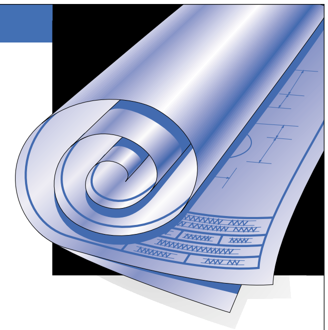

Minimizing Floor Vibration By Design And Retrofit

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1. INTRODUCTION

Floor vibration is a natural phenomenon of a floor system in response to dynamic forces, such as people walking or a washing machine's spinning, applied directly to the floor. In some cases, these forces are transmitted from other floors or adjacent buildings through columns. All suspended floors vibrate to some degree regardless of the floor type, whether steel, concrete, or wood. Unfortunately, excessive floor vibration can make people feel insecure, uncomfortable, and afraid of structural failure. Such fear, of course, is usually unwarranted since the displacement and stresses induced by floor vibration are generally small in view of the design criteria for structural safety.

The issues associated with floor vibration are not new and have been the subjects of international research. In the United States, floor vibration is generally considered a serviceability concern and not explicitly regulated in the model building codes. In Canada, on the other hand, the National Building Code of Canada (NBCC) has stipulated a criterion to control floor vibration of single-family dwellings built since 1990 with solid-sawn lumber. Since 1996, the Canadian Construction Materials Centre (CCMC) has adopted a similar criterion for approval of engineered wood products, such as prefabricated wood I-joists, structural composite lumber, and parallel chord trusses.

2. FACTORS INFLUENCING FLOOR VIBRATION

Floor vibration is a complicated phenomenon influenced by a number of parameters, including its subjective evaluation. Studies have demonstrated that people have different sensitivity levels to floor vibration, and these differences are compounded by the circumstances. For example, a person sitting in a room has less tolerance for floor vibration than the same person walking around a room, while auditory counterparts to floor vibration, such as rattling dishes in a china cabinet, can influence the acceptability of a floor system. The subjective nature of floor vibration perception makes an objective evaluation standard difficult to achieve.

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Efforts to quantify floor vibration behavior have led researchers to identify many factors influencing human response. The most prominent factors are the frequency content, damping, and vibration amplitude.

- The frequency content is a term used to describe the sum of all frequency modes for a product or system. For floor-vibration, the first frequency (f_1), also known as the fundamental natural frequency, is used for design purposes. With respect to fundamental natural frequencies, humans are more sensitive to a low-frequency than a high-frequency vibration. The sensitive range for humans in response to floor vibration is typically between 4 and 8 Hz.

  The fundamental natural frequency of a floor system can be expressed in the following general form:

  $$f_1 \text{ is a function of } \left(\frac{1}{\ell^2}, \sqrt{EI_x}, \frac{1}{\sqrt{m}}\right)$$

  where f_1 = fundamental natural frequency,
  ℓ = joist span,
  EI_x = flexural stiffness of floor along the floor joist direction, and
  m = unit mass of floor

  As shown above, the fundamental natural frequency of a floor is a function of the floor span, floor stiffness in the joist direction, and unit mass of the floor.

  Note that the frequency spacing in Hz of two adjacent natural frequencies in a floor system could also negatively affect the floor performance if the spacing is close enough to cause extensive interaction. The spacing, governed by the ratio of joist stiffness in the cross-span direction, EI_y, to the along-span direction, EI_x, increases with a larger EI_y. Because they contribute to the effective EI_y, construction details like joist spacing, bridging, ceiling details, and floor sheathing thickness, material type, and attachment to the joists could affect floor performance.

- Floor systems with high damping capacities reduce vibrations from peak amplitude to zero. Each component's material damping and the friction between components contribute to the system damping. Because the damping ratio for a wood floor system varies widely and cannot be reliably measured in many instances, its effect on floor vibration is often ignored in vibrational analyses.

- Amplitude is the magnitude of the floor movement due to vibration, and it is apparent that a low-amplitude vibration is less annoying to humans than a high-amplitude one.

Based on the discussions given above, it is reasonable to state that the ideal floor system, from the perspective of floor vibration control, should have a high frequency content, high damping, and low amplitude.

3. FLOOR VIBRATION CONTROL BY DESIGN

Many criteria for floor vibration control have been proposed or adopted in different countries. Some of those criteria are reviewed below. Any one of those criteria, or a combination of multiple criteria, may be used at the design stage to evaluate the expected floor performance. Unfortunately, researchers generally agree that no single criterion has proven effective under all circumstances.

3.1 Uniform-Load Static Deflection Limit

Most building codes use the uniform-load deflection criteria to satisfy the serviceability limit state through the maximum static deflection of a joist under a specified uniformly distributed live load. The prefabricated wood I-joist industry recommends a lower deflection than the conventional L/360 limit for live load deflection to address floor-vibration concerns. L/480 and L/600 are both common recommendations for floors constructed with I-joists, offering a generally effective solution for most floor systems. This approach has not completely eliminated floor vibration problems however, especially for long-span floors, because this criterion is based on the behavior of a single I-joist rather than the two-way action of a floor system.

3.2 Point-Load Static Deflection Limit

Some argue that a static deflection under a point load would be a better criterion for floor vibration control because human activities on the floor, such as footsteps, generally cause the vibration. The NBCC's 1990 change to Part 9 reflects this philosophy, now requiring floor systems made of solid timber joists to meet the following criteria:

$$\text{If } \ell < 3 \text{ m}, \ \delta \leq 2 \text{ mm} \tag{1}$$

$$\text{If } \ell \geq 3 \text{ m}, \ \delta \leq \frac{8.0}{\ell^{1.3}} \tag{2}$$

where δ = deflection under a static deflection of 1 kN (225 lbf) at the center of the floor system (mm), and
ℓ = floor span (m)

Appendix A of the NBCC gives the equation used to calculate δ, which accounts for all the stiffness contributions from the two-way action in the floor system and is based on the empirical relationship between a single joist mid-span deflection and the deflection of the floor under a point load. CMCC has recognized the same criteria for floor systems made of engineered wood products like I-joists since 1996, with the following criteria[(2)]:

$$\text{If } 5.5 \text{ m} \leq \ell < 9.9 \text{ m}, \ \delta \leq \frac{2.55}{\ell^{0.63}} \tag{3}$$

$$\text{If } \ell \geq 9.9 \text{ m}, \ \delta \leq 0.6 \text{ mm} \tag{4}$$

These criteria work well in general but are known to be questionable for floor systems with heavy topping or joists with bridging.

3.3 Fundamental Natural Frequency

The range of vibration frequency for wood floors is generally between 8 and 30 Hz. Researchers have proposed limiting the floor vibration frequency as one of several methods to reduce the risk of excessive floor vibration. For example, they suggested that the fundamental natural frequency of floor joists or girders made of solid timber and engineered wood joists can be calculated as follows(4):

$$f_1 = \frac{\pi}{2}\sqrt{\frac{g\,EI}{W\ell^3}} \tag{5}$$

where
- f_1 = fundamental natural frequency of the joist or girder (Hz),
- g = gravity acceleration = 386 in./sec^2,
- E = modulus of elasticity (psi),
- I = moment of inertia of the joist or girder alone without consideration of the composite action with the subfloor (in.^{4}),
- W = total weight of the structural system (the weight of the joist and its tributary flooring and subfloor) without the weight of ceiling, floor covering, furniture, and occupancy for unoccupied floors (lbf). For occupied floors, W is equal to the total weight of the structural system tributary to the joist or girder plus 2 psf for lightly loaded floors or 4 psf for heavily loaded floors, and
- ℓ = joist or girder span (in.)

If the floor system consists of both joists and girders, the fundamental frequency of the floor system should be calculated as follows:

$$f_{1,system} = \sqrt{\frac{f^2_{1,joist} \times f^2_{1,girder}}{f^2_{1,joist} + f^2_{1,girder}}} \tag{6}$$

where
- $f_{1,system}$ = fundamental natural frequency of the floor system (Hz),
- $f_{1,joist}$ = fundamental natural frequency of the joist alone (Hz), and
- $f_{1,girder}$ = fundamental natural frequency of the girder supporting the joists (Hz)

Researchers suggested that the fundamental natural frequency of the joists and girders (Equation 5), and the floor system (Equation 6) be limited to a minimum of 14 Hz for occupied floors and 15 Hz for unoccupied floors to avoid excessive floor vibration. These simple criteria work well for lightweight floors, but may be conservative for heavier floors, such as those with concrete topping and ceiling.

3.4 Combined Criteria

The criteria for floor-vibration control, as mentioned above, are mostly calibrated to a specific type of floor construction based on empirical data. Therefore, it is obvious that none of the criteria alone can be applied universally to all types of floors. To account for the various factors affecting the floor vibration, researchers have made an attempt to combine the 1 kN static point load deflection, fundamental natural frequency, and initial velocity due to unit impulse into the draft of EuroCode 5. Unfortunately, the combined criteria have not been validated with a wide variety of floor construction methods and appear to be overly complicated for use in engineering design.

A similar effort to combine multiple factors into a simple floor-vibration criterion has also been reported in Canada even though the confirmation of the criterion to cover a broad range of floor construction details is still pending. This new criterion combines the fundamental natural frequency with the 1 kN static point load deflection as follows(5):

$$\frac{f_1}{\delta^{0.44}} \geq 18.7 \tag{7}$$

where
- f_1 = fundamental natural frequency of a two-way floor system (Hz), and
- δ = deflection under a static deflection of 1 kN (225 lbf) at the center of the floor system (mm)

4. FLOOR VIBRATION RETROFIT

While any of the criteria mentioned above can be used as a design guide to provide a high percentage of acceptable or high-performance floors, the same principles are applicable to retrofitting existing floors with excessive vibration. This section provides some general guidelines to remedy floor vibration problems in existing buildings. A variety of options (or a combination of multiple options) can be taken to correct floor vibration problems, but their effectiveness may vary. It is important first to identify the cause of floor vibration and then to determine the appropriate action.

- Removal of vibrating articles: Vibrating articles in a room, such as rattling dishes, make noise and draw attention to floor vibration. In this case, the elimination of noise by removing or rearranging the articles may be sufficient to remedy the floor vibration problem.
- Soft-spot correction: Some floor vibration is caused by unsupported joist ends due to support settlement, the dimensional change of the supporting member, or inadequate attachment of floor sheathing to joists. In this case, the elimination of soft spots may be sufficient to remedy the floor vibration problem. Soft spots can often be eliminated by the use of shims, additional fasteners, or construction adhesives.
- Increase in fundamental natural frequency and reduction in vibration amplitude: If the fundamental natural frequency of the floor system is in the low frequency range, the floor vibration problem may be resolved by increasing the fundamental natural frequency. On the other hand, if the floor vibration is caused by large vibration amplitude, the floor vibration problem may be resolved by increasing the floor mass or stiffness. The following is a list of options even though some of the options may not be feasible due to the available floor space and/or economic considerations:

  a) Floor joist reinforcement: As shown on page 2, the fundamental natural frequency of a floor system can be increased by increasing the floor stiffness. For I-joist floor systems, the floor joists may be stiffened by attaching 19/32- or 23/32-in.-thick wood structural panels to both sides of each I-joist in the problem area. The structural panels should have the same depth as the I-joist and preferably be installed with the strong panel axis running parallel to the joist length. When nailing into the I-joist flanges, the minimum nail spacing should be in accordance with the recommendations published by the I-joist manufacturer. The use of construction adhesives in addition to nailing is also recommended at these locations.

  b) Floor sheathing/covering: Thicker floor sheathing increases the floor stiffness across the support when properly attached (i.e., glue-nailed) to the existing floor. On the other hand, it also increases the floor mass, which tends to lower the fundamental natural frequency and the vibration amplitude. Overall, the added mass of an additional floor layer to the top of the floor joists has a positive effect on floor performance. Hardwood flooring has also been reported to improve floor performance by reducing floor vibration.

  c) Ceiling-board attachment: The attachment of gypsum ceiling boards to the bottom of the floor joists has a similar effect as the attachment of an additional floor layer to the top of the floor joists. The addition of gypsum ceiling boards may also improve the fire rating of the floor system. The use of construction adhesives in addition to nailing is also recommended.

  d) Bridging: Between-joist bridging, which is normally achieved by blocking, cross bridging, and bottom strapping, can significantly increase the floor stiffness in the across-the-joist direction. This bridging has very little effect on the fundamental natural frequency but can significantly reduce the vibration amplitude if it is achieved with a continuous bottom strap. For floor systems with a span of less than 14 feet, a single line of between-joist bridging should be installed at mid-span. For longer spans, it is generally recommended that two lines of between-joist bridging be installed at the third-span locations.

  e) Span reduction: If possible, a reduction in the floor span by adding a support can drastically reduce the floor vibration problem.

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