Control of Floor Vibration

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Excessive floor vibration has become a greater problem as new rhythmic activities, such as aerobics, and long-span floor structures have become more common. This Update describes the nature of floor vibration and provides options for avoiding it through design, or in the case of existing buildings, reducing or eliminating it through alterations.

Floor vibration is up-and-down motion caused by forces applied directly to the floor by people or machinery, or by vibration transmitted through building columns, from other floors or from the ground.

The problems associated with floor vibration are not new. In 1828 Tredgold wrote "girders should always be made as deep as they can to avoid the inconvenience of not being able to move on the floor without shaking everything in the room."[1] A simple floor deflection criterion (deflection of less than span/360 under distributed live load) has been used to control 'excessive shaking' for more than 100 years. But today, when longer spans, thinner floor decks, less structural damping (an absence of materials and components that absorb vibration energy), or the use of buildings for activities such as aerobics are responsible for vibration problems, this approach does not work. However, new guidelines that address and deal with these problems — based on what people perceive and find acceptable in terms of floor vibration — have recently been introduced.

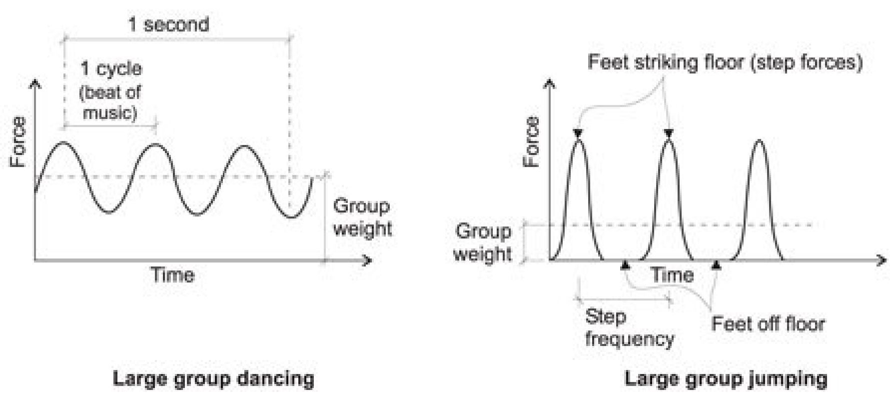

Figure 1. Repetitive forces produced by human activities

Vibration Limits

Floor vibration generally makes people uneasy and creates fear of structural collapse, although such fear is usually unwarranted because of the small displacements and stresses that are actually produced. Nevertheless, perceptible vibration is usually considered to be undesirable because it affects people's sense of well being and their ability to carry out tasks.

Vibration limits, or acceptable thresholds, are best expressed in terms of acceleration, as a percentage of the acceleration due to gravity (g). The limit depends primarily on the context, that is, on what people are doing when they experience the vibration. For example, people sitting or lying down in offices or residences find distinctly perceptible vibration (accelerations of about 0.5% g) unacceptable, whereas those taking part in an activity such as aerobics will accept much greater vibration (about 10% g). People dining beside a dance floor or standing in a shopping mall will find vibrations that fall between these two extremes (about 2% g) acceptable.

Generally, it is not the participants in a particular activity or event who are most disturbed by floor vibration, but those who are located in adjacent spaces, as they find it annoying or disruptive to their own activities.

If the vibration is very large (more than 20% g), and occurs frequently (e.g., in a health club), then fatigue failure of the floor can occur. To prevent collapse due to fatigue or overloading, the National Building Code of Canada (NBC) requires a dynamic analysis of a floor structure if it has a natural frequency of less than 6 Hz.[2]

Principal Cause

The main factor underlying most vibration problems is resonance, which occurs when a load is exerted on a floor at a particular frequency. For example, a group of people dancing applies a cyclic force (their footsteps) to the floor at the frequency corresponding to the beat of the music (see Figure 1). The cyclic force produces a maximum floor acceleration, which depends on the ratio of the natural frequency of the floor structure to the cyclic frequency of the applied force (see Figure 2). When the natural frequency of the floor coincides with, or is close to, the forcing frequency, resonance occurs and the consequences are most severe. During each cycle of loading, more energy is fed into the system and the magnitude of vibration grows, until a maximum is reached. This maximum is dependent on the amount of damping in the floor.

During any rhythmic activity, people apply repeated forces to the floor, ranging from 2 to 3 Hz. (This frequency is known as the step frequency). For dancing, resonance occurs if the natural frequency of the floor is between 2 and 3 Hz.

If the repeated force has an impact component, as is the case for aerobics in which everyone jumps at the same time (see Figure 1), then resonance can occur not only at the step frequency, but also at multiples, or harmonics, of this frequency. For example, an aerobics class jumping to a beat of 2.5 Hz (the step frequency) will produce harmonic vibrations at multiples of 2.5 Hz — i.e., at 2.5 Hz (first harmonic), 5 Hz (second harmonic), and 7.5 Hz (third harmonic). Since the natural frequencies of most floors are greater than 3 Hz (they often fall between 4 Hz and 8 Hz), problems are most likely to occur as a result of the second and third harmonics. However, the lower the harmonic the larger the vibration produced by resonance.

Rhythmic Activities
Vibration problems due to rhythmic activities occur in stadiums, auditoriums, buildings with dance and health clubs, and convention centres, which are used for a wide variety of activities.

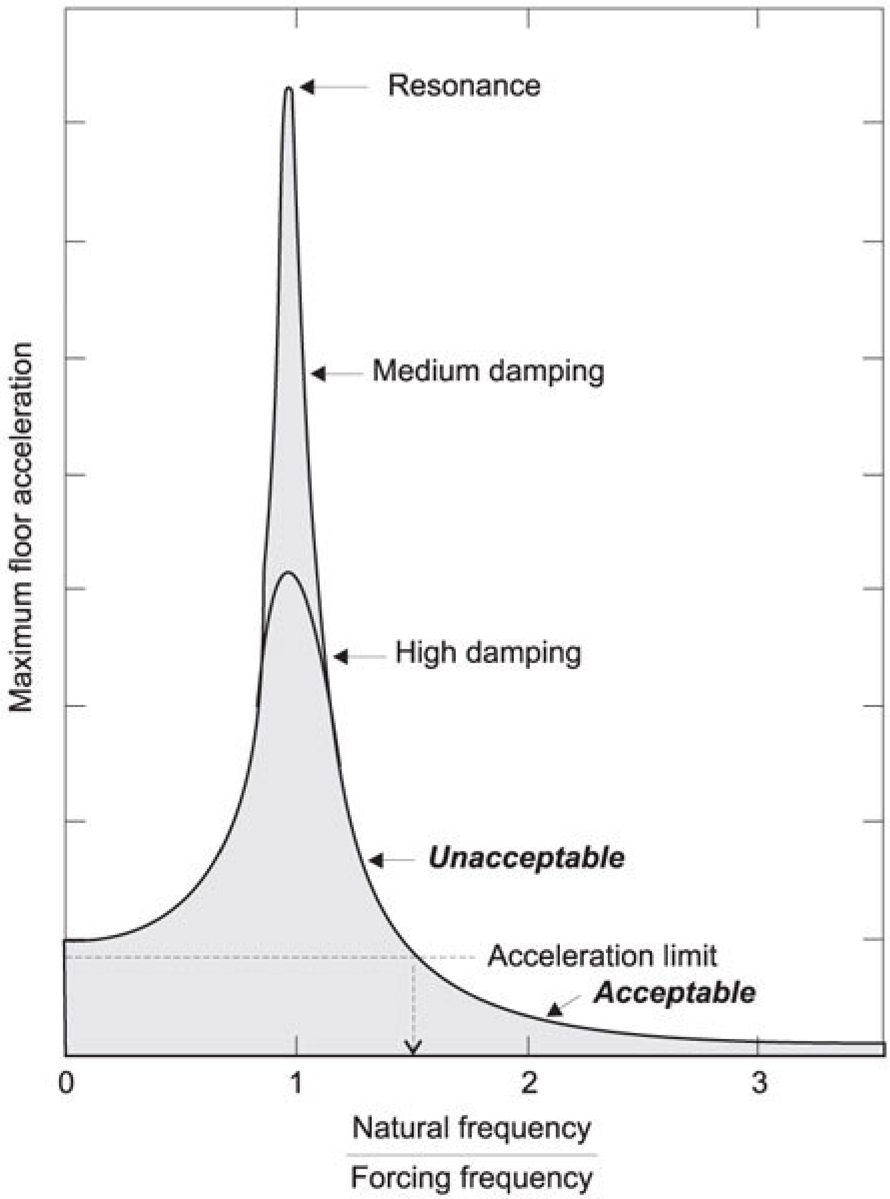

Figure 2. Floor acceleration due to a cyclic force for a range of natural frequencies

Because of the large forces generated by rhythmic activities, resonance vibration is generally too large to be acceptable. To control floor vibration due to a rhythmic activity, the floor structure must be designed to have a natural frequency greater than the forcing frequency of the highest significant harmonic, as shown in Figure 2. Minimum acceptable natural frequencies are provided in Table 1 for several combinations of activities and floor constructions.

For design purposes, the natural floor frequency (f_n in Hz) can be estimated using a simple formula,

f_n (Hz) =18   D(mm)

where D is the total deflection of the floor structure due to the weight supported by all its members (joists, girders and columns). For example, if the floor deflects 9 mm, the natural frequency is 6 Hz. To get a natural frequency of 9 Hz, the floor must deflect only 4 mm, which is practically impossible for floors supported on very long members to achieve. (See References 2 – 4 for methods of calculating natural frequency and floor acceleration.)

The primary factors affecting the design of floor structures for rhythmic activities are:

Span. The longer the floor span the lower the natural frequency. Convention centres, in particular, have very long floor spans (approximately 30 m). It is generally not practical to design such floor structures to achieve the minimum natural frequency shown in Table 1 for rhythmic activities that have impact (e.g., aerobics). In this situation, the choice is to relocate either the rhythmic activity (to a stiffer floor) or the sensitive occupants.

Table 1. Minimum Floor Frequencies (Hz) for Typical Activities and Floor Constructions

Rhythmic Activity	Steel/Concrete Floor	Light-Frame Floor
Dancing and Dining	5	10
Aerobics	9	13

Storey height.
The taller the columns supporting the floor on which the rhythmic activity takes place the lower the natural frequency of the floor. An example of this occurred when aerobics on the top storey of a 26-storey building caused second harmonic resonance due to the axial flexibility of the columns. This resonance produced annoying vibrations of approximately 1% g in the offices below. Because the aerobics activity could not be relocated in the building, it had to be terminated.

Selecting the location for a rhythmic activity (i.e., storey, floor area, etc.) is therefore the most important consideration in the design of floors. Properly positioning sensitive occupancies relative to rhythmic activities is also important. See the "Measures to Remedy Vibration Problems" section of this Update for guidance.

Walking Vibration.
Walking vibration, which is largely dependent on the type of floor construction, is also an important consideration in the design of floor structures of most buildings.

Steel/Concrete Floor Construction.
A steel floor with a concrete deck usually has a natural frequency of between 3 Hz and 10 Hz. A person walking across a floor applies a force at a step frequency of approximately 2 Hz, which can result in resonance build-up when the natural floor frequency is around 2, 4, 6 or 8 Hz. As for previously mentioned activities, the higher the harmonic the lower the magnitude of resonance.

A design criterion has recently been developed[3] in which the acceleration due to harmonic resonance is calculated and compared with a vibration limit, e.g., 0.5% g, for office and residential occupancies. If the limit is exceeded, design alterations can include:

Increased damping.
Damping of the floor system (increasing the rate of removal of vibrational energy) reduces resonance vibration (see Figure 2) and thus annoyance. It depends primarily on the presence of nonstructural components such as partitions, ceilings, mechanical services and furnishings. Full-height partitions are most effective in adding damping to the floor system.[3]

Increased stiffness.
This raises the natural frequency of the floor, shifting resonance to a higher harmonic, which reduces the magnitude of resonance vibration and hence annoyance. Stiffening methods include increasing floor member depths and ensuring that there is composite action between the beams and the concrete slab.[3] In the case of solid concrete floors, which have high mass and stiffness, walking vibration is rarely a problem. Some precast concrete floor systems may, however, require evaluation.[4]

Light-Frame Construction.
Light-frame floors of wood or cold-formed steel joists with a wood deck typically have floor frequencies of between 10 Hz and 30 Hz. Someone walking across a floor can be a source of annoyance to a person sitting in a room because of the jolts caused by sudden changes in floor elevation produced by each footstep.

Design considerations for light-frame construction include:

Stiffening.
The actual stiffness of a lightframe floor depends not only on the stiffness of the joists but also on the transverse stiffness of the floor system (from floor deck, cross bridging, blocking, etc.) and on the composite action of the joists and deck. Increasing floor stiffness reduces the jolts due to walking.

Deflection criterion.
When walking vibration is likely to be an issue, e.g., in a house or multi-family dwelling, light-frame floors should be designed to meet the deflection criterion for a 1 kN concentrated force (as shown in Figure 3). This decrease in allowable deflection with increase in span is due to a number of factors described in Reference 4.

The most practical approach for designing light-frame floors to minimize the effects of walking is to develop span tables based on calculations that satisfy the Figure 3 criterion, e.g., those contained in Part 9 of the NBC. To evaluate floor systems not covered by the NBC span tables, see Reference 4.

Measures to Remedy Vibration Problems

There are a wide variety of actions that can be taken to correct floor vibration problems in existing buildings. These actions can be categorized as follows:

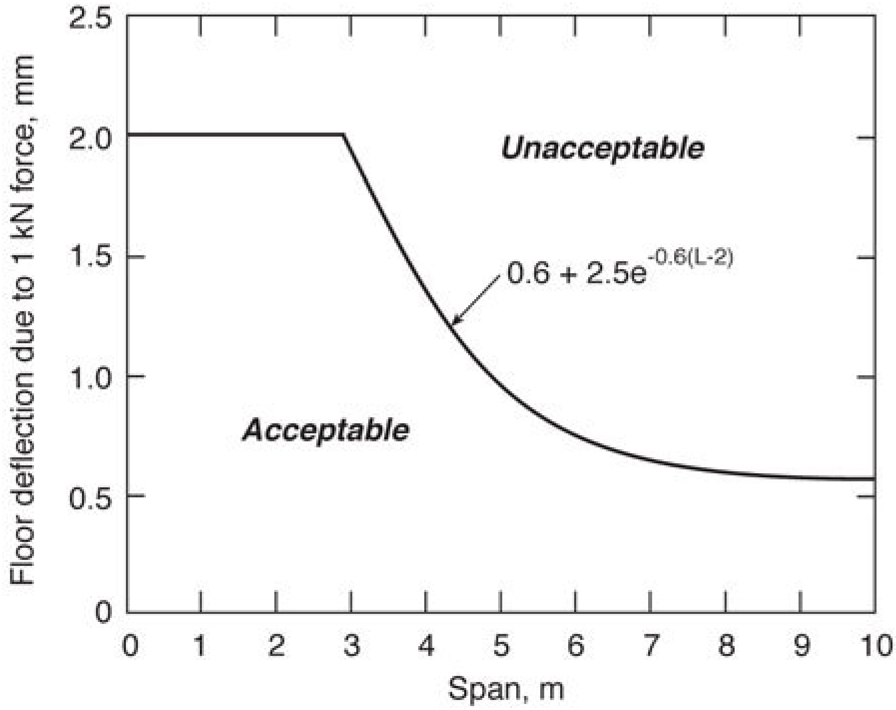

Figure 3. Design criterion for light- frame floors

Reduction of effects.
It may suffice to do nothing about the floor vibration itself, but rather to make alterations that reduce the annoyance associated with the vibration.

These include the elimination of noise (e.g., rattling) due to floor vibration, and removing or rearranging articles that vibrate noticeably.

Relocation of activities.
Either the source of vibration (e.g., aerobics or machinery) or the sensitive occupancy may be relocated. For example, a planned aerobics exercise area might be relocated from the top floor of a building to the ground or first floor. Complaints of walking vibration can sometimes be resolved by relocating people, or equipment, to areas where vibration is less likely to occur, e.g., placing them near a column.

Stiffening.
Increasing the stiffness of the floor can reduce vibration due to walking or other

rhythmic activities. Introducing new columns between existing columns from the affected floor down to the foundations is very effective in the case of flexible floor structures, but is often unacceptable to the owner. If there is sufficient ceiling space, welding new components to the bottom flanges of steel beams or joists (as shown in Figure 4) is an effective technique.[3]

Light-frame floors can be stiffened by adding transverse stiffening, such as decking or blocking.[4] However, it is important to determine whether the vibration is caused by flexible supports (poor seating, flexible beams, etc.) before proceeding with stiffening the joists.[4]

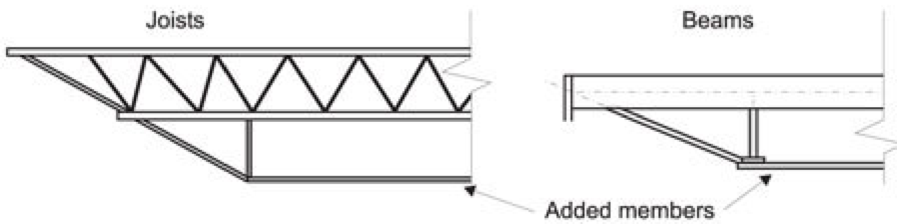

Figure 4. Stiffening technique for steel joists and beams

Damping.
For steel/concrete construction, walking vibrations can be improved by increasing the amount of damping of the floor system. The less damping there is in the existing floor, the more effective the added damping. The addition of nonstructural components that interact with the floor structure, such as drywall in the ceiling space, provides some damping if there is little to begin with. There are also other damping devices, such as damper posts or tuned mass dampers, that can be effective in reducing floor vibration.[3]

Isolation.
An effective method for reducing floor vibration due to machinery is to isolate the machine from the floor by placing it on soft springs.[3,4]

Summary

Most floor vibration problems are caused by resonance and, for light-frame construction, sudden deflections due to footsteps. Vibration can usually be controlled by stiffening the floor structure, although sometimes the problems can be addressed by adding damping or by isolating equipment. Proper placement of an activity (e.g., aerobics) or machinery in the building is the most important consideration.

References

1. Tredgold, T., 1824, Elementary Principles of Carpentry, 2nd Ed., Publisher unknown.

2. User's Guide — NBC 1995 Structural Commentaries (Part 4). Commentary A: Serviceability Criteria for Deflections and Vibrations.

3. AISC/CISC Steel Design Guide Series No. 11: Floor Vibrations Due to Human Activity. American Institute of Steel Construction, Chicago, Ill., 1997.

4. ATC Guide on Floor Vibration. Applied Technology Council. Redwood City, CA, 1999.

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