Facts for Steel Buildings number 5

Vibration

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Section 1
Introduction

Vibration of structural systems caused by human activity is a significant serviceability design consideration. The structural system must protect occupants from excessive vibrations. Likewise, when sensitive equipment is present, it must be protected from vibrations, which might affect its operation or quality of work product. To prevent unacceptable vibration, the response of proposed structural framing due to human activity should be considered early in the design process. Humans are very sensitive vibration sensors, and tolerance limits for sensitive equipment can be extremely strict.

This *Facts for Steel Buildings* summarizes basic facts about vibration control in steel-framed structures, including floors, pedestrian bridges, monumental stairs and balconies. Both walking and rhythmic activities are considered. It is aimed at providing building owners, developers, architects and users with useful background information for design. More detailed information and specific design guidance may be found in AISC Design Guide 11, *Vibrations of Steel-Framed Structural Systems Due to Human Activity*, 2nd Edition (Murray et al., 2016). The first edition of this Design Guide, *Floor Vibrations Due to Human Activity*, was published in 1997 (Murray et al., 1997). The second edition updates calculation approaches and certain criteria in the first edition using research results and experience of the authors since the publication of the first edition.

The goal of this *Facts for Steel Buildings* is to provide the construction community, from owners to engineers, with an understanding of vibration issues in steel-framed structures. The desired vibrational performance of a steel-framed structure can be achieved by appropriate design use of the guidance in AISC Design Guide 11.

Section 2
General Topics

This section includes a number of questions concerning topics that are relevant to vibrations of structural framing in general.

2.1 Why is vibration of steel-framed structural systems supporting human activity a serviceability issue?

In environments like quiet offices and residences, structural vibrations are a serviceability issue because humans are very sensitive vibration sensors. Movements with vibrational displacements as low as 10- to 40-thousandths of an inch can be annoying. Humans can readily perceive motions of about 0.005 times the acceleration of gravity—that is, 0.5%*g*. Many factors influence human sensitivity to floor motion, including disposition (some people are more sensitive than others), position (sitting is the most sensitive position), and surrounding noise (vibration sensitivity decreases with increasing noise level).

Structural vibrations caused by rhythmic activity can be particularly annoying to occupants of surrounding areas. There are even a number of reported instances where rhythmic activity on a lower floor of a tall building caused annoying vibrations on upper floors and vice versa.

Structural vibrations caused by human movement can be detrimental to the operation of sensitive equipment, such as MRI scanners, sensitive scales, nuclear cameras and electron microscopes.

2.2 What types of steel-framed systems should be considered for vibration serviceability evaluation?

The simple answer is that all types of steel-framed systems, floors, balconies, monumental stairs, pedestrian bridges, and more should be considered for vibration serviceability evaluation. Lightweight and long floor-span systems are more susceptible; floor systems with very short spans are less so. Open, long-span monumental stairs are very susceptible to complaints, especially because of rapid descents. Long-span floors supporting rhythmic activities like group exercising or dancing should be evaluated. Cantilever balconies supporting concert or sporting event spectators need particular evaluation. Systems supporting sensitive equipment require careful evaluation at the design stage.

2.3 What is resonance?

Resonance is the condition where a forcing frequency matches the natural frequency of a structural system—it occurs, for example, if walking is at 2 Hz on a floor with a 4-Hz natural frequency. In this case, the second harmonic of the walking-induced force has a frequency of (2)(2 Hz) = 4 Hz, equaling the natural frequency of the floor. At resonance frequencies, relatively severe vibrations usually occur. In the foregoing example, walking at 1.8 Hz or 2.2 Hz would result in much less vibration than walking at 2 Hz.

2.4 What is the major cause of annoying vibrations because of human activity?

The major cause of annoying vibrations is matching of the beat or cadence of the activity (walking, running, exercising, marching) or of one of its harmonics with a structural system natural frequency. The highest response of a structural system will often occur if an integer multiple of the beat or cadence of the activity matches the framing natural frequency and causes resonance.

2.5 What are the major causes of complaints because of human activity?

Recently a major source of complaints from office workers is vibration of computer monitors caused by walking, although complaints of annoying floor motion felt by people are also received. For areas with sensitive equipment, it is simply that the equipment does not function properly because of floor movement. Excessive perceived vibration of balconies or stadia during lively concerts or sporting events is, likewise, a source of complaints.

2.6 What are some myths versus reality about floor vibrations?

Myth: "There have been warnings in some open-web steel joist publications that joist spans of 28 ft typically cause vibration problems."

Reality: If the recommended acceleration limits in AISC Design Guide 11 are satisfied, floors with 28-ft spans will exhibit acceptable vibration behavior.

Myth: "Steel framing is too expensive for floors supporting sensitive equipment."

Reality: Although framing for floors supporting sensitive equipment may require relatively heavy members, a steel-framed system still may be economical. For some categories of sensitive equipment, the required sizes are only moderately larger than those required for human comfort and other limit states. Steel framing has the advantage of less costly modification as compared to concrete framing.

Myth: "Normal weight concrete is better than lightweight concrete (or vice versa)."

Reality: Neither is true. Normal weight concrete provides more mass; use of lightweight concrete of the same depth results in a higher natural frequency. Floor response is a function of both mass and natural frequency, and the use of one weight or the other may result in acceptable design. Generally, lightweight concrete is better for floors supporting rhythmic activities because the resulting frequency will be higher than if normal weight concrete is used.

Myth: "I have 25 years of experience without problems and have no need to perform a vibration check."

Reality: Lack of previous problems is not a reason for omitting a valid vibration analysis.

Myth: "Prestressing of concrete elements improves vibration response."

Reality: Prestressing probably has an insignificant effect on floor vibration because it does not significantly change stiffness (EI) or mass. Note that the vibrational displacement amplitudes are extremely small, so the effect of cracking is probably insignificant for typical systems.

Myth: "Cambering improves vibration response."

Reality: Cambering does not improve floor response because it does not change stiffness or mass.

Myth: "It's sufficient to consider only a beam or girder instead of a bay to analyze a floor."

Reality: Both the beams and girders are sources of flexibility, so both must be considered when evaluating typical floor bays.

Myth: "Floor systems must have a fundamental natural frequency greater than 8 Hz."

Reality: There is no basis for this statement, even for floors supporting rhythmic activities. The most reliable metric for evaluating floor framing is acceleration as a function of frequency.

2.7 Which is better, a hot-rolled beam or an open-web steel-joist-supported floor?

This question is like asking which is stronger, a hot-rolled beam or an open-web steel joist-supported floor. Both can be designed to meet specific requirements, but it is generally more difficult to meet stringent vibration limits with floors supported with open-web steel joists.

2.8 What do architects need to consider with respect to vibration?

In open-area office layouts, long walking paths and walking paths perpendicular to the beam or joist span at mid-bay should be avoided. Significantly deeper members may be required for longer spans when vibration is considered than may be needed for strength alone.

For floors supporting rhythmic activity, floor natural frequency is the most important parameter. To achieve a specific frequency, the required total load deflection magnitude is the same regardless of span; therefore, long span floors require very deep framing.

Computer monitors or other items supported on relatively flexible arms may jiggle, causing user complaints, although these vibrations may not be associated with floor motion.

Vibration is usually maximal near the center of the bay, so locating sensitive equipment as close as possible to girders or columns should be considered.

2.9 What are the differences among the analysis procedures for evaluating walking-caused vibration in SJI Technical Digest No. 5, the CRSI Design Guide, the PCI Handbook, the SCI P354 guide, and the UK Concrete Centre CCIP-016 versus those in AISC Design Guide 11?

All methods for evaluating walking-caused vibration discussed in these publications are based on a single-degree-of-freedom system with sinusoidal load at the natural frequency. In each method, the acceleration due to walking induced loading is computed using a modified form of the classical equation for determining acceleration of single-degree-of-freedom systems as found in textbooks.

In AISC Design Guide 11, the walking-induced load is given as the product of body weight and a dynamic coefficient that is a smooth function of the natural frequency, varying from approximately 0.29 to 0.35. A reduction factor, $R = 0.5$, for floors accounts for the fact that the walker and affected occupant are not at the same location and will probably not be at mid-bay and for incomplete resonant build-up. In AISC Design Guide 11, the frequency-dependence of human vibration perception and tolerance is not considered separately because the vibrations due to walking occur essentially only between 3 Hz and 9 Hz. In this range, tolerance of vibration parallel to the spine is essentially constant. Higher modes are assumed to make insignificant contributions. The peak acceleration tolerance limit for quiet spaces such as offices is stated as $0.5\%g$.

The Steel Joist Institute (SJI) Technical Digest No. 5 (Murray and Davis, 2015) walking evaluation criterion is identical to that in AISC Design Guide 11, except the tolerance limit for walking in quiet spaces ranges from $0.5\%g$ to $0.55\%g$.

Table 2-1. Summary of Design Guide Comparisons

Guide	Load Amplitude / Body Weight, 2nd–4th Harmonics	Walker and Affected Occupant Locations	Incomplete Resonant Build-Up	Frequency Weighting of Sensitivity	Higher Modes Considered	Tolerance Limit for Quiet Spaces[7]
DG11[1]	Smooth function of f_n. $0.035 \le \alpha \le 0.29$	Constant factor	Constant factor	No	No	0.5%g
SJI[2]	Smooth function of f_n. $0.035 \le \alpha \le 0.29$	Constant factor	Constant factor	No	No	0.5–0.55%g
CRSI DG[3]	Smooth function of f_n. $0.035 \le \alpha \le 0.29$	Constant factor	Constant factor	No	No	0.5%g
PCI Handbook[4]	Smooth function of f_n. $0.035 \le \alpha \le 0.29$	Constant factor	Constant factor	No	No	0.5%g
CCIP-016[5]	Stepped function of f_n. 0.09, 0.07, 0.06 (approximate)	No adjustment	Envelope factor	No	Variable factor	0.58%g
P354[6]	0.1	Scaled by mode shape values	Envelope factor	Yes	No	0.58%g

[1] Murray et al. (2016) based on Allen and Murray (1993)

[2] Murray and Davis (2015)

[3] Fanella and Mota (2014)

[4] PCI (2004)

[5] Willford and Young (2006)

[6] Smith et al. (2009)

[7] Sinusoidal peak acceleration

The Concrete Reinforcing Steel Institute (CRSI) Design Guide, Section 3.2.2 (Fanella and Mota, 2014), is practically identical to AISC Design Guide 11, Section 4.1. The Prestressed Concrete Institute (PCI) Handbook, Section 9.7.6 (PCI, 2004), suggests a minimum natural frequency criterion. This equation is identical to the walking criterion in AISC Design Guide 11. The two publications also provide natural modal property prediction equations that are specific to reinforced and prestressed concrete systems. AISC Design Guide 11 assumes a resonant response, so it is not applicable to floors with natural frequencies above approximately 9 Hz at which no significant resonant responses occur; however, this is ignored in the CRSI and PCI publications.

In the UK Concrete Centre CCIP-016, Section 4.4.2 (Willford and Young, 2006), "Simplified Calculation of Resonant Response," the walking-induced force is a sinusoid with amplitude equal to the body weight multiplied by the dynamic coefficient for the force harmonic that can cause resonance. The dynamic coefficients for the second, third and fourth harmonics are approximately 0.09, 0.07 and 0.06, respectively, at the middle of each harmonic frequency range. There is no mention in the simplified procedure of the effects of walker and affected occupant location or of the effect of frequency on human tolerance. Incomplete resonant build-up is considered using the classical equation solution for a single-degree-of-freedom system in resonance. CCIP-016 includes the contributions of higher modes using a "resonant response multiplier" that depends on the floor dimensions and orthotropic stiffnesses. The CCIP-016 tolerance limit is expressed in terms of a response factor. For offices, it corresponds to a peak acceleration of 0.58%g.

In the low-frequency floor procedure given in the UK Steel Construction Institute *Design of Floors for Vibration: A New Approach*, SCI P354, Chapter 7, "Simplified Assessment for Steel Floors," the walking-induced force is a sinusoid with an amplitude of 10% of body weight (Smith et al., 2009). The equation provided accounts for walker and affected occupant locations using mode shape values. It accounts for incomplete resonant build-up using the classical equation solution for a single-degree-of-freedom system in resonance. The equation is adjusted for the effect of frequency on vibration tolerance using a weighting factor, where the tolerance limit is expressed as a response factor. For offices, it corresponds to a peak acceleration of 0.58%g.

A summary of the design recommendations in these publications appears in Table 2-1.

Section 3
Some Basics

This section includes questions on the basic principles of how structural systems respond to movement by humans and on tolerance criteria for evaluating structural framing for human occupancies. There are also questions concerning frequency and damping.

3.1 How does human activity cause structural framing to vibrate?

As a person walks across a floor, a brief impact occurs with each step, and each impact results in a floor vibration. Each such floor vibration decays, but a series of impacts associated with continuous walking tends to result in building up of a relatively steady floor vibration. This phenomenon also applies to rhythmic activity.

3.2 What is an evaluation criterion?

An evaluation criterion is a basis for evaluating structural framing, such as whether or not the predicted vibrations of a floor will be acceptable for occupants or sensitive equipment under given conditions. A criterion consists of two parts: (a) a prediction of the response of the system and (b) a tolerance limit. The response and limit are usually expressed in terms of acceleration or velocity. A satisfactory design is one where the response does not exceed the limit, that is:

$$\text{Predicted response} \le \text{Tolerance limit} \tag{3-1}$$

3.3 How is human tolerance measured?

Humans are extremely sensitive to vertical vibration. Researchers have established the minimum threshold of perception of continuous sinusoidal vibration. They have also established approximate limits for transient vibration, expressed as multiples of the threshold of perception, which are expected to be tolerated in various environments. AISC Design Guide 11 expresses these tolerance limits as fractions of gravitational acceleration. For example, the tolerance limit for offices is 0.005 times or 0.5% of the acceleration of gravity, expressed as $0.005g$ or $0.5\%g$. For participants of rhythmic activities, the tolerance limit can be as high as $10\%g$.

3.4 How is sensitive equipment tolerance measured?

Tolerance limits for sensitive equipment are usually stated in terms of velocity (μ-in./s^2, sometimes abbreviated as "mips") or acceleration. Suppliers of sensitive equipment often provide specific tolerance limits in terms of (a) peak (zero-to-peak) or peak-to-peak velocity or acceleration, (b) narrow-band spectral velocity or acceleration, or (c) one-third octave spectral velocity or acceleration. If the equipment model or tolerance is not known at the time of design, typical practice is to rely on generic tolerance limits for specifying the required vibration performance of floors. See Question 6.5 for generic tolerance limits.

3.5 What are the most important parameters that must be considered when evaluating a structural system for vibration serviceability?

Natural frequency (affected by mass and stiffness), damping, effective mass (expressed as weight in AISC Design Guide 11), mode shape, forcing frequency, and tolerance limits are the most important parameters to be considered when evaluating structural framing.

3.6 What is natural frequency, and how is it determined?

If an elastic structure is displaced from the rest position and released, it will execute back-and-forth motions at definite frequencies (cycles per unit of time). These frequencies are called the natural frequencies.

A continuous dynamic system has an infinite number of natural frequencies; the lowest is called the fundamental natural frequency. The higher natural frequencies, in general, are not harmonics (integer multiples) of the fundamental frequency. In AISC Design Guide 11 and here, "the frequency" or "the natural frequency" of a structure refers to the fundamental natural frequency. Frequency generally is measured in Hertz, abbreviated as Hz, representing cycles per second.

The fundamental natural frequency of simply supported, uniformly loaded beams or of monumental stairs can be computed using Equation 3-2, which is based on classical vibration theory for elastic beams. It is noted that the natural frequency is proportional to the square root of the rigidity of the supporting member, E_sI_t, and inversely proportional to the square root of the supported mass (expressed as weight) and inversely proportional to the square of the span length.

$$f_n = \frac{\pi}{2}\left(\frac{gE_sI_t}{wL^4}\right)^{1/2} \tag{3-2}$$

where

E_s = modulus of elasticity of steel = 29,000 ksi

I_t = transformed moment of inertia; effective transformed moment of inertia if shear deformations are included; reduced transformed moment of inertia to account for joist seat flexibility, in.^{4}

L = member span, in.
g = acceleration of gravity = 386 in./s^2
w = uniformly distributed weight per unit length (actual, not design, dead and live loads) supported by the member, kip/in.

Natural frequencies can also be computed using finite element analysis methods. With these methods, a three-dimensional model of a relevant portion of the structure is developed in a finite element analysis program. The natural frequencies and mode shapes are predicted using typical eigenvalue analysis, which is included in most programs. Because numerous modes can be predicted, frequency response functions are also predicted and used to determine which modes will provide high accelerations if excited by a human-induced force (See Chapter 7).

3.7 What is forcing frequency?

Forcing frequency in general is associated with a repeating force, often characterized by the number of impacts per unit time from, say, walking or rhythmic activity. For the purposes herein, forcing frequency is expressed in Hertz, abbreviated as Hz, representing steps or impacts per second.

3.8 What is a low-frequency floor (LFF)? High-frequency floor (HFF)?

A low-frequency floor (LFF) and a high-frequency floor (HFF) are "subject to resonant responses" and "not subject to resonant responses," respectively.

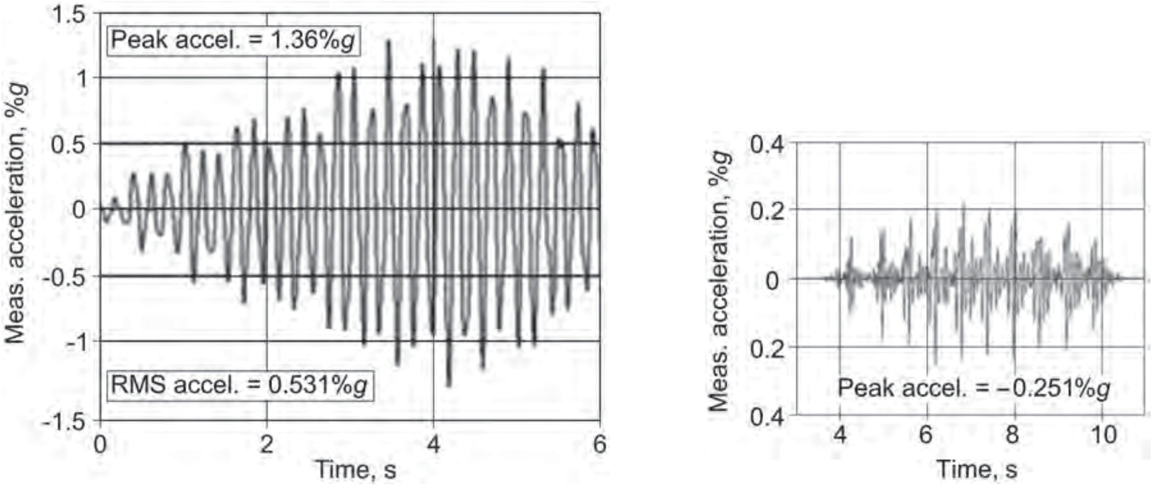
The human walking force has significant contributions at the step frequency and at the first four harmonics (integer multiples) of the step frequency. The higher harmonics have low force contributions.

The maximum step frequency of typical normal walking is approximately 2.2 Hz; therefore, the maximum fourth harmonic frequency is 8.8 Hz. If a structure's fundamental natural frequency is lower than approximately 9 Hz, then a harmonic frequency can match the natural frequency and cause resonance. Otherwise, a significant resonant response is unlikely. Thus, if a floor is subjected to normal walking and has a natural frequency below approximately 9 Hz, it is considered to be an LFF. Otherwise, it is considered as an HFF.

A resonant build-up response is shown in Figure 3-1(a) and an impulse response is shown in Figure 3-1(b). The demarcation between LFF and HFF is not always between 8.8 and 9 Hz, however. If a definite walking speed other than rapid walking is used, as may be specified for floors supporting sensitive equipment, the fourth harmonic maximum frequency of that particular walking speed determines the beginning of the HFF range. For example, if the fourth harmonic maximum frequency is 6.8 Hz for slow walking, then floors with natural frequencies only above 6.8 Hz are HFF.

3.9 Is there a frequency range where humans are most sensitive?

Yes, people are most sensitive to vibrations with frequencies between approximately 4 and 8 Hz, which is the range of the natural frequencies of some internal organs. The sensitivity decreases slowly as frequencies deviate above or below this range. See *Guide for the Evaluation of Whole-Body Vibration—Part 2: Human Exposure to Continuous and Shock-Induced Vibration in Buildings (1 to 80 Hz)*, ISO 2631-2 (ISO, 1989).



(a) Resonant build-up response (LFF)

(b) Impulse response (HFF)

Fig. 3-1. Floor response to walking.

3.10 What is the contribution of the deck slab to the natural frequency of floors?

Increasing slab thickness will increase the composite moment of inertia of the member, which tends to increase its natural frequency, but the associated increase in mass will tend to decrease the frequency as can be seen from Equation 3-2.

For beam or joist spacing less than about 15 ft, deck slab frequency itself has negligible effect on the bay frequency and is ignored in the AISC Design Guide 11 methods for estimating frequency.

3.11 What effect does composite action have on vibration response?

Human-induced loads typically cause mid-bay displacement amplitudes smaller than 0.01 in.—implying very low horizontal shears between the steel framing members and the slab. Also, deck fasteners, including spot welds and screws, provide enough slip resistance to warrant using the composite transformed moment of inertia in vibration analyses. Members with physical separations between the member and the slab—for example, girders supporting open-web steel joists with seats—behave as partially composite members with an effective moment of inertia that may be two to three times greater than the corresponding noncomposite moment of inertia of the member.

When evaluating a structural system for annoying vibrations, it is necessary that the system be modeled as closely as possible to the conditions that cause the maximum response. For instance, using the noncomposite moment of inertia instead of the composite moment of inertia generally leads to erroneous results.

3.12 How does member continuity affect the natural frequency?

Member continuity has very little effect on frequency. If there is a line of beams of the same size and span that are moment-connected, the natural frequency of the line is the same as the natural frequency of a single span. Continuity will increase the effective mass, however. (Note that the elastic buckling strength of a continuous column of equal unbraced lengths is the same as the buckling strength of a single length, pinned-pinned column. The differential equation for buckling of a continuous column is basically the same as that for determining the frequency of a continuous beam.) If a line of beams has unequal spans or stiffnesses, then the natural frequency is higher than the natural frequency of the longer span in a simply supported configuration. Figure 3-2 is an example mode shape. The shorter span provides restraint for the longer span.

In-situ testing has not shown that a girder moment-connected to a column causes a significantly higher frequency than the girder simple span frequency, with one exception. If the girder is continuous over the top of the column and the adjacent span is significantly less than or significantly larger than the span under consideration, there may be a continuity effect on the frequency.

3.13 What is damping? How is damping expressed?

When a system is displaced, released, and allowed to undergo free vibration (vibration in absence of applied forces), the vibratory energy decreases over time. This loss of energy is called damping. Several types of damping are described in vibration textbooks. Viscous damping is an adequate approximation for civil engineering structures, so it is used almost exclusively in human-induced vibration analysis.

A system with minimally sufficient damping to prevent oscillations in free vibrations, meaning it will come to rest within one half-cycle when disturbed, is called "critically damped." Damping is usually expressed as the ratio of actual damping to critical damping, called the "critical damping ratio" or simply "damping ratio." It is also sometimes expressed as a percent of critical damping.

Floors, stairs and other structures have low damping ratios, typically between 0.01 and 0.05 (1% and 5% of critical damping). The level of damping is primarily affected by the presence of nonstructural elements. Bare structural systems often have damping ratios approximately equal to 0.01 (1%). The addition of ceilings, ductwork and build-out can increase the damping ratio to 0.03 (3%) or higher. The addition of drywall partitions can increase the damping ratio to 0.05 (5%) or higher if the partitions are very closely spaced as in hotel and dormitory rooms.

3.14 How does damping affect vibration response?

Low-frequency floors with higher damping ratios have lower resonant responses. For high-frequency floors, the damping ratio does not affect the initial peak response resulting from a footfall impact, but higher damping ratios result in more rapid decay of the vibration after the impact, as shown in Figure 3-1(b), and therefore in lower spectral responses.

Fig. 3-2. Example mode shape for continuous beam with unequal spans.

3.15 What is mode shape? What is modal mass?

A structure vibrating at a natural frequency—in a "mode"—moves with a characteristic spatial pattern with every point on the structure moving at the same frequency. This spatial pattern is called a mode shape. Each natural frequency of a structure has a mode shape associated with it. Because the amplitudes of mode shapes are undefined, they may be scaled to simplify calculations—for example, by "normalizing" them so that each mode shape has a maximum magnitude of 1.0.

Figure 3-3 shows example mode shapes generated from a finite element analysis. The 5.3-Hz mode corresponds to the structural floor framing fundamental mode. Finite element analysis often predicts many modes with closely spaced frequencies. The fundamental mode is often (but not always) the most critical mode because it tends to be associated with the most severe vibration responses.

The vibration of a bay is the same as that of a classical spring-mass-damper system with the same natural frequency if the system has the same mass as the bay's modal mass. The modal mass, in effect, is the part of the total mass that participates in the modal motion. A larger area in motion indicates a higher modal mass and lower response to human-induced loads. The product of modal mass, the acceleration of gravity, and a factor of 2.0 is referred to as effective weight in AISC Design Guide 11.

3.16 How is the response of a structure due to human activity predicted?

Vibration due to human activity is predicted by (a) computing the modal properties, (b) estimating the damping ratio, (c) mathematically representing the human-induced force, and (d) computing the response.

Fundamental modal properties can be computed using equations from vibration theory. For example, the fundamental natural frequency of a simple structure can be computed by use of Equation 3-2. Properties of the modes of even complex structures can be computed using finite element analysis methods. Because many modes are often predicted, frequency response functions are also usually computed to determine which modes are most responsive to human-induced forces.

Damping ratios for components of a structural system cannot be calculated; they can only be determined from experiments. Based on such experiments and engineering judgment, guidelines are available for estimating the damping ratio of an occupied area by summing damping ratios estimated for the relevant components (see AISC Design Guide 11, Table 4-2).

3.17 What are the components of forces produced by human activities?

The walking force is approximately a periodic repeating force, so it has significant components at the step frequency and integer multiples of the step frequency. Each of these components is called a "harmonic" of the walking force and has force units such as pounds. Several researchers have measured walking forces and represented the harmonics by "dynamic load factors" (*DLF*) or "dynamic coefficients." For example, the dynamic coefficients used in AISC Design Guide 11, Chapter 4, for walking on a flat surface are 0.5, 0.2, 0.1 and 0.05, corresponding to the first four harmonics. Other sets of coefficients are used to predict responses due to running and rhythmic activities.

Practically, since the response of a floor is greatest if the forcing frequency matches the natural frequency, the fact that the dynamic coefficients decrease with increasing harmonic number means that the response of a structural system will generally decrease with increasing natural frequency. For example, using the AISC Design Guide 11 dynamic coefficients for walking and assuming a step frequency of 2 Hz, if the natural frequency of the system is 4 Hz, the fraction of body weight to be used to determine the maximum acceleration response is 20% (corresponding to a dynamic coefficient of 0.2.) If the natural frequency is 6 Hz, the fraction is only 10%.

The harmonics with high-force amplitudes occur only in limited frequency ranges. For example, normal walking on a flat surface almost always takes place between 1.6 Hz and 2.2 Hz. Because only the first four harmonics have high amplitudes, the highest harmonic frequency with a high amplitude is (4)(2.2 Hz) = 8.8 Hz. Practically, this means that only a structure with a natural frequency below approximately 9 Hz can undergo relatively high resonant responses to walking.

Fig. 3-3. Example finite element analysis mode shapes.

The greatest responses of floors with natural frequencies at or below the fourth harmonic of the walking force correspond to resonances of the floors at the harmonic whose frequency matches the natural frequency. The greatest responses of floors with higher natural frequencies are not resonant and are due to the footfall impulses. AISC Design Guide 11 includes an effective impulse that can be used to compute the peak velocity or acceleration immediately after a footstep.

3.18 How large is the variation in footstep forcing functions?

The walking-induced dynamic force has been measured by several researchers and has been shown to have significant variability. For example, the scatter of the individual measured third harmonic dynamic coefficients from Willford et al. (2007), shown in Figure 3-4, illustrates the great variation in these coefficients. (The variation is similar for the first, second and fourth harmonics.) Thus, there is a large variation in the response of systems between walkers. To account for this variation, most prediction methods in AISC Design Guide 11 have been calibrated so that the final evaluation (satisfactory or unsatisfactory) is accurately predicted or so that the predicted response to walking has a known probability of exceedance. The methods of AISC Design Guide 11 do not predict the exact response of the system for a given individual; only the overall evaluation of occupant acceptance or nonacceptance of the resulting motion.

3.19 How can the walker and affected occupant or equipment be accounted for when they are not at mid-bay?

The effect of the walker, affected occupant or equipment (receiver), or both, not being at mid-bay is accounted for generically by multiplying the mid-bay predicted acceleration by a reduction factor. For instance, the AISC Design Guide 11 acceptance criterion for walking in quiet spaces includes a generic reduction factor of 0.5 to account for incomplete resonant build-up and the effect of the walker and affected receiver not being at the same location. Because the walker and the affected occupant can be much closer on a pedestrian bridge, the reduction factor is 0.7.

An analytical method for determining a reduction factor to account for the walker and receiver not being at the same location is discussed in Question 6.8.

3.20 How does exterior cladding affect floor response?

If the exterior cladding is connected to the floor slab, the stiffness of the spandrel member is increased. Results of in-situ testing have shown that exterior cladding increases the spandrel stiffness by a factor of approximately 2.5. For manual vibration analysis, connected exterior cladding can be assumed equivalent to a wall. For finite element analysis the 2.5 factor can be used to model the spandrel stiffness.

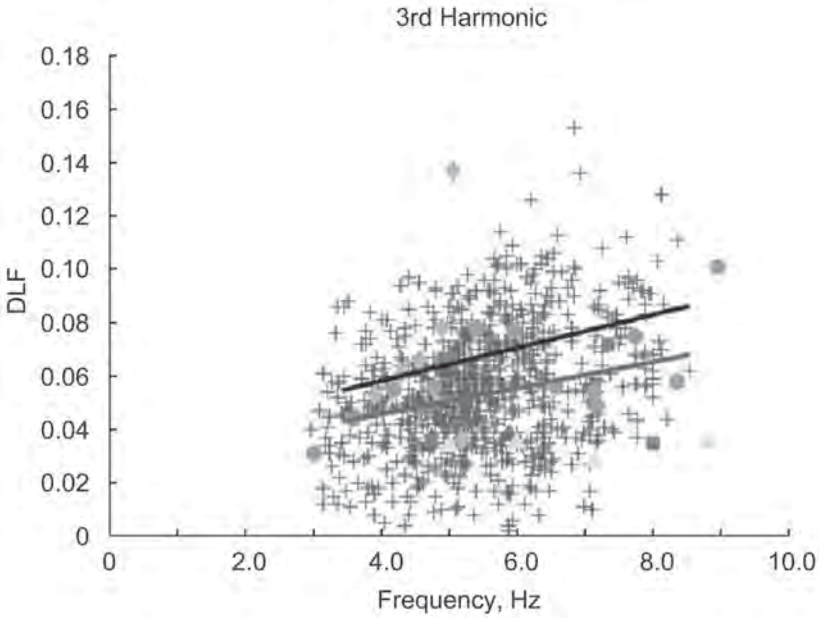


Fig. 3-4. Variation of third harmonic dynamic coefficients (Willford et al., 2007).

3.21 How do interior dry wall partitions affect floor response?

Nonstructural drywall partitions, below or on the floor, restrain vertical floor motion even when they are constructed with typical slip-tracks at the top of wall. Consequently, the addition of partitions often increases natural frequencies and damping significantly and sometimes changes the mode shapes.

The addition of full-height partitions increases the damping ratio by 0.02 to 0.05. A damping ratio of 0.05 is recommended for bays with significant full-height partitions in the bay. Partitions perpendicular to the beam or joist span and located in the middle half of the beam or joist span have the greatest effect.

In-situ testing has shown that such interior partitions can be modeled in finite element analyses by linear vertical springs with a stiffness of 2 kip/in. per foot of wall. Engineering judgment must be employed to select which partitions to include in the model. Only partitions considered to be relatively permanent should be included to avoid an unconservative evaluation.

3.22 How are irregular bays analyzed?

With engineering judgment, a not-too-irregular nonrectangular bay might be idealized as a rectangular bay. For instance, if the bay is trapezoidal with edges less than 10° or so from square, the bay might be considered a rectangular bay using the longest span. For other cases, finite element analysis should be used. In cases where it is obvious that the bay is so stiff that it will not vibrate significantly due to walking personnel, such as for triangular bays with relatively small edge dimensions, analysis may not be necessary.

Section 4
Floors for Quiet Occupancies

This section includes questions concerning the AISC Design Guide 11, Chapter 4, evaluation criterion for floors supporting quiet spaces such as offices, residences, assembly areas, schools and churches. The evaluation criterion in AISC Design Guide 11 is

$$\frac{a_p}{g} = \frac{P_o e^{-0.35 f_n}}{\beta W} \le \frac{a_o}{g}$$

(AISC Design Guide 11, Eq. 4-1)

where

a_o/g = vibration tolerance limit expressed as an acceleration ratio

a_p/g = ratio of the peak floor acceleration to the acceleration of gravity

P_o = amplitude of the driving force, 65 lb

W = effective weight supported by the beam or joist panel, girder panel, or combined panel, as applicable, lb

e = base of natural logarithm = 2.718

f_n = fundamental natural frequency of a beam or joist panel, a girder panel, or a combined panel, as applicable, Hz

β = viscous damping ratio

4.1 Is the evaluation criterion for quiet occupancies empirical?

No. The bay is idealized as a single-degree-of-freedom system using the bay's natural frequency, f_n, effective mass, M, and viscous damping ratio, β. The excitation is a sinusoidal load, with amplitude P, at the natural frequency so that it causes resonance. The steady state acceleration from vibration theory, shown in Figure 4-1, is the starting point of the derivation.

To derive the acceleration due to walking: (a) P is replaced by a curve-fit of harmonic components of the walking force (Question 3.16); (b) the effective mass of the bay is computed using orthotropic plate theory; and (c) a judgment-based adjustment factor, R, is included to account for incomplete resonant build-up and the locations of walker and affected occupant. The equation is then simplified.

4.2 Why does it appear that the walker's full weight is not used in the evaluation criterion?

The forcing load, P_o, in the criterion is not the walker's body weight, but represents the effective force component, including some adjustments. It is the product of the assumed body weight, 157 lb; an adjustment factor, R (equaling 0.5 to account for incomplete resonant build-up and for the walker and affected occupant not being at the same location); and 0.83. The 0.83 factor comes from the curve fit to the walking force dynamic coefficients. For floors, $P_o = (157 \text{ lb})(0.5)(0.83) = 65.1$ lb, rounded to 65 lb.

4.3 What typical superimposed loads should be considered?

All superimposed dead loads must be considered; however, actual, not design, values should be used. For floors supporting typical hung ceilings and typical mechanical loading, 4 psf is recommended. This value should be increased or decreased for other conditions; such as for a heavy acoustical ceiling or heavy mechanical loading as might be found in a medical facility.

Recommended live loads are 11 psf for "paper offices," 6 to 8 psf for "electronic offices," and 6 psf for residences. A "paper office" is one furnished with heavy desks, bookcases, file cabinets and demountable partitions. An "electronic office" is one with widely spaced work stations and few bookcases, file cabinets and demountable partitions. Photographs of example paper and electronics offices are shown in Figure 4-2.

For schools, churches, public areas of shopping malls, and assembly areas, the recommended live load for vibration analysis is zero. It is noted that complaints have only been reported when there are few people in such areas—for instance, early church arrivers.

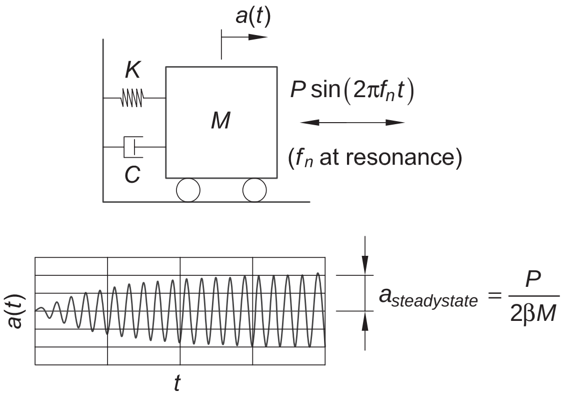


Fig. 4-1. Idealized single-degree-of-freedom system.

(a) Paper office

(b) Electronic office

Fig. 4-2. Office classifications for vibration analyses.

Recommended live loads for rhythmic events are 12.5 psf for dancing, 31.0 psf for lively concerts with fixed seating, and 4.20 psf for aerobics. These values are from the *National Building Code of Canada* and its Commentaries (NRCC, 2010a and 2010b).

4.4 What is meant by a floor panel, a beam or joist panel, and a girder panel?

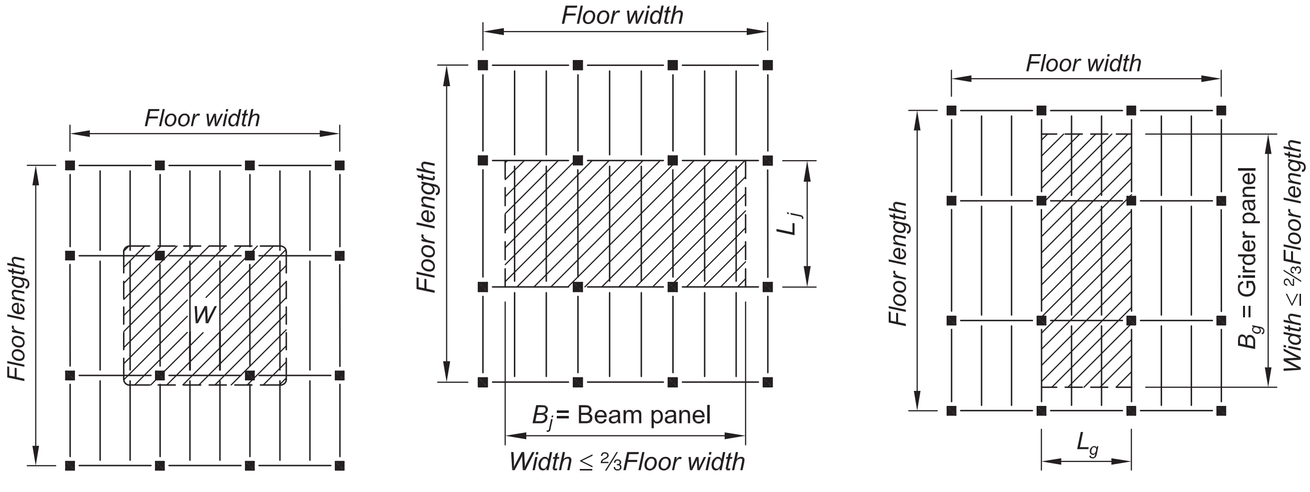
The concept of panels is used to help estimate the modal (or moving) mass for manual vibration analysis. The floor panel is the rectangular area that contributes to the total modal mass. The beam or joist panel is the moving area associated with the beam or joist and the girder panel is the moving area associated with the girder. A floor panel usually will be larger than the bay under consideration. Floor, beam or joist, and girder panels are illustrated in Figure 4-3. The effective weight, W, in the evaluation criterion is determined from the area of the floor panels.

4.5 How do *floor width* and *floor length* affect the response of floors?

Floor width and *floor length* are used to determine the limits of the rectangular plan portion of the floor from which the effective modal mass is determined. As shown in Figure 4-3, the beam panel width is limited to two-thirds the *floor width*, and the girder panel width is limited to two-thirds the *floor length*. The larger the rectangular area, the larger the effective mass, and consequently, the lower the acceleration caused by walking.

4.6 How do I determine *floor width* and *floor length*?

Floor width is the distance perpendicular to the span of the beams or joists in the bay under consideration over which the structural framing (beam or joist and girder size, spacing, length, etc.) is identical, or nearly identical, in adjacent bays. *Floor length* is the distance perpendicular to the span of the girders in the bay under consideration over which the structural framing (beam or joist and girder size, spacing, length, etc.) is identical, or nearly identical, in adjacent bays. To determine these lengths, one has to consider the nonregularity of the framing plan. One way to do this is to visualize the framing as a body of water, then visualize how far in each direction a wave would travel undisturbed if a pebble is dropped in the center of a bay. Consider the framing plan shown in Figure 4-4. If a pebble is dropped at A, the ripple would flow in the east-west direction to the openings in the framing or 90 ft. In the north-south direction, it would flow in the entire width of the building or 90 ft. If a pebble is dropped in Bay B, the ripples will flow east-west until they are interrupted by the change in framing beginning 30 ft from the east and west building extents, so the *floor width* is taken as 150 ft. North-south, the ripples will flow until they are stopped by the north and south building extents, hence a *floor length* of 90 ft. Table 4-1 shows the *floor widths* and *floor lengths* for the designated bays in Figure 4-4.



(a) Floor panel (b) Beam or joist panel (c) Girder panel

Fig. 4-3. Types of panels.

Table 4-1. *Floor Lengths* and *Floor Widths* for Figure 4-4 Framing		
Bay	***Floor Width*, ft**	***Floor Length*, ft**
A	90	90
B	150	90
C	150	30
D	30	90

4.7 How are mezzanines (flat rectangular balconies) analyzed?

For manual vibration analysis, to account for the reduced effective mass due to a free edge parallel to the girder span, the girder panel width is limited to two-thirds of the supported beam or joist span. If the free edge is parallel to the beam span, the effective mass is taken as one-half of the effective mass of an identical interior bay.

4.8 Why is there a 3-Hz minimum natural frequency recommendation for floors?

Floor systems with fundamental frequencies less than 3 Hz should generally be avoided because they are liable to be subject to severe vibrations due to “rogue or vandal jumping”—that is, people generating greater vibrations on purpose. However, if the fundamental frequency is less than 3 Hz, a careful evaluation of the system may show that it is acceptable, especially if there is large participating mass. Such floor systems should be evaluated using rhythmic activities criteria. Floors with spans of approximately 90 ft with a natural frequency of less than 3 Hz have been successfully designed.

4.9 How accurate are the AISC Design Guide 11 predictions for floors supporting quiet occupancies?

Over the last 20 years or so, a database of 105 floor bays, 76 with complaints of lively vibration and 29 without complaints, has been assembled and analyzed. The database includes 50 floors with W-shape beams and girders, 27 with open-web steel joists and W-shape girders, 22 with open-web steel joists and joist girders, and six with castellated beams and girders.

The AISC Design Guide 11 evaluation criterion correctly predicted unsatisfactory evaluations for 74 of the 76 bays with complaints (97.4% accurate predictions). It correctly predicted satisfactory evaluations for 28 of the 29 bays without complaints (96.6% accurate predictions). In this study, predicted and measured accelerations were not compared; only the occupant responses (complaints or no complaints) were considered.

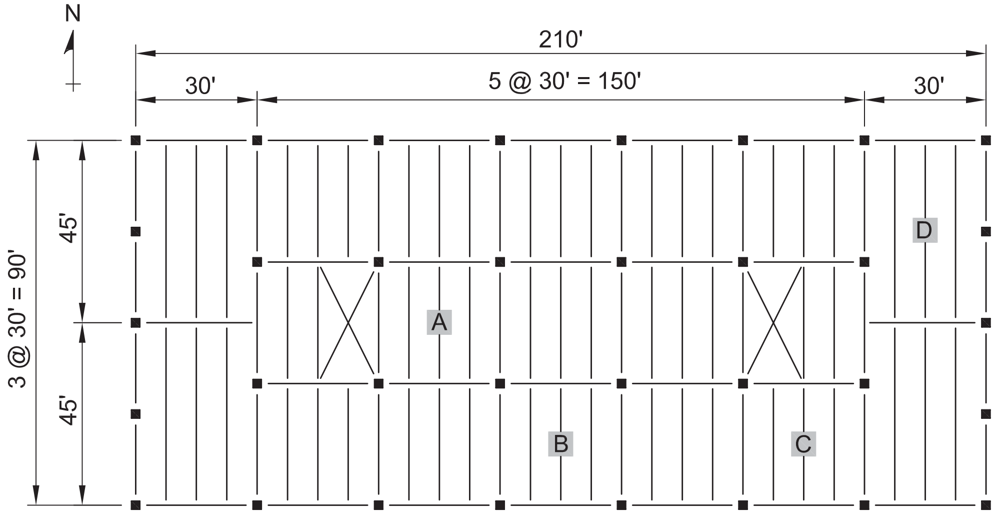


Fig. 4-4. Floor width *and* floor length *example framing.*

Section 5
Framing for Rhythmic Activities

This section includes questions concerning the AISC Design Guide 11, Chapter 5, evaluation criterion for floors supporting rhythmic activities. The evaluation criterion is

$$\frac{a_p}{g} = \frac{\left(\sum a_{p,i}^{1.5}\right)^{1/1.5}}{g} \leq \frac{a_o}{g}$$

(AISC Design Guide 11, Eq. 5-1)

where a_o/g is the tolerance limit expressed as an acceleration ratio, and the peak acceleration ratio due to the *i*th harmonic is computed using

$$\frac{a_{p,i}}{g} = \frac{1.3\alpha_i w_p/w_t}{\sqrt{\left[\left(\frac{f_n}{if_{step}}\right)^2 - 1\right]^2 + \left(\frac{2\beta f_n}{if_{step}}\right)^2}}$$

(AISC Design Guide 11, Eq. 5-2)

where

f_n = fundamental natural frequency, Hz
f_{step} = step frequency, Hz
i = harmonic number, 1, 2, 3
w_p = unit weight of rhythmic activity participants distributed over the entire bay, psf
w_t = distributed weight supported, including dead load, superimposed dead load, occupants, and participants distributed over the entire bay, psf
α_i = dynamic coefficient for the *i*th harmonic of the rhythmic activity (AISC Design Guide 11, Table 5-2)
β = damping ratio, usually taken as 0.06 for rhythmic crowd loading

The summation extends over all harmonics listed in AISC Design Guide 11, Table 5-2.

5.1 What is the major cause of high accelerations from rhythmic activities?

If a harmonic of the dynamic force due to a rhythmic activity (beats per minute, bpm, to be divided by 60 to obtain the first harmonic of the forcing frequency) matches or nearly matches a structural natural frequency, then resonance and large accelerations may result. For example, consider a floor with a natural frequency of 5 Hz, subjected to a rhythmic activity at 2.5 Hz. The second harmonic of the force is at (2)(2.5 Hz) = 5.0 Hz. This harmonic causes resonance and unacceptable accelerations may be expected.

5.2 What limit state is being satisfied by the AISC Design Guide 11 rhythmic predictions?

The limit state satisfied in AISC Design Guide 11 is serviceability. Strength and fatigue limit states are not considered.

5.3 What tolerance criterion is used for rhythmic activities?

In the second edition of AISC Design Guide 11, the recommended tolerance limit is acceleration. (This differs from the first edition where a frequency limit was also suggested.) The recommended acceleration tolerance limits are given in Table 5-1, which is AISC Design Guide 11, Table 5-1, and vary depending on the affected occupancy. (Affected occupancy is occupancy in the rhythmic activity bay(s) or adjacent bays.) The recommended limits are from the 2010 *National Building Code of Canada* (NRCC, 2010a) and range from 0.5%g for affected quiet spaces to 7%g when there is only rhythmic activity in the area.

5.4 Why is there a separate acceleration tolerance limit when weight lifters are present?

Weightlifters, for unknown reasons, are especially sensitive to floor motion. Weightlifting areas tend to have mirrors on walls, and it is possible that mirror vibration disturbs the participants.

5.5 What is the difference between resonant and off-resonant activity?

Resonant activity occurs when a harmonic of the activity frequency (activity frequency times an integer) matches the floor natural frequency. Off-resonant activity is when such matching does not occur. For instance, if the activity is 2.5 Hz and the floor natural frequency is 6.6 Hz, there is no activity harmonic frequency that matches the floor natural frequency. However, if the activity frequency is 2.2 Hz, resonance can occur because (3)(2.2 Hz) = 6.6 Hz.

5.6 When is it difficult to satisfy the rhythmic acceleration tolerance limit?

It is not difficult to satisfy rhythmic acceleration tolerance criteria for spans less than about 35 ft but very difficult for spans exceeding 50 ft. It is also difficult to satisfy the criterion when beam and girder depths must be shallow.

Table 5-1. Recommended Tolerance Acceleration Limits for Rhythmic Activities in Buildings

Affected Occupancy	Tolerance Acceleration Limit, a_o, %g
Office or residential	0.5
Dining	1.5–2.5
Weightlifting	1.5–2.5
Rhythmic activity only	4–7

Note: The information in this table is taken from AISC Design Guide 11, Table 5-1.

5.7 Can spaces designed for offices or retail space be used for fitness centers?

Generally no. The natural frequency of office or retail space floors is usually in the 4- to 6-Hz range. These frequencies are susceptible to harmonic resonance for typical rhythmic activities between 2 Hz and 2.5 Hz, resulting in high to very high accelerations. See AISC Design Guide 11, Example 5.2, for the evaluation of an existing office space for aerobic activity.

5.8 Is it possible to isolate bays supporting rhythmic activities from surrounding bays?

One approach is to completely isolate the bay or bays supporting the rhythmic activities by supporting the perimeter of the area on separate beams and girders (i.e., two beam or girder lines between the rhythmic area bay(s) and adjacent bays ideally with an expansion joint in the slab) as shown in Figure 5-1. Another approach is to place a concrete masonry unit (CMU) wall on beams and girders between the areas. A CMU wall increases the support member stiffness essentially to infinity for vibration analysis.

5.9 Is flooring that is designed to reduce leg strain helpful in reducing floor motion?

No. This type of resilient flooring does not increase damping or reduce the response of floors supporting rhythmic activities. It does add some mass to the floor system but the effect on frequency is not significant. The net result is that the floor motion is essentially unchanged with the addition of this type of flooring. An example of such flooring is shown in Figure 5-2.

5.10 Can checkerboard framing be used to reduce girder size in floors supporting rhythmic activities?

Yes. A long span girder supporting two bays with rhythmic activities as shown in Figure 5-3(a) may require a heavy, deep girder. If the secondary framing is alternately turned 90° (so-called checkerboard framing), as shown in Figure 5-3(b), the girder size—particularly depth, but also weight—required for vibration can often be significantly reduced. However, the framing must be fully analyzed because the effective mass is reduced in some cases due to the lack of continuity of beams. Also, the number of girders is increased and the floor system is somewhat more complicated. These are considerations that must be weighed against the savings in girder size.

5.11 What are floating floors and their applications?

A floating floor can be used to isolate rhythmic activities if the supporting structure has sufficient strength to support it. A floating floor is usually a concrete slab on very soft mats or springs that is supported by the building floor structural system. If properly designed, the floating floor isolates rhythmic activity energy from the building itself. However, spring elements that are soft enough to isolate rhythmic activities considerably are often impractical.

5.12 Have there been problems reported because of fitness centers in lower floors of tall buildings?

Yes. Cases have been reported in Canada (Allen, 1990), South Korea (Lee et al., 2013), and the United States where rhythmic activities in health clubs on low level floors have caused annoying vibrations of upper floors in the building

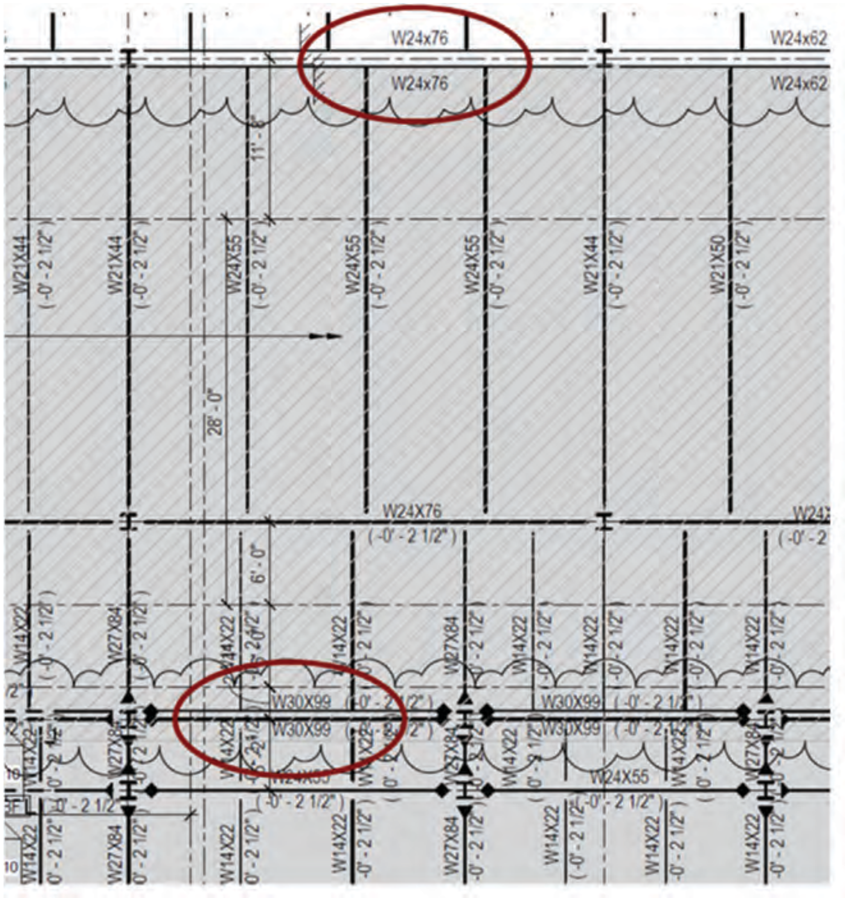


Fig. 5-1. Double framing for isolating rhythmic activity vibrations.

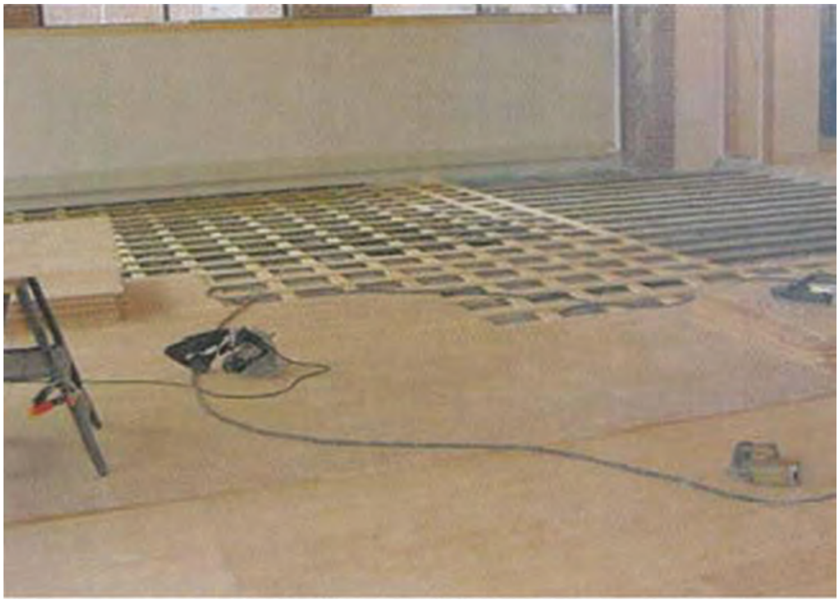


Fig. 5-2. Flooring to reduce leg strain.

and vice versa. The cause is elastic deformation of the columns, which can be accounted for in design by including column axial deformation when computing the system frequency:

$$f_n = 0.18\sqrt{\frac{g}{\Delta_j + \Delta_g + \Delta_c}}$$

(AISC Design Guide 11, Eq. 3-5)

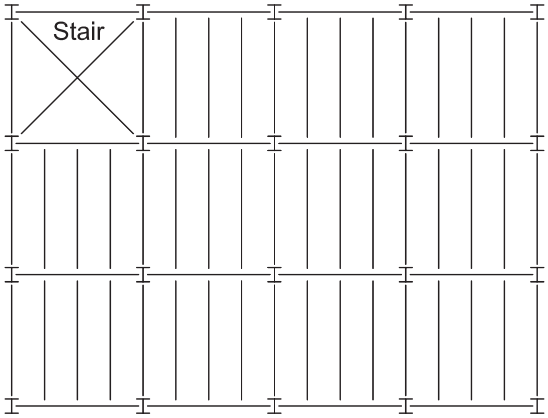
where

Δ_c = axial shortening of the column or wall due to the weight supported, in.

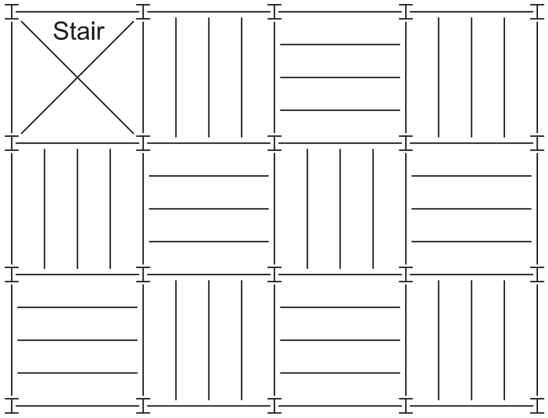
Δ_g = midspan deflection of girder due to the weight supported by the member, in.

Δ_j = midspan deflection of the beam or joist due to the weight supported by the member, in.

AISC Design Guide 11, Example 5.2, is an example where column axial shortening is considered when determining frequency.



(a) Girder supporting two bays



(b) Turned secondary framing

Fig. 5-3. Reducing girder size.

Section 6
Floors for Sensitive Equipment

This section includes questions on evaluating floors supporting sensitive equipment. Questions on tolerance limit and on evaluating the effects of walker and sensitive equipment locations are included.

6.1 What is the recommended approach for evaluating bays for sensitive equipment?

(a) Determine the vibration tolerance of the sensitive equipment, ideally from manuals provided by the equipment's supplier.

(b) Note in terms of which vibration measures this tolerance is stated (e.g., RMS velocity or acceleration, peak—i.e., zero-to-peak acceleration or peak-to-peak acceleration). For spectral quantities, determine what frequency bands must be considered.

(c) Define where walking is expected and the locations of the sensitive equipment.

(d) Consider appropriate walking speeds—for example, very slow walking in confined areas, slow to moderate walking in more open areas, or fast walking in actual or virtual corridors.

(e) Use the relations in Chapter 6 of AISC Design Guide 11 to determine the mid-bay vibrations and adjust these for the walking and equipment locations.

(f) Compare the predicted vibration response at the equipment location to the equipment tolerance limit.

6.2 What are some common vibration response metrics?

Vibration metrics may be stated in terms of displacement, velocity or acceleration; their various measures [often root-mean-square (RMS) or peak values]; and the frequency bands in which these measures are evaluated. The most common frequency bands are one-third octave or constant-width (often 0.0625 to 1 Hz) bands.

6.3 What do sensitive equipment vibration tolerance specifications look like?

There is a wide variation in how equipment tolerance limits are specified by equipment suppliers. Often these limits are given in terms of peak accelerations or velocities in specific frequency ranges or bands, and often in terms of root-mean-square (RMS) velocity in given frequency bands. Sometimes these limits are stated by referring to generic tolerance limits.

Note that specific limits are sometimes stated in unfamiliar terms. Spectral limits are sometimes specified without stating whether the values are peak (amplitude) or RMS ($1/\sqrt{2} = 0.707$ times the amplitude for sinusoidal motion). Also, spectral limits are sometimes stated without complete information—for example, without an indication of the type and width of bands (e.g., narrow bands or one-third octave). Thus, it is often necessary to ask for clarification to ensure that the limit is fully understood.

6.4 What is meant by generic tolerance limits?

The generic tolerance limits are represented by a set of curves of RMS velocity versus one-third octave band center frequency, generally intended to characterize the vibration environment of a floor (see Figure 6-1). These so-called vibration criteria (VC) curves are labeled by letters, with letters later in the alphabet corresponding to more stringent limits. The generic tolerance limits may be used to evaluate the acceptability of vibrations for equipment or activities when no specific tolerance limits are available.

6.5 What set of generic tolerance limits is recommended?

Table 6-2 of AISC Design Guide 11, reproduced here as Table 6-1 for convenience, shows generic tolerance limits

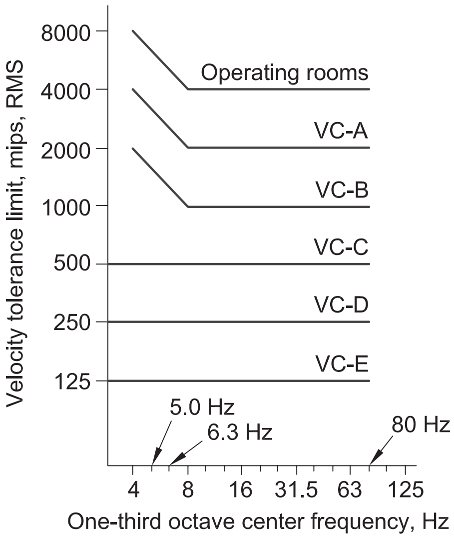


Fig. 6-1. AISC Design Guide 11, Figure 6-2, generic vibration criteria (VC) curves.

Table 6-1. Generic Vibration Criteria Tolerance Limits

Designation	Tolerance Limit[1], mips	Applicability
—	32,000	Ordinary workshops[2]
—	16,000	Offices[2]
—	8,000	Computer equipment, residences[2,3]
—	6,000	Hospital patient rooms[4]
—	4,000	Surgery facilities, laboratory robots, bench microscopes up to 100×, operating rooms[5]
VC-A	2,000	Microbalances, optical comparators, mass spectrometers, industrial metrology laboratories, spectrophotometers, bench microscopes up to 400×
VC-B	1,000	Microsurgery, microtomes and cryotomes for 5- to10-μm slices; tissue and cell cultures; optical equipment on isolation tables; bench microscopes at greater than 400×; atomic force microscopes
VC-C	500	High-precision balances, spectrophotometers, magnetic resonance imagers, high-precision balances, microtomes and cryotomes for <5-μm slices, chemotaxis, electron microscopes at up to 30,000×
VC-D	250	Cell implant equipment, micromanipulation, confocal microscopes, high-resolution mass spectrometers, electron microscopes (SEMs, TEMs)[6] at greater than 30,000×
VC-E	125	Unisolated optical research systems, extraordinarily sensitive systems

Note: This table is taken from AISC Design Guide 11, Table 6-2.

[1] As measured in one-third octave bands over the frequency range 8 to 80 Hz (VC-A and VC-B) or 1 to 80 Hz (VC- C through VC-E). See AISC Design Guide 11, Figure 6-2.

[2] Provided for reference only. Evaluate using AISC Design Guide 11, Chapter 4 or Chapter 7.

[3] Corresponds to approximate average threshold of perception.

[4] When required by FGI (2014), *Guidelines for Design and Construction of Hospitals and Outpatient Facilities*.

[5] Corresponds to approximate average threshold of perception of most sensitive humans.

[6] SEM = scanning electron microscope; TEM = transmission electron microscope.

recommended for various sensitive occupancies and equipment. The tolerance limits for ordinary workshops, offices and residences are listed for reference ony, and are not used in any evaluation method in AISC Design Guide 11. Other limits in the literature may be used based on the engineer's judgment.

6.6 What is the difference among resonant, impulse and intermediate responses?

Resonance refers to the condition in which the frequency associated with a continuous force; for instance, walking, matches a natural frequency of a structure. At resonance, a structure generally is subject to vibrations that are more severe than those at nonmatching frequencies.

Only the four lowest harmonics of forces resulting from walking at a given speed have appreciable magnitude. If a structure has a natural frequency below the fourth harmonic maximum frequency, f_{4max} in AISC Design Guide 11, Chapter 6, then one of the harmonics of the walking-related force may match this natural frequency. The structure may respond at its resonance to the essentially continuous harmonic forcing and the greatest vibrations tend to occur under this condition. See Figure 3-1(a).

A floor or other structure with all natural frequencies higher than f_{4max} does not experience continuing walking-related forcing at its natural frequency and thus does not respond at resonance. The walking-induced vibrations of such a floor result predominantly from a series of impulses resulting from footfalls. See Figure 3-1(b).

Due to the variability of actual walking speeds and forces and the limited precision with which a structure's natural frequency can be predicted, the extent of the frequency range in which resonant responses can occur is uncertain. Thus, for example, one would not expect a structure with a natural frequency of 6.5 Hz to vibrate very differently from a structure with a natural frequency of 7 Hz. Similarly, one would not expect walking at 1.6 Hz to result in vibrations that differ greatly from those due to walking at

1.7 Hz. For these reasons, it does not make practical sense to consider an abrupt transition from resonant responses to impulse response behavior with a slight increase in natural frequency; rather, it is more appropriate to consider a "transition" region of natural frequencies in which there is a gradual change from resonant to impulse responses. The responses in this region are "intermediate" between resonant and impulse responses. The limits of these regions for various walking speeds are given in AISC Design Guide 11, Table 6-1, and taken into account in the design aid plots, such as AISC Design Guide 11, Figures 6-3 and 6-9.

6.7 What is the meaning of the walking speeds given in AISC Design Guide 11, Chapter 6?

Four walking speeds (very slow, slow, moderate and fast) are considered to be typical. Very slow walking (1.25 Hz, 75 bpm) pertains to confined areas, such as small and congested rooms. Slow walking (1.60 Hz, 96 bpm) is appropriate for midsized rooms with some obstructions to walking, and moderate walking (1.85 Hz, 111 bpm) is appropriate for relatively large rooms with few obstructions. Fast walking (2.1 Hz, 126 bpm) is appropriate for areas with extended clear walking paths, such as actual or virtual corridors. Note that the walking speed definitions in the second edition of AISC Design Guide 11 are different from those in the first edition and are believed to be more realistic.

6.8 How are response predictions adjusted for walker and sensitive equipment location?

Response prediction equations in AISC Design Guide 11, Chapter 6, predict vibration levels at the middle of a floor bay caused by walking at the same location. This is the worst-case scenario. However, fit-out and floor layout often do not permit walking through the middle of the bay. Also, the equipment is often located away from mid-bay. In these situations, the aforementioned prediction should be multiplied by the mode shape values at the walker and equipment locations. For regular structural bays, these mode shape values are calculated from AISC Design Guide 11, Equation 6-2a or 6-2b. For irregular and other complex configurations, the mode shape functions should be determined by the use of finite-element analysis.

6.9 How are generic tolerance limits used to evaluate a floor bay?

Because the generic tolerance limits are stated in terms of velocity, mips, in one-third octave bands of frequency, the expected vibrations need to be determined in this form. This may be done by use of AISC Design Guide 11, Equations 6-3a and 6-3b. A floor design may be deemed to be acceptable if the expected vibrations do not exceed the applicable tolerance limit.

6.10 How are specific tolerance limits used to evaluate a floor bay?

Specific tolerance limits are usually found in sensitive equipment supplier installation documents. Once the variables (acceleration or velocity) and metrics (waveform peak, narrow-band spectrum peak, one-third octave band spectrum peak) in terms of which the tolerance limits of interest are known, the applicable equation from AISC Design Guide 11 (Equations 6-3 through 6-8) is used to predict the floor response in these same terms. A floor design may be deemed to be acceptable if the expected vibrations do not exceed the applicable tolerance limit.

6.11 What structural parameters affect vibration response?

Two structural parameters have the greatest effect on the vibration response of a structure caused by walking: the structure's mass (represented by its effective weight) and its stiffness (represented by the ratio of an applied static force to the deflection caused by that force). In most cases, increases in the mass and/or the stiffness result in reduced vibrations. The amount of the reduction depends on the vibration variable and metric under consideration. See AISC Design Guide 11, Table 6-3, for the variation of response measures as a function of effective weight and stiffness. The resonant responses also vary inversely with the structure's damping, which may be due in part to the structure itself and in part due to partitions and the like supported by the structure.

6.12 What nonstructural changes can reduce vibration response?

The vibrations to which an item of equipment may be subjected due to walking in a structural bay depend on the location of the equipment and the walking path. Thus, one may reduce the vibrations to which an equipment item is exposed by placing it in a "quieter" location and/or by moving the walking path to where walking will induce lesser vibrations. Because the vibrations generated by walking increase with walking speed, walking-induced vibrations may also be reduced by placing obstructions (detours, doors, etc.) in the walking path.

Furthermore, the addition of full-height drywall partitions to the floor structure provides damping, mass and stiffness, and thus helps to reduce the responses to walking. Furnishings located on the floor also increase the damping, as does the presence of people on the floor.

6.13 How are patient rooms and operating rooms evaluated?

The tolerance limits of such rooms stems from the *Guidelines for Design and Construction of Hospitals and Outpatient Facilities* (FGI, 2014). This document indicates

4,000 mips and 6,000 mips RMS velocity limits, measured in one-third octave frequency bands, for operating rooms and patient rooms, respectively.

The vibrations resulting from various walking conditions may be evaluated by use of the methods applicable to sensitive equipment and generic limits, but the calculations may be carried out from AISC Design Guide 11, Equation 6-9a or 6-9b, instead of Equation 6-3a or 6-3b. Equations 6-9a and 6-9b result in slightly lower predictions, allowing for the subjective nature of human perception. Locations of the sensitive areas and of the walking paths may be taken into account as described in Question 6.8

Section 7
Monumental Stairs

Evaluation of monumental stairs is basically the same as for floors. The major differences are higher walking speeds, the effect of walker and affected occupant locations, and determining the effective length of linear stairs with intermediate landings.

7.1 What are monumental stairs, and why are they vulnerable to annoying human-induced vibration?

Monumental stairs are major architectural features in prominent areas of hotels, condominiums, offices, and other major structures. An example is shown in Figure 7-1.

The aesthetics of such stairs is a very high priority, meaning they often have long spans and shallow stringers, resulting in low natural frequencies. Stride lengths are short, so step frequencies can be high: 2.5 Hz (150 bpm) for regular descents and 4.0 Hz (240 bpm) for fast, but easily manageable, descents. Therefore, one of the first four harmonics of the dynamic force can match a natural frequency and cause resonance. Monumental stairs are usually lightly damped and have low mass, so they are potentially very responsive to resonant build-ups.

7.2 Which causes a more severe dynamic load—a stair ascent or a stair descent?

Table 7-1 summarizes the average dynamic coefficients for stair ascents and descents. (First harmonic coefficients are excluded because no stair should be designed such that the first harmonic can cause resonance.) The table shows that descents cause significantly higher forces than ascents. People comfortably ascend stairs only at approximately 2 Hz (120 bpm) and 3.3 Hz (≈200 bpm) whereas they comfortably

Fig. 7-1. Example monumental stair.

Table 7-1. Approximate Average Dynamic Coefficients, α, for Stair Ascents and Descents

Harmonic	Ascent	Descent
2	0.13–0.07	0.2
3	0.06	0.09
4	0.03	0.06

descend stairs at any frequency below approximately 4 Hz (240 bpm), so it is more likely that stair descents will be at step frequencies that will cause resonance. Thus, stair descents generate more severe dynamic loads than stair ascents.

7.3 How are the modal properties of a monumental stair calculated?

Modal properties—natural frequencies, mode shapes and effective mass—of linear stairs can be predicted using a simply supported beam idealization. Using finite element analysis, modal properties for any stair, including circular stairs, stairs with intermediate supports, stairs supported by flexible framing, and switchback stairs, can be predicted.

A straight or linear stair can be modeled as a beam with length L_s along the diagonal between supports as shown in Figure 7-2. This idealization is used in the development of AISC Design Guide 11, Section 4.3.

The fundamental natural frequency of a linear stair can be computed using AISC Design Guide 11, Equation 4-7, which is the classical equation for the fundamental frequency of a beam with uniform mass. This equation illustrates that the natural frequency is proportional to the rigidity, E_sI_t, and inversely proportional to the supported mass and length.

$$f_n = \frac{\pi}{2}\left(\frac{gE_sI_t}{W_sL_s^3}\right)^{1/2}$$

(AISC Design Guide 11, Eq. 4-7)

where

E_sI_t = stringer vertical flexural stiffness, including stringers and any other elements that provide stiffness; stair lateral flexural stiffness, lb-in.^{2}

L_s = stringer length measured along the diagonal between supports, in.

W_s = weight of stair, lb

g = acceleration of gravity = 386 in./s^2

If the stair is supported on girders, the vertical combined mode or system frequency can be estimated using the Dunkerley relationship in AISC Design Guide 11, Equation 3-2.

The mode shape of a linear stair is assumed to be a half sine wave between supports as shown in Figure 7-3. The mode shape value at the walker or affected occupant location is computed using AISC Design Guide 11, Equations 4-9 and 4-10:

$$\phi_W = \sin\left(\frac{\pi x_W}{L_s}\right)$$

(AISC Design Guide 11, Eq. 4-9)

$$\phi_R = \sin\left(\frac{\pi x_R}{L_s}\right)$$

(AISC Design Guide 11, Eq. 4-10)

where

L_s = stair stringer length measured along the diagonal between supports, in.

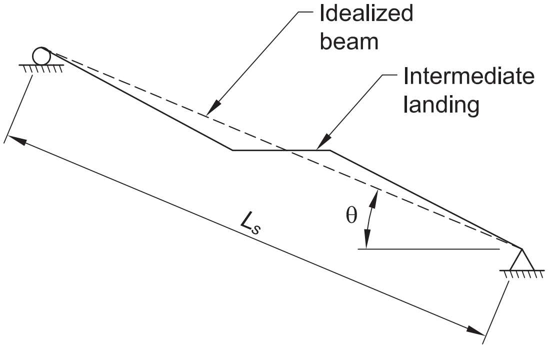


Fig. 7-2. Linear stair idealization.

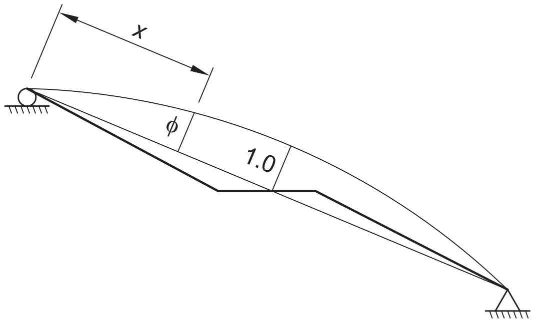


Fig. 7-3. Mode shape of beam idealization of a stair.

x_R = distance from end of stringer to response location, measured on the diagonal, in.

x_W = distance from end of stringer to walker excitation force location, measured on the diagonal, in.

ϕ_R = unity-normalized mode shape value at the response location

ϕ_W = unity-normalized mode shape value at the walker location

The effective weight (mass) of a linear stair is one-half the weight (mass) of the stair, which is from the classical result for a simply supported beam with uniform mass and flexural rigidity. This is consistent with assuming a half-sine wave deflection shape.

The modal properties of any stair can be computed using the finite element analysis method. With this method, a three-dimensional model of the stair is developed in a finite element analysis program. If the stair is supported by flexible framing, then a relevant portion of the floor framing must be included. A large area of floor should usually not be included because the floor has much higher mass and small errors in floor mass prediction may cause large errors in the stair analysis. The natural modes are predicted using typical eigenvalue analysis, which is included in most finite element analysis programs. Because numerous modes are often predicted, frequency response functions are used to determine which modes will provide high accelerations if excited by a human-induced force. (See Section 8 for more details.)

7.4 How is damping estimated for stairs?

The damping ratio is estimated by engineering judgment and is illustrated using the following two examples. The measured damping ratio for the stair in Figure 7-4(a), which has no soffit and the treads and guardrails are attached such that there is little or no friction at the interfaces, is 0.01(1% of critical damping). The reported damping ratio for the stair in Figure 7-4(b), which has a drywall soffit (not visible in the picture), treads, risers, and guardrails with potentially frictional interfaces, is approximately 0.04 (4%).

7.5 What are the vibration tolerance limits for stationary occupants on a stair?

According to AISC Design Guide 11, Table 4-5, the acceleration tolerance limit is 1.7%*g* peak sinusoidal acceleration for normal descents at regular speeds. (This limit is approximately equal to the limit for indoor footbridges.) People will probably tolerate higher accelerations due to fast descents, so the recommended limit is 3.0%*g* for fast descents.

7.6 How should the effect of walker and affected occupant locations be included in the evaluation of a monumental stair?

The manual evaluation method for linear monumental stairs is based on a simply supported beam idealization. The midspan acceleration due to sinusoidal load at midspan—the worst case scenario—is computed using classical equations. The mode shape of the idealized beam is a half sine wave (Figure 7-3) with a value of 1.0 at midspan.

Monumental stairs usually have one or two intermediate landings. The walker is assumed to cause resonance along the series of seven or eight treads nearest to midspan. People must be stationary to feel stair vibration, so the affected occupant is usually assumed to be on the landing nearest to midspan.

If a landing is at midspan, as in Figure 7-3, then the assumed walker location will be three or four treads above or below the landing. The predicted acceleration is the product of the midspan acceleration due to a walker at midspan and the mode shape value at the walker location.

If the affected occupant is assumed to be away from midspan, as is usually done if there is no landing at mid-span, then the predicted acceleration is the product of the midspan acceleration and the mode shape value at the affected occupant location.

If the walker and affected occupant locations are away from midspan, then the predicted acceleration is the product of the midspan acceleration due to walker at midspan, mode shape value at the walker location, and mode shape value at the affected occupant location.

When the finite element method is used, the effects of walker and affected occupant locations are directly included in the calculations, so no mode shape scaling is required. The frequency response function is computed for load applied at the walker location and acceleration at the affected occupant location. The frequency response function maximum magnitude is used to predict the acceleration.

7.7 Are there minimum vertical and lateral natural frequency recommendations?

Yes. The first harmonic of the dynamic force has a very high amplitude; therefore, a stair must be designed so that it cannot cause resonant vertical or lateral vibration.

People comfortably descend stairs at step frequencies up to 4 Hz (240 bpm) to 4.5 Hz (270 bpm) in some cases. Thus, to allow for slight errors in natural frequency prediction, the natural frequency of vertical vibration should not be below 5 Hz to avoid resonance with the first walking harmonic.

(a) $\beta = 0.01$

(a) $\beta = 0.038$

Fig. 7-4. Examples of monumental stair damping ratios.

As illustrated by Figure 7-5, the period of the lateral forces is double the period of the vertical forces, so the lateral forcing frequency is half the vertical forcing frequency. Consequently, the lateral vibration natural frequency should not be less than 2.5 Hz.

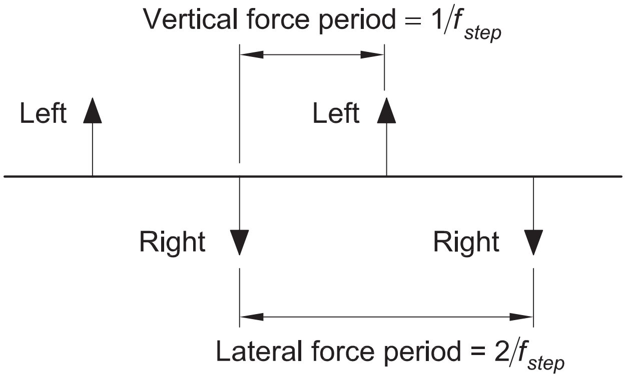


Fig. 7-5. Lateral forces due to footsteps.

Section 8
Pedestrian Bridges

This section includes questions concerning the AISC Design Guide 11, Chapter 4, evaluation criterion for pedestrian bridges. The evaluation criterion for a single walker is found in AISC Design Guide 11, Equation 4-1:

$$\frac{a_p}{g} = \frac{P_o e^{-0.35 f_n}}{\beta W} \le \frac{a_o}{g}$$

(AISC Design Guide 11, Eq. 4-1)

where

a_o/g = vibration tolerance limit expressed as ratio of acceleration to acceleration of gravity (1.5% for indoor bridges and 5% for outdoor bridges)
a_p/g = ratio of the peak floor acceleration to the acceleration of gravity
P_o = amplitude of the driving force, 92 lb
W = effective weight of pedestrian bridge, lb
f_n = natural frequency, Hz
β = viscous damping ratio

8.1 Why is the amplitude of the driving force, P_o, different for pedestrian bridges than that of floors?

The development of the equation for predicting the acceleration of pedestrian bridges includes a reduction factor, *R,* to account for the walker and affected occupant not being at the same location and for lack of resonant build-up. It is assumed that the walker and affected occupant will be near each other on pedestrian bridges and the reduction factor is taken as 0.7, resulting in a P_o value of 92 lb. For offices, the reduction factor is taken as 0.5 as the walker and affected occupant will not be as near to each other as on a pedestrian bridge, resulting in a P_o value of 65 lb. See Question 4.2 for more details.

8.2 How is the acceleration caused by a marching group predicted?

The driving force, $P_o = 92$ lb, assumes there is only one walker on the pedestrian bridge. If marching groups are a possibility, the driving force should be increased to nP_o, where n is the number of walkers.

8.3 How is the acceleration caused by random walking predicted?

For groups of random walkers, the driving force should be increased to $\sqrt{n}P_o$, where n is the number of walkers in the random group. Engineering judgment is required for determining the number of walkers.

8.4 Why is there a 3-Hz minimum frequency recommended for pedestrian bridges?

A minimum frequency of 3 Hz is recommended to avoid very high accelerations due to rogue or vandal jumping.

8.5 Is lateral motion a vibration issue?

Yes. There have been a number of cases reported in the literature where pedestrian bridges vibrated laterally when a relatively large group of pedestrians walked in the same direction. Because the maximum walking step frequency is about 2.2 Hz, the maximum lateral forcing frequency is about (2.2 Hz)/2 = 1.1 Hz, as explained in Question 7.7. Synchronization of walking with lateral sway will not occur if the natural frequency of lateral vibration exceeds 1.1 Hz. For this reason, the American Association of State Highway and Transportation Officials *LRFD Guide to Specification for the Design of Pedestrian Bridges* (AASHTO, 2009) recommends that the lateral frequency of pedestrian bridges not be less than 1.3 Hz.

8.6 How do the AASHTO (2009) criteria for assessing vertical pedestrian bridge vibration differ from the AISC Design Guide 11 criteria?

The AASHTO *LRFD Guide Specifications for the Design of Pedestrian Bridges* requires that the vertical natural frequency of pedestrian bridges be greater than 3 Hz. If this criterion is not satisfied, then one of the following limitations must be satisfied.

$$f \ge 2.86 \left(\frac{180}{W}\right) \quad \text{(AASHTO Eq. 6-1)}$$

or

$$W > 180 e^{(-0.35 f)} \quad \text{(AASHTO Eq. 6-2)}$$

where

W = weight of the supported structure, including only dead load, kips
f = fundamental frequency in the vertical direction, Hz

These equations are the same as the AISC Design Guide 11, Equation 4-1, acceleration tolerance criteria for walking on floors, but with $P_o = 92$ lb, $\beta = 0.01$, W in kips, and an acceleration limit $a_p/g = 0.05$ (5%g) substituted in the criterion and W defined in kips.

It is noted that the AASHTO criteria differ from the AISC Design Guide 11 criteria. The AASHTO criteria allow for pedestrian bridges with a frequency less than 3 Hz if the predicted acceleration is less than 5%g and does not require an acceleration check if the frequency is greater than 3 Hz. In AISC Design Guide 11, it is recommended that pedestrian bridges have a natural frequency greater than 3 Hz with limiting accelerations of 1.5%g for indoor bridges and 5%g for outdoor bridges.

Section 9
Finite Element Analysis

Basic concepts required for structural vibration evaluation based on finite element analysis are found in this section.

9.1 When should finite element analysis be used in vibration evaluation?

The well-established methods in AISC Design Guide 11, Chapters 4, 5 and 6, should be used for structures within the scope limitations of those chapters. With those methods, the modal properties—natural frequency, mode shape and modal mass—are computed using classical equations that apply to typical rectangular floor bays and some other simple structures such as linear stairs.

The classical equations do not apply to structures with other geometries, such as cantilevers, balconies, curved stairs, or floors hanging from a flexible structure. They are also not able to capture the beneficial effect of significant nonstructural partitions. Examples are in Figure 9-1. Finite element analysis methods in AISC Design Guide 11, Chapter 7, should be used to predict the modal properties and vibration due to human activities for such structural systems.

9.2 What are the disadvantages of modeling a large portion of the structure for vibration evaluation?

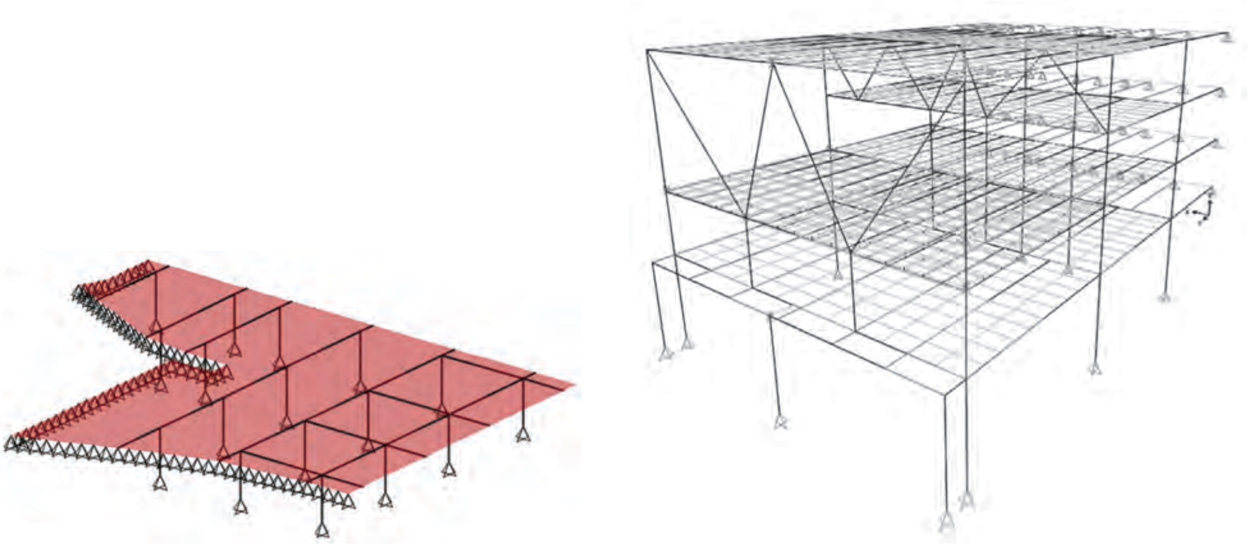
Vibration usually occurs in the bay with the human-induced excitation and at most surrounding bays. Transmission of significant vibration to distant bays is likely prevented generally by friction and by nonuniformity of mass and stiffness.

Damping is usually idealized as viscous for the purposes of structural vibration evaluation. This idealization assumes energy dissipation is only a function of time and does not account for lack of vibration transmission, possibly caused by friction, to areas far from the area subjected to human-induced loads. Natural modes are usually predicted using eigenvalue analysis, which often predicts motion over unrealistically very large areas, sometimes including the entire structure. Thus, a finite element analysis potentially predicts motion over unrealistically large areas, causing an unconservative overestimate of the effective mass.

The model may be constructed of the entire floor. However, if key modes have motion over very large areas, the model extent should be reduced to avoid the effective mass contribution of distant bays, as shown in Figure 9-2.

9.3 Why are continuous member end connections used in the model?

Human-induced excitations are very small and thus cause very small member end moments that are easily resisted by bolt friction and by the couple between the slab and bolt forces. Also, mode shapes are often in the alternating down-up-down pattern shown in Figure 9-3. In these shapes,



(a) Cantilevered floor *(b) Floor with transfer trusses*

Fig. 9-1. Examples of irregular structures.

curvature is often low at the beam end connections, so the rotational demand on the end connections is low, further justifying the continuous member end connection assumption for finite element analyses. (Note: The manual methods in AISC Design Guide 11, Chapters 4, 5 and 6, were calibrated assuming pinned connections.)

9.4 What concrete material properties should be used in the model?

Concrete is stiffer when loaded dynamically at low stresses than when loaded pseudo-statically at moderate to high stresses. In AISC Design Guide 11, this is taken into account by using a concrete elastic modulus, E_c, equal to 1.35 times the modulus used for strength and stiffness analyses—that is, $1.35E_c$. Poisson's ratio, ν, is taken as 0.2.

9.5 How are member moments of inertia computed?

In finite element models of floors, slabs are usually represented by shell elements that have bending stiffnesses. Hot-rolled or open-web members are usually represented by frame elements in the plane of the shells. The frame element moment of inertia is the transformed or effective transformed moment of inertia from AISC Design Guide 11, Chapter 3. Because the slab bending stiffness is included in the shell elements, the slab moment of inertia about its centroidal axis is deducted from the member transformed moment of inertia, and the result is assigned to the member in the program.

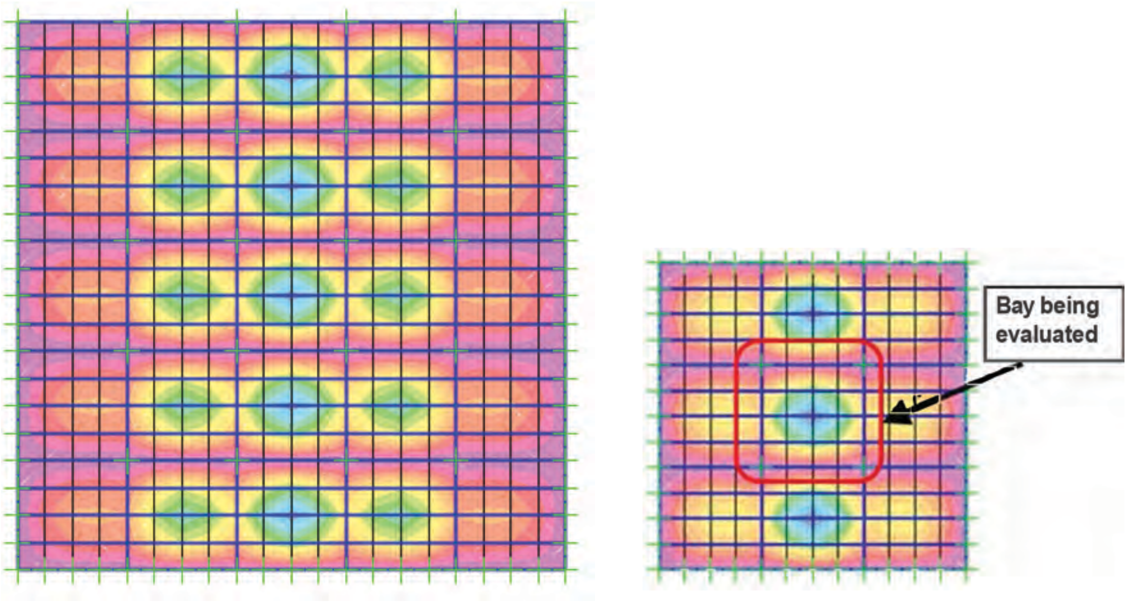
9.6 How are nonstructural partitions modeled?

Human-induced vibration results in extremely small vertical displacements. For example, a sinusoidal acceleration amplitude of 0.5%g (the tolerance limit in offices) at 5 Hz corresponds to a 0.002-in. displacement amplitude. At such small displacement amplitudes, full-height—meaning that they extend to the deck—nonstructural partitions below the floor behave as partially effective load-bearing walls. Full-height partitions on the slab do the same. This is true even when vertical slip connections are used at the tops of the studs. The increase in stiffness can be modeled using vertical linear springs with stiffness equal to 2 kip/in. per horizontal foot of wall at nodes along the wall. Figure 9-4 is an example of a floor model with springs representing nonstructural partitions.

Significant nonstructural partitions increases damping more than any other element typically found in buildings. Thus, a high (in the realm of structural vibrations) damping ratio, β, of 0.05 is recommended for bays with multiple full-height partitions below and on the slab.

9.7 What masses should be applied in the model?

The best estimate of mass should be used in the model. An underestimate of the mass results in an unconservative overprediction of the natural frequency and a conservative underprediction of the effective mass, potentially leading to an overestimation of the acceleration. The converse is



(a) Model of entire floor

(b) Model of reduced area

Fig. 9-2. Example mode shape with motion over a huge area.

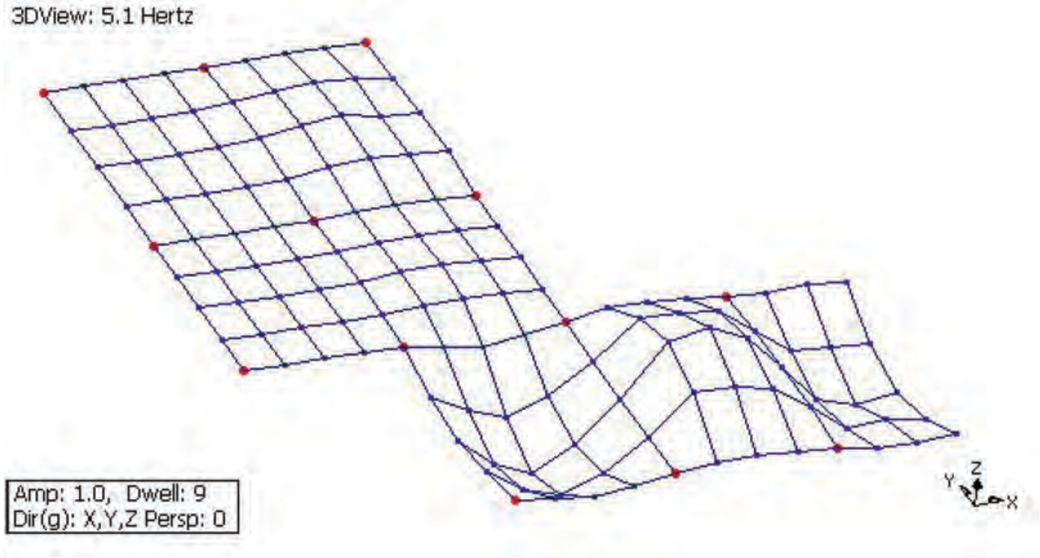


Fig. 9-3. Example measured mode.

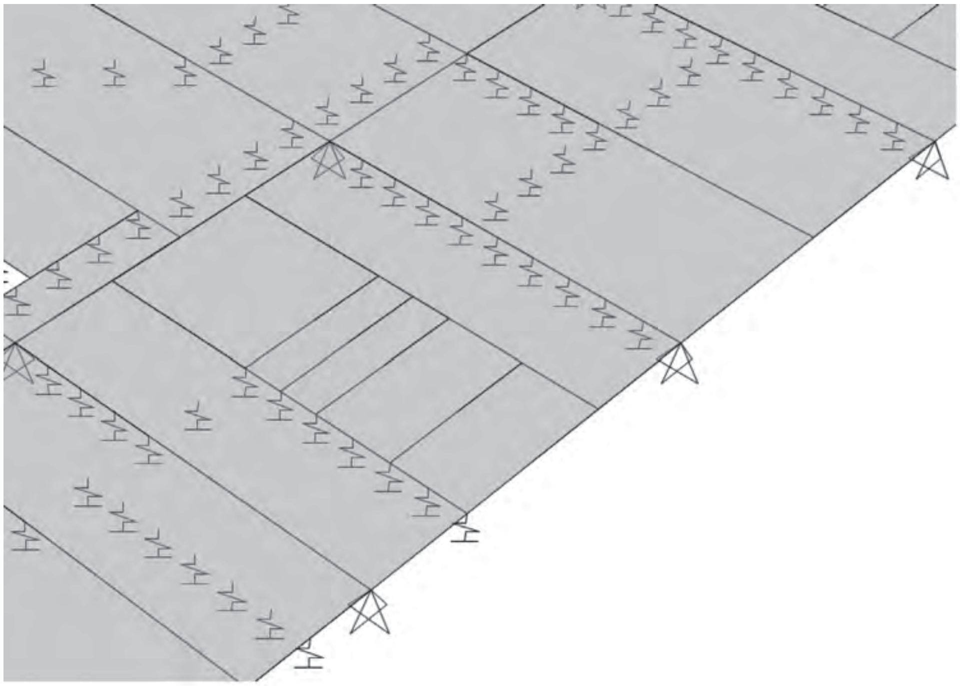


Fig. 9-4. Floor model with partition springs.

true for an overestimate of the mass. For a given design, an underestimate or overestimate of the mass might result in an invalid final evaluation. Because vibration is a serviceability limit state, no load factors should be applied.

The structural mass is computed using nominal densities and volumes. Superimposed dead load and live load masses, usually far below values used for strength and stiffness design, are established using engineering judgment and AISC Design Guide 11, Section 3.3. For example, an 8-psf live load is used for offices with few heavy furnishings.

9.8 How should the natural modes be predicted?

The two major options in most finite element analysis programs are eigenvalue analysis and Ritz vector analysis. With the former, the multiple-degree-of-freedom undamped free vibration problem is solved, resulting in a set of natural frequencies and mode shapes. With the latter, a load pattern is specified in an attempt to affect the selection of modes.

Eigenvalue analysis produces seemingly more logical mode shapes for planar floor models, so this method should typically be used. Ritz vectors might occasionally be useful for "filtering out" modes with extraneous motion, such as a truss bottom chord moving transversely.

9.9 What is a frequency response function (FRF), and how should it be predicted?

A frequency response function (FRF) is a plot of steady-state vibration output amplitude per force input amplitude versus frequency. Typical units are %*g*/lb for walking and %*g*/psf for rhythmic activity excitations.

In general, an FRF is a complex quantity with real and imaginary parts, or equivalently, magnitude and phase, at each frequency. The magnitude is used in AISC Design Guide 11. The example FRF magnitude in Figure 9-5 indicates two responsive natural frequencies between 8 Hz and 9 Hz. The dominant mode, at 8.3 Hz, has a 0.181%*g*/lb magnitude. The physical interpretation is that a sinusoidal load with a 1-lb amplitude and 8.3-Hz frequency will cause steady-state sinusoidal acceleration with 0.181%*g* acceleration amplitude. The frequency of the response will also be at 8.3 Hz.

Some finite element analysis programs automatically compute frequency response functions. The features are usually named "frequency domain analysis," "steady-state analysis," "harmonic analysis," or similar. These features can be used to compute the FRF over a bandwidth of interest, for user-selected load and acceleration locations.

9.10 How are human-induced forces modeled?

Low-frequency floors are subject to resonant build-up due to human-induced forces. Figure 3-1(a) is an example. The acceleration is predicted using resonant response equations that are functions of sinusoidal load amplitude. For this reason, the load on a low-frequency floor is represented as a Fourier series with one harmonic frequency matching the dominant natural frequency, and force amplitudes established from experimental programs. The answer to Question 3.17 provides more information.

High-frequency floors are not subject to resonant build-ups, so walking results in a series of impulse responses to individual footsteps. Figure 3-1(b) is an example. Figure 9-6 is an example computed impulse response to one footstep. The force imparted by a footstep is represented as an "effective impulse" in force-time units such as lb-s. In the analysis of a high-frequency floor, the peak velocity is predicted by dividing the effective impulse by the effective mass. (In some cases, the decay portion of the response is also computed.) The effective impulse magnitude is based on experimental measurements.

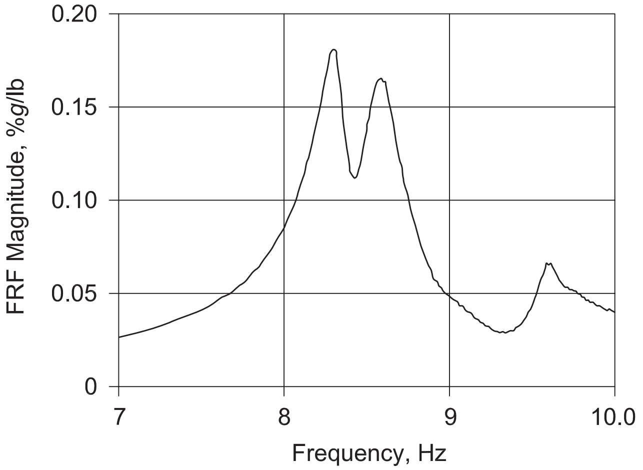


Fig. 9-5. Example frequency response function.

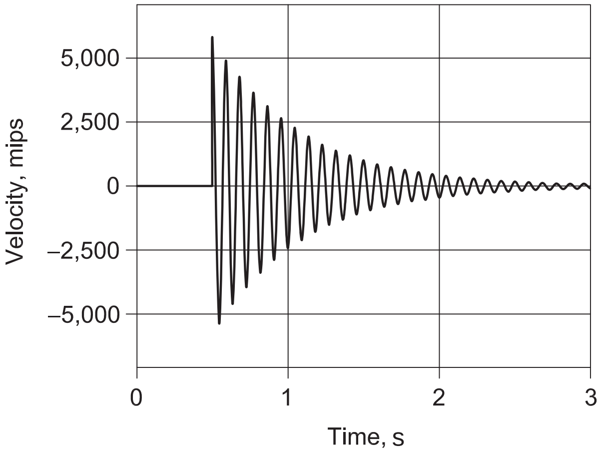


Fig. 9-6. Computed impulse response due to one footstep.

9.11 What is the FRF method for assessment of systems due to human activity, and what are some of its advantages?

With the FRF method, the primary finite element analysis based method in AISC Design Guide 11, the acceleration due to human-induced loads, is the product of the FRF maximum magnitude, harmonic load amplitude, and applicable adjustment and calibration factors.

The FRF method has a few advantages over the other major option—response history (sometimes called "time history") analysis.

Eigenvalue analysis often results in numerous natural modes, making it difficult to determine which mode, or combination of modes, results in the maximum response to human-induced loads. With response history analysis, sinusoidal load functions must be developed for each natural frequency. This is a time-consuming task that must be repeated each time the model is modified. The FRF method is faster and easier, especially when iterations are required.

The FRF magnitude plot clearly indicates the most responsive frequency. For example, in Figure 9-5, the maximum response is caused when the harmonic load frequency is 8.3 Hz. This allows the structural engineer to focus on the important mode or modes.

The maximum response is sometimes due to the combination of responses from several modes, and the FRF maximum magnitude is between natural frequencies. With the FRF method, this is automatically taken into account.

9.12 How is the FRF method applied for walking on low-frequency floors?

The FRF method implementation for walking on low-frequency floors is in AISC Design Guide 11, Section 7.4.1.

The first step is to predict the FRF magnitude for frequencies below about 9 Hz, for acceleration at the affected occupant location due to concentrated force at the critical walker location. The maximum magnitude, FRF_{Max}, and its frequency, f_n, are then determined from the plot. The next step is to define the harmonic load due to walking as the product of body weight, Q, and dynamic coefficient, α, which is a curve fit of the second through fourth harmonic amplitudes.

The product of FRF_{Max}, Q and α is the peak acceleration for a full resonant build-up. In some cases, especially for structures with low damping, the full resonant build-up will not occur, and this is taken into account with the resonant build-up reduction factor, ρ. Thus, the predicted peak acceleration due to walking is the product of the peak acceleration and the resonant build-up reduction factor.

The predicted peak acceleration is compared to the tolerance limit to evaluate the floor.

9.13 How is the FRF method applied for rhythmic group loads?

The FRF method implementation for rhythmic group loads is in AISC Design Guide 11, Section 7.4.4.

The first step is to predict the FRF magnitude for acceleration at the affected occupant location due to a 1-psf uniform force applied over the anticipated area of synchronized group loading. The units will be $\%g/\text{psf}$ or similar. The frequency range should encompass the harmonic frequencies in AISC Design Guide 11, Table 7-4. For example, for jumping exercises, the range of harmonic frequencies is 2 to 11 Hz; therefore, the FRF should be computed over the 1- to 12-Hz range, or similar.

The next step is to compute the acceleration due to each harmonic, which is the product of the FRF magnitude at the harmonic frequency, the unit weight of participants, w_p, and the dynamic coefficient, α. The number of harmonics depends on the type of rhythmic load, as indicated by AISC Design Guide 11, Table 7-4.

The total response is computed using the 1.5 power combination rule, AISC Design Guide 11, Equation 5-1, and then compared to the tolerance limit to evaluate the structure.

$$a_p = \left(\sum_i a_{p,i}^{1.5} \right)^{1/1.5}$$

(from AISC Design Guide 11, Eq. 5-1)

9.14 How are finite element analysis methods applied to floors supporting sensitive equipment?

AISC Design Guide 11, Section 7.5, provides guidance on the use of finite element analysis for evaluation of floors supporting sensitive equipment. Its development parallels that of AISC Design Guide 11, Chapter 6, in that resonant, intermediate and impulse responses are computed for floors with low, medium and high natural frequencies. Also, equations are provided for waveform peak acceleration and velocity, narrow-band spectral acceleration and velocity, and one-third octave spectral acceleration and velocity. As in AISC Design Guide 11, Chapter 6, each equation is calibrated so that it provides 90th percentile predictions compared to a large database of measurements.

AISC Design Guide 11, Section 7.5.2, provides equations for resonant responses using the FRF method in a manner similar to that described in Question 9.12. The peak acceleration is the product of the FRF maximum magnitude, dynamic coefficient, body weight, and calibration factor.

AISC Design Guide 11, Section 7.5.3, uses the effective impulse approach to compute the peak acceleration from each natural mode. The remainder of each modal response is constructed assuming viscous decay of vibration until the next footstep. Each modal response is superimposed and the maximum value is the peak acceleration. Figure 9-7 is an example response of one mode and the summation of all considered modes for a floor bay. The peak acceleration is 0.156%*g* for this example.

AISC Design Guide 11, Sections 7.5.2 and 7.5.3, also contain equations for the narrow-band and one-third octave spectral acceleration and velocity maximum magnitudes. The narrow-band spectral response equations were derived by assuming the shape of the waveform—resonant build-up followed by decay for resonant responses and repeated impulse responses with decay for impulse responses—and performing the analytical Fourier transformation. Each one-third octave velocity equation was derived by bandwidth, converting the narrow-band spectrum one-third octave bands.

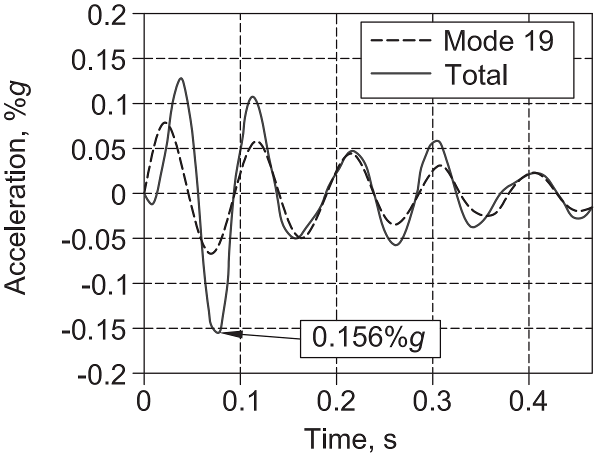


Fig. 9-7. Example superposition of impulse responses.

Section 10
Measurements and Retrofit

Questions concerning the evaluation of lively structural framing and retrofit options are found in this section.

10.1 How can an unacceptable response of structural framing due to human activity be reduced?

Options to reduce unacceptable response of steel framing due to human activity include stiffening the steel framing, adding mass, passive control usually using a tuned mass damper (TMD), and active control using a computer-controlled electromagnetic shaker. Each option has advantages and disadvantages. Stiffening steel framing is the preferred option but usually requires welding, which may not be acceptable in an occupied building. TMD installation is relatively simple, but if the occupancy changes, for instance, a new furniture layout, retuning of the TMD may be necessary. Active control is very effective but requires electrical connections, computers and specialized maintenance.

10.2 Are measurements needed before designing a retrofit?

It is highly recommended that measurements be made before designing a retrofit. Manual and finite element analyses include a number of assumptions (damping, superimposed dead load, live load, and restraints), and therefore predicted frequencies and accelerations may not match actual conditions, which need to be known for design of a successful retrofit.

10.3 What techniques are used to measure the response of occupied floors?

Experimental modal testing, which measures both the input force and the resulting acceleration response, is the best means for estimating the dynamic properties of a structure. Input force is often applied using an electrodynamic shaker, which provides the most controllable source of dynamic loading to a structure. An electrodynamic shaker has the ability to provide an input force at a relatively constant amplitude and within a very specific frequency range of interest by using a swept sine signal. However, experimental modal testing requires a significant amount of time, which can be disruptive in an occupied building, and there is potential for damaging sensitive equipment. It is expensive, especially if an electrodynamic shaker is used.

A much less disruptive and less costly testing method is described in AISC Design Guide 11, Section 8.2. The only instrumentation needed is a handheld, single-channel, spectrum analyzer and a seismic accelerometer. Heel-drop tests are used to determine the natural frequencies of the structural system and then timed walking is used to obtain the maximum expected vibration response. A metronome is used to define the required walking step frequency.

10.4 What walking speed should be used to measure the highest vibration amplitude?

Walking at a subharmonic of the natural frequency—that is, the natural frequency divided by an integer—will result in the highest vibration amplitude. The step frequency to be considered must be within the normal range of walking speeds. For walking on a flat floor or footbridge, this range is 96 bpm (1.6 Hz) to 132 bpm (2.2 Hz). For monumental stairs, the same approach applies except that the maximum step frequency is 150 bpm (2.5 Hz) for regular descents and 240 bpm (4 Hz) for fast descents.

10.5 What is the value of long-term measurements?

There is very little value to long-term measurements unless video is simultaneously recorded for the area. Without video, there is no way to know from the record what caused a specific floor response. For instance, it could be someone jumping on the floor while telling a joke or a janitor dropping something while cleaning the area.

10.6 Why doesn't the vibration record I received from a measurement company look like measurement records shown in AISC Design Guide 11?

Vibrations can be measured and reported in many different formats. They may be in the form of narrow-band or one-third octave band spectra, in terms of acceleration or velocity, for example. They may represent the maxima or statistical measures of vibrations observed for brief or extended periods and may include the effects of all disturbances, such as those from HVAC systems and external traffic and loading dock activities. Vibration records from measurement companies are often long-term measurements and only show floor response that exceeds a trigger level (to save data storage space). They normally do not include video records. The records in AISC Design Guide 11 show the response of the floor due to timed walking from which the record can be processed for comparison to the predicted responses using the procedures in AISC Design Guide 11.

10.7 How can the stiffness of steel framing be increased?

The only permanent method for increasing the stiffness of steel framing significantly is to add structural steel, such as plates, rods, sections, or columns or posts, to the existing structural framing. (Partitions may provide sufficient stiffness, but there is a possibility that they may be removed during the life of the structure.) However, adding structural steel also increases the mass, decreasing frequency, and thus, may or may not reduce floor response. Careful analysis is required when considering whether to increase framing stiffness.

10.8 Is finite element analysis needed to design a retrofit?

For rectangular bays that are suitable for analysis using the AISC Design Guide 11, Chapters 4, 5 and 6, procedures, finite element analysis is generally not needed if the retrofit involves adding structural steel to hot-rolled beams and/or girders. If the framing to be retrofitted includes open web joists or joist girders, finite element analysis is usually required because adding steel to a chord can significantly affect the magnitude of shear deformations and the effect of joint eccentricity on member flexibility resulting in the invalidity of AISC Design Guide 11, Equation 3-9a or 3-9b , which account for both effects.

10.9 Why is jacking and welding required for structural retrofits?

As noted in Question 2.1, displacements as low as 10- to 40-thousands of an inch are involved in motions annoying to humans. For a retrofit to be effective, there must not be any movement between the added steel and the original framing. From experience with unsuccessful attempts to use bolted retrofit steel and turnbuckles, it is highly recommended that only welding be considered when adding steel to existing framing.

However, simply welding the added steel to the existing framing will not be effective unless strain is introduced into the added steel. For an unoccupied building, the addition of the superimposed dead and live loads at the time of occupancy may be sufficient. For an occupied building, jacking up of the existing framing before adding the retrofit steel is necessary. Once the retrofit steel is welded to the existing steel, the jacking is released resulting in strain in the added steel. Jacking up the existing steel ¼ to ½ in. is generally sufficient; engineering judgment is required.

10.10 Is monitoring of construction work recommended during retrofitting?

Monitoring is definitely recommended during retrofitting. Jacking structural framing prior to modifying existing members is not typical steel erection work and can easily be misunderstood by supervisors or incorrectly done by workers. Also, the effectiveness of the retrofit in a given area can be measured to verify that the required reduction in response has been achieved before proceeding to additional areas.

10.11 How do tuned mass dampers reduce vibrations?

A tuned mass damper (TMD) is a mass attached to a structure through a spring and damping device. For floor or pedestrian bridge vibrations, the mass of the TMD moves in the opposite direction of the structural motion, producing forces (in a limited frequency range) that oppose the structural motion. The damping element also removes a small amount of energy, but its primary purpose is to increase the effective frequency range of the TMD. Because a TMD is "tuned" to a particular resonant frequency, individual TMD may need to be installed for each excited floor frequency. TMD are most effective when attached where floor vibration amplitudes are the greatest. A TMD will not decrease the initial motion of a floor at the beginning of the action of a force and therefore is not effective for single impacts.

10.12 Is active control a viable option for controlling annoying vibrations?

Active control of a structure means the use of controlled energy from an external source to mitigate the motion. Use of an electromagnetic shaker to exert control forces on a floor system, with the shaker controlled in a feedback system via a personal computer, has been reported. Active control can be very effective but is expensive and not widely available; it also requires qualified personnel for maintenance.

Glossary

Bay. A rectangular plan portion of a floor defined by four column locations.

Beam or joist panel. A rectangular area of a floor associated with movement of its beams or joists. The area is equal to the beam or joist span times an effective width determined from the floor system structural properties.

Damping and critical damping. Damping refers to the loss of mechanical energy in a vibrating system over time. Viscous damping is associated with a retarding force that is proportional to velocity. Damping is usually expressed as the percent of critical damping, which is the ratio of actual damping (assumed to be viscous) to critical damping. Critical damping is the smallest amount of viscous damping for which a free vibrating system that is displaced from equilibrium and released comes to rest without oscillation. For damping that is smaller than critical, the system oscillates freely as shown in Figure G-1. Damping cannot be calculated and must be determined experimentally, usually using experimental modal analysis techniques that result in detailed identification of modal properties. In some cases, it can be measured using the decay of vibration following an impact such as a heel-drop. Damping ratios for the structural systems considered in this document are usually between 1% and 8% of critical viscous damping.

Dynamic coefficient. Ratio of harmonic force magnitude to body weight.

Dynamic loadings. Dynamic loadings can be classified as harmonic, periodic, transient and impulsive as shown in Figure G-2. Harmonic or sinusoidal loads are usually associated with rotating machinery. Periodic loads may be caused by rhythmic human activities such as dancing and aerobics, or by machinery that generate repetitive impacts. Transient loads occur from the movement of people and include walking and running. Single jumps and heel-drop impacts are examples of impulsive loads.

Dynamic load factor (DLF). See dynamic coefficient.

Effective impulse. For the purposes of AISC Design Guide 11 and this document, an effective impulse is a mathematical representation of a human footstep. It is used to scale the unit impulse response of a single-degree-of-freedom system to the response of the system to a human footstep.

Evaluation criterion. An inequality used to predict whether or not vibration will be objectionable. Criteria consist of a predicted structural vibration response and a tolerance limit.

Floor length. Distance perpendicular to the span of the girders in the bay under consideration over which the structural framing (beam or joist and girder size, spacing, length, etc.) is identical, or nearly identical, in adjacent bays.

Floor panel. A rectangular plan portion of a floor encompassed by the span and an effective width or length.

Floor width. Distance perpendicular to the joist or girder span of the beams or joists in the bay under consideration over which the structural framing (beam or joist and girder size, spacing, length, etc.) is identical, or nearly identical, in adjacent bays.

Fourier series. A series of sinusoids used in AISC Design Guide 11 and this document to represent human-induced forces. Each sinusoidal term is known as a harmonic and is characterized by its amplitude, frequency and phase lag.

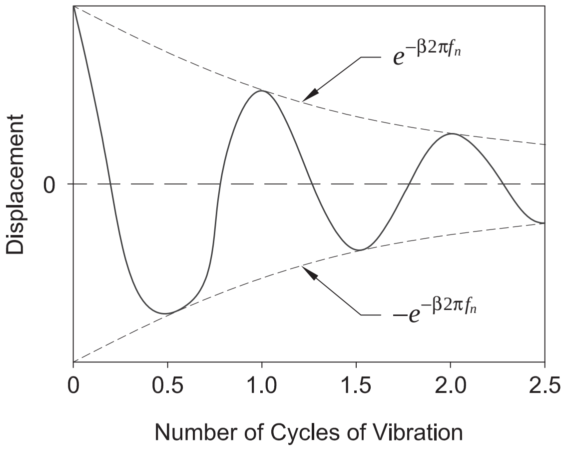


Fig. G-1. Decaying vibration with viscous damping.

Fourier transformation. A mathematical procedure to transform a time record into a complex frequency spectrum (Fourier spectrum) without loss of information is called a Fourier transformation.

Frequency response function (FRF). For the purposes of AISC Design Guide 11 and this document, a frequency response function is a plot of sinusoidal response (ratio of acceleration amplitude to force amplitude, with units of %*g*/lb) versus frequency. High FRF magnitudes indicate dominant natural frequencies.

Fundamental modal mass and effective mass. For the purposes of AISC Design Guide 11 and this document, the fundamental modal mass, also called effective mass of the structural system, is the mass of a single-degree-of-freedom system whose steady-state response to sinusoidal forcing is equal to the response of the structural system being evaluated.

Girder panel. A rectangular area of the floor associated with girder movement. The area is equal to the girder span times an effective length determined from the floor system structural properties.

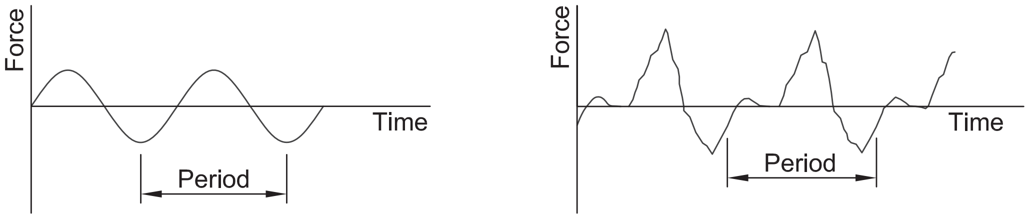
Harmonic and subharmonic frequency. For the purposes of AISC Design Guide 11 and this document, a harmonic frequency is an integer multiple of the step frequency. For example, the harmonic frequencies of a 2-Hz step frequency are 2 Hz, 4 Hz, 6 Hz, etc. A subharmonic frequency is an integer subdivision of a frequency. For example, the fourth subharmonic frequency of an 8-Hz natural frequency is 2 Hz.

Heel-drop. A means of producing an impact on a floor, produced by a person standing on his or her toes and letting their heels drop without the toes lifting from the floor.

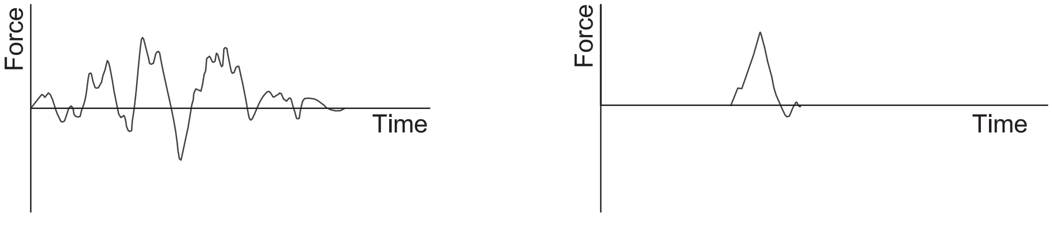
Impulse, unit impulse, and unit impulse response. An impulse is a high force that acts for an extremely short time duration. Impulses are expressed using force-time units such as lb-s. When a single-degree-of-freedom system is subjected to a unit impulse, the resulting unit impulse response is characterized by an initial peak velocity proportional to the reciprocal of the mass, followed by sinusoidal decay at the natural frequency.

Low- and high-frequency systems. A low-frequency system is one that can undergo resonant build-up due to the applicable human-induced dynamic loading. A resonant build-up can occur if at least one responsive natural mode has a frequency less than the maximum considered harmonic frequency. A high-frequency system is one that cannot undergo resonant build-up due to the applicable dynamic loading because all responsive frequencies are greater than the maximum considered harmonic frequency. The response of a high-frequency system resembles a series of individual impulse responses to individual footsteps.

Mode shape. When a structure vibrates freely in a particular mode, it moves with a certain deflection configuration referred to as a mode shape. Each natural frequency has a mode shape associated with it. Figure G-3 shows typical mode shapes for a simple beam and for a slab/beam/girder floor system. A mode shape normalized such that all mass matrix entries are 1 is referred to as a mass-normalized



(a) Harmonic load *(b) Periodic load*



(c) Transient load *(d) Impulsive load*

Fig. G-2. Types of dynamic loadings.

mode shape. A mode shape normalized such that the maximum amplitude, usually at mid-bay or midspan, is 1 is referred to as a unity-normalized mode shape.

Narrow-band spectrum. A narrow-band spectrum shows vibration magnitudes in closely spaced frequency bands—usually 0.05 Hz wide. The spectral magnitude in each frequency band corresponds to the energy at frequencies within that band. Figure G-4(a) shows an acceleration waveform. The corresponding narrow-band spectrum is shown in Figure G-4(b).

Natural frequency, free vibration, modal frequencies, fundamental natural frequency, and dominant frequency. Natural frequency is a frequency at which a body or structure will vibrate when displaced and then cleanly released. This state of vibration is referred to as free vibration. All structures have a large number of natural frequencies that are also referred to as modal frequencies; the lowest frequency is referred to as the fundamental natural frequency and generally is of most concern. The dominant frequency is the frequency with the most energy or highest response compared to all other frequencies.

One-third octave-band spectrum. A one-third octave band has a bandwidth equal to the cube-root of 2 times its center frequency. The following are the standard center frequencies in the range of typical structure vibrations: 4 Hz, 5 Hz, 6.3 Hz, 8 Hz, 10 Hz, 12.5 Hz, 16 Hz and 20 Hz. Each band is defined by its center, lower-bound, and upper-bound frequencies. The magnitude of vibration in a band represents the vibrational energy within that band.

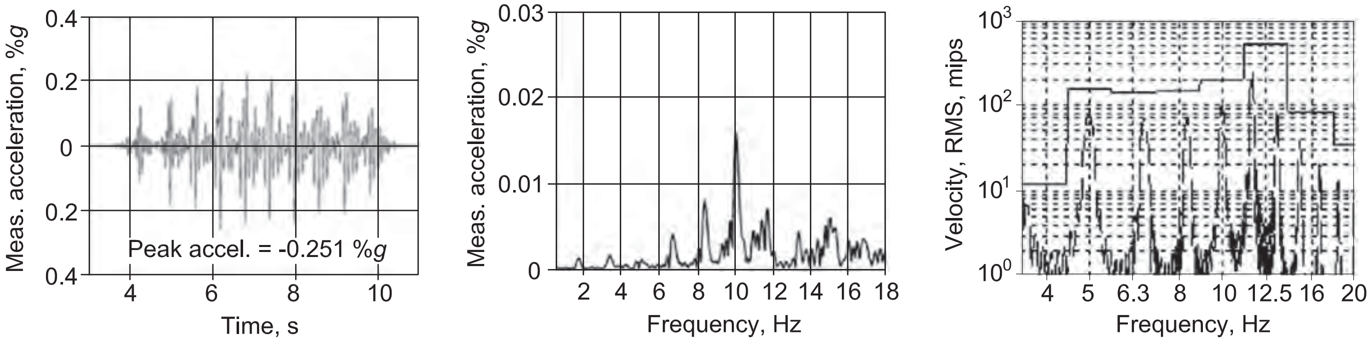
The lower and upper bounds of a one-third octave band differ from its center frequency by factors equal to the one-sixth power of 2. These limits are rounded off in the standardly defined frequency bands. For example, the lower and upper bounds of the 12.5-Hz one-third octave band are 11.2 Hz and 14.1 Hz, respectively. Figure G-4(c) shows an acceleration waveform and corresponding one-third octave velocity spectrum.

Period and frequency. Period is the time, usually in seconds, between successive peak excursions in uniformly repeating or steady state events. Period is associated with harmonic (or sinusoidal) and periodic (repetitive) time functions as shown in Figures G-2(a) and (b). Frequency is the reciprocal of period and is usually expressed in Hertz (cycles per second).

Resonance. If a harmonic frequency of an exciting force is equal to a natural frequency of the structure, resonance will occur. At resonance, the amplitude of the motion tends to become large to very large, as shown in Figure G-5.

(a) Beams *(b) Floor*

Fig. G-3. Typical mode shapes.



(a) Acceleration waveform *(b) Narrow-band acceleration spectrum* *(c) One-third octave velocity spectrum*

Fig. G-4. Example acceleration waveforms, narrow-band acceleration spectrum, and one-third octave velocity spectrum.

Resonant build-up. If a harmonic frequency of an exciting force is equal to a natural frequency of the structure that initially is at rest, the vibration will increase as shown in Figure G-6. If the force is applied for a short duration, as with most human-induced loads, a partial resonant build-up occurs. If the force is applied for a long duration, steady-state motion is achieved.

Root-mean-square (RMS). The root-mean-square of a set of values is the square root of the sum of the squares of these values. For a sinusoid, the root-mean-square is the peak value divided by $\sqrt{2}$.

Spectrum, spectral accelerations and spectral velocities. A spectrum shows the variation of relative amplitude, by frequency, of the vibration components of a time-history waveform, such as load or motion. Any time history waveform—such as force or acceleration—can be equivalently represented by an infinite series of sinusoids with different frequencies, magnitudes and phases. For the purposes of AISC Design Guide 11 and this document, a spectrum is a plot of these magnitudes versus frequency. Magnitudes in a spectrum have the same units as the waveform, such as lb or %*g*, and usually represent amplitudes (peak) or

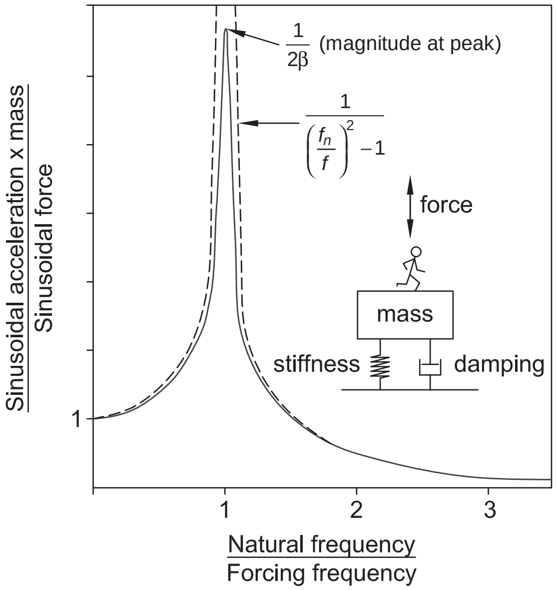


Fig. G-5. Steady-state response of mass-spring-damper system to sinusoidal force.

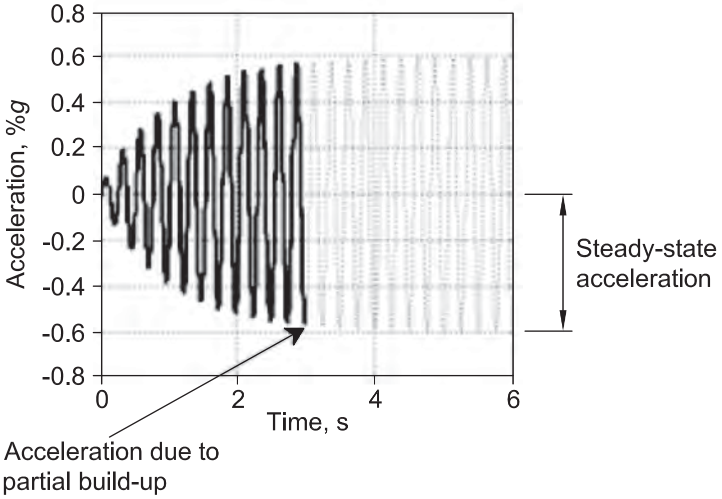


Fig. G-6. Partial resonant build-up due to walking.

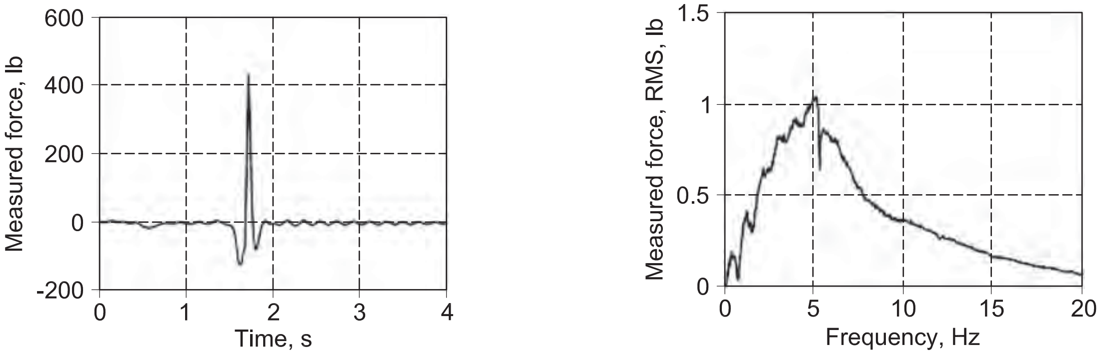
root-mean-square (rms) values. Acceleration and velocity spectrum magnitudes are referred to as spectral accelerations and spectral velocities. Figure G-7 is an example of a waveform and corresponding frequency spectrum.

Steady-state motion, transient motion, and impulse response. If a structural system is subjected to a continuous harmonic load, vibration response will be sinusoidal, building up to steady-state motion as shown in Figure G-6. If a structural system is subjected to a transient load such as a series of footsteps, vibration response will be a combination of frequency components as shown in Figure G-8. Such vibration is referred to as transient motion. If a structural system is subjected to an impulsive load, the impulse response will consist of an initial peak response followed by decaying free vibration as shown in Figure G-1. Individual footstep responses on a high-frequency floor, such as those in Figure G-4(a), are approximated by impulse responses.

Step frequency. Frequency at which a foot or feet impact the supporting structure—for example, in walking, running, dancing or aerobics.

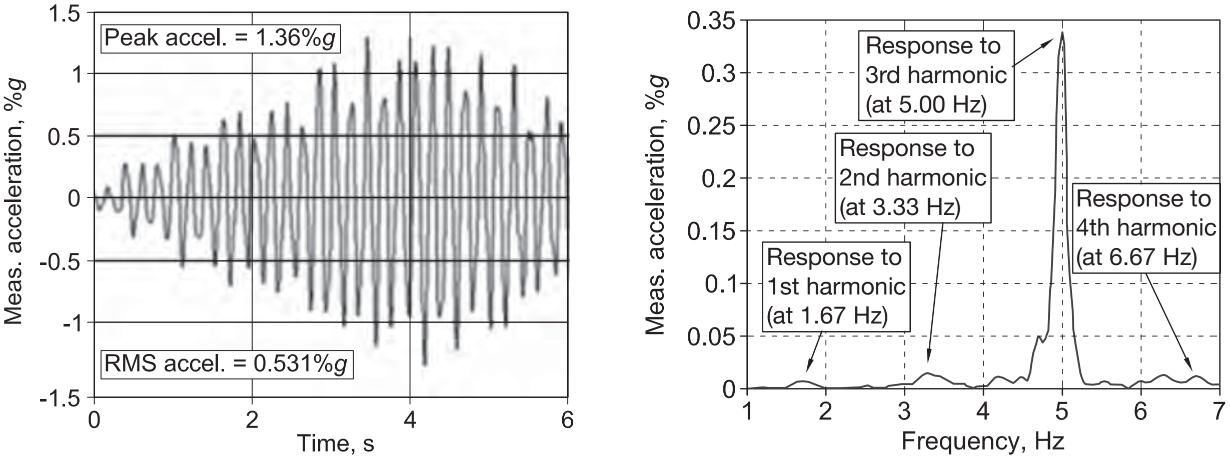
Tolerance limit. Vibration level above which vibrations are predicted to be objectionable.

Tuned mass damper (TMD). Mass attached to a floor structure through a spring and damping device. The primary beneficial effect of a TMD comes from its generating forces that oppose the motion of the point on the structure where it is attached. This effect occurs only in a limited range of frequencies centered on the natural frequency



(a) Heel drop dynamic force waveform *(b) Spectrum*

Fig. G-7. Example waveform and corresponding spectrum.



(a) Walking dynamic force waveform due to walking at 1.67 Hz *(b) Spectrum*

Fig. G-8. Resonant response due to walking.

of the TMD. To be effective, a TMD's natural frequency needs to be set to the frequency of the structural motion that is to be attenuated. A TMD also can limit build-up of resonant vibration of a floor somewhat by removing energy from the floor vibration and dissipating it.

Vandal or rogue jumping. For the purposes of AISC Design Guide 11 and this document, this is when an individual or group deliberately excites a structural system by jumping or moving the body at a subharmonic of a natural frequency of the system causing large deflection amplitudes.

Waveform. A plot of a function, such as a dynamic loading or an acceleration versus time—see Figures G-4(a) and G-7(a). It is also known as a time history or time domain representation.

Symbols and Abbreviations

B_g	girder panel mode effective width, ft
B_j	joist panel mode effective width, ft
C	linear viscous damping coefficient
DLF	dynamic load factor
E	modulus of elasticity, ksi
E_c	modulus of elasticity of concrete = $w^{1.5}\sqrt{f_c'}$, ksi
E_s	modulus of elasticity of steel = 29,000 ksi
EI_t	stringer vertical flexural stiffness, including stringers and any other elements that provide stiffness, kip-in.^{2}
FEA	finite element analysis
FRF	frequency response function
FRF_{Max}	maximum FRF magnitude, $\%g$/lb
HFF	high-frequency floor
I_t	transformed moment of inertia, in.^{4}
L	joist or joist girder span; member span, in.
L_g	girder span, ft
L_j	joist or beam span, ft
L_s	stair stringer length measured along the diagonal between supports, in.
LFF	low-frequency floor
M	effective mass, lb-s^2/in.
P	amplitude of sinusoidal load, lb
P_o	amplitude of driving force, lb
Q	body weight, lb
R	reduction factor
TMD	tuned mass damper
RMS	root-mean-square
W_s	effective weight of pedestrian bridge, lb
W_s	weight of stair, kips
a_o	acceleration tolerance limit, in./s^2
a_p	peak acceleration, in./s^2
$a_{p,i}$	peak acceleration due to harmonic, i, in./s^2
a_o/g	vibration tolerance limit expressed as an acceleration ratio
a_p/g	ratio of the peak floor acceleration to the acceleration of gravity
e	base of natural logarithm, 2.718
f_n	fundamental frequency, Hz
f_{step}	step frequency, Hz
g	acceleration of gravity = 386 in./s^2
i	harmonic number
mips	micro-inches per second
n	number of walkers
t	time, s
w	uniformly distributed weight per unit length (actual dead and live loads, not design loads) supported by the member, kip/in.
w_p	unit weight of rhythmic activity with participants distributed over the entire bay, psf
w_t	distributed weight supported, including dead load and superimposed dead load with occupants and participants distributed over the entire bay, psf
x	distance measured along the diagonal between supports, in.
x_R	distance from end of stringer to response location, measured on the diagonal, in.
x_W	distance from end of stringer to walker excitation force location, measured on the diagonal, in.
α	dynamic coefficient
α_i	dynamic coefficient (ratio of harmonic force magnitude to body weight) for the ith harmonic
β	viscous damping ratio
Δ_c	axial shortening of the column or wall due to the weight supported, in.
Δ_g	midspan deflection of girder due to the weight supported by the member, in.
Δ_j	midspan deflection of the beam or joist due to the weight supported by the member, in.
ϕ	mode shape value
ϕ_E	unity-normalized mode shape value at the sensitive equipment location

ϕ_R	unity-normalized mode shape value at the response location
ϕ_W	unity-normalized mode shape value at the excitation (walker) location
θ	stair inclination angle from horizontal, measured with respect to support points, degrees
ν	Poisson’s ratio = 0.2

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