Steel TIPS

STRUCTURAL STEEL EDUCATIONAL COUNCIL

TECHNICAL INFORMATION & PRODUCT SERVICE

SEPTEMBER, 1991

Design Practice to Prevent Floor Vibrations

by

Farzad Naeim

Design Practice to Prevent Floor Vibrations

About the Author:

Farzad Naeim, Ph.D., S.E., is Director of Research and Development for the Structural Engineering firm of John A. Martin and Associates, Inc., Los Angeles, California. He has been in charge of design review and analysis of numerous complex projects across the United States for vibration as well as other serviceability concerns. Dr. Naeim has regularly lectured on various aspects of structural design and earthquake engineering at University of Southern California and California State University, Northridge. He is an active member of several professional organizations and has more than 30 publications covering a wide spectrum of structural and earthquake engineering applications.

INTRODUCTION

The current trend towards longer spans and lighter floor systems, combined with reduced damping and new activities, such as aerobics exercises, have resulted in a significant increase in the number of floor vibration complaints by building owners and occupants. This has increased the degree of attention paid during the design process, to preventing, or reducing floor vibration problems.

The purpose of this publication is to provide design engineers with a practical yet comprehensive review of the criteria and methods available to prevent floor vibration problems.

Because of the complexities involved in human response to vibration and the different objectives persued by various investigators, the predictions of the methods presented here are not always consistent. Unfortunately, a general consensus on the relative accuracy and reliability of these methods does not yet exist. However, it is hoped that collective review, application, and comparison of these methods will help to form this seriously needed consensus in the near future.

Annoying floor vibrations may be caused by occupant activities. Walking, dancing, jumping, aerobics, and audience participation at music concerts and sporting events are some prime examples of occupant activities which create floor vibrations.

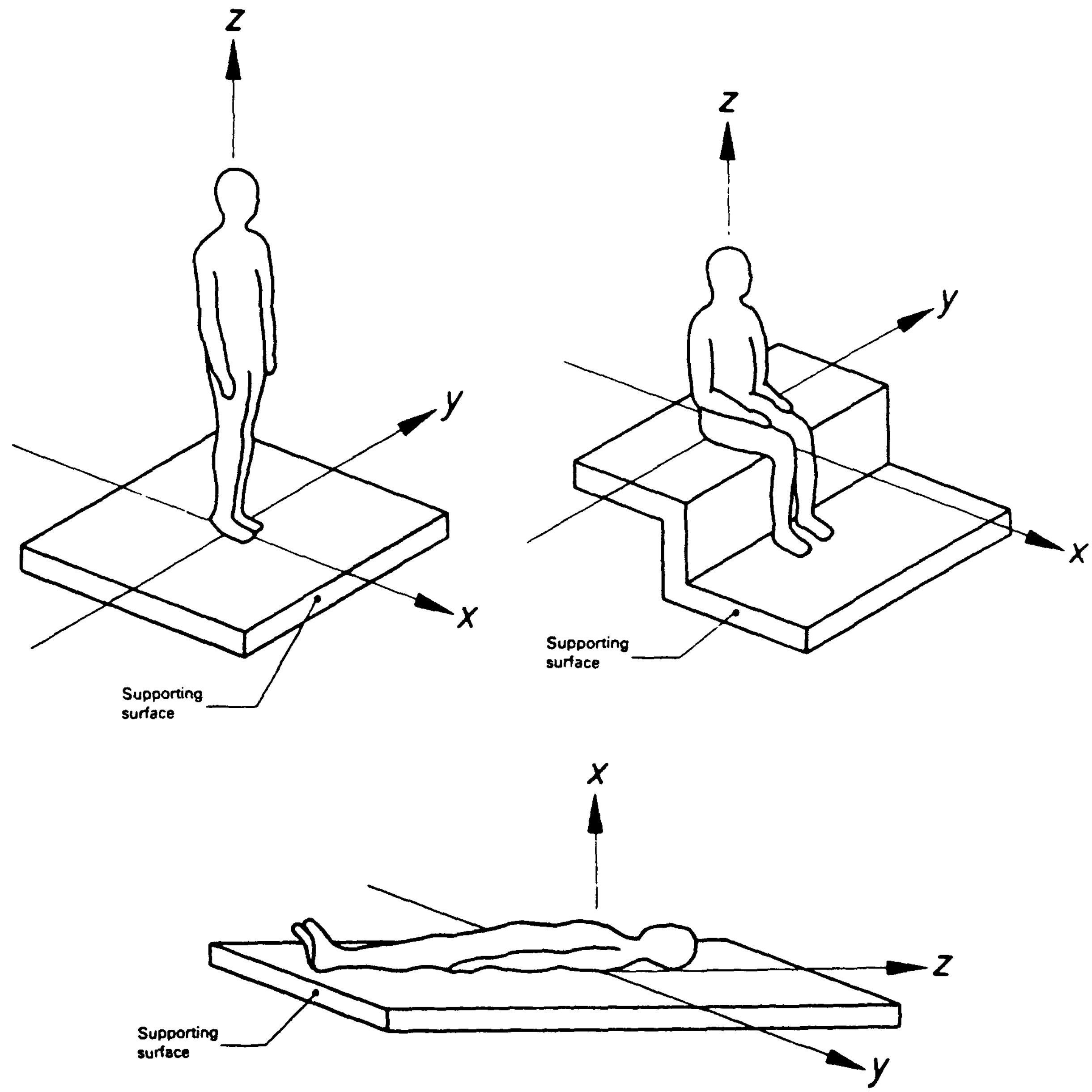
Operation of mechanical equipment is another cause for concern. Heating, ventilation, and air-conditioning systems (HVAC) as well as washing and drying machines, if not properly isolated, can cause serious vibration problems.

Most of the sources contributing to reported human discomfort rest on the floor system itself. However, human activities or machinery off a floor can cause significant floor vibrations. On more than one occasion, aerobics on one floor of a high-rise building has been reported to cause vibration discomfort at another level in the building. The vibrations caused by automobiles on parking levels below have been reported to disrupt sensitive laboratory work on upper floors. Other equipment and activities off the floor that can contribute to a floor vibration problem are ground or air traffic, drilling, impact of falling objects, and other construction related events.

FACTORS INFLUENCING VIBRATION PERCEPTIBILITY

Several factors influence the level of perception and the degree of sensitivity of people to vibrations. Among them are:

(a) *Position of the human body.* Consider the human body coordinate system defined in Figure 1. Here, the x-axis defines the back-to-chest direction, the y-axis defines the right side to left side direction, and the z-axis defines the foot -(or-buttocks-)to-head direction. According to ISO[9,10], the frequency range of maximum sensitivity to acceleration for humans is between 4 to 8 Hz for vibration along the z-axis and 0 to 2 Hz for vibration along the x- or y- axes. While z-axis vibration is most important in the design of offices and other workplaces, all three axes become important in the design of residences and hotels where sleeping comfort should be considered.



a_x, a_y, a_z = acceleration in the directions of the *x*-, *y*-, *z*-axes

x-axis = back-to-chest

y-axis = right side to left side

z-axis = foot-(or buttocks-)to-head

Figure 1. Directions of basicentric coordinate systems for vibrations influencing humans.[10]

(b) *Excitation source characteristics* such as amplitude, frequency content and duration.

(c) *Exposure time.* As shown in Figures 2 and 3, human tolerance of vibration decreases in a characteristic way with increasing exposure time[9].

(d) *Floor system characteristics* such as natural frequency (stiffness; mass), and damping.

(e) *Level of expectancy.* The more one expects vibration and knows about its source the less startling the vibration becomes. Because people expect more vibration in workshops than in hotel lobbies, they can put up with more in the former than in the latter. Anxiety and discomfort can be reduced if occupants are made aware of the nature of vibrations and are assured that they are not a threat to their safety and well being.

(f) *Type of activity engaged in.* The level of perception varies with the nature of activity that one is engaged in such as office work, dinning, walking, or dancing.

CATEGORIES OF HUMAN RESPONSE

ISO[9] classifies human response to vibrations into three categories:

(a) limit beyond which the comfort is reduced ("reduced comfort boundary")

(b) limit beyond which the working efficiency is impaired (" fatigue-decreased proficiency boundary")

(c) limit beyond which the health or safety is endangered ("exposure limit")

These categories were derived from various studies conducted for transportation industries and generally reflect a much higher level of tolerance than what would be acceptable in a building environment. According to ISO 2631-2[10]:

> *"Experience has shown in many countries that complaints regarding building vibrations in residential situations are likely to arise from occupants of buildings when the vibration magnitudes are only slightly in excess of perception levels. In general, the satisfactory magnitudes are related to the minimum adverse comment level by the occupants and are not determined by any other factors, such as short-term health hazard and working efficiency. Indeed, in practically all cases the magnitudes are such that there is no possibility of fatigue or other vibration-induced symptoms."*

Murray's[13] categorization of human response is more design oriented and hence more useful. He defines four response categories, among which the first two are acceptable as far as design is concerned:

(a) Vibration, though present, is not perceived by the occupants.

(b) Vibration is perceived but does not annoy.

(c) Vibration annoys and disturbs.

(d) Vibration is so severe that makes occupants ill.

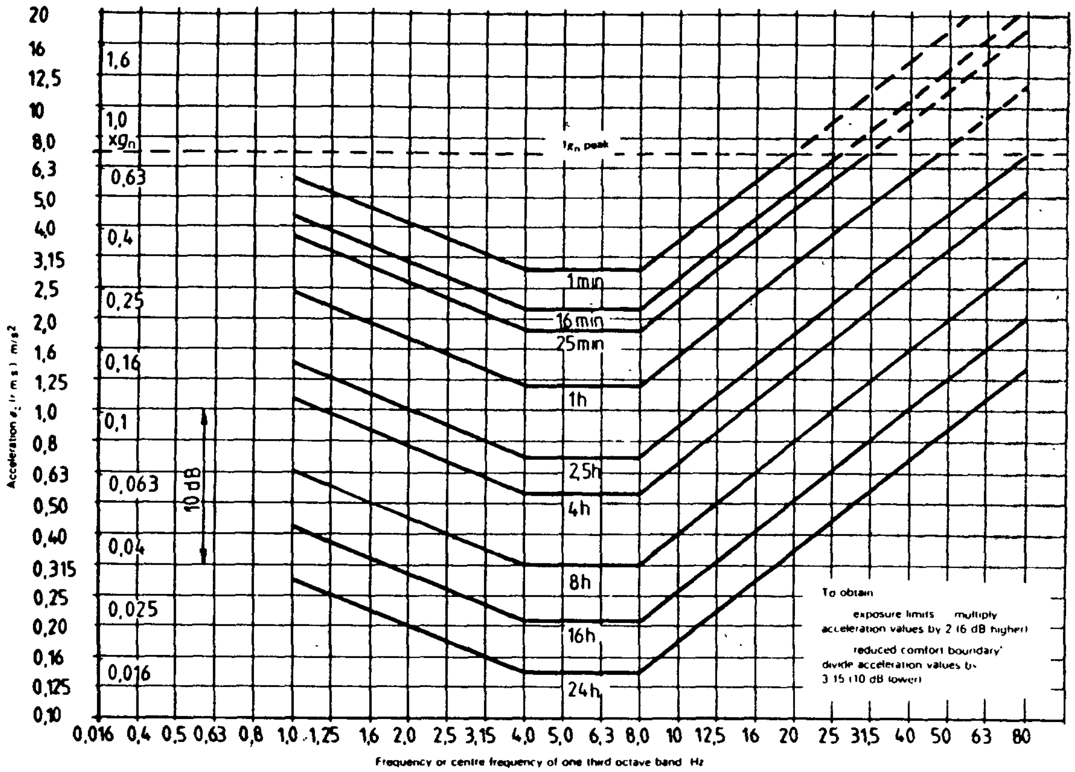


Figure 2. Longitudinal (a_z) acceleration limits as a function of frequency and exposure time (fatigue-decreased proficiency boundary).

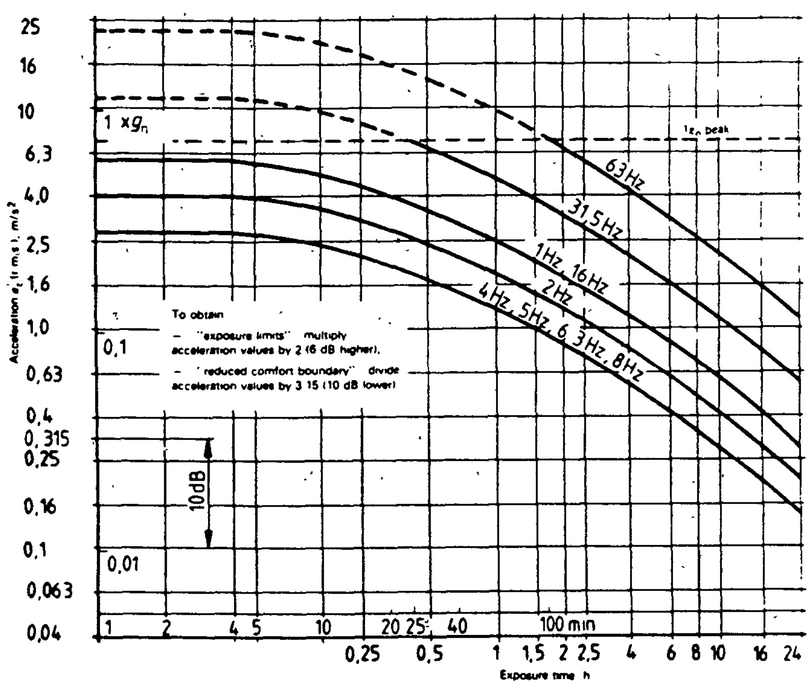


Figure 3. Longitudinal (a_z) acceleration limits as a function of exposure time and frequency (fatigue-decreased proficiency boundary).

ISO INTERNATIONAL STANDARD 2631 PROVISIONS

ISO 2631-2[10] provides a number of human perceptibility base curves for floor velocity and acceleration. According to ISO, at vibration magnitudes below the base curves, adverse comments, sensations, or complaints are very rare. They note however, that this does not mean that the values above the base curves will give rise to adverse comments or dissatisfaction. Since the magnitude which is considered to be satisfactory depends on the circumstances, ISO suggests specifying satisfactory vibration levels in terms of multiples of these base curves. Base curves for foot-to-head, back-to-chest, and side-to-side accelerations are shown in Figures 4 and 5.

In terms of human response, ISO divides vibrations into two classes: (a)*transient* (also called *impulsive*) and (b)*continuous* or *intermittent*. Transient vibration is defined as a rapid build-up to a peak followed by a damped decay, such as vibration caused by the impact of a single heavy object on a floor system. It can also consist of several cycles of vibration at approximately the same amplitude, providing that the duration is short (less than about 2 seconds).

Continuous vibration on the other hand is vibration which remains uninterrupted over the time period under consideration. Intermittent vibration is defined as a string of vibration incidents, each of short duration, separated by intervals of much lower vibration magnitude (for example vibration caused by a group of people walking or elevators operating).

In an appendix to ISO 2631-2, a set of state of the art multiplication factors frequently used with the ISO base curves are presented. These factors which lead to magnitudes of vibration below which the probability of reaction is low are summarized in Table 1.

In many situations the same building space, residences and hotel guest rooms, for example, may be used in both standing and lying positions. For these cases, ISO 2631-2 suggests using a combined standard that represents the worst case combination of z-axis and x/y axes conditions. The combined standard curves for acceleration response are presented in Figure 6. Notice that the multiplication factors in Table 1 have already been applied to these curves.

COMPUTING FLOOR SYSTEM CHARACTERISTICS

Unless otherwise noted the following assumptions are used in this publication for calculating floor system vibration characteristics:

(1) Full composite action is assumed to exist between the concrete slab and steel beam regardless of the number of shear studs present[12].

(2) The beam is modeled as a single degree of freedom (SDOF) system.

(3) The transformed moment of inertia (I_t) is calculated using Murray's assumptions[12,13,14].

As pointed out by Allen[3,4,5], it is better to calculate the first natural frequency, *f*, based on deflection:

$$[1] \qquad f = \frac{1}{2\pi}\sqrt{\frac{\text{stiffness}}{\text{mass}}} = \frac{1}{2\pi}\sqrt{\frac{g}{\Delta}}$$

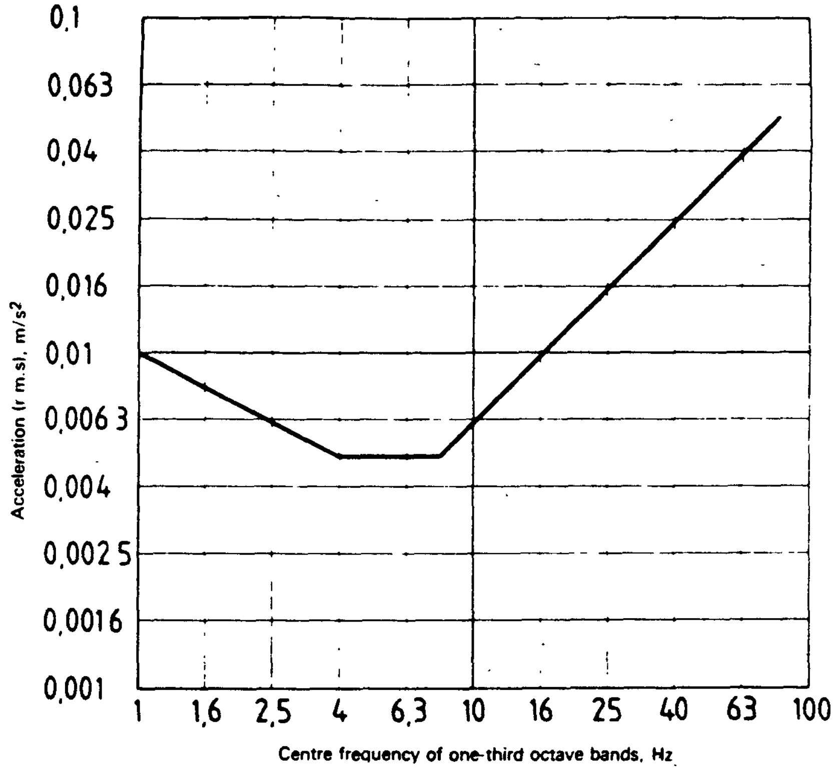


Figure 4. Building vibration z-axis base curve for acceleration[10]

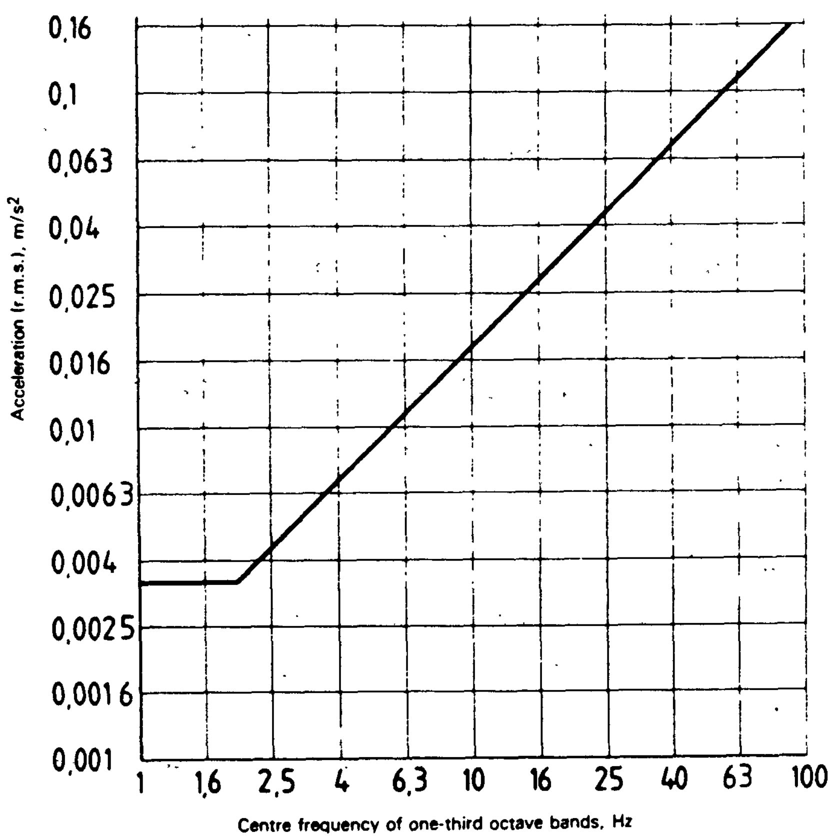


Figure 5. Building vibration x- and y-axis base curve for acceleration[10]

TABLE 1 — Ranges of multiplying factors used in several countries to specify satisfactory magnitudes of building vibrations with respect to human response[1]
(from ISO 2631-2: 1989)

PLACE	TIME	Continuous or Intermittent Vibration	Transient Vibration (Excitation with several occurrences per day)
Critical Working Areas (for example some hospital operating-theatres, some precision laboratories)	Day Night	1	1[2,3]
Residential	Day	2 to 4	30 to 90[4,5,6,7]
	Night	1.4[4]	1.4 to 20
Office	Day Night	4[8]	60 to 128[8]
Workshop[9]	Day Night	8[8,10]	90 to 128[8,10]

1) Table leads to magnitudes of vibration below which the probability of reaction is low. (Any acoustic noise caused by vibrating walls is not considered.)

2) Also includes quasi-stationary vibrations caused by repetitive shocks. Shock is defined in ISO 2041 : 1975, clause 3, and is sometimes referred to as transient (impulsive) vibration.

3) Magnitudes of transient vibration in hospital operating-theatres and critical working places pertain to periods of time when operations are in progress or critical work is being performed. At other times, magnitudes as high as those for residence are satisfactory provided that there is due agreement and warning.

4) Within residential areas there are wide variations in vibration tolerance. Specific values are dependent upon social and cultural factors, psychological attitudes and expected interference with privacy.

5) The "trade-off" between number of events per day and magnitudes is not well established. The following provisional relationship shall be used for cases of more than three events a day pending further research into human vibration tolerance. This involves further multiplying by a number factor $F_n = 1{,}7\,N^{-0{,}5}$ where N is the number of events per day. This "trade-off" equation does not apply when values are lower than those given by the factors for continuous vibration. When the range of event magnitudes is small (within a half amplitude of the largest), the arithmetic mean can be used. Otherwise only the largest need be considered.

6) For discrete events with durations exceeding 1 s, the factors can be adjusted by further multiplying by a duration factor, F_d :

$F_d = T^{-1{,}22}$ for concrete floors and T is between 1 and 20

$F_d = T^{-0{,}32}$ for wooden floors and T is between 1 and 60

where T is the duration of the event, in seconds, and can be estimated from the 10 percentage (– 20 dB) points of the motion time histories.

7) In hard rock excavation, where underground disturbances cause higher frequency vibration, a factor of up to 128 has been found to be satisfactory for residential properties in some countries.

8) The magnitudes for transient vibration in offices and workshop areas should not be increased without considering the possibility of significant disruption of working activity.

9) Vibration acting on operators of certain processes, such as drop forges or crushers which vibrate working places, may be in a separate category from the workshop areas considered here. Vibration magnitudes, for the operators of the exciting processes, which are specified in ISO 2631-1, will then apply.

10) Doubling the suggested vibration magnitudes for continuous or intermittent vibration and repeated transient vibration (fourth column) may result in adverse comment and this may increase significantly if the levels are quadrupled (where available, dose/response curves can be consulted).

where Δ is the mid-span deflection of an equivalent SDOF system due to its own weight and g is the gravitational acceleration (386.4 in./sec^2). For a floor system, Δ may be approximated by

[2] $$\Delta = \frac{(\Delta_B + \Delta_G)}{1.3} + \Delta_S$$

where Δ_B is deflection of floor beam due to flexure and shear, Δ_G is the deflection of the girder at the beam support due to flexure and shear, and Δ_S is the shortening of the column or wall support. The constant 1.3 in the above equation applies to both simply supported and fixed-end beams. For fixed-cantilevers a value of 1.5 should be used. In the calculation of Δ, continuous beams on pin supports should be treated as simply supported, since vibration nodes exist at the supports.

If shearing deformations are negligible, then the transformed moment of inertia of the floor beam, I_t, may be used to estimate its natural frequency:

[3] $$f = K\sqrt{\frac{gEI_t}{WL^3}}$$

where $K = \frac{\pi}{2}$ for simply supported beams. Values of K for various end conditions are readily available from tables such as those contained in Reference [7]. I_t is the transformed moment of inertia of the composite beam section, E is the modulus of elasticity of steel (29000 ksi) and W is total weight supported by the beam. Usually a sustained portion of the live load (about 10% to 25% of the total design live load) is included in this weight estimate. Finally, L is the span length of the beam. For computation of I_t, the effective slab depth (d_e) is assumed equal to the depth of a rectangular slab having the same weight as the actual slab, including the concrete in valleys of the decking and the weight of the metal deck (see Figure 7).

The effect of girder and column support flexibilities on the first natural frequency of the system, may also be approximated by:

[4] $$\frac{1}{f^2} = \frac{1}{(f_b)^2} + \frac{1}{(f_g)^2} + \frac{1}{(f_s)^2}$$

where f_b, f_g, and f_s are the natural frequencies of the beam, girder, and column supports each computed individually.

The reader should note that floor systems are complex and have multiple natural frequencies. The above simplified procedures usually provide a good estimate of the first natural frequency. However, depending on the activity of concern, this might or might not be the natural frequency of greatest concern. For example, for most non-rhythmic activities (i.e. walking) it is very unlikely that the column supports will have a significant participation in the response. For these cases, the natural frequencies of great interest are those of the floor beam alone, the girder alone, and the combined beam and girder system. On the other hand, all three natural frequencies (i.e. beam; beam+girder; beam+girder+support) should be considered in design for rhythmic activities.

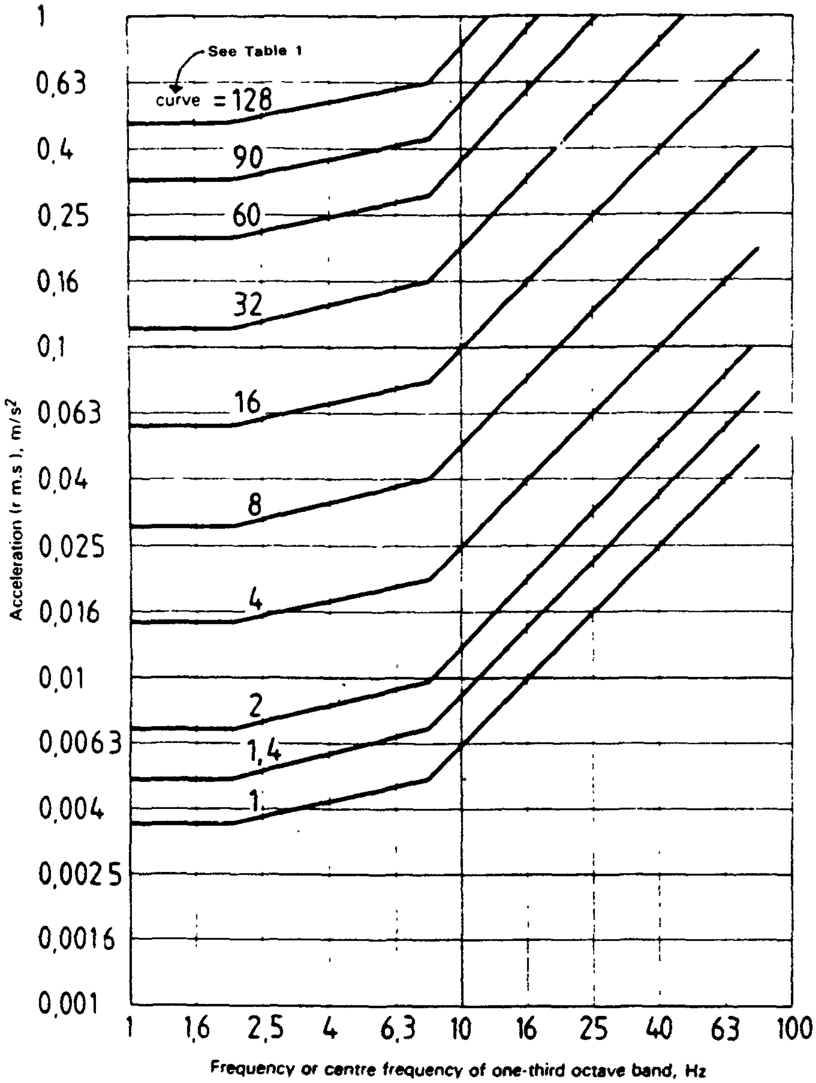


Figure 6. Combined direction criteria curves for vibration in buildings[10]

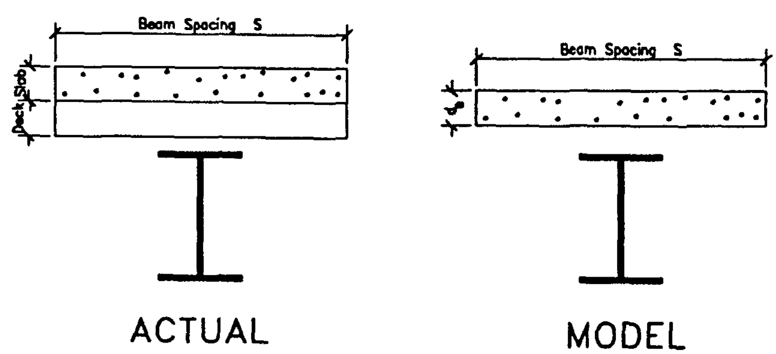


Figure 7. Tee-Beam model for computing transformed moment of inertia[14].

EXAMPLE 1[6]: Estimate the natural frequency of the following floor beam. The girder and column support motions are small and can be ignored.

GIVEN:

BEAM: W21x44 SLAB: 2 in. metal deck + $3\frac{1}{4}$" light weight concrete

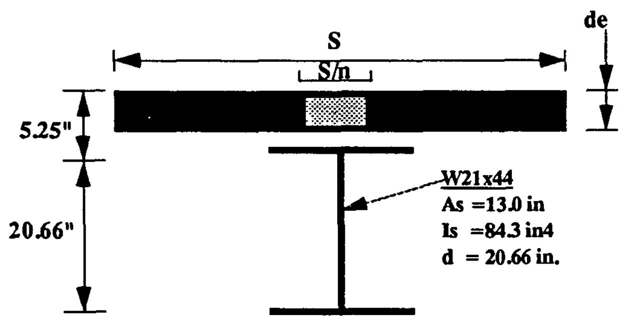
(slab weight = 41 psf; f'c = 3000 psi; Concrete weight = 115 pcf)

SPAN = 41' - 0" SPACING = 10'-0"

LIVE LOADS: Office --------- 50 psf
Partitions ----- 20 psf
Misc. ---------- 10 psf ===> Total Live Load = 80 psf

SOLUTION:

Support motions are negligible and the beam is not deep. Hence, the shearing deformations may be ignored as well and we can use the I_t formula to calculate *f*.



BEAM MODEL

$$E_C = (W_c)^{1.5}\sqrt{f'_c} = (115\text{ pcf})^{1.5}\sqrt{3\text{ ksi}} = 2136\text{ ksi}$$

$$n = \frac{E_s}{E_c} = \frac{29000\text{ ksi}}{2136\text{ ksi}} = 13.6 \qquad d_e = \frac{\text{actual slab weight}}{\text{concrete weight}} = \frac{41\text{ psf}}{115\text{ pcf}}(12\frac{\text{in}}{\text{ft}}) = 4.3"$$

Distance from c.g. to slab top, Y_t is calculated as:

$$Y_t = \frac{(\frac{1}{2})(\frac{10'\text{x}12}{13.6})(4.3")^2 + (13.0\text{ in}^2)(\frac{20.66"}{2} + 5.25")}{(\frac{10'\text{x}12}{13.6})(4.3") + 13.0\text{ in}^2} = 5.6"$$

The transformed moment of inertia is:

$$I_t = (\frac{1}{12})(\frac{10'\text{x}12}{13.6})(4.3")^3 + (\frac{10'\text{x}12}{13.6})(4.3)(5.6 - \frac{4.3"}{2})^2 + 843\text{ in}^4 +$$

$$+ (13.0\text{ in}^2)(\frac{20.66"}{2} + 5.25" - 5.6")^2 = 2648\text{ in}^4$$

Assuming that10% of the design live load acts as a sustained load during vibration, the participating weight is calculated as:

$W_{DL} = W_{Slab} + W_{Beam} = (0.041 \text{ ksf})(41')(10') + (0.044 \text{ k/ft})(41') = 18.6 \text{ k}$

$W_{LL} = (0.10)(0.080 \text{ ksf})(41')(10') = 3.3 \text{ k}$

$W = W_{DL} + W_{LL} = 18.6 + 3.3 = 21.9 \text{ k}$

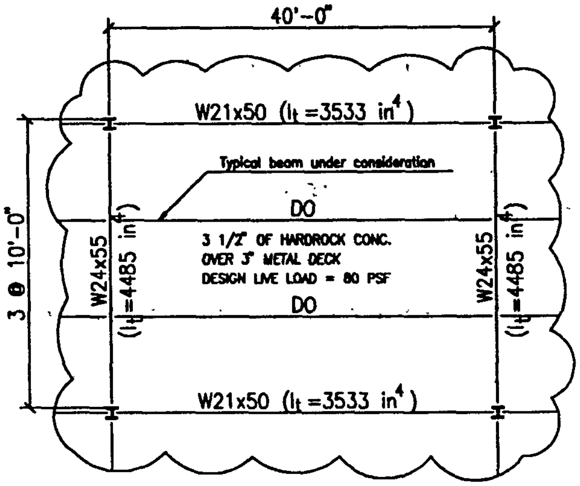
Hence, the natural frequency is:

$$f = K\sqrt{\frac{gEI_t}{WL^3}} = (\frac{\pi}{2})\sqrt{\frac{(386.4)(29000)(2648)}{(21.9)(41'\text{x}12)^3}} = \underline{5.3} \text{ Hz}$$

EXAMPLE 2: For the typical interior beam shown below, estimate the first natural frequency by :

(a) using [3] and [4]; (b) using [1] assuming column shortening is inconsequential; (c) using [1] assuming column shortening of $\Delta_S = 0.50^*$ inches should be considered.

Assume the beam self-weight and 10% of the design live load are included in the 80 psf estimate of floor weight.



SOLUTION:

Since both beams and girder are shallow, shearing deformations may be ignored.

(a) For the beam: $W = (80 \text{ psf})(10')(40') = 32{,}000 \text{ lb} = 32 \text{ kips}$

$$f_b = K\sqrt{\frac{gEI_t}{WL^3}} = (\frac{\pi}{2})\sqrt{\frac{(386.4)(29000)(3533)}{(32)(40'\text{x}12)^3}} = 5.25 \text{ Hz}$$

For the girder: $W = 2(32 \text{ kips}) + (0.055)(30') = 65.65 \text{ kips}$

$$f_g = K\sqrt{\frac{gEI_t}{WL^3}} = (\frac{\pi}{2})\sqrt{\frac{(386.4)(29000)(4485)}{(65.65)(30'\text{x}12)^3}} = 6.36 \text{ Hz}$$

---

* Calculated based on a total column height of 130 ft. and an average sustained axial stress of 12 ksi.

$$\Delta = \frac{L\sigma}{E} = \frac{(130 \text{ ft})(12)(12 \text{ ksi})}{29000} = 0.64 \text{ in.}$$

The factor 1.30 is applicable to Δ for frequency calculations since uniform mass distribution along the column height is assumed: $\Delta s = \frac{\Delta}{1.3} = \frac{0.64}{1.3} = 0.50 \text{ in.}$

From [4]: $\frac{1}{f^2} = \frac{1}{(5.25)^2} + \frac{1}{(6.36)^2}$ ===> f = 4.05 Hz

(b) The beam deflection at midspan is:

$$\Delta_B = \frac{5wL^4}{384EI_t} = \frac{5(32)(40x12)^3}{384(29000)(3533)} = 0.45 \text{ in.}$$

The girder deflection at the beam support (1/3rd point) is:

$$\Delta_G = \frac{5PL^3}{162EI_t} = \frac{5(32)(30x12)^3}{162(29000)(4485)} = 0.35 \text{ in.}$$

The natural frequency of the system is then determined:

$$\Delta = \frac{(\Delta_B + \Delta_G)}{1.3} = \frac{(0.45 + 0.35)}{1.3} = 0.62 \text{ in.}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{\Delta}} = \frac{1}{2\pi}\sqrt{\frac{386.4}{0.62}} = \underline{3.97} \text{ Hz}$$

(c) Adding column shortening to the natural frequency calculation:

$$\Delta = 0.62" + 0.50" = 1.12"$$

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{\Delta}} = \frac{1}{2\pi}\sqrt{\frac{386.4}{1.12}} = \underline{2.96} \text{ Hz}$$

FLOOR VIBRATION DUE TO WALKING

To model the impulse caused by a person walking, a standard heel drop impact has been defined[2,11]. This is the impulse initiated by a person weighing 170 pounds who supports his weight on his toes with the heels raised about 2.5 inches, and then suddenly drops his weight through his heels to the floor. A plot of the resulting heel drop impact and a typical floor response to such impact are shown in Figures 8 and 9, respectively.

Several investigators have suggested methods to evaluate and design for floor vibrations caused by heel drop impacts[2,8,11,13,14,17,18]. Among them, Murray's acceptability criterion[13,14] enjoys the most wide-spread use by structural designers in United States. In this section, six such methods are introduced and applied to a sample floor vibration design example.

<u>Murray's Acceptability Criterion</u>

Murray[13,14] provides a step-by-step procedure for evaluating potential floor vibration problems in *residential* and *office* environments. Design tables have been published which simplify application of this technique[6]. The method is based on field measurements and human response studies performed on approximately 100 floor systems. For *commercial* environments, the use of the criteria suggested by an ASCE Ad Hoc committee chaired by Ellingwood [1986] and covered later in this publication is recommended.

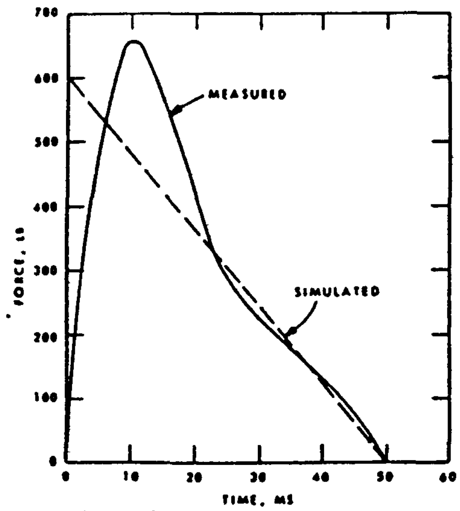


Figure 8. Average plot of force versus time for heel impact[4]

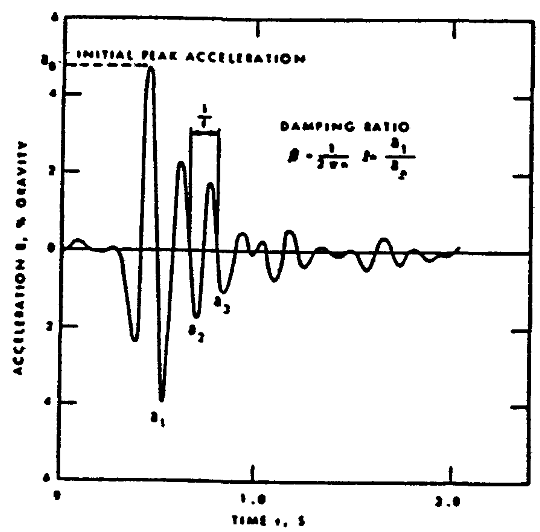


Figure 9. Typical floor response to heel impact (High frequencies filtered out).[4]

TABLE 2 --- Suggested ranges for available floor system damping
(after Murray [12,13,14])

Source	Damping	Comments
Bare Floor	1% - 3%	Lower limit for thin slab of lightweight concrete; upper limit for thick slab of regular weight concrete
Ceiling	1% - 3%	Lower limit for hung ceiling; upper limit for sheetrock on furring attached to beams
Mechanical Systems	1% - 10%	Depends on amount and attachment
Partitions	10% - 20%	If attached to the floor at three points or more and not spaced more than every five floor beams.

The procedure for applying Murray's acceptability criterion is as follows[6]:

(1) Estimate the total amount of damping that will be available, D_{avail}. Murray's estimates of available damping which are based on observation only are shown in Table 2. If the total available damping is greater than 8 to 10%, the beam is satisfactory and further investigation is not necessary.

(2) Compute composite section properties and the first natural frequency of the beam, *f*. If *f* is greater than 10 Hz, the beam is satisfactory regardless of the damping provided.

(3) Compute the initial maximum amplitude of the beam, A_{ot}, due to a standard heel-drop impact as:

[5] $$A_{ot} = (DLF)_{max} \times \left(\frac{L^3}{80EI_t}\right)$$

where all units are in kips and inches and $(DLF)_{max}$ is the dynamic load factor. Values of DLF for various natural frequencies are listed in Table 3.

(4) Account for the stiffness contribution of adjacent beams by estimating the total effective number of beams, N_{eff}, where:

[6] $$N_{eff} = 2.97 - 0.0578\left(\frac{S}{d_e}\right) + 2.56\text{x}10^{-8}\left(\frac{L^4}{I_t}\right)$$

where S is beam spacing and d_e is the effective slab thickness, both in inches (see Figure 7).

(5) Divide A_{ot} by N_{eff} to obtain a modified initial maximum amplitude, A_o, which accounts for the stiffness of adjacent beams:

[7] $$A_o = \frac{A_{ot}}{N_{eff}}$$

(6) Estimate the required level of damping, D_{reqd} as:

[8] $$D_{reqd} = 35A_o f + 2.5$$

(7) Compare values of D_{avail} and D_{reqd}:

[9] If $D_{reqd} \leq D_{avail}$ = = = > The beam is satisfactory

If $D_{reqd} > D_{avail}$ = = = > Redesign is recommended

If the available damping cannot be estimated, Murray suggests the comparison summarized in Table 4.

TABLE 3 --- Dynamic load factors for heel-drop impact.[14]

f, Hz	DLF	F, Hz	DLF	F, Hz	DLF
1.00	0.1541	5.50	0.7819	10.00	1.1770
1.10	0.1695	5.60	0.7937	10.10	1.1831
1.20	0.1847	5.70	0.8053	10.20	1.1891
1.30	0.2000	5.80	0.8168	10.30	1.1949
1.40	0.2152	5.90	0.8282	10.40	1.2007
1.50	0.2304	6.00	0.8394	10.50	1.2065
1.60	0.2456	6.10	0.8505	10.60	1.2121
1.70	0.2607	6.20	0.8615	10.70	1.2177
1.80	0.2758	6.30	0.8723	10.80	1.2231
1.90	0.2908	6.40	0.8830	10.90	1.2285
2.00	0.3058	6.50	0.8936	11.00	1.2339
2.10	0.3207	6.60	0.9040	11.10	1.2391
2.20	0.3356	6.70	0.9143	11.20	1.2443
2.30	0.3504	6.80	0.9244	11.30	1.2494
2.40	0.3651	6.90	0.9344	11.40	1.2545
2.50	0.3798	7.00	0.9443	11.50	1.2594
2.60	0.3945	7.10	0.9540	11.60	1.2643
2.70	0.4091	7.20	0.9635	11.70	1.2692
2.80	0.4236	7.30	0.9729	11.80	1.2740
2.90	0.4380	7.40	0.9821	11.90	1.2787
3.00	0.4524	7.50	0.9912	12.00	1.2834
3.10	0.4667	7.60	1.0002	12.10	1.2879
3.20	0.4809	7.70	1.0090	12.20	1.2925
3.30	0.4950	7.80	1.0176	12.30	1.2970
3.40	0.5091	7.90	1.0261	12.40	1.3014
3.50	0.5231	8.00	1.0345	12.50	1.3058
3.60	0.5369	8.10	1.0428	12.60	1.3101
3.70	0.5507	8.20	1.0509	12.70	1.3143
3.80	0.5645	8.30	1.0588	12.80	1.3185
3.90	0.5781	8.40	1.0667	12.90	1.3227
4.00	0.5916	8.50	1.0744	13.00	1.3268
4.10	0.6050	8.60	1.0820	13.10	1.3308
4.20	0.6184	8.70	1.0895	13.20	1.3348
4.30	0.6316	8.80	1.0969	13.30	1.3388
4.40	0.6448	8.90	1.1041	13.40	1.3427
4.50	0.6578	9.00	1.1113	13.50	1.3466
4.60	0.6707	9.10	1.1183	13.60	1.3504
4.70	0.6835	9.20	1.1252	13.70	1.3541
4.80	0.6962	9.30	1.1321	13.80	1.3579
4.90	0.7088	9.40	1.1388	13.90	1.3615
5.00	0.7213	9.50	1.1434	14.00	1.3652
5.01	0.7337	9.60	1.1519	14.10	1.3688
5.20	0.7459	9.70	1.1583	14.20	1.3723
5.30	0.7580	9.80	1.1647	14.30	1.3758
5.40	0.7700	9.90	1.1709	14.40	1.3793

TABLE 4 --- Required damping comparison chart
(after Murray[12,13,14])

Computed Required Damping Range	Comments
$D_{reqd} \leq 3.5\%$	System will be satisfactory even if supported areas are completely free of fixed partitions.
$3.5\% < D_{reqd} \leq 4.2\%$	Designer must carefully consider the office environment and the intended use.
$D_{reqd} > 4.2\%$	Designer must be able to identify an exact source of damping or artificially provide additional damping to be sure the floor system will be satisfactory. If this can not be accomplished, redesign is necessary.

EXAMPLE 3[6]: Use Murray's acceptability criterion to investigate the adequacy of the floor beam of Example1 for walking induced vibration. This is a floor beam in an office building where the girder and column support motions are small and can be ignored.

SOLUTION:

(1) Estimate available damping:

(Floor at 1%) + (Ceiling at 1%) + (Mechanical at 3%)
= = = = > D_{avail} = 5% < 8% = = = = > Continue the analysis

(2) Calculate natural frequency, *f*:

from EXAMPLE 1: $f = 5.3$ Hz $< 10.$ Hz
Since *f* is less than 10 Hz, the analysis procedure is continued.

(3) Compute the initial maximum amplitude of the beam, A_{ot}:

For $f = 5.3$ Hz from Table 3 $(DLF)_{max} = 0.7580$

$$A_{ot} = (DLF)_{max} \times \left(\frac{L^3}{80EI_t}\right) = (0.7580) \times \left[\frac{(41'\times12)^3}{80(29000)(2648)}\right] = 0.015 \text{ in.}$$

(4) Calculate N_{eff}:

$$N_{eff} = 2.97 - 0.0578\left(\frac{S}{d_e}\right) + 2.56\times10^{-8}\left(\frac{L^4}{I_t}\right) =$$

$$= 2.97 - 0.0578\left(\frac{10'\times12}{4.3"}\right) + 2.56\times10^{-8}\left(\frac{(41'\times12)^4}{2648}\right) = 1.92$$

(5) Calculate the modified initial maximum amplitude, A_o:

$$A_o = \frac{A_{ot}}{N_{eff}} = \frac{0.015 \text{ in}}{1.92} = 0.0078"$$

(6) Estimate D_{reqd}:

$$D_{reqd} = 35A_o f + 2.5 = 35(0.0078)(5.3) + 2.5 = 3.9\%$$

(7) Compare the values of D_{avail} and D_{reqd}:

$$D_{reqd} = 3.9\% \leq D_{avail} = 5.0 \quad ===> \text{The beam is satisfactory}$$

<u>Ellingwood et. al Recommendations for Commercial Environments</u> As a part of a report issued by an Ad Hoc ASCE committee on serviceability research, a vibration criterion for commercial floor systems, for example in shopping centers, was recommended[1,8]. The criterion is considered satisfied if the maximum deflection for a 450 lb force applied anywhere on the floor does not exceed 0.02 inches. Both the Canadian Standards Association[5] and Murray[14] recommend that the natural frequency of commercial floor systems be kept greater than 8 Hz in order to minimize the possibility of resonance due to walking.

EXAMPLE 4: Determine if the floor system of Example 2(b) satisfies Ellingwood et. al. recommendations as a part of a shopping center floor system. Assume the number of effective tee-beams, $N_{eff} = 1.96$.

SOLUTION:

Examine the maximum deflection due to a 450 lb load on the beam:

$$\Delta_{max} = \Delta_{beam} + \frac{\Delta_{girder}}{2} + \frac{\Delta_{support}}{4}$$

$$\Delta_{beam} = \left(\frac{0.450L^3}{48EI_t}\right)\left(\frac{1}{N_{eff}}\right) = \left(\frac{0.450(40'x12)^3}{48x29000x3533}\right)\left(\frac{1}{1.96}\right) = 0.0052 \text{ in.}$$

$$\Delta_{girder} = \left(\frac{0.450L^3}{48EI_t}\right) = \left(\frac{0.450(30'x12)^3}{48x29000x4485}\right) = 0.0034 \text{ in.}$$

$$\Delta_{max} = 0.0052 + \frac{0.0034}{2} + \frac{0.00}{4} = 0.0069 \text{ in.} < 0.020 \text{ in."} \quad ====> \underline{\text{O.K.}}$$

However, since the floor system natural frequency of 3.21 Hz is significantly less than Murray's suggested value of 8.0 Hz, ***<u>redesign is recommended</u>***.

<u>Wiss-Parmelee Rating Factor Criterion</u>

Wiss and Parmelee[18] conducted a laboratory study to investigate human perception of transient floor vibrations. 40 volunteers were subjected to platform motions designed to simulate floor vibrations due to heel-drop impact. An empirical formula was developed which related human response to the floor system's maximum displacement amplitude A_0, the first natural frequency, f, and available damping, D_{avail}, such that:

$$[10] \qquad R = 5.08 \left[\frac{f A_0}{(D_{avail})^{0.217}}\right]^{0.265}$$

where R is the mean response rating, interpreted as follows:

$$[11] \quad R = \begin{Bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{Bmatrix} = \begin{Bmatrix} \text{imperceptible} \\ \text{barely perceptible} \\ \text{distinctly perceptible} \\ \text{strongly perceptible} \\ \text{severe} \end{Bmatrix}$$

The Wiss-Parmelee rating factor was adopted by the United States Department of Housing and Urban Development as a criteria for acceptability of floor systems where a limit of $R \leq 2.5$ was established. The Wiss-Parmelee rating method, which is also referred to as the GSA/PBS acceptability criterion has been criticized for not being sufficiently sensitive to floor system damping[13,17].

EXAMPLE 5: Determine if the floor beam of Example 3 is acceptable according to the GSA/PBS criterion.

SOLUTION: With *f*, A_0, and D_{avail} already known from Example 3, we can directly proceed with calculation of the Wiss-Parmelee rating factor:

$$R = 5.08 \left[\frac{fA_0}{(D_{avail})^{0.217}}\right]^{0.265} = 5.08 \left[\frac{(5.3 \text{ Hz})(0.0078")}{(0.05)^{0.217}}\right]^{0.265} = 2.59 > 2.50$$

= = = = > Beam not acceptable according to GSA/PBS provisions.

Modified Reiher-Meister Scale

As early as 1931, Reiher and Meister reported results of their investigation of human perceptibility to steady state vibration[16]. Their studies covered a forcing frequency range of 3 to 100 Hz and a displacement amplitude range of 0.0004 inches to 0.40 inches. In the early 1960's, Lenzen suggested that if the Reiher-Meister amplitude scale was multiplied by a factor of 10, the resulting scale would be applicable to lightly damped floor systems (damping less than 5% of critical). The resulting scale which correlates human perceptibility with natural frequency and displacement amplitude, is called the Modified Reiher-Meister Scale and is shown in Figure 10. As a result of studies conducted on numerous beams, Murray in a 1975 paper[12] suggested that

> "*steel beam-concrete slab floors with 4% to 10% critical damping which plot above the upper one-half of the distinctly perceptible range will result in complaints from the occupants; and systems in the strongly perceptible range will be unacceptable to both occupants and owners.*"

The Modified Reiher-Meister scale is frequently used by designers along with an additional method (for example Murray's acceptability criterion) to pass judgement on border-line situations. The main criticism of this scale is its lack of explicit consideration of damping, which is considered to be the most important factor involved[11].

EXAMPLE 6: Use the Modified Reiher-Meister scale to determine a vibration perceptibility level for the floor beam of Example 3.

SOLUTION:

With f = 5.3 Hz and A_0 = 0.0078 inches enter the Modified Reiher-Meister chart of Figure 10. The beam plots below the *distinctly perceptible* range and hence is acceptable.

Canadian Standards Association Scale (CSA)

Based on the extensive research work by Allen and Rainer[2] an annoyance criteria for floor vibrations in residential, office and school room environments was adopted by the Canadian Standards Association (CSA) and was included as Appendix G to CSA Standard S16.1-1974 (Steel Structures for Buildings -- Limit States Design). This criteria sets limits on peak acceleration experienced by the floor system in terms of its natural frequency and available damping (see Figure 11).

For design purposes, the peak acceleration, γ may be estimated from the now familiar maximum displacement amplitude, A_0, assuming a harmonic floor response at the floor's first natural frequency:

$$\gamma = (2\pi f)^2 (A_0)$$

The chart in Figure 11 consists of a base curve for continuous vibration, and three limit curves for walking vibration, for 3%, 6%, and 12% available damping. A floor system plotting below the corresponding limit curve is considered satisfactory.

EXAMPLE 7: Use the CSA scale as devised by Allen and Reiner[2] to determine acceptability of the floor beam in Example 3.

SOLUTION: For f = 5.3 Hz and A_0 = 0.0078 inches, estimate the peak acceleration:

$$\gamma = (2\pi f)^2(A_0) = (2\pi \times 5.3)^2(0.0078) = 8.64 \text{ in/sec}^2 = 2.2\ \%g$$

Enter the chart of Figure 11 with these values. The required damping suggested by the chart is less than the 5% provided. Hence, the beam is satisfactory.

Tolaymat's Criterion

Tolaymat[17] reviewed results of 96 composite floor systems studied by Murray as a basis for his acceptability criterion[13], and suggested a new rating system that is claimed to provide a better correlation between test results and reported human perceptibility levels. In contrast to most other methods covered in this section, which are based on study of a single heel drop impact, Tolaymat used a series of impacts to simulate excitation caused by walking humans.

According to this approach, a floor system is rated acceptable if it satisfies one of the following two conditions:

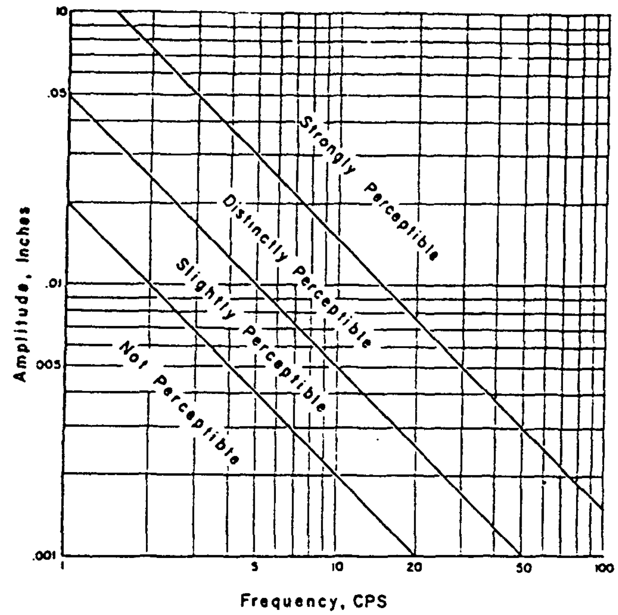


Figure 10. Modified Reiher-Meister perceptibility chart.

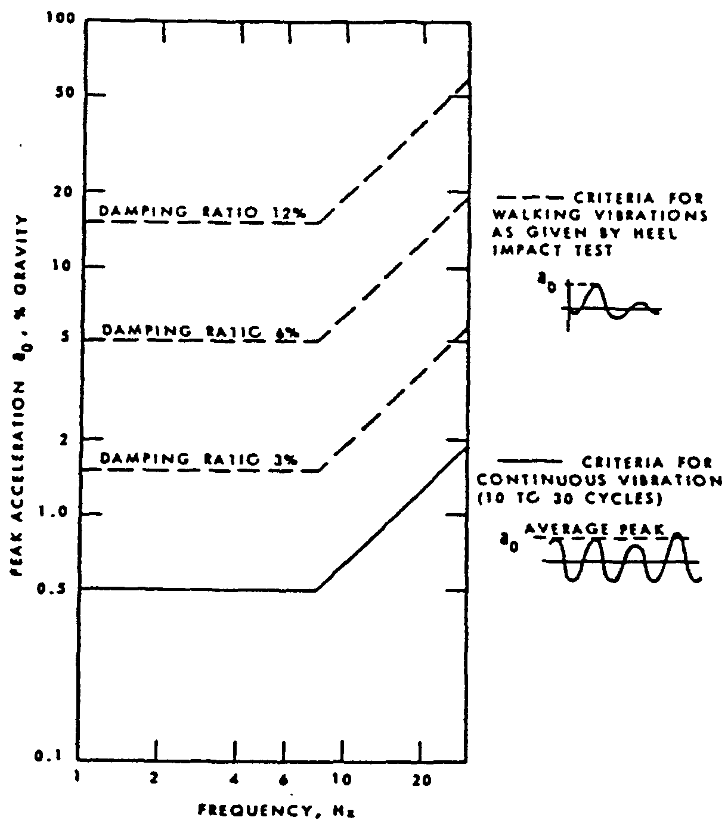


Figure 11. CSA annoyance criteria chart for floor vibrations[2].

[13] (1) $\frac{A_2}{A_0} \leq 1.15$ with $A_{max} \leq 0.015$ in.

[14] (2) $(A_{max}) \times (f) \leq 0.050$

where A_0 and f are as defined previously, A_2 is the second heel drop maximum amplitude and A_{max} is the absolute maximum heel drop amplitude, both in inches. While on the surface the application of this approach seems simple, the reader should be reminded that determination of A_2 and A_{max} ,in general, requires calculation of the dynamic response of a SDOF system (i.e. floor beam) to a general excitation (i.e. a series of heel drop impacts). A procedure not suitable for hand calculations. A rather simple computer program, however, can do the job and a diskette containing one such program accompanies Reference 15.

FLOOR VIBRATION FROM RHYTHMIC ACTIVITIES

Coordinated rhythmic activities such as dancing, audience participation in arenas and concert halls, and most importantly aerobics can result in undesirable levels of vibration. For rhythmic activities, it is resonant or near resonant behavior that results in significant dynamic amplification and hence human discomfort. The most rational design strategy is to provide enough of a gap between the natural frequency of the floor system, and the dominant frequencies excited by planned human activities to reasonably assure that resonance will not occur. Multi-purpose facilities, such as floor systems in aerobics gyms and office space on the same floor, pose the most difficult vibration design task.

Allen[3,4,5] has reported the most comprehensive design guidelines on this subject. His recommendations have been reflected in the recent serviceability criteria supplement to the National Building Code of Canada. Not surprisingly, the material presented in this section is mainly based on information contained in References 3,4, and 5.

While for most rhythmic activities, consideration of the first harmonic (main frequency) of the activity is sufficient, for aerobics and other coordinated jumping exercises, the second and third harmonics can make significant contributions and should be considered in the analysis. Figure 12 shows such a third harmonic resonance which was caused by aerobics activity at 2.25 Hz on a 6.7 Hz floor system[4].

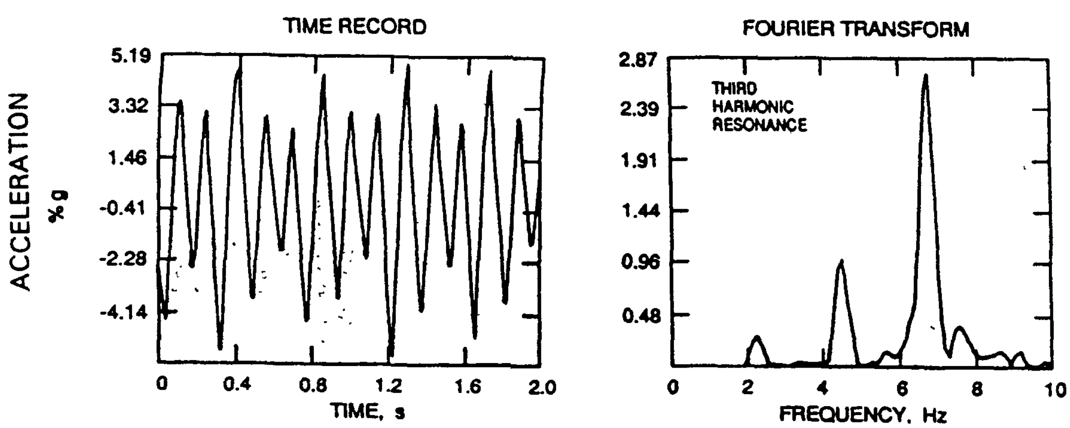


Figure 12. Vibration of a 6.7 Hz floor due to aerobics at 2.25 Hz[4].

According to Allen[5]:

> *"Resonance is the most important factor affecting aerobics vibration, hence natural frequency is the most important structural design parameter. The problem is to get the natural frequency away from the three harmonics."*

Design steps to prevent floor vibration from rhythmic activities may be summarized as follows:

(1) For each type of activity, determine the dominant range of forcing frequency, f_f (see Table 5). Notice that for aerobics and jumping exercises, the first three harmonics should be considered.

(2) Select a maximum acceptable limit for floor acceleration, a_o. Use the values recommended in Table 6, or ISO charts as discussed previously

(3) Select a dynamic load factor, α. See Table 5 for guidance. Estimate the distributed weight of the participants, w_p. When only a portion of span is used for the activity the load w_p can be estimated by taking the total load on the partially loaded span and distributing it uniformly over the entire span. Table 5 may be used to arrive at a reasonable estimate for w_p.

(4) Compute the total floor load, w_t by adding the normally sustained, non-active load and w_p.

(5) Compute the natural frequency of the floor system, *f*, using an appropriate method such as one of the methods discussed in this publication.

(6) Check the following criterion for the minimum natural frequency of the floor system:

[15] $$f \geq f_f \sqrt{1 + \frac{1.3}{a_o/g} \frac{\alpha\, w_p}{w_t}}$$

where a_o/g is the acceleration limit discussed in step 2 above, expressed in percent of gravitational acceleration. The factor 1.3 in [15] is subject to the same discussion provided for [2].

For aerobics and jumping exercises, the first three harmonics of the forcing frequency should be considered. However, since these harmonics add together, the factor 1.3 in [15] should be increased to 2.0. Hence, the governing criterion for aerobics becomes:

[16] $$f \geq (i)(f_f) \sqrt{1 + \frac{2.0}{a_o/g} \frac{\alpha\, w_p}{w_t}}$$

where $i = 1,2,3$ is the harmonic number. Condition [16] should be satisfied for each of the three harmonics.

Furthermore, Allen[3] recommends that floor systems in assembly occupancies that do not meet the minimum natural frequencies of Table 7 should be evaluated more carefully.

TABLE 5 --- Suggested design parameters for rhythmic events[3,4,5].

Activity	Forcing frequency f_f, Hz	Weight of participants* w_p, psf	Dynamic load factor** α	Dynamic load αw_p, psf
Dancing	1.5 - 3.0	12.5 (27 ft^2/couple)	0.5	6.25
Lively concert or sport event	1.5 - 3.0	31.3 (5 ft^2/person)	0.25	7.83
Aerobics				
1st Harmonic	2 - 2.75	4.2 (42 ft^2/person)***	1.5	6.30
2nd Harmonic	4 - 5.50	4.2 (42 ft^2/person)***	0.6	2.52
3rd Harmonic	6 - 8.25	4.2 (42 ft^2/person)***	0.1	0.42

* Density of participants is for commonly encountered conditions. For special events the density of participants can be greater.

** Values of α are based on commonly encountered events involving a minimum of about 20 participants. Values of α should be increased for well-coordinated events (e.g. jump dances) or for fewer than 20 participants.

*** Suggested revision to the 1985 supplement of CSA code[5].

TABLE 6 --- Recommended acceleration limits for vibration due to rhythmic activities[4]

Occupancies affected by the vibration	Acceleration limit, percent gravity
Office and residential	0.4 to 0.7
Dining, Dancing, Weight-lifting	1.5 to 2.5
Aerobics, rhythmic activities only	4 to 7
Mixed use occupancies housing aerobics	2

TABLE 7 --- Minimum recommended natural assembly floor frequencies, Hz[3].

Type of floor construction	Dance floors*, gymnasia**	Stadia, arenas**
Composite (steel - concrete)	9	6
Solid Concrete	7	5
Wood	12	8

* Limiting peak acceleration 0.02 g.

** Limiting peak acceleration 0.05 g.

EXAMPLE 8: Determine the minimum natural frequency needed for a composite floor system in a gymnasium to be used exclusively for aerobics and other similar exercises.

EXAMPLE 8: Determine the minimum natural frequency needed for a composite floor system in a gymnasium to be used exclusively for aerobics and other similar exercises. The total normally sustained load on the floor including the dead weight and the weight of non-participating audience is estimated at 80 pounds per square foot.

SOLUTION: Following the forementioned step-by-step procedure:

(1) From Table 5, select a reasonable value for forcing frequency, say 2.5 Hz.

(2) Since the floor is to be used for aerobics and rhythmic activities only, from Table 6 an acceleration limit of 4% to 7%g is reasonable. For this example we select an acceleration limit of $a_0 = 0.05g$.

(3) We use the suggested values from Table 5 for weight of the participants, dynamic load factors, and dynamic loads. Hence, dynamic loads for the three harmonics are 6.30, 2.52, and 0.42 psf, respectively.

(4) $w_t = w_{D.L.} + w_p = 80 + 4.2 = 84.2$ psf

(5) This step does not apply to this problem.

(6) Check [16] for each of the three harmonics

1st harmonic:

$$f \geq (1)(2.50)\sqrt{1 + \frac{2.0}{0.05}\frac{6.30}{84.2}} = 5.00 \text{ Hz}$$

2nd harmonic:

$$f \geq (2)(2.50)\sqrt{1 + \frac{2.0}{0.05}\frac{2.52}{84.2}} = 7.41 \text{ Hz}$$

3rd harmonic:

$$f \geq (3)(2.50)\sqrt{1 + \frac{2.0}{0.05}\frac{0.42}{84.2}} = 8.21 \text{ Hz} \quad \underline{\text{Controls}}$$

The floor system should be designed to have a first natural frequency larger than 8.21 Hz. Notice that Table 7 suggests a minimum natural frequency of 9 Hz for this case.

ACKNOWLEDGMENTS

The author's work on this publication was sponsored in part by John A. Martin and Associates, Inc. Critical review of the manuscript by Dr. Roger M. DiJulio and Mr. James Marsh is gratefully appreciated.

REFERENCES

[1] Ad Hoc Committee on Serviceability Research, "Structural Serviceability: A Critical Appraisal and Research Needs," *Journal of Structural Engineering*, ASCE, Vol. 112, No. 12, Dec., 1986.

[2] Allen, D.E. and Rainer, J.H., "Vibration Criteria for Long Span Floors," *Canadian Journal of Civil Engineering*, The National Research Council of Canada, Vol. 3, No. 2, Jun., 1976.

[3] Allen, D.E. , Rainer, J.H.and Pernica, G., "Vibration Criteria for Assembly Occupancies," *Canadian Journal of Civil Engineering*, The National Research Council of Canada, Vol 12. No. 3, 617-623, 1985.

[4] Allen, D.E. , "Building Vibrations form Human Activities," *Concrete International: Design and Construction*, American Concrete Institute, Vol 12., No. 6, 66-73, 1990.

[5] Allen, D.E., " Floor Vibrations from Aerobics,"*Canadian Journal of Civil Engineering*, The National Research Council of Canada, Vol 12. No. 3, 617-623, 1985.

[6] AISC Marketing, Inc., "Floor Vibrations in Steel Framed Buildings," Pittsburgh, PA, September, 1989.

[7] Belvins, mm, "Formulas for Natural Frequency and Mode Shapes," Van Nostrand Reinhold, 1979.

[8] Ellingwood, B. and Tallin, M., "Structural Serviceability: Floor Vibrations," *Journal of Structural Engineering*, ASCE, Vol. 110, No. 2, Feb., 1984.

[9] International Organization for Standards, "Evaluation of human exposure to whole-body vibration -- Part 1: General requirements," International Standard ISO-2631/1-1985(E), Geneva, Switzerland.

[10] International Organization for Standards, "Evaluation of human exposure to whole-body vibration -- Part 2: Continuous and shock-induced vibration in buildings (1 to 80 Hz)," International Standard ISO-2631/2-1989(E), Geneva, Switzerland.

[11] Lenzen, K.H., "Vibration of steel joist-Concrete slab Floors," *Engineering Journal*, AISC, Vol. 3., No. 3., 133-136, 1966.

[12] Murray, T.M., "Design to Prevent Floor Vibrations," *Engineering Journal*, AISC, Vol. 12, No. 3., 1975.

[13] Murray, T.M., "Acceptability Criterion for Occupant-Induced Floor Vibrations," *Engineering Journal*, AISC, Vol. 18, No. 2, 62-70, 1981.

[14] Murray, T.M., "Building Floor Vibrations," *T.R. Higgins Lectureship paper* presented at the AISC National Steel Construction Conference, Washington, D.C., June, 1991.

[15] Paz, M, "Microcomputer Aided Engineering -- Structural Dynamics," Van Nostrand Reinhold, 1986.

[16] Reiher, H. and Meister, F.J., "The Effect of Vibration on People," Published in German in 1931, English Translation in Report No. F-TS-616-R.E.H.Q. Air Material Command, Wright Field, Ohio, 1949.

[17] Tolaymat, R. A., "A New Approach to Floor Vibration Analysis," *Engineering Journal*, AISC, Vol. 25, No. 4., 137-143, 1988.

[18] Wiss, J.F. and Parmelee, R.H., "Human Perception of Transient Vibrations," *Journal of the Structural Division*, ASCE, Vol. 100, No. ST4, April, 1974.

STRUCTURAL STEEL EDUCATIONAL COUNCIL

Northern California
1250 Pine St. No. 301
Walnut Creek, CA 94596
(415) 932-0909

Southern California
9420 Telstar Ave. No. 207
El Monte, CA 91731
(818) 444-4519

SPONSORS

The local structural steel industry (above sponsors) stands ready to assist you in determining the most economical solution for your products. Our assistance can range from budget prices, estimated tonnage, cost comparisons, fabrication details, and delivery schedules.

Funding for this publication provided by the California Field Iron Workers Administrative Trust.