Office Fit-Out and Floor Vibrations

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Taking a fresh look at the damping criteria you've been using to design offices can help you to eliminate floor vibration issues from the very start.

Gone are the days of offices with tall partitions, heavy file cabinets, and large, filled bookshelves, and with them has gone the inherent redundancy of office buildings against floor vibration. Although sometimes mistakenly associated with the choice of structural material for a floor system, the perceptibility of floor vibrations is actually dependent on proper consideration of the available damping in a space. A paper by Robert F. Mast "Vibration of Precast Prestressed Concrete Floors," *PCI Journal*, November-December 2001, outlines this problem in concrete systems, and AISC's *Design Guide 11* addresses floor vibration concerns for steel systems.

Damping, as referred to in current floor vibration analysis criteria, is modal damping (β) and is expressed as the ratio of actual damping to critical damping, or as the "percent of critical damping." Damping is dependent upon the structural and non-structural elements that dissipate energy when a floor system moves, which includes office fit-out.

Historically, offices had tall partitions, heavy file cabinets, and large bookshelves. Typical bays were 25′ by 25′ and floor slab thicknesses were between 5-½″ and 7-½ ″. Office fit-out resulted in an actual loading of between 15 psf and 25 psf and modal damping of 5% to 7%.

Today, typical damping ratios in office buildings range from 0.02 to 0.05 (2% to 5%). Electronic offices are becoming common, and new trends in tenant fit-out are a common cause of lively floors. Lightweight computers replace traditional file cabinets and bookshelves, and cubicle walls and open workstations are preferred to full-height partitions. New construction has typical bays of 25′ to 30′ wide by 40′ or more in length, with slab thicknesses of 4″ to 5-¼″. Office fit-out only contributes 6 psf-8 psf of the total loading, and modal damping can be as low as 2% to 3%.

Why are modern floors so much more sensitive to damping than older ones?

Consider the plot in Figure 1, where an acceleration-related amplitude is plotted on the vertical axis and the ratio of natural frequency to forcing frequency is plotted on the horizontal axis. When the frequency ratio is one, the phenomenon of resonance occurs. If there is no damping, the theoretical amplitude goes to infinity. If there is a small amount of damping, say 2% to 3%, the amplitude is greatly reduced, as shown in the Figure, but still significant. If the damping is increased to 5% to 7%, the amplitude is reduced very significantly. Floors designed in the 1960s and 1970s were in the 5% to 7% range and resonance was not a problem. (That is why the older criteria could be based on heel-drop impacts and not walking resonance.) Modern floors are in the 2% to 3% range, making damping an important design variable. In addition, the amount of energy required to excite a floor decreases to zero as the damping decreases, so it takes considerably less energy to excite a floor if there is only 2% to 3% damping as opposed to 5% to 7% damping available.

How can we deal with these changes?

The shift in fit-out of office spaces makes the older vibration-design recommendations obsolete for today's office buildings. Because of this, we recommend that you **do not use** the Modified Reiher-Meister or Murray Criterion procedures under any circumstances. These criteria were developed in the 1960s and 1970s and were calibrated against floors of that era. They are simply not applicable to newer floor systems and fit-out conditions.

Modern floors should be analyzed for walking-induced vibration using the recommendations in the AISC's *Design*

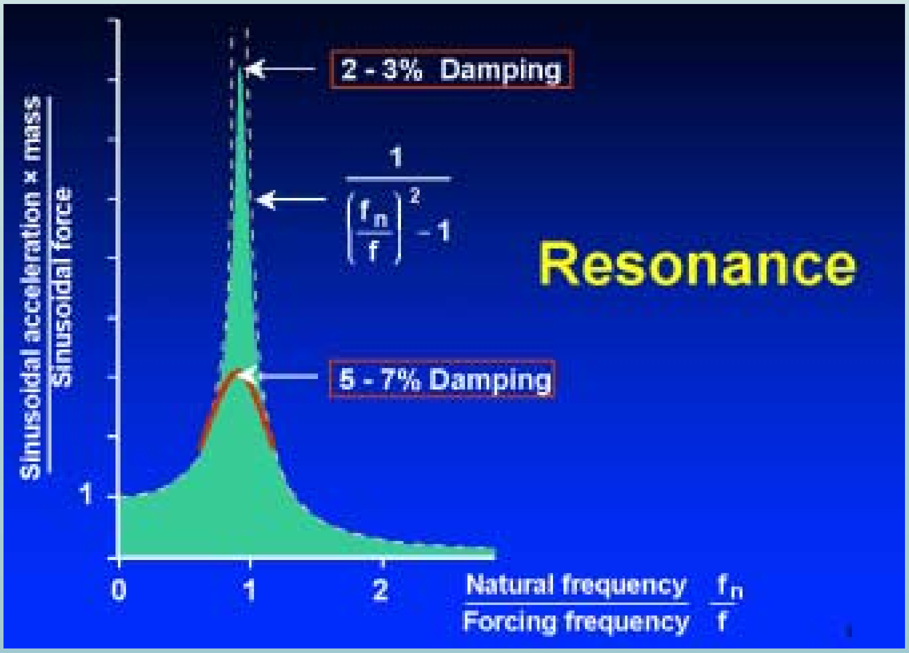

Figure 1. Acceleration-related amplitude vs. ratio of natural frequency to forcing frequency.

Guide 11: Floor Vibrations due to Human Activity. All floors vibrate to some extent, but the vibration only becomes a problem when it is at an acceleration that people can perceive or find annoying. In the design guide procedure, the estimated acceleration of the system from walking is compared to a tolerable acceleration. If the estimated acceleration is less than the tolerable acceleration, as determined from the following inequality, the floor system is considered to be satisfactory.

$$\frac{a_p}{g} = \frac{P_o \exp(-0.35 f_n)}{\beta W} < \frac{a_o}{g} = 0.005$$

or 0.5% of gravity for offices

where:

a_p/g = the predicted peak acceleration of the floor due to walking as a fraction of gravity,

a_o/g = the tolerance acceleration for the environment, 0.005g or 0.5%g for office environments,

P_o = a constant force representing the excitation, 65 lb for office floors,

f_n = the natural frequency of the floor system,

β = the modal damping in the floor system, and

W = the effective weight, which moves because of the excitation.

The terms f_n and W require an estimate of the actual live loading, but the predicted peak acceleration is not particularly sensitive if the estimate is reasonable. The design guide recommended actual live loadings (11 psf for paper offices and 6 psf to 8 psf for electronic offices) are generally adequate, but any expected lower-than-typical loadings should be taken into account in the analysis of the floor system.

The modal damping term, β, must also be estimated. *Design Guide 11* recommends a value between 0.02 and 0.05 (2% to 5% of critical damping) for floors supporting quiet areas like offices, churches, and residences. The predicted peak acceleration is very sensitive to the damping value.

For example, if an estimate of 3% damping for a paper office correlates to a predicted acceleration of 0.4% of gravity, the system is acceptable. However, if the actual damping is only 2% as for an electronic office, the predicted acceleration rises to 0.6% of gravity, and the floor system is unacceptable. Obviously, the perceptible acceleration is dependent on the damping, which is highly dependent on the tenant fit-out of the space. In this case, complaints will not be received if the fit-out is a paper office, but complaints are expected if the space is fit-out as an electronic office.

How do I estimate damping for the design? And, what do I tell the owner?

First, determine the intended office fit-out. If the fit-out is known and not expected to change over the life of the building, the damping ratio can be estimated at about 0.03 (3%) for paper offices without permanent partitions or 0.02 to 0.025 (2-2.5%) for electronic or paperless offices. If permanent, drywall partitions are in all of the bays, the damping ratio is about 0.05. To aid you in making this assessment, several typical office fit-outs with recommended live-loading and damping estimates are shown in Figure 2.

If the office fit-out is not known, discuss the consequences of damping estimates with the owner. Changes in fit-out translate to changes in the damping ratio for the floor system. If a lower than expected damping ratio is used, the floor could vibrate at an intolerable acceleration. The owner might want the space to be designed conservatively for vibration, using damping ratios consistent with those of an electronic office. Conservatism in the design will add some weight to the structural system, but will make the space more adaptable to future fit-out changes.

In a retrofit situation, the *Design Guide 11* recommended tolerable acceleration can be used to back-calculate the required damping for a proposed framing scheme, and to determine acceptable office fit-out schemes for the space. If the fit-out options that provide a sufficient level of damping are not acceptable to the owner, the structural system can be retrofit to provide the necessary damping for the desired fit-out design. This situation should be avoided where possible.

Looking Forward

As floor vibration concerns become more common in all types of framing, the structural system is often blamed for this annoying phenomenon, but office fit-out plays a very important role in the vibration characteristics of the floor system. The designer must carefully consider the effects of modern office layouts on this serviceability condition considering the structural performance of office spaces. ★

Stop Shaking!

Longer spans, stronger steel, and open office layouts have all dramatically changed steel design in the office market over the last 15 years. How do all of these factors impact the floor system? Below is a typical (by today's standards) 30'-0" by 40'-0" bay, designed for a traditional office fit-out of full height partitions: LL = 50 psf; partitions = 20 psf; DL = self + 10 psf mechanical; damping = 5%; AISC *Design Guide 11* vibration criteria. Using Parametric Bay Studies V4.1 from AISC's Steel Solutions Center (available at **www.aisc.org/steeltools**), the design results in a steel weight of 6.9 psf for the gravity framing.

Using this design as a base line, what happens if:

1. The traditional office becomes an open office with cubes (damping reduces to 3%), while maintaining the original beam depths? Result: in-fill beams and girders remain the same, and there is no increase in weight. This is because vibration did not control the original design.

2. The traditional office becomes an electronic office, such as a telephone call center (damping reduces to 2%), while maintaining the original beam depths? Result: in-fill beams and girders increase to W18x65 and W24x94, respectively. The gravity steel weight increases to 8.9 psf-29% more than the traditional office.

3. The slab thickness increases to 2" metal deck with 4" concrete for a total slab depth of 6", while maintaining the original beam depths? Result: The in-fill beams and girders increase to W18x65 and W24x62, respectively. The total weight increases to 8.0 psf, which is a 17% increase in gravity steel weight

4. The depth of the infill beams increases to W21, while maintaining the original girder and slab depths? Result: The in-fill beams and girders increase to W21x55 and W24x84, respectively. The total weight increases to 7.6 psf, which is a 10% increase in gravity steel weight.

The percentages above reflect only the increase in weight of the gravity framing (which commonly ranges from 50% to 65% of the total frame weight, depending on building height.) Keep in mind that total frame weight usually only makes up 25% of the total steel-frame budget, and that the usual steel frame budget only makes up 10% of the total project cost! With these facts, assuring your client that a vibration-less floor is inexpensive will be easy.

—Todd Alwood, Advisor, AISC's Steel Solutions Center

Figure 2: Office Fit-Outs and Recommended Damping Ratios

Traditional Office. Full-height partitions running parallel to the beam span.

With suspended ceiling and ductwork attached below the slab. Estimated actual dead load: 4 psf Estimated actual floor live load: 11 psf Estimated actual partition load: 4 psf	**Effective Damping:** β = 5% Full-height partitions running perpendicular to the beam span will provide sufficient damping to eliminate floor-vibration problems, and the damping ratio need not be considered.
Without suspended ceiling or ductwork attached below the slab. Estimated actual dead load: 4 psf Estimated actual floor live load: 11 psf Estimated actual partition load: 4 psf	**Effective Damping:** β = 5% Full-height partitions running perpendicular to the beam span will provide sufficient damping to eliminate floor-vibration problems, and the damping ratio need not be considered.

Electronic Office. Nearly no paperwork. Limited numbers of file cabinets. No full-height partitions.

With suspended ceilings and ductwork attached below the slab. Estimated actual dead load: 4 psf Estimated actual floor live load: 8 psf Estimated actual partition load: 0 psf	**Effective Damping:** β = 2 - 2.5%
Without suspended ceilings or ductwork attached below the slab. Estimated actual dead load: 1-2 psf Estimated actual floor live load: 8 psf Estimated actual partition load: 0 psf	**Effective Damping:** β = 2%

Open Office. Cubicles and no full-height partitions.

With suspended ceiling and ductwork attached below the slab. Estimated actual dead load: 4 psf Estimated actual floor live load: 8 psf Estimated actual partition load: 0 psf	**Effective Damping:** β = 2.5 - 3%
Without suspended ceiling or ductwork below the slab. Estimated actual dead load: 2 psf Estimated actual floor live load: 8 psf Estimated actual partition load: 0 psf	**Effective Damping:** β = 2 - 2.5%

Office Library. Full-height bookcases in heavily loaded room.

With suspended ceiling and ductwork attached below the slab. Estimated actual dead load: 4 psf Estimated actual floor live load: 11-15 psf Estimated actual partition load: 0 psf	**Effective Damping:** β = 3 - 4%
Without suspended ceiling or ductwork attached below the slab. Estimated actual dead load: 4 psf Estimated actual floor live load: 11-15 psf Estimated actual partition load: 0 psf	**Effective Damping:** β = 3%

All office photos courtesy Steelcase.