Design Chart for Vibration of Office and Residential Floors

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INTRODUCTION

Occupants of some buildings may observe that routine activities cause floors to vibrate noticeably. This may be a consequence of the high strength-to-weight ratio of the structural material and system, and is not necessarily indicative of inadequate strength or excessive deflection. In addition to assuring that a floor satisfies strength and static deflection requirements, the designer should be concerned with vibration perceived by occupants. The chart presented as Fig. 1 facilitates estimating the level of acceptability of the expected vibration of an office or residential floor. The chart implements two acceptance criteria[8,10] of many that have been proposed. Those criteria were developed by determining occupants' perceptions of vibrations caused by routine activities and then correlating those perceptions to measured or predicted levels of vibration caused by heel-drop tests. Application of the criteria embodied in Fig. 1 is limited to quiet but tolerant environments such as offices and residences, and to vibration caused by activities normally associated with those occupancies. In particular, the criteria in the chart may be unconservative for floors supporting precise work such as surgery, and for excitation by vehicles, machinery, or rhythmic activities such as dancing and aerobic exercise.

BACKGROUND

In 1931 Reiher and Meister[11] published a study on human sensitivity to continuous vibration that included empirical functions of amplitude and frequency that define thresholds of various levels of perception. The perceptibility scale for standing persons subjected to vertical vibration suggests a methodology for rating floors.

People are less sensitive to vibration of short duration than to continuous vibration. In order to develop acceptance criteria for transient floor vibration, Lenzen[7] conducted laboratory tests on concrete floors supported on steel joists and also collected data on actual building floors. Based on results of those tests, he modified the Reiher and Meister functions by a factor of 10. However, Lenzen observed that his data supported an alternative interpretation, namely that the floors for which vibrations were barely or not at all perceptible had damping exceeding five percent of critical, and that vibrations were definitely perceptible in floors with damping less than three percent of critical. He stated that "The main factor influencing the effect of vibrations on the human was the damping."

Wiss and Parmelee[12] conducted experiments in which human subjects recorded their responses to the vibration of a shaker on which they stood. The amplitude of vibration first increased over several cycles, peaked, and then decreased over several cycles, with total duration ranging from one-third to five seconds. The rate of decrease in amplitude simulated damping, and that parameter was included in the rating formula that resulted from the study.

D. L. Allen[4] reviewed perceptibility scales for floor vibration and methodology for estimating vibrational response, presented guidelines for estimating damping, and discussed remedial modifications.

D. E. Allen and Rainer[3] developed acceptance criteria for floor vibration based on peak acceleration, frequency, and damping. The criteria were presented as a chart that is applicable to offices, residences, and schoolrooms, and for either

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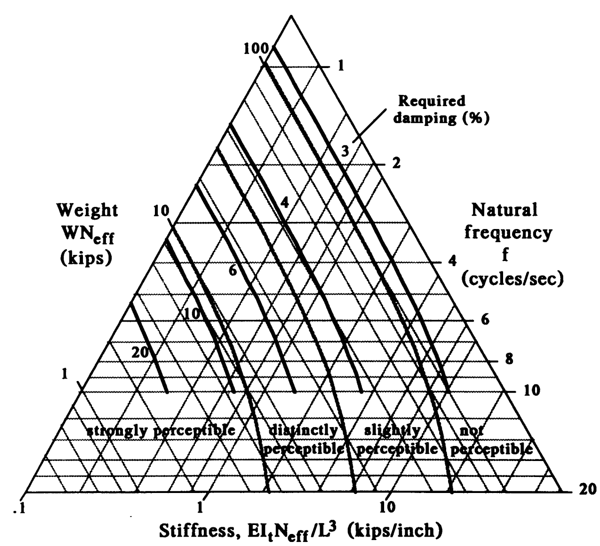

Fig. 1. Perceptibility of vibration, and required damping.

continuous or transient vibration caused by walking and other routine activities. The criteria for transient vibration were developed by correlating subjective evaluations of performance to the measured vibrations caused by heel-drop tests. A heel-drop is the dynamic load caused by a 170- to 190-pound person free-falling about 2.5 inches and landing on both heels. It is represented analytically as the instantaneous application of a 600-pound force that linearly diminishes to zero in 0.05 seconds. Allen and Rainer noted that the strong dependence of acceptability on damping shown by their own studies and those of Lenzen[7] is not supported by the Wiss and Parmelee[12] experiments, which involved isolated transients. Allen and Rainer concluded that "The heel impact test, which produces an isolated transient vibration, should therefore be viewed as providing a correlation between certain dynamic floor properties and acceptability of walking vibrations, not as a direct simulation of the problem."

Murray[10] presented details of a procedure for predicting human response to vibration of a steel beam and concrete slab floor. He gave subjective guidelines for estimating damping and stated that if it exceeds eight to 10 percent of critical, vibration will not be objectionable. For lower values of damping, he linked perceptibility of vibration to the estimated response of the beams, girders, and floor system to a heel-drop, using a chart representing the following four of the six ranges from Lenzen's[7] modification of Reiher and Meister's scale.[11]

$A_o f < 0.018$	vibration is not perceptible	(1)
$0.018 \le A_o f < 0.06$	vibration is slightly perceptible	
$0.06 \le A_o f < 0.18$	vibration is distinctly perceptible	
$0.18 \le A_o f$	vibration is strongly perceptible	

Murray stated that in his experience "...steel beam-concrete floor systems, with relatively open areas and damping between four and 10 percent, which plot above the upper one-half of the distinctly perceptible range, will result in complaints from the occupants and that those systems that plot in the strongly perceptible range will be unacceptable to both occupants and owners." In Eq. 1, f is the fundamental natural frequency in cycles per second and A_o is the deflection amplitude in inches caused by a heel-drop at mid-span. For the small deflections associated with vibration, friction is sufficient to develop composite action. Therefore, natural frequency and deflection amplitude are computed from the transformed composite moment of inertia in which the effective slab width is taken as the sum of the halves of the distances to adjacent beams. A formula was given for computing the number of beams that are effective in resisting the heel-drop. It was suggested that the total weight used in computing natural frequency should include 10 to 25 percent of the design live load in addition to self-weight and other dead load. The formulas for heel-drop deflection amplitude and fundamental natural frequency are, respectively

$$A_o = \frac{0.60(DLF)}{48}\left(\frac{L^3}{EI_t N_{eff}}\right) \tag{2}$$

$$f = 1.57\sqrt{\frac{g}{WN_{eff}}\left(\frac{EI_t N_{eff}}{L^3}\right)} \tag{3}$$

where DLF is the dynamic load factor (from table[9] or formula[10]), L is length of the beam, E is modulus of elasticity of steel, I_t is moment of inertia of the transformed cross section of a beam with composite concrete flange, N_{eff} is the number of beams considered to be effective, g is the acceleration of gravity, and W is the total weight supported by the beam. Units are inches, kips, and seconds. The formulas apply also to girders supporting the beams. The fundamental natural frequency of a beam and girder floor system is computed from an approximation also used by D. L. Allen[4]

$$\frac{1}{f_s^2} = \frac{1}{f_b^2} + \frac{1}{f_g^2} \tag{4}$$

where f_b and f_g are the fundamental natural frequencies of a beam and girder, respectively.

In a later work[8] Murray compared five scales for rating perception of floor vibration, including his own[10] and those based on the work of Wiss and Parmelee[12] and Allen and Rainer.[3] He noted inconsistencies and demonstrated that the performance of real floors could be predicted incorrectly by all of the scales. Based on heel-drop tests of real floors and on owners' and occupants' ratings of those floors, he developed the following criterion

$$\text{If } D > 35A_o f + 2.5\text{, the floor will be acceptable} \tag{5}$$

where D is damping in percent of critical.

The detailed procedure[9] for implementing the criterion includes appropriate formulas and guidelines from an earlier paper.[10] This rating scheme enables a designer to exploit the damping effect of partitions, ceilings, and other attachments.

Acceptance criteria based on heel-drop tests have been correlated only to levels of vibration and tolerance normally associated with offices and residences. For other situations a more general approach is needed. The American National Standards Institute promulgated a standard5 governing evaluation of the measured vibration of a building according to an acceptability threshold that may be adjusted for type of occupancy and for duration and frequency of occurrence of the vibration.

Ellingwood and Tallin[6] explored the dynamic forces and structural responses associated with walking. They also compiled a table of acceptance limits for acceleration of floors for various types of occupancy and for both steady-state and transient vibrations. In order to evaluate the acceptability of a floor design, the designer must predict the amplitudes and frequencies of dynamic floor loads associated with expected uses of the building and then for each load estimate the acceleration response of the floor and compare it to the appropriate acceptance limit. Computation of the acceleration response must include an amplification factor, which can be as high as 20 for lightly damped floors if the frequency of the load matches a natural frequency of the floor. Therefore it is advisable that office and residential floors have fundamental natural frequencies exceeding four cycles per second, which is about the upper limit for footfall frequency of a running human.

Recently D. E. Allen[1,2] focused attention on building vibration caused by aerobic exercise, audience participation, and dancing. He discussed dynamic loads, estimation of vibrational response, acceptance limits, and remedial measures, as well as presenting case studies.

DESIGN CHART

Figure 1 is a chart that implements two acceptability criteria proposed by Murray.[8,10] The criteria, and therefore the chart, are applicable for quiet but tolerant environments such as offices and residences, and to vibration caused by routine human activities normally associated with those occupancies.

The relationship of the three axes is expressed by Eq. 3.

Using Eqs. 2 and 3, the product of the deflection amplitude caused by a heel-drop and the fundamental natural frequency may be written

$$A_o f = \frac{0.386(DLF)}{\sqrt{\left(\frac{EI_t N_{eff}}{L^3}\right)(WN_{eff})}} \quad (6)$$

Equation 6 was used to plot the perceptibility ranges defined by Eq. 1 and damping criteria based on Eq. 5. The latter curves end at a natural frequency of 10 because Murray recommended that his criterion not be used if natural frequency exceeds that value.[9]

The chart is meant to be used in conjunction with Murray's paper,[9] which provides complete instructions for computing the necessary parameters, as well as guidelines for assessing available damping. To use the chart, the designer first computes the stiffness coordinate ($EI_t N_{eff} / L^3$) and the weight coordinate (WN_{eff}), then locates the corresponding point. Fundamental natural frequency (f) is read from the third axis. If fundamental natural frequency does not exceed four cycles per second, redesign is necessary to prevent resonant response to walking or running. The position of the point within a region bounded by the textured curves indicates the estimated perceptibility of vibration for a lightly damped floor. The position of the point relative to the solid lines indicates the damping required to achieve acceptability. If the damping provided by ceilings, partitions, and other attachments will be less than the level required, the design should be modified.

EXAMPLES

Murray[9] investigated an example slab-beam-girder floor system. The following parameters of a beam were given and computed[9]

L = 432 in.
W = 21.87 kip (including 20 percent live load)
I_t = 1,765 in.^{4}
N_{eff} = 1.93

Chart coordinates are

$$WN_{eff} = (21.87)(1.93) = 42.2 \text{ kip}$$

$$\frac{EI_t N_{eff}}{L^3} = \frac{(29 \times 10^3)(1{,}765)(1.93)}{432^3} = 1.23 \text{ kip/in.}$$

Using those coordinates, the designer may read from Fig. 1 that the fundamental natural frequency of a beam is about 5.3 cps, that vibration due to routine activities will be "slightly perceptible" if the beams are lightly damped, and that the vibration will be acceptable for an office, residence, or similar environment if damping of about four percent or more is provided. According to Murray's guidelines,[9] that damping requirement will be satisfied if the beams have directly attached to them partitions, or at least a moderate amount of ductwork and mechanical equipment, or a sheetrock ceiling.

The girder may be analyzed similarly, and Fig. 1 indicates a fundamental natural frequency of about 7.2 cps. The perceptibility rating and damping requirement of the girder are found to be essentially the same as those for the beam. The results for the beam and the girder necessarily match those given by Murray[9] since Fig. 1 is an exact implementation of his methods.

The fundamental natural frequency of the beam and girder system is approximated by Eq. 4

$$f_s = \left(\frac{1}{5.3^2} + \frac{1}{7.2^2}\right)^{-1/2} = 4.3 \text{ cps}$$

The supported weight of the system is taken as that of a girder

$$WN_{eff} = (45.39)(1) = 45.39 \text{ kip}$$

Those two coordinates locate a point on the chart that is in the "slightly perceptible" range and just below the four percent damping requirement. Rather than approximating the weight of the system, Murray[9] approximated the heel-drop response amplitude. For this example the two approaches give similar results but, in general, consistency is not guaranteed. Published observations are insufficient to demonstrate that either approach is correct.

CONCLUSION

Figure 1 is a chart that is useful for estimating the perceptibility of vibration of a steel beam and concrete slab floor being designed for an office or residential building. It is hoped that a graphic representation will provide clearer insight into the relative effectiveness of controlling vibration by increasing stiffness, mass, or damping.

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