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Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/40000762
Canadian Building Digest, 1975-09

Canadian Building Digest

Division of Building Research, National Research Council Canada

CBD 173

Floor Vibration

Originally published September 1975.

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People generally do not like floors to vibrate. In fact, noticeable vibration leads many to fear structural collapse, although such fear is unwarranted in most cases because of the small displacements and stresses produced. Noticeable vibration is nevertheless undesirable in many occupancies because of its adverse psychological effect. Recently, problems of annoying vibrations have increased with the development of floors of lighter construction, longer span, and less inherent damping. This Digest will discuss the nature of floor vibrations and how they affect people and structural safety. It will offer guidelines for design and for correcting unsatisfactory floors, and will discuss, briefly, vibrations of footbridges.

Floor vibration is oscillatory movement of a floor about a position of rest. The motion is a complicated one but it can be described as the combined effect of oscillations of different modes, each with its own displacement configuration and frequency (cycles per second or hertz - Hz). When oscillating in any mode the floor divides itself into panels, with adjacent panels vibrating in opposite directions. The panels are large for low-frequency modes (panel length usually corresponds to floor span) and small for high-frequency modes. If the floor is left to vibrate in any mode, the motion will die out (Figure 1) at a rate determined by the damping in the floor. Experience has shown that in most cases the high frequency modes can be neglected since they die out quickly and do not cause discomfort. Only the fundamental mode corresponding to the lowest frequency need usually be considered.

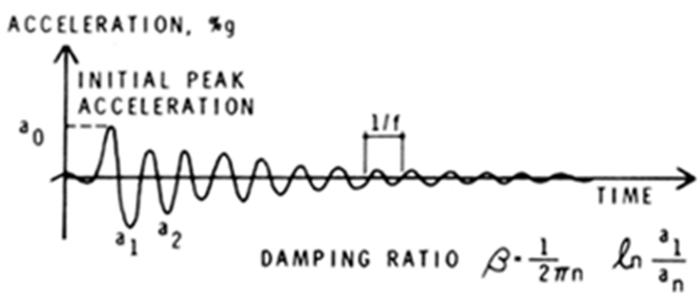

Figure 1. Typical transient vibrations from heel drop(high frequencies filtered out).

How Vibrations Affect People and Structural Safety

It has been observed that continuous vertical floor oscillation becomes distinctly perceptible to people when peak acceleration reaches approximately 0.5 per cent g, where g is the acceleration due to gravity. People in residential, office and school occupancies do not like to feel distinct continuous vibration and this value can be used to approximate an annoyance criterion for these occupancies; Figure 2 shows criteria for continuous vibration of both short (10 to 30 cycles) and long (8 hours) duration. Annoyance criteria will be lower for sensitive occupancies (operating rooms, laboratories, etc.) and higher for walking areas or industrial working areas.

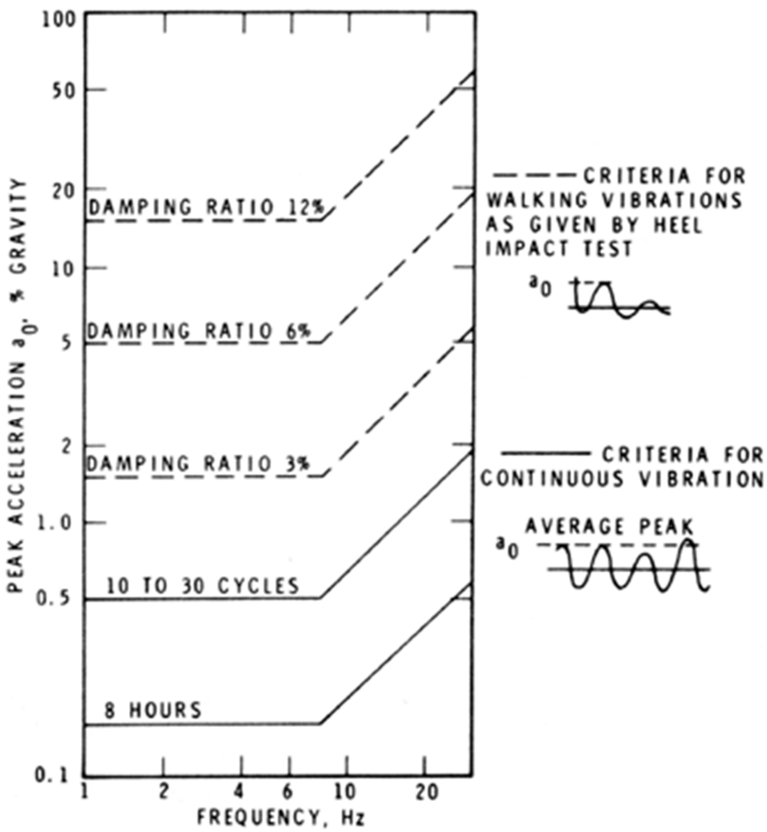

Figure 2. Annoyance criteria for floor vibrations: residences, offices, and school rooms.

Transient vibrations caused by footsteps are less annoying than continuous vibrations. Experience with existing floors has shown that damping, or rate of decay of vibration, strongly affects vibration acceptability. The less the damping the more continuous is the motion of the floor from walking and the more annoying the vibration. Annoyance criteria for residential, office and school occupancies are shown in Figure 2 for walking vibrations for different levels of floor damping; the use of these criteria is explained later. As is the case for continuous vibration, the criteria should be decreased for sensitive occupancies and increased for walking or industrial working areas.

Vibrations may be accompanied by noise, i.e., rattling of glass doors, china, etc., or "drum effect," which can occur if high frequency floor vibrations do not damp out quickly. Such noise considerably aggravates human reaction to floor vibration.

If vibrations are sufficiently large they can damage the building. Experience with blasting has shown that cracking may begin at vibration accelerations of about 10 per cent g and that serious damage generally occurs at about 100 per cent g (**CBD 63**), levels 10 and 100 times greater than those causing discomfort. Thus vibrations that are only irritating will not trigger collapse unless the structure is already on the verge of it.

Continuous Vibration - Resonance

Continuous vibrations, defined here as vibrations lasting more than about 10 cycles, can arise from the periodic forces of machinery, from certain human activities such as dancing, or from vehicle traffic nearby. They can be considerably amplified when the periodic forces causing vibration are synchronized with a natural frequency of the structure - a phenomenon called resonance. Repeated jumping on a diving board or trampoline or repeated swinging to build up large oscillations are examples of resonance.

Accelerations from continuous vibrations can be compared to the criteria shown in Figure 2, corrected where necessary for sensitivity of the occupancy. There are various methods of avoiding or reducing continuous vibrations:

Removal of source of vibration

Machinery can be balanced to reduce eccentric forces or connected to a large mass to increase inertial resistance to movement. Repetitive human activities such as marching across bridges can be restricted and road or rail surfaces can be smoothed to reduce traffic impact.

Location of vibrating source

Machinery or dance floors should be located as far away as possible from sensitive occupancies such as offices or sleeping quarters. In addition, care should be taken to avoid resonance by making the floor frequency of the sensitive occupancy different from that of the floor directly vibrated.

Vibration isolation

Vibration can be isolated by "flotation," by putting either the vibration source (machinery) or the sensitive occupancy (floor, building) on soft springs or isolation pads. A record turntable, for example, is placed on soft springs to prevent transmission of floor vibration to the record needle. To isolate vibrations the frequency of whatever is to be isolated should be less than the forcing frequency; if it is 33 per cent of the forcing frequency the transmitted vibration is reduced approximately 80 per cent; if less than this the reduction is even more. If, however, the two frequencies are the same, or nearly so, the transmitted vibration is greatly increased owing to resonance.

Floors supporting sensitive instruments can be isolated from ground and building vibrations by supporting them on cork, springs or other special bearings. Even buildings can be isolated from certain traffic vibrations by providing pads in the supports, but this method is usually effective only for high frequency vibration components and noise. For further information on vibration isolation the specialist literature should be consulted.

Effect of floor properties

If forcing frequencies are known, a structure can be designed to avoid resonance. For activities such as dancing or sports, people alone or in unison can create periodic forces in the approximate frequency range 1 to 4 Hz; in floors supporting such activities, natural frequencies less than about 5 Hz should therefore be avoided. For very repetitive activities such as dancing, the possibility of amplification exists when the beat is on every second cycle of floor vibration; it is therefore recommended that the frequency of such floors be 8 Hz or more. In calculating frequency, the mass of people should be taken into consideration.

Resonance effects can also be reduced by incorporating increased damping, but this is usually effective only if the existing damping is already very small. An effective way of altering floor properties is by means of vibration absorbers. These are damped, spring-mass units that can be attached to a structure to absorb the vibrations in a certain frequency range.

Vibrations from Walking

Uncomfortable vibration from walking can occur on floors in normal occupancies unless care is taken in the design of the floor or in its use. This is not a new problem. In 1828 Tredgold wrote:

"Girders should always, for long bearings, be made as deep as they can be got; an inch or two taken from the height of a room is of little consequence compared with a ceiling disfigured with cracks, besides the inconvenience of not being able to move on the floor without shaking everything in the room."

He proposed that floor beams be designed so that the static deflection (under an estimated concentrated load of approximately 750 lb) not exceed span/480. In time this criterion was changed to a maximum deflection of span/360 under uniform design load, a criterion that is still used for most residential floors. For steel beams in vibration-sensitive areas it has traditionally been recommended that the ratio of span to depth not exceed 20. Such rules generally produce satisfactory results for light, short-span floors of traditional construction, although not for long-span floors.

Long-span floors

Footstep vibrations may be a problem for long-span floors, generally 25 to 65 feet, particularly if there is low damping. The annoyance criteria in Figure 2 can be used in evaluating long-span floors of residential, office or school occupancies. They are based on the "heel impact" test, where a person standing on his toes drops suddenly to his heels. From the resulting floor motion the frequency, damping ratio (β) and initial peak acceleration in the fundamental mode are determined as shown in Figure 1 and are then entered in Figure 2 for comparison with the criteria. For design these parameters can be estimated by calculation as follows:

Frequency for simply supported, one-way systems is given by

$$f_1 = 31\sqrt{\frac{EI}{wL^4}}$$

(1)

where E is the modulus of elasticity, I the moment of inertia, L the span, and w the dead weight per unit length of span. All units are in pounds and inches. For steel joist or beam with concrete deck, fully composite action between steel and concrete can usually be assumed for determining I in Equation (1), even for structurally non-composite construction. Special considerations are required in determining the frequency of more complex floor systems, for example, one-way systems supported on girders.

Damping ratio of a floor system must be estimated. The following values are suggested for long-span floors with concrete deck: bare floor - 3 per cent; finished floor (ceiling, ducts, flooring, furniture, etc.) - 6 per cent; finished floor with partitions - 12 per cent. Partitions, either above or below the floor, provide an effective source of damping, especially when they are located in both directions. Even light partitions that do not extend to the ceiling can provide considerable damping. Partitions along the supports or parallel to the floor joists and further apart than approximately span/1.5, however, may not be effective because the floor vibrates between them without gaining any damping benefit. People also provide damping, but this is less effective for heavy, long-span floors than for light, short-span floors.

Peak acceleration from heel impact for one-way steel joist-concrete deck floors of spans greater than 25 ft and frequencies less than about 10 Hz can be estimated as follows:

$$a_o = \frac{350f}{Lt_c\,(t_c + 1)}\left(\frac{150}{\rho_c}\right)$$

(2)

where a_o is the peak acceleration in per cent g, f is the frequency in Hz, L the span in feet, t_c the average thickness in inches, and ρ_c the unit weight of concrete deck in pounds per cubic foot. Equation (2) and Figure 2 show that for long spans both damping and concrete thickness are very effective in reducing footstep vibration. On the other hand, increasing beam stiffness is not beneficial.

Remedial measures for troublesome long-span floors include: change of occupancy; additional partitions, damper posts or vibration absorbers; increased concrete thickness if the floor can safely carry it.

Short-span floors

The criteria of Figure 2 and Equation 2 are restricted to spans greater than about 25 feet and frequencies less than about 10 Hz. For light floors of the residential type the persons involved, both the one causing and the one receiving the motion, interact with the floor to damp out walking vibrations. As a result human response depends more on the motion of the floor due to repeated static deflection from walking than on its vibration in the fundamental or higher modes.

Studies of light joist (wood or steel) floors with wood deck, in progress at the Forest Products Laboratory at Ottawa, indicate that for spans up to 15 feet acceptable vibration performance for most residential occupancies is obtained if the static deflection does not exceed 0.05 inch under a point load of 220 lb. This is close to the current design requirement of a maximum joist deflection of span/360 under 40 psf for traditional floor framing, a requirement with the advantage of simplicity in calculation. For floor systems whose stiffness perpendicular to joist span is less than that for traditional systems, however, the latter requirement may not be adequate for vibration comfort.

Some special effects in light joist floors can aggravate the human response to vibration. One is noise. Very small vibrations can cause china, cabinet doors or similar objects to rattle and are best overcome by placing a rug under the cabinet, felt pads in the door guides, etc. Drum noise from high frequency torsional vibrations of cold-formed steel C joists may be overcome by attaching ceiling brackets or straps to the bottom flange. Another is vibrations originating outside people's homes; as these are more annoying than vibrations from within, joists continuous over party walls should be avoided.

Footbridges

Footstep vibrations in footbridges can be treated in the same way as footstep vibrations in long-span floors. People are less sensitive, however, to vibration on footbridges than to vibration in residential, office and school occupancies, and the criteria in Figure 2 can be multiplied by approximately 3.

Frequency in both bending and torsion should be estimated by the designer. For simply supported beams it may be determined by Equation (1); for shallow arches it is approximated by

$$f_{arch} = 4\ [1\text{-}7.7\ (\frac{c}{L})^2]\ f_1$$

(3)

where L is the span, c is the rise of the arch, and f_1 determined by Equation (1). Torsional frequency requires special determination. A torsionally flexible cross-section such as a T or V may result in large joist oscillation due to human activity.

Initial peak acceleration, in per cent g, of a footbridge responding in bending to heel impact is approximated by

$a_o = 13.3\ f/W$ (4)

where W is the weight of the footbridge in kips. For shallow arches use W/2 instead of W.

To avoid resonance from human activities it is recommended that fundamental frequency lie outside the range 1 to 4 Hz. Other sources of resonance for relatively long, light bridges, especially those that are cable supported, are wind effects of vortex shedding and flutter. If such effects are a possibility, it is recommended that specialists be consulted.