant peaks, which occur at odd multiples of the fundamental resonance, are diminished in actual field conditions by the damping in the surface treatment.

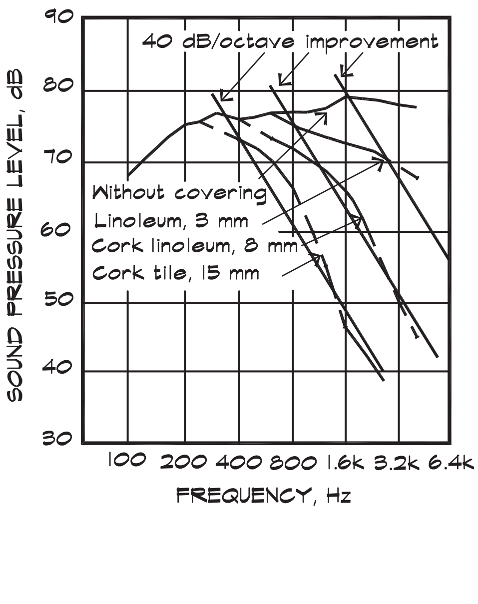
The normalized impact sound level for composite floor systems is given by

$$L_{n\ comp} = L_{n\ bare} - \Delta L_n \tag{12.46}$$

which is shown in Fig. 12.18 and compared with measured data. Note that while carpet and other elastic surface treatments improve the high-frequency loss for tapping noise, they

FIGURE 12.18 Calculated and Measured Impact Noise Levels

Footfall noise level under a 12 cm thick concrete floor with various floor coverings (Measured data by Cremer and Heckl, 1973)



do not change the low-frequency transmission due to the weight of the walker, which is controlled by the stiffness and damping of the structural system. Likewise, they have little effect on the sound transmission loss of the structure since they do not alter the mass or stiffness of the floor system.

Improvement Due to Locally Reacting Floating Floors

A number of systems have been developed to provide noise and vibration isolation through the use of resilient floor or ceiling supports. These include continuous and point-supported floating floors, which are built on top of the structural floor system, as well as resiliently hung or separately supported ceilings. Each of these systems can provide improved isolation for footfall noise and some for walking noise, which as we will see, will depend on the softness of the mounts.

A locally reacting floating floor is one in which the influence of the initial force impulse is confined to the region around the point of impact. There is no vibrational wave in the upper slab, which is considered highly damped. An example might be a single layer of plywood without structural support other than the resilient mounts. Since the upper surface is hard the Fourier amplitude coefficients of the force pulse given in Eq. 12.24 can still be used. Ver (1971), citing Cremer (1952), has published the expected improvement

$$\Delta L_n = 20 \log \left[1 + \left(\frac{f}{f_1} \right)^2 \right] \cong 20 \log \left(\frac{f}{f_1} \right)^2 \tag{12.47}$$

where f_1 is the resonant frequency of the floating floor system is

$$f_1 = \frac{1}{2\pi} \sqrt{\frac{k'}{\rho_{S1}}} \tag{12.48}$$

and k' is the dynamic stiffness per unit area of the resilient layer between the floors, including the stiffness of the trapped air, and ρ_{S1} is the mass per unit area of the upper floor. As with a resilient surface, the result is a 12 dB per octave decrease in level above the resonant frequency. Below resonance there is no improvement.

Improvement Due to Resonantly Reacting Floating Floors

A resonantly reacting floor is a rigid, lightly damped floating slab in which bending waves are generated in response to the impulsive load. The input power into the upper slab is given by Eq. 12.9. The power balance equation for the upper slab is

$$W_{in} = W_{dis(1)} + W_{12} - W_{21} \tag{12.49}$$

and for the lower slab is

$$W_{12} = W_{dis(2)} + W_{21} \tag{12.50}$$

where powers with the subscript "dis" are the dissipated powers in slabs 1 and 2. The numerical subscripts indicate the direction of travel of the particular transmitted power through the mounts. Three equations permit the calculation of the transmitted power through the mount

$$F = (u_1 - u_2)\, z_m$$
$$u_1 = u_0 - \frac{F}{z_1} \qquad (12.51)$$
$$u_2 = \frac{F}{z_2}$$

where u_n = peak velocity amplitude in slab n (m / s)
z_n = point impedance of slab n (Ns / m)
z_m = point impedance of the support system (Ns / m)

When these equations are solved (Beranek and Ver, 1992) for the transmitted forces in terms of the point impedances, the improvement in the high-frequency limit, given in terms of the ratio of the initial to the transmitted forces is

$$\Delta L_n(\omega) \cong 10 \log \left[2.3\, c_{L1}\, h_1\, \eta_1\, n' \left(\frac{\omega^3}{\omega_1^4} \right) \right] \qquad (12.52)$$

where c_{L1} = speed of longitudinal waves in the floating slab (m / s)
h_1 = thickness of the floating slab (m)
η_1 = damping factor in the floating slab
n' = number of resilient mounts per unit area (m^{-2})
$\omega_1 = \sqrt{\dfrac{k_m\, n'}{\rho_{s1}}}$ = resonant frequency of the floating slab (s^{-1})
k_m = dynamic stiffness of an individual mount (N / m)
ρ_{m1} = surface mass density per unit area of the floating slab (kg / m^2)

In obtaining this relationship we have assumed that the power is transmitted only through the mounts, which can be represented by a spring constant, and that the point impedance of the slab is that of an infinite thin plate. Typical material constants are given in Table 12.1 and calculated data are shown in Fig. 12.19, along with measured results published by Josse and Drouin (1969). The improvement follows a 9 dB/octave slope above the resonant frequency.

12.4 STRUCTURAL DEFLECTION

Sound can be produced by the deflection of the structure in a gross way under the weight of a walker or other moving object. When a load is applied to a floor, the structure will deflect and transmit the movement to the space below. The weight may be statically or dynamically applied. We have discussed the vibrations induced in a floor system due to a walker in Chapt. 11. Where the floor system is a slab or a nonisolated structure the motion imparted to the floor will be faithfully reproduced on the ceiling side. Where the ceiling is decoupled from the floor support system considerable improvement can be expected.

Floor Deflection

If a person stands in the center of an upper-story floor, the structure will deflect under the concentrated load of his weight. This is a static, as contrasted to a dynamic, effect since it

TABLE 12.1 Speed of Longitudinal Waves, Density, and Internal Damping Factors for Common Building Materials (Beranek and Ver, 1992)

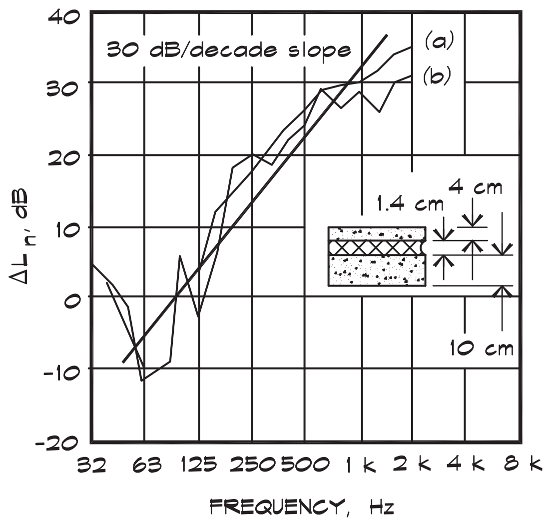
Material	c m/sec	ρ lb/ft^3	ρ kg/m^3	Damping Factor η*
Aluminum	5,150	170	2,700	10^{-4}- 10^{-2}
Brick	......	120-140	1,900-2,300	0.01
Concrete, poured	3,400	150	2,300	0.005-0.02
Masonry block				
Hollow cinder (nominal 6 in. thick)	......	50	750	0.005-0.02
Hollow cinder 5/8 in. sand plaster each side (nominal 6 in. thick)	......	60	900	0.005-0.02
Hollow dense concrete (nominal 6 in. thick)	......	70	1,100	0.007-0.02
Hollow dense concrete, sand-filled (6 in. thick)	......	108	1,700	Varies with frequency
Solid dense concrete block (4 in. thick)	.....	110	1,700	0.012
Fir timber	3,800	40	550	0.04
Glass	5,200	156	2,500	0.001-0.01†
Lead:				
Chemical or tellurium	1,200	700	11,000	0.015
Antimonial (hard)	1,200	700	11,000	0.002
Plaster solid, on metal or gypsum lath	......	108	1,700	0.005 - 0.01
Plexiglas or Lucite	1,800	70	1,150	0.002
Steel	5,050	480	7,700	10^{-4}- 10^{-2}
Gypboard (0.5 to 2 in)	6,800	43	650	0.01 - 0.03
Plywood (0.25 to 1.25 in)	......	40	600	0.01 - 0.04
Wood chip board, 5 lb/ft^2	......	48	750	0.005 - 0.01

*The range in values of η are based on limited data at 1000 Hz. The lower values are typical for the material alone.

† The loss factor for structures of these materials is very sensitive to construction techniques and edge conditions.

FIGURE 12.19 Improvement in Impact Noise Isolation for a Resonantly Reacting Floating Floor (after Beranek and Ver, 1992)

a) Standard tapping machine b) High heeled shoes
Note the negative ΔL_n in the vicinity of the resonant frequency.



takes place without any repetitive motion—at zero frequency. The deflection of the floor can be modeled in a number of ways, but let us take a simple example using standard structural equations (Roark and Young, 1975). If we assume that the load is supported entirely by a simply supported beam, the midpoint deflection, ignoring the weight of the beam, is

$$\delta = -\frac{\mathrm{W}\,L^3}{48\,\mathrm{E}\,\mathrm{I}} \tag{12.53}$$

where δ = deflection at midspan (in)
W = weight of the impressed load (lbf)
L = length of the beam (in)
E = modulus of elasticity (lb / in^2)
= 1.92×10^6 lb / in^2 for douglas fir
I = moment of inertia (in^4) = b d^3 / 12
b = beam width and d = beam depth (in)

If the beam is a wood 2 × 12 that is 20 feet long and a 200 lb man is standing at the midpoint, the deflection is about 0.16 inch and the natural frequency, using a simple spring mass relationship is about 8 Hz.

If the floor is 5/8” plywood with a 1.5” lightweight concrete topping, each beam (assuming 16” centers) bears a distributed load of about 20 lbs/ft (w = 1.7 lbs/in). The midspan deflection is

$$\delta = -\frac{5\,\mathrm{w}\,L^4}{384\,\mathrm{E}\,\mathrm{I}} \tag{12.54}$$

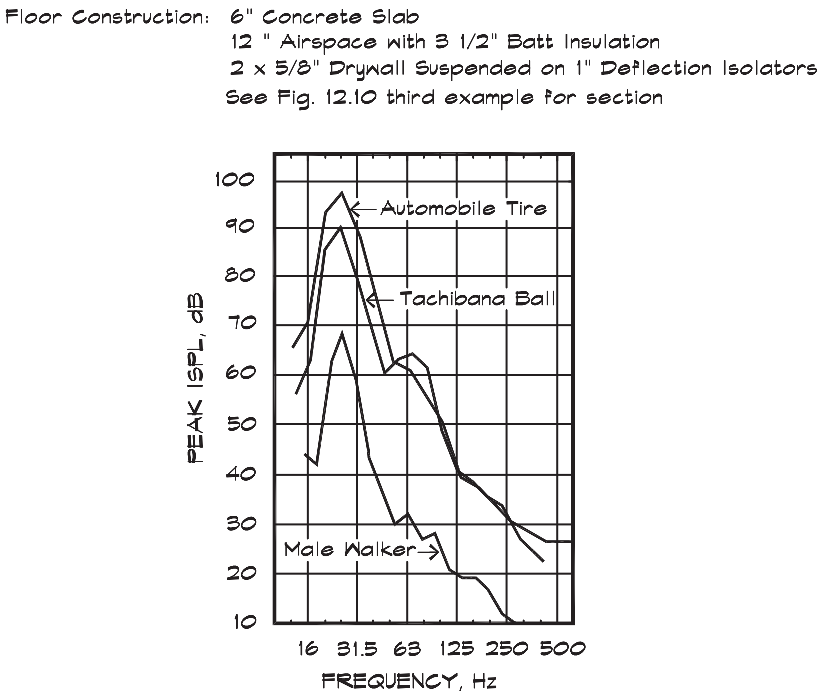
For the same beam the deflection is about 0.2” with no concentrated load, and adding the deflection due to the weight of a person it is about 0.36”. The natural frequency of this system, modelled as a spring mass, is 5 Hz.

Now this is a very simple model. The plywood flooring can increase the moment of inertia of the beam somewhat. The point load may be distributed over more than one beam. The beams may not be simply supported. So we may get a bit higher resonant frequency. The result, however, will be a relatively low frequency, less than 10 to 15 Hz at these spans, and somewhat higher frequencies at shorter spans. When the floor resonance is excited by a walker we can get a high ceiling deflection unless the floor is stiffened, damped, and decoupled from the ceiling support structure.

Low-Frequency Tests

There are a few tests available to measure the results of noise generated by floor deflection. A few years ago ASTM committee E33 proposed a single microphone located 1 m below the midpoint of the ceiling. The receiving room is deadened by placing absorbing material in it. Three types of sources are used: a male walker, a heavy ball, and an automobile tire. The Japanese measurement standard JIS 1418 specifies an automobile tire mounted on an arm attached to a motor. The motor arm lifts the tire and drops it on the floor. A cam system catches the tire on the rebound before it can strike the floor again and lifts it again to the proper height. The standard specifies many drop positions and several microphone positions; however, since the fundamental resonance is excited, only a few drop positions and a single mic position are adequate for comparative measurements. Test results are shown in Fig. 12.20

FIGURE 12.20 Peak Impact Sound Level Measurements Using Various Excitation Sources (Kinetics, 1990)



for a 6” thick concrete slab floor with a resiliently suspended drywall ceiling below. Note the peak impulse response is around 25 Hz, which is characteristic of the short span concrete floor used in these tests. The Tachibana ball, used in a Japanese test, is 180 mm in diameter and weighs 2.5 kg and is dropped from a height of 900 mm, and produces a very similar curve. A male walker yields similar results although the absolute levels vary.

Blazier and DuPree (1994) published measurements of the impact sound pressure level, taken on the wood floor system shown in Fig. 12.21, using a standard tapping machine as a source. Part of their study sought to quantify the importance of structural flanking in floating floors; however, these authors also extended their measurements to very low frequencies. In Fig 12.22 we see a comparison of a tapping test done on carpeted floor, a floating tile floor, and a partially floating tile floor. Below the 63 Hz band, there is little difference between surface treatments and we see two resonant peaks associated with the structural modes of the floor. Note that the difference between the unflanked and the partially flanked floating floor does not exceed 5 to 6 dB until the frequency is around 500 Hz, indicating a very

FIGURE 12.21 Wood Framed Floating Floor

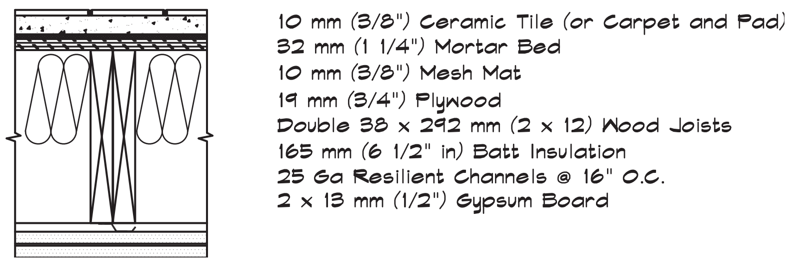


FIGURE 12.22 Impact Noise Spectrum of ISO Tapping Machine on a Floated Floor vs Percent of Floor Area Flanked and Type of Surface Covering (Blazier and DuPree, 1994)

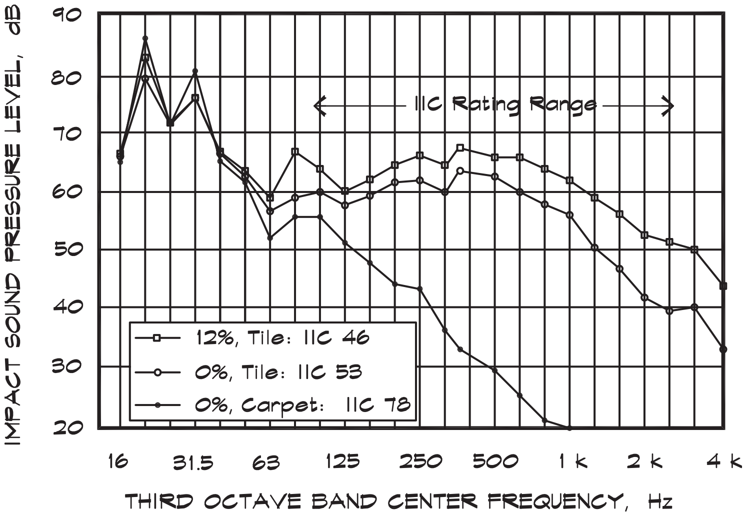
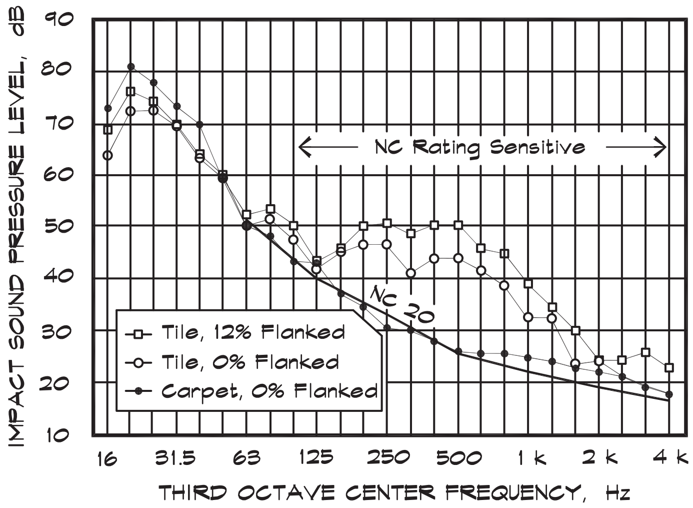


FIGURE 12.23 Impact Noise Spectrum of a Male Walker on a Floated Floor vs Percent of Surface Area Flanked and Type of Surface Covering (Blazier and DuPree, 1994)



low deflection support system. The structural flanking referred to in Fig. 12.22 was due to concrete in the mortar bed flowing around the pour dam and under the matting.

Figure 12.23 shows additional measurements from the same study on the noise produced by normal walking compared with a standard NC curve. Even with carpet the levels are audible at low frequencies and very audible for tile floors. At these very low frequencies, it is the structural resonance that is being excited by the walker. Since the effect is a gross property of the structure, it is unaffected by the surface covering. For this construction there is little decoupling between the floor and the ceiling, so relatively poor isolation results.

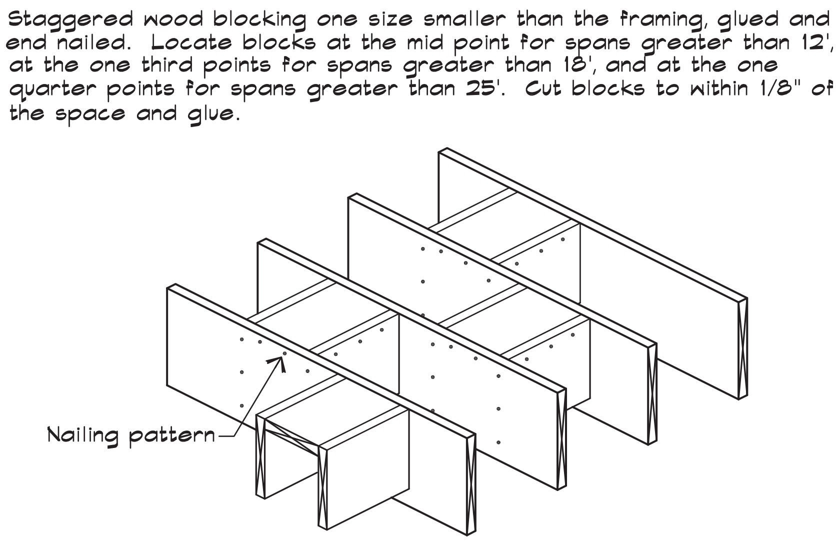
It is interesting to compare the data from the walking test in Fig. 12.20 for a concrete slab with similar tests done on the Fig. 12.23 construction, which is poorly isolated. The difference above 20 Hz is at least 10 dB and as much as 30 dB quieter in the concrete structure.

Structural Isolation of Floors

Three mechanisms are available to improve low-frequency sound transmission: 1) increase the stiffness of the floor support system, 2) increase the structural damping, and 3) increase the vibrational decoupling between the floor and the ceiling. In concrete structures both the stiffness and the damping increase with slab thickness. In Chapt. 11 we discussed the treatment of vibrations in concrete slab floors.

In wood floor structures both stiffness and damping can be increased by using stepped blocking, shown in Fig. 12.24. Blocking, using 2 × lumber one size smaller than the joist material, is installed in a series of inverted U shapes, glued and end-nailed into place. The next set of blocks is stepped (i.e., installed in a position that is offset relative to the first set) so that it can also be end-nailed. Both careful trimming and liberal application of glue are important to the installation. Blocks must be trimmed so that no more than a 1/8" gap is left between the block and the joist. The object of the blocking is to build an additional beam at right angles to the joists near the midpoint of the span and to provide additional damping.

FIGURE 12.24 Stepped Blocking in 2 × Wood Framing



Stepped blocking is used at the midspan in wood floors having a joist span of more than 12 feet (3.7 m) and less than 18 feet (5.5 m), and at the one-third points in spans 18 feet or greater. This type of blocking is most effective when it is installed before the floor is covered with a diaphragm and concrete, since the additional loads cause the structure to deflect and distributes some of the static load to the blocking. It can also be used as a retrofit; however, the joists have already deflected and the static load is not distributed as efficiently.

Figure 12.25 shows the results of tapping machine tests done on the floor system, drawn in Fig. 12.26, that incorporates stepped blocking, compared with the mesh mat construction. Note that the low-frequency transmission loss is much better than the Blazier and DuPree results.

12.5 FLOOR SQUEAK

Shiners

Floor squeak is generated most often in wood construction by the rubbing of a joist or panel on a nail that is not completely embedded. Called *shiners*, these nails occur when framers use nail guns to secure the plywood diaphragms to the joists and miss their target. If the nail is not centered it will pass through the plywood and lay alongside the joist as in Fig. 12.27. When the floor deflects due to the passage of a walker, the joist moves and the nail rubs against the wood, creating a high-pitched squeak much like a bird call.

If shiners are found in the field they should be removed by pounding them up from the bottom and pulling them out from the top. It is critical to listen below to the floor response, while someone walks over each portion of the floor, to locate nonbedded nails before any lightweight concrete or other flooring is applied. Since squeak is not dependent on mass or damping in the floor structure, it is not affected by the addition of lightweight concrete, and the presence of these materials make the nails much more difficult to remove.

FIGURE 12.25 Impact Noise Spectrum of ISO Tapping Machine on Two Types of Floors, Both Carpeted

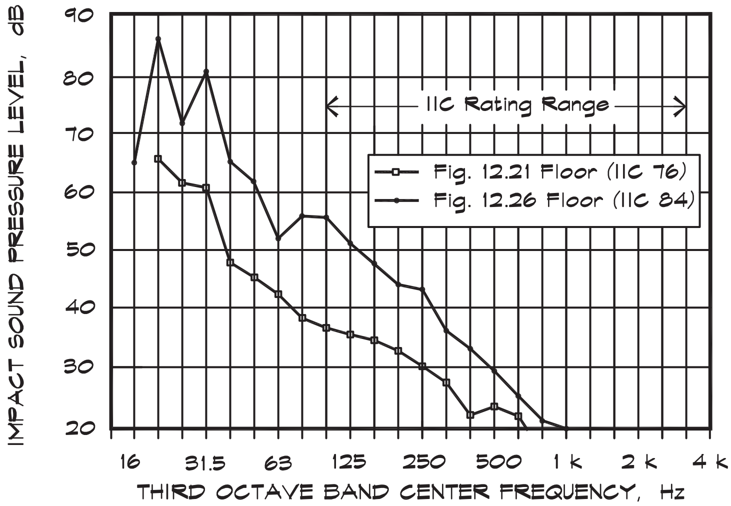


FIGURE 12.26 Separately Supported Wood Floor

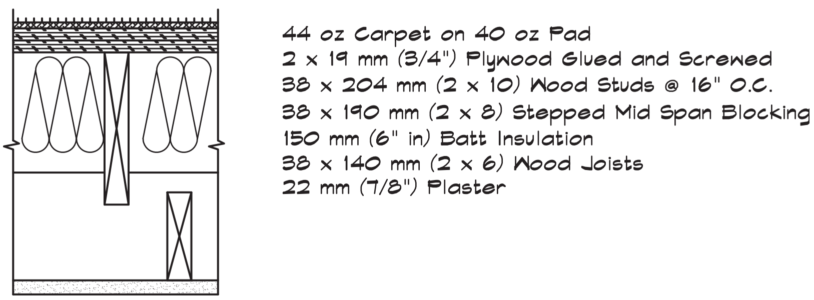


FIGURE 12.27 Sources of Floor Squeak

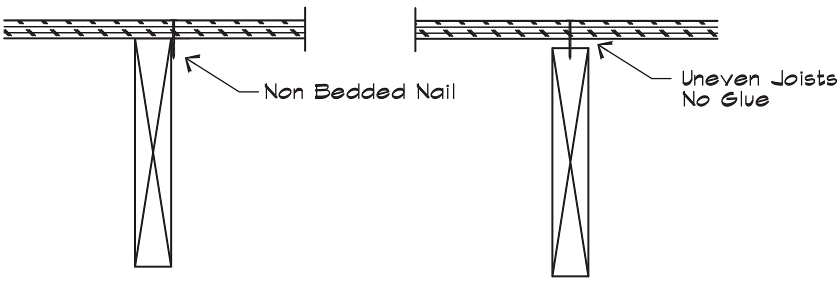
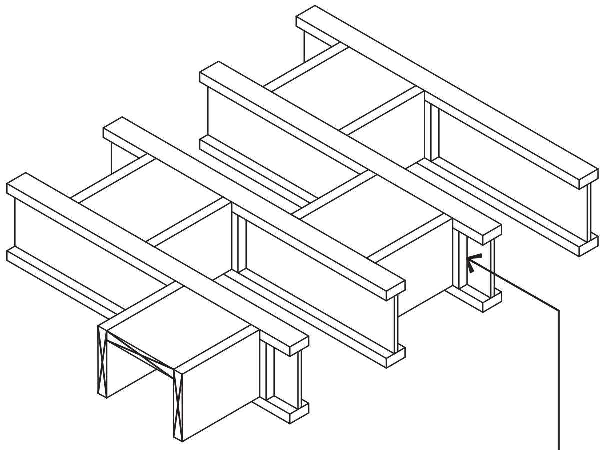


FIGURE 12.28 Truss Joists with Stepped Blocking



Uneven Joists

Nail squeak also can occur in a wood floor when the joists are of an uneven height. In these cases, the diaphragm does not make contact with the top of the joist and, in time, can move up and down on a nail, even one embedded in the joist. These conditions are particularly difficult to locate and remedy after the fact. Liberal application of panel adhesive to the top side of the joist before the plywood is installed will bond the subfloor to the joist and help fill in gaps that may be present. Factory manufactured truss joists can provide a better size consistency, which helps problems due to the variability in lumber. With truss joists, however, it is more difficult to construct stepped blocking since a spacer piece is required to fill the webbing, as illustrated in Fig. 12.28.

Hangers

Squeak can also occur when metal hangers are used to support the joists. In these cases the nails securing the hanger to the joist may rub on the hanger as the joist deflects. If the lumber varies in size, the diaphragm may not make contact with the joist and a gap will result. The best solution in these cases is to shim the joist so the top is even, and to glue the plywood down before nailing. It is preferable to frame the joists on the top plate of the bearing wall rather than being carried on wall-mounted metal hangers.

Nailing

A smooth nail, which does not grip the wood, is more prone to squeak than a ribbed nail. Ribbed or ring shank nails are helpful in preventing squeak since the wood is less likely to move vertically. Floor panel materials fabricated from strands of wood glued together are more prone to squeak than plywood since the high glue content material abrades and leaves a small hole where the nail can rub. Panel screws along with glue can give additional protection against squeak since they grip the wood more firmly. Drywall screws can be used; however, they are thinner than panel screws and more prone to break off.

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