Natural Frequency Lower Limit for Floors

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INTRODUCTION

Floor vibration serviceability due to human activities is a critical consideration for all floor systems. Practical design criteria for steel-framed floors and other structures are provided in the second edition of SJI Technical Digest 5, *Vibration of Steel Joist-Concrete Floors* (TD5; Murray and Davis, 2015) and in the second edition of AISC Design Guide 11, *Vibrations of Steel-Framed Structural Systems Due to Human Activity* (DG11; Murray et al., 2016).

In each design criterion, the primary check is a comparison of predicted vibration level (usually acceleration) due to human activity and an appropriate tolerance limit. TD5 and DG11 provide a second design check for floors that are subjected to walking: the natural frequency of vertical vibration should exceed a 3 Hz lower limit. (Other natural frequency lower limits are provided for floors and tracks subjected to running, pedestrian bridges and monumental stairs. This article does not pertain to those.) The 3 Hz lower limit was also in the first edition of Design Guide 11 (Murray et al., 1997).

TD5 and DG11 provide only brief explanations of the natural frequency lower limit, so several questions need to be answered, such as: Why does this limit exist? Does it apply universally? If not, then how would one evaluate a floor with natural frequency below 3 Hz for vibration? This article helps answer such questions by providing background and evaluation recommendations.

While the article primarily cites TD5 and DG11, which cover steel-framed floor systems, the fundamental principles apply to floor systems constructed of any material.

Note that this article is limited to vertical vibration of floors subjected to human-induced loads, and with human comfort as the vibration design consideration. It does not apply to floors supporting sensitive equipment because those will universally need to have natural frequencies above 3 Hz. It also does not apply to pedestrian bridges or balconies.

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BACKGROUND

Natural Frequency Predictions

TD5 Chapter 2 and DG11 Chapter 3 provide a manual calculation method for the fundamental natural frequency, typically referred to as “the natural frequency.” Most floors have joists or beams supported by girders, so the fundamental mode shape has two-way bending. The manual method begins with computing the natural frequency of an idealized joist or beam mode, f_j, and the natural frequency of an idealized girder mode, f_g, using the following equation:

$$f_{j,g} = 0.18\sqrt{\frac{g}{\Delta_{j,g}}} \qquad \text{(TD5 Eq. 2.3 / DG11 Eq. 3-3)}$$

where g is the acceleration due to gravity on the Earth’s surface, 386 in./s^2 and $\Delta_{j,g}$ is the deflection of joist or girder, in., due to slab weight, framing weight, and superimposed dead and live loads recommended in DG11 Chapter 3. These are unfactored best estimates of the loads that will be present during a vibration event, not higher-end values used for strength or stiffness design.

In TD5 Chapter 2 and DG11 Chapter 3, the floor bay frequency is predicted by combining the joist or beam and girder natural frequencies using the Dunkerley equation, shown below. This combined mode frequency was used in the original development of the acceleration prediction equations, so it must be used when predicting accelerations in TD5 Chapter 3 and DG11 Section 4.1. However, it underpredicts the natural frequency by about 25% (Pabian et al., 2013).

$$f_n = 0.18\sqrt{\frac{g}{\Delta_j + \Delta_g}} \qquad \text{(TD5 Eq. 2.4 / DG11 Eq. 3-4)}$$

A more accurate prediction of the floor bay natural frequency results from taking the minimum of the joist or beam and girder frequencies as shown below (Pabian et al., 2013). Herein, this frequency is referred to as f_{n1}, a variable name that does not appear in TD5 or DG11. This prediction cannot be used in the TD5 Chapter 3 and DG11 Section 4.1 acceleration predictions, but it can be used for other purposes.

$$f_{n1} = \min(f_j, f_g) \qquad \text{(DG11 Eq. 6-1)}$$

The finite element analysis methods in DG11 Chapter 7 also result in accurate predictions of natural frequencies.

Walking

Walking on floors can cause resonant build-ups. To understand why, we need to look at the dynamic forces due to walking.

The dynamic force due to repeated footsteps or other human-induced forces is represented by a Fourier series of the following form. Each term in the summation is a sinusoid called a harmonic.

$$F(t) = Q + \sum_{i=1}^{N} \alpha_i Q \sin(2\pi i f_{step} t - \phi_i) \qquad \text{(DG11 Eq. 1-1)}$$

where

i = harmonic number

N = number of harmonics with significant force amplitude ($N = 4$ for walking)

α_i = i^{th} harmonic dynamic coefficient, i.e., the ratio of harmonic force amplitude to bodyweight

f_{step} = step frequency, Hz

ϕ_i = i^{th} harmonic phase lag, radians

The bodyweight, Q, is 157 lb in TD5 Chapter 3 and DG11 Section 4.1, which stem from Allen and Murray (1993). In most new formulations in DG11, Q is 168 lb.

For the i^{th} harmonic, the frequency is if_{step} and the sinusoidal force amplitude is $\alpha_i Q$. The following table summarizes the harmonics of the force caused by a 157 lb walker.

Table 1. Walking Force Harmonics

Harmonic, i	if_{step} range (Hz)	α_i	$\alpha_i Q$ (lb)
1	1.6 – 2.2	0.5	78.5
2	3.2 – 4.4	0.2	31.4
3	4.8 – 6.6	0.1	15.7
4	6.4 – 8.8	0.05	7.85

Key takeaways from Table 1:

- If the natural frequency is below about 2.2 Hz, the first harmonic might cause resonance. The first harmonic has a high force amplitude, so this would often result in high accelerations.
- If the natural frequency is between 2.2 Hz and about 9 Hz, one of the higher harmonics could cause resonance. Such floors are referred to in DG11 as low frequency floors (LFFs). Most steel-framed floors are LFFs. The higher harmonics have lower force amplitudes, so it is typically straightforward to design these to satisfy human comfort vibration limits.

Another key piece of information: The walking acceleration predictions in TD5 Equation 3.1 and DG11 Equation 4-1 are based on a curve fit of the second through fourth harmonic dynamic coefficients, as explained above DG11 Equation 2-4. The underlying assumption is that the first harmonic will not cause resonance; this is equivalent to assuming the natural frequency exceeds 2.2 Hz.

It is important to prevent the first harmonic from causing resonance. Walking at 2.2 Hz will include some energy at slightly higher frequencies, say 2.3-2.4 Hz. Also, walking at slightly above 2.2 Hz, and short instances of running or bouncing in place occasionally occur, even on non-gym floors. There should be a cushion between 2.2 Hz and the natural frequency, so 3 Hz seems like a prudent lower limit on the natural frequency.

Vandal Jumping

When occupants perceive very low frequency floor vibration, they might form a group and mischievously jump or bounce in place to intentionally cause high vibration levels. This activity is called vandal jumping or rogue jumping. The group attempts to synchronize the jumping frequency with the frequency of vibration, which is predominately at the natural frequency.

Vandal jumping is similar to aerobics. The second and third columns in Table 2 list the harmonic frequency ranges and dynamic coefficients that are recommended in TD5 Chapter 4 and DG11 Chapters 5 and 7. The size of the group is unknown, but three vandal jumpers is a reasonable assumption. The last column lists the harmonic force amplitudes due to a group of three 168 lb vandal jumpers.

Table 2. Vandal Jumping Force Harmonics

Harmonic, i	if_{step} range (Hz)	α_i	$nQ\alpha_i$ (lb)
1	2.0 – 2.75	1.5	760
2	2.75 – 5.5	0.6	302
3	5.5 – 8.25	0.1	50

Key takeaways from Table 2:

- The jumping frequency, equal to the first harmonic frequency, has a maximum value of 2.75 Hz.
- The harmonic force magnitudes due to three vandal jumpers are much higher than the forces due to walking, shown in Table 1.

A group of vandal jumpers is like a small aerobics class on a floor that was not designed for aerobics. For aerobics floors, the strategy is to increase the natural frequency beyond 6 Hz so that neither the first nor second harmonic can cause resonance. An aerobics floor with a natural frequency below 3 Hz has very little chance of acceptable vibration performance. In a nutshell, this is why it is critical to prevent vandal jumping.

Without vibration testing equipment, a group can only attempt to synchronize the jumping frequency with the natural frequency. They cannot intentionally synchronize the higher harmonic frequencies, $2f_{step}$

or $3f_{step}$, with the natural frequency. For example, if the natural frequency is 5 Hz, they would need to jump at 5 Hz / 2 = 2.5 Hz, which would require jumping every other time the floor oscillates.

Thus, if the natural frequency exceeds 3 Hz, the group will not attempt to – or be able to – synchronize the jumping frequency and natural frequency. This is the most important reason for designing floors so that the natural frequency is at least 3 Hz.

NATURAL FREQUENCY LOWER LIMIT RECOMMENDATION

Due to the reasons explained above, the floor natural frequency should be at least 3 Hz for the vast majority of floors. The first step is to determine if the floor satisfies this design check. As explained above, f_{n1} is an accurate prediction of the natural frequency. Including consideration of a potential 10% overprediction of f_{n1}, the frequency check is:

$$\begin{gathered} 0.9 f_{n1} \geq 3 \text{ Hz} \\ f_{n1} \geq 3.3 \text{ Hz} \end{gathered} \tag{1}$$

Equation 1 approximately corresponds to limiting the traditional Dunkerley f_n to 2.5 Hz, so it is more lenient than the traditional check.

Note that the Dunkerley f_n must be used in the acceleration predictions in TD5 Chapter 3 and DG11 Section 4.1.

EVALUATION OF ULTRA-LOW FREQUENCY FLOORS

Some floors not conforming to Equation 1, referred to herein as ultra-low frequency floors (ULFFs) might be satisfactory for vibration relative to human comfort. This is especially true of those with extremely large masses, high damping ratios, and lenient tolerance limits.

The following ULFF evaluation criterion applies when $f_{n1} \geq 2.5$ Hz. When the natural frequency is below that, more elaborate analyses would be required.

An ULFF should have satisfactory vibration performance when Equation 2 is satisfied for walking and for vandal jumping, with the latter being more severe by an order of magnitude.

$$\frac{a_p}{g} \leq \frac{a_o}{g} \tag{2}$$

Equation 2 is extremely difficult to satisfy for vandal jumping, even with massive floors, high damping ratios, and lenient tolerance limits. An engineer might decide to evaluate the floor for walking and ignore vandal jumping based on engineering judgment for a particular project. However, ignoring vandal jumping would be a departure from design recommendations dating back to the first edition of Design Guide 11 in 1997, so it is not recommended in general.

The tolerance limit for human comfort, a_o, is from TD5 Figure 1.1 and DG11 Figure 2-1. For each occupancy, the limit is most stringent between 4 Hz and 8 Hz and is more lenient below 4 Hz. However, it is recommended that the most stringent range be used below 4 Hz also. Because this article is limited to floors subjected to walking, the set of limits is reduced to the following:

- For quiet areas with seated occupants, such as offices, residences, churches, and schools, the limit is 0.5%g.
- For open areas with higher ambient noise and with affected occupants who are predominately standing, the limit is 1.5%g.
- Limits for other scenarios would need to be established using engineering judgment.

Manual calculation methods for computing the predicted acceleration, a_p, for walking or vandal jumping on ULFF are given in the following sections. Walking will not control; its equation is provided for cases in which the engineer chooses to ignore vandal jumping.

Similar finite element analysis methods could be derived also.

Acceleration due to Walking on Ultra-Low Frequency Floors

The predicted acceleration of an ULFF caused by walking is derived using the single degree of freedom (SDOF) approach used in DG11 Equation 2-5. For an ULFF, the key assumption is that the first harmonic of the walking force causes resonance. The resulting equation is:

$$\begin{aligned} a_p &= R\frac{\text{Sinusoidal Force Amplitude}}{2\beta M} \\ &= \frac{RQ\alpha_1}{2\beta M} \\ &= \frac{(0.5)(157\text{ lb})(0.5)}{2\beta(0.5W/g)} \\ &= \frac{39\text{ lb}}{\beta W}g \end{aligned} \qquad (3)$$

where

R = reduction factor, 0.5 for floors

α_1 = dynamic coefficient of the first harmonic of the walking force, 0.5 (Table 1)

β = damping ratio from TD5 Table 3.2 / DG11 Table 4-2

M = fundamental modal mass, lb-s^2/in.

W = effective weight from TD5 Equation 3.6 / DG11 Equation 4-5, lb

The criterion defined by Equations 2 and 3 is fairly difficult to satisfy. For example, if a floor bay supports an electronic office and a typical ceiling, so that the damping ratio is 0.025, the required effective weight, W, is 312,000 lb. Another example: if a bay supports an office and has significant full-height partitions, so that the damping ratio is 0.05, the required effective weight is 156,000 lb. Bays with such large effective weights occur in practice but are not common.

Acceleration due to Vandal Jumping on Ultra-Low Frequency Floors

The predicted acceleration due to vandal jumping on an ULFF is also derived using the SDOF approach. The underlying assumption is that the first harmonic will dominates the response, so there is no need to compute the responses to higher harmonics.

The resulting equation for the predicted acceleration caused by vandal jumping is:

$$\begin{aligned} a_p &= \frac{nQ\alpha_1}{2\beta M} \\ &= \frac{(3)(168\text{ lb})(1.5)}{2\beta(0.5W/g)} \\ &= \frac{756}{\beta W}g \end{aligned} \tag{4}$$

where

n = number of vandal jumpers

Q = weight of one vandal jumper, lb

α_1 = dynamic coefficient of the first harmonic of the force due to aerobics, 1.5 (Table 2)

β = damping ratio from TD5 Table 3.2 / DG11 Table 4-2

M = fundamental modal mass, lb-s^2/in.

W = effective weight from TD5 Equation 3.6 / DG11 Equation 4-5, lb

To the writer's knowledge, there is no research that could be used to determine the number of vandal jumpers in the group. From engineering judgment, it is reasonable to consider three vandal jumpers.

The reference bodyweight for this equation is 168 lb, which is commonly used in DG11 for newer derivations.

A comparison of Equations 3 and 4 indicates vandal jumping is much more severe than walking. Thus, if vandal jumping is evaluated, there is no need to evaluate walking also.

The criterion defined by Equations 1 and 4 is extremely difficult to satisfy, even with extremely massive floors with high damping ratios and lenient tolerance limits.

SUMMARY

Practical vibration evaluation criteria for steel-framed structures are provided in the SJI Technical Digest 5 and AISC Design Guide 11. In each criterion, the primary design check is a comparison of the predicted acceleration and tolerance limit. Most criteria also state that the natural frequency should exceed a lower limit. For floors, that limit has been 3 Hz since the first edition of Design Guide 11 in 1997. This article provides background on this limit and design recommendations.

A natural frequency below the lower limit results in the following consequences:

- The first harmonic of the walking force can cause resonance, so the typical acceleration prediction equations do not apply. Also, the predicted acceleration due to walking is substantially increased.
- A group of occupants might “vandal jump” to intentionally cause much higher accelerations. This is an extremely severe analysis case.

The primary recommendation is to design the floor so that the natural frequency, taken as the minimum of the joist or beam and girder natural frequencies, called f_{n1} herein, is at least 3.3 Hz. This recommendation is more lenient than the traditional check in which the Dunkerley natural frequency is compared to 3 Hz.

It is possible that a very massive floor with high damping and a lenient tolerance limit might be satisfactory even if f_{n1} is lower than 3.3 Hz. An evaluation criterion was given for such cases. Prediction equations suitable for manual calculations were derived for acceleration due to first harmonic walking and vandal jumping. Vandal jumping, which controls over first harmonic walking by an order of magnitude, would be very difficult to satisfy.

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