Design to Prevent Floor Vibrations

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EFFICIENTLY DESIGNED floor systems are occasionally found to be susceptible to annoying vibrations induced by human occupancy. Improved methods of construction and design, which make use of high strength-lightweight concrete and high strength steels resulting in reduced mass and rigidity of the floor systems without loss of structural soundness, may make large floor areas, free of partitions, susceptible to transient vibrations induced by small impacts such as human footfalls. Under certain circumstances these vibrations can be very annoying to occupants of buildings. Since the occupants are both the source and the sensor, the vibration cannot be isolated as with mechanical equipment, and must be controlled by the structural system.

Vibrating floors have been categorized with respect to human response as follows:[1]

(a) Vibration, though present, is not perceived by the occupants.
(b) Vibration is perceived but it does not annoy.
(c) Vibration annoys and disturbs.
(d) Vibration is so severe that it makes people sick.

Most floors fall into the first two categories. Obviously, the last category cannot be tolerated, and the writer is unaware of any floor system which falls into this category. The subject of this paper is a method, suitable for design office use, to determine if a steel beam-concrete slab floor system is in the third category.

Because the psychological response of humans is involved in determining the threshold of disturbing vibrations, the problem is complex and only guidelines and judgments can be presented. The design method presented has resulted from tests and analyses of over 100 steel beam-concrete slab floor systems and is felt to be as accurate as the state-of-the-art permits. The design method consists of a human perceptibility scale based on amplitude and frequency of floor motion caused by a heel-drop impact, formulas for determining frequency and amplitude caused by a heel-drop impact, and guides for estimating damping.

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HUMAN PERCEPTIBILITY

Human perceptibility to transient floor vibrations depends on three factors: frequency, initial amplitude, and damping. Although a number of scales have been developed to measure human sensitivity to steady state (zero damping) vibration,[2] only two scales are available which include the effects of damping: the modified Reiher-Meister scale and the Wiss-Parmelee scale.

The modified Reiher-Meister scale, Fig. 1a, relates the effects of amplitude and frequency to four levels of human perception. The original Reiher-Meister scale was developed for steady state vibrations.[3] Lenzen,[4] after studying 46 steel joist-concrete slab floor systems subjected to single heel-drop impacts, modified the scale by multiplying the amplitude axis by a factor of 10 to account for the transient nature of the vibration. For transient vibrations "amplitude" is defined as the first maximum amplitude. Lenzen, therefore, implicitly accounts for damping found in typical floor systems. Although the Reiher-Meister curves were developed for steady state vibration using a limited number of subjects and have been shown to be statistically inaccurate,[5] the modified curves have been verified by different researchers for several types of floor systems: Lenzen,[4] steel joist-concrete slab systems; Lenzen and Murray[6] and Rahman and Murray,[7] steel beam-concrete slab systems; Polensek,[8] wood joist systems; Commonwealth Experimental Building Station,[9] various systems.

Wiss and Parmelee[10] have conducted the only known laboratory study to determine human perception to transient vibration of the type normally found in floor systems. A total of 40 humans were subjected to a waveform "designed to simulate vibrations caused in floor systems by one foot fall." Frequency, amplitude and damping were varied through a range found in normal floor systems, and the following human response formula was developed from statistical analysis of the subjective ratings of the vibrations:

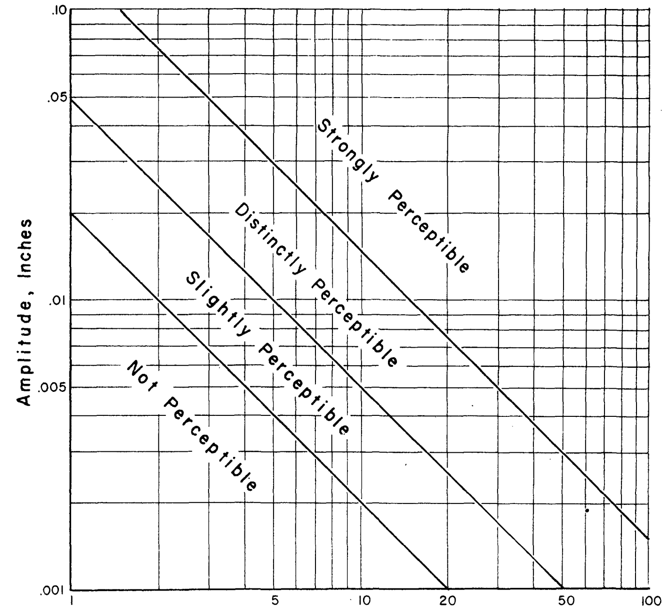
$$R = 5.08 \left[\frac{f A_0}{D^{0.217}} \right]^{0.265} \quad (1)$$

where

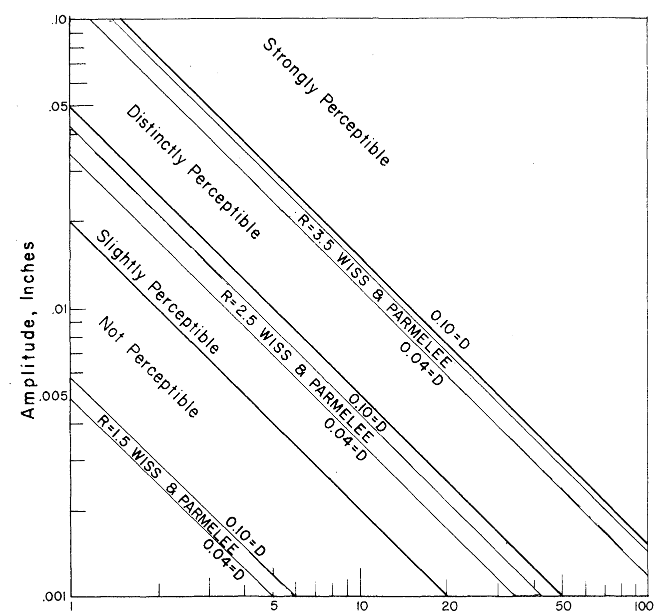
R = the mean response rating
= 1, imperceptible vibration
= 2, barely perceptible vibration
= 3, distinctly perceptible vibration
= 4, strongly perceptible vibration
= 5, severe vibration
f = frequency
A_0 = maximum amplitude
D = damping ratio

A comparison of the modified Reiher-Meister curves, taken from Ref. 1, and the predictions from Eq. (1) is shown in Fig. 1b. The shaded regions were obtained by assuming R = 1.5, 2.5, and 3.5 by varying the damping from 4% to 10% of critical (typical values for concrete slab-steel beam floor systems). Since whole number R values represent the center of perceptible regions, the shaded regions separate relevant regions, as do the diagonal lines of the modified Reiher-Meister plot. In all regions the Wiss-Parmelee human response formula is more critical than the modified Reiher-Meister curve, which can be explained from the fact that the data was obtained in a laboratory from humans expecting motion and knowing that they must judge it, while the modified curve was developed from data taken from humans subjected to actual, on site, floor motion. Because of this difference, Ref. 5 recommends the use of the modified Reiher-Meister plots for making judgments about vibration perceptibility of steel joist concrete slab floor systems.

From measurements and subjective evaluations obtained by the author, it has been found that steel beam-concrete slab systems, with relatively open areas free of partitions and damping between 4 and 10%, which plot above the upper one-half of the distinctly perceptible range, will result in complaints from the occupants and that systems that plot in the strongly perceptible range will be unacceptable to both occupants and owners. Although this conclusion cannot be proven statistically, it substantially agrees with the modified Reiher-Meister curvers and with the Wiss-Parmelee human response formula, and is recommended for design use.



(*a*) *Modified Reiher-Meister scale*



(*b*) *Comparison of modified Reiher-Meister and Wiss-Parmelee scales*

Figure 1

FREQUENCY

From analysis of field measurements of steel beam-concrete slab floor systems subjected to a heel-drop, it is shown in Reference 6 that the frequency of the system can be accurately predicted using the frequency formula for a simply supported tee-beam if the transformed moment of inertia is computed assuming:

(a) Composite action, regardless of the method of construction
(b) An effective slab width, S, equal to the sum of half the distance to adjacent beams
(c) An effective slab depth, d_e, such that the rectangular slab used to compute the moment of inertia is equal in weight to the actual slab including concrete in the valleys of decking and the weight of decking

Figure 2 shows the tee-beam model for computing the transformed moment of inertia.

The first natural frequency of a simply supported tee-beam is given by

$$f = 1.57 \left[\frac{gEI_t}{WL^3}\right]^{1/2} \quad (2)$$

where

g = 386 in./sec
E = modulus of elasticity, ksi
I_t = transformed moment of inertia, in.^{4}
W = total weight supported by the tee-beam, kips
L = tee-beam span, in.

The total weight W used in Eq. (2) should include all of the dead load plus an estimate of the live load at times when floor motion might be more annoying. For instance, complaints have been received from grade school teachers concerning motion of classroom floors after school hours when most of the children had gone home. A reasonable estimate for live load to be included in W is 10% to 25% of the design live load.

AMPLITUDE

The impact of a 190-lb man executing a heel drop was measured by Ohmart[11] and is shown by the solid line in Fig. 3. An approximation to the actual impact is given by the dashed line and has been shown to be sufficiently accurate.[11] The amplitude of a single simply supported tee-beam subjected to the approximate impact can be determined from Eq. (3) or (4):

If $t_0 = (1/\pi f) \tan^{-1} \alpha \leq 0.05$:

$$A_{ot} = \frac{246L^3}{EI_t}(0.10 - t_0) \quad (3)$$

If $t_o > 0.05$:

$$A_{ot} = \frac{246L^3}{EI_t}\left[\frac{1}{2\pi f}\sqrt{2(1 - \alpha \sin \alpha - \cos \alpha) + (\alpha)^2}\right] \quad (4)$$

In the above equations, $\alpha = 0.1\pi f$.

More simply, for any value of t_o, use Eq. (5a) or (5b):

For $E = 29 \times 10^6$ psi:

$$A_{ot} = (DLF)_{max} \times \frac{600L^3}{48EI_t} \quad (5a)$$

For $E = 29 \times 10^3$ ksi:

$$A_{ot} = (DLF)_{max} \times \frac{L^3}{80EI_t} \quad (5b)$$

where $(DLF)_{max}$ = maximum dynamic load factor, which can be obtained from Fig. 4.

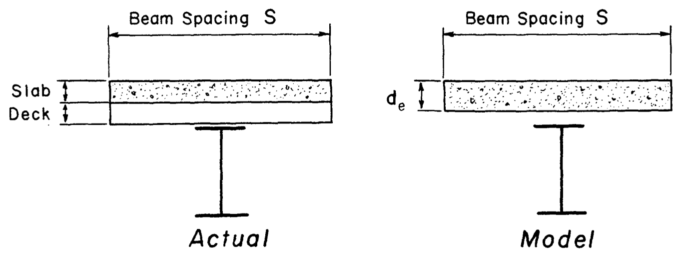


Fig. 2. Tee-beam model for computing transformed moment of inertia

The amplitude of a single tee-beam usually overestimates the amplitude of a floor system subject to the heel-drop impact. Using the computer program developed by Ohmart for predicting the amplitude of stiffened floor slabs, it was determined in Ref. 12 that, for slabs supported by at least five parallel, equally spaced beams, the effective number of tee-beams resisting a heel-drop impact is given by the multiple linear regression equation:

$$N_{eff} = 2.967 - 0.05776(S/d_e) + 2.556 \times 10^{-8} (L^4/I_t) + 0.00010(L/S)^3 \quad (6)$$

A slightly less accurate multiple linear regression model results in the curves shown in Fig. 5. In both Eq. (6) and Fig. 5, S = beam spacing, d_e = effective slab depth, L = span, and I_t = transformed moment of inertia using the model shown in Fig. 2. Note that each parameter is dimensionless.

The amplitude of a floor system subjected to a heel-drop impact is then given by

$$A_o = A_{ot}/N_{eff} \quad (7)$$

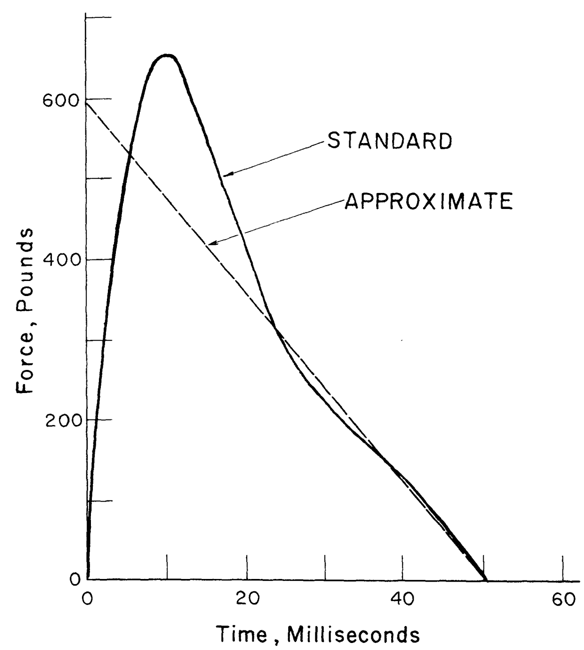


Fig. 3. Measured and approximate heel-drop impact

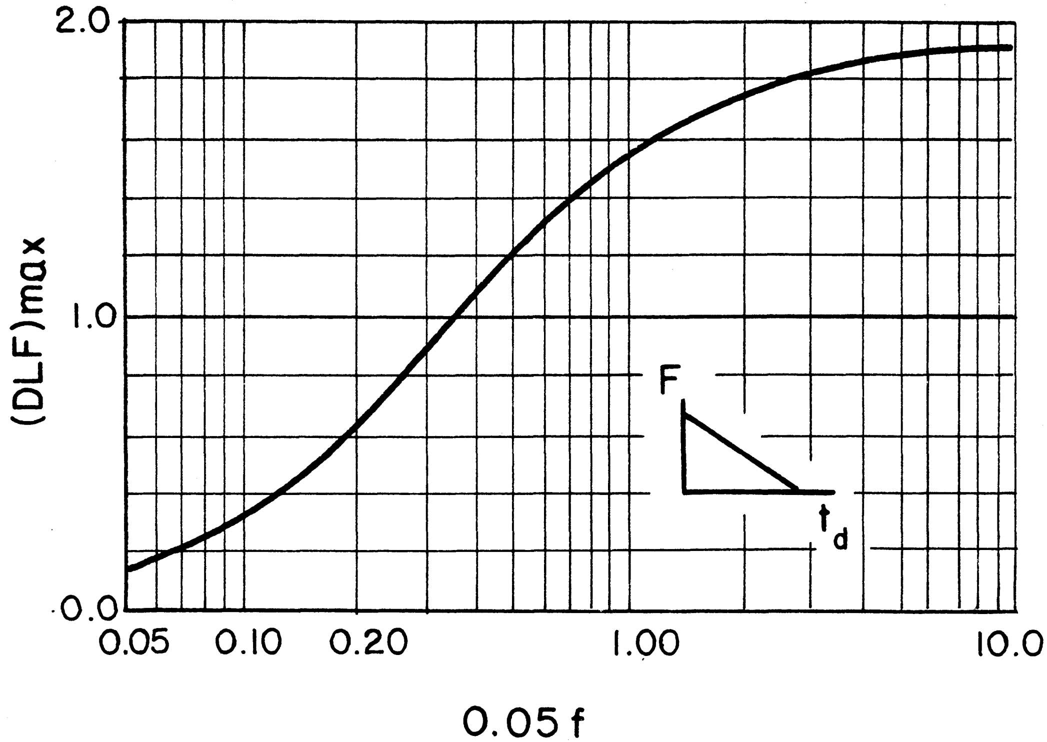


Fig. 4. Dynamic load factors for single tee-beam

DAMPING

Although damping is the most important floor vibration parameter, it is not presently possible to accurately predict the damping that will exist in a floor system. Damping in a floor system is thought to be influenced by the type of construction, slab thickness, concrete weight, fire protection, partitions, ceiling, ductwork, plumbing, etc. Very little research has been conducted to determine the amount of damping contributed by the various components of a completed floor system and only rough guidelines are available.

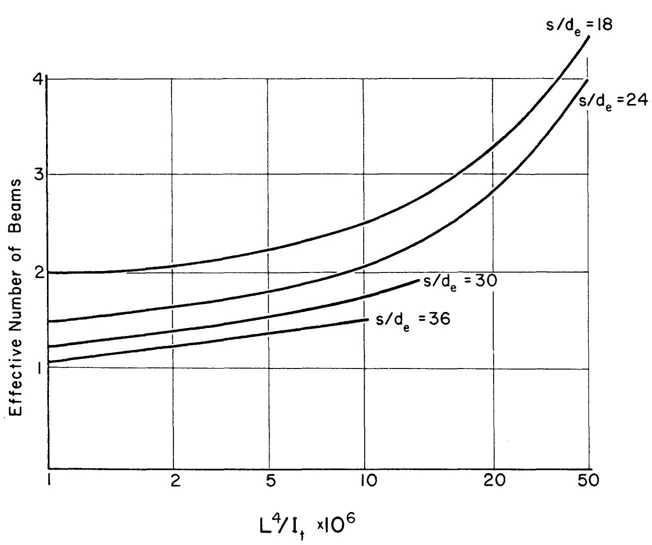


Fig. 5. Effective number of tee-beams

The Canadian Standards Association[13] suggests the following damping ratios: bare floor, 3%; finished floor (ceiling, ducts, flooring, furniture), 6%; finished floor with partitions, 13%. (The damping ratio or fraction of critical damping for a system with viscous damping is the ratio of the actual damping to the critical damping. Critical damping is the minimum viscous damping that will allow a displaced system to return to its initial position without oscillation.)

Based on observation *only*, the author recommends that damping in the final floor system be estimated from the following ranges for floor components: bare floor, 1–3% (lower limit for thin slab of lightweight concrete, upper limit for thick slab of normal weight concrete); ceiling, 1–3% (lower limit for hung ceiling, upper limit for sheetrock on furring attached to beams); ductwork and mechanical, 1–10%, depending on amount; partitions, 10–20%, if attached to the floor system and not spaced more than every five floor beams. *It is important to note that the above percentages are not the result of a systematic study and should be used with caution.* The values are presented in attempt to give some guidelines until badly needed research is completed.

If the estimated damping in a floor is less than 8–10% the method presented here should be used; if the estimated damping is greater than 8–10% there is no need to perform a vibration analysis.

DESIGN PROCEDURE

1. Estimate the damping in the finished floor system; if greater than 8–10% there is no need for a vibration analysis.
2. Compute the transformed moment of inertia of a single tee-beam, I_t, using the model of Fig. 2.
3. Compute the frequency, f, from Eq. (2).
4. Compute the heel-drop amplitude of a single tee-beam, A_{ot}, using Eq. (5) and Fig. 4.
5. Estimate the effective number of tee-beams, N_{eff}, using Fig. 5.
6. Compute the amplitude of the floor system, $A_o = A_{ot}/N_{eff}$.
7. Plot on the Reiher-Meister scale, Fig. 1a.
8. Redesign if necessary.

Example

Given:

Check the following floor system for susceptibility to vibration:

2½-in. lightweight concrete slab (110 pcf, $n = 14$)
2-in. metal deck (concrete in deck + deck = 9.1 psf)
Span: 25 ft-6 in.; Beam Spacing: 8 ft-6 in.
W14×30 A36 steel: $A = 8.83$ in.², $I = 290.0$ in.⁴
Non-composite construction
Hung ceiling; very little ductwork

Solution:

Damping:		
	Slab and beam	1.5%
	Hung ceiling	1.0
	Ductwork	1.0
		3.5% < 8%

∴ Need to investigate floor system

Transformed Section Properties (see Fig. 6):

$$d_e = 2.5 + [(9.1 \times 12)/110] = 3.5 \text{ in.}$$

$$Y_b = \frac{25.5(16.61) + 8.83(13.86/2)}{25.5 + 8.83} = 14.12 \text{ in.}$$

$$I_t = \frac{7.29(3.5)^3}{12} + 25.5(2.49)^2 + 290 + 8.83[14.12 - (13.86/2)]^2 = 93 \text{ in.}^4$$

$$A_c/n = 102(3.5)/14 = 25.52 \text{ sq. in.}$$

Frequency:

$$W = [(3.5/12) \times 110 \times 8.5 \times 25.5] + (30 \times 25.5) = 7719 \text{ lbs} = 7.72 \text{ kips}$$

$$f = 1.57\sqrt{\frac{gEI_t}{WL^3}} = 1.57\left[\frac{386 \times 29 \times 10^3 \times 931}{7700 \times (25.5 \times 12)^3}\right]^{1/2} = 10.78 \text{ cps}$$

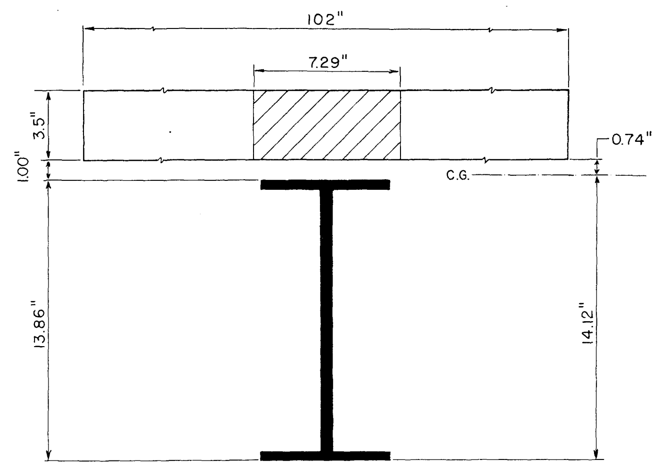


Figure 6

Single Tee-Beam Amplitude:

$$0.05f = 0.05 \times 10.78 = 0.539$$

From Fig. 4:

$$(DLF)_{max} = 1.22$$

$$A_{ot} = (DLF)_{max}\frac{L^3}{80EI_t} = \frac{1.22 \times (25.5 \times 12)^3}{80 \times 29 \times 10^3 \times 931} = 0.0162 \text{ in.}$$

Effective Number of Tee-Beams:

$$s/d_e = 102/3.5 = 29.14$$

$$L^4/I_t = (25.5 \times 12)^4/931 = 9.42 \times 10^6$$

From Fig. 5:

$$N_{eff} = 1.53$$

System Amplitude:

$$A_o = A_{ot}/N_{eff} = 0.0162/1.53 = 0.0106 \text{ in.}$$

Perceptibility:

With a frequency of 10.78 cps and an amplitude of 0.0106 in., the system plots in the upper third of the "Distinctly Perceptible" range on the modified Reiher-Meister scale, Fig. 7. Since the damping is very low, redesign is necessary.

Redesign:

As shown in Fig. 7, increasing the beam size is not an effective method for decreasing vibration perceptibility. When the supporting beam is increased two depths, there is very little change in the rating.

By increasing the slab thickness, a significant change is obtained. As shown in Fig. 7, the floor system becomes acceptable when the slab is increased to 3.5 in. If head-room is available, a better design is a W16×31 with 3.5-in. slab.

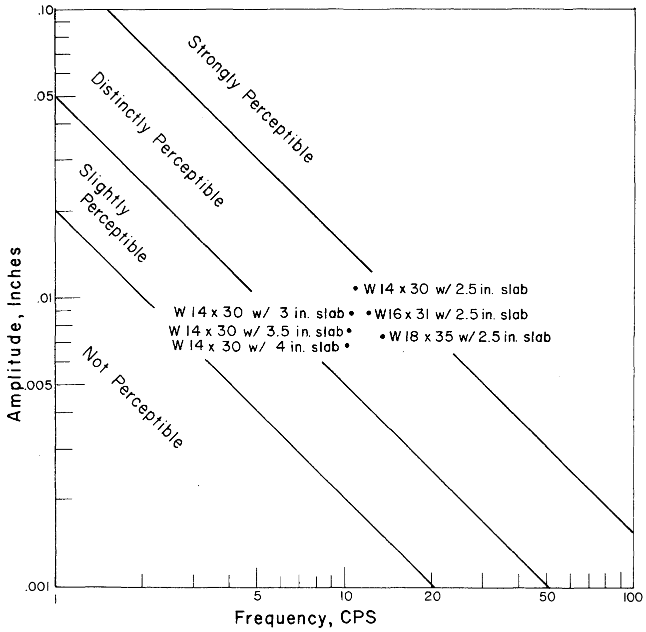


Figure 7

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