Acceptability Criterion for Occupant-Induced Floor Vibrations

THOMAS M. MURRAY

Improved methods of construction and design, which make use of materials with low weight-to-strength ratios, 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 source and sensor, the vibration cannot be isolated as with mechanical equipment and must be controlled by the structural system. In the past, it was possible for the structural designer to safely overlook these vibrations for two reasons. The first and most important is that the vibrations have no effect on the structural integrity of the building. Occupant induced vibrations are so small (initial amplitude from 0.005 to 0.08 in.) they may be ignored structurally. Second, the vibrational response of older floor systems is usually negated by damping in the heavy structural floor system or that associated with closely spaced partitions.

If the response of the completed floor system is such that occupants are uneasy or annoyed, the intended use of the building can be radically affected. The writer is aware of the closing of a new department store because of uncomfortable floor motion and of the complete loss of secretarial efficiency in a new office building due to occupant induced floor vibration. Correcting such situations is usually very difficult and expensive, and success has been limited.[1,16,19] Equally important is the tremendous waste of material in trying to prevent the problem. Most structural designers are acutely aware of potential floor vibration problems, but, until very recently, guidelines were not available to aid in the determination of the suitability of a proposed floor system. As a consequence, design tends to be overly conservative, resulting in heavier than necessary floor systems. The unneeded material in the floor system causes a pyramiding effect because additional material is required in the remaining structural system and foundations to support the added weight.

Vibrating floors have been categorized with respect to human response as follows: (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 it makes occupants ill.[6] A floor system to be acceptable must fall into the first two categories, and the structural designer needs a criterion to determine the suitability of a proposed floor system. Recently four guidelines have been proposed to aid the structural designer.[3,8,17,26] Unfortunately, there is little consistency between the scales, and a floor system may be entirely adequate by one scale and unacceptable by a second. The purpose of this article is to review the existing criteria and to propose a new scale based on the results of field tests of 91 steel joist- and steel beam-concrete slab floor systems.

HUMAN RESPONSE SCALES

Human response to floor motion is a very complex phenomenon, involving the magnitude of the motion, the environment surrounding the sensor, and the sensor himself. A continuous motion (steady-state) may be more annoying than motion caused by an infrequent impact (transient). The threshold of perception of floor motion in a busy office may be higher than in a quiet apartment. The reaction of a senior citizen living on the fiftieth floor might be considerably different from that of a young adult living on the second floor of an apartment complex when subjected to the same motion. Attempts to quantify the response of humans to floor motion have been tried for many years. Three excellent literature reviews have been conducted[7,9,21] representing approximately 1,000 papers on the subject of human response to vibration; however, most of the cited research is concerned with ability to perform when subjected to steady-state or random vibrations associated with automobiles, ships, or airplanes. Very little research has been completed concerning response to motion of building structures. Nearly all of the work has involved the testing of human response using shaketables or the experimental determination of floor motion when subjected to a specific impact. One exception is a 1966 Commonwealth Experimental Building Station study where a vibrator was attached "clandestinely to floors on which a

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Thomas M. Murray is Associate Professor, School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, Oklahoma.

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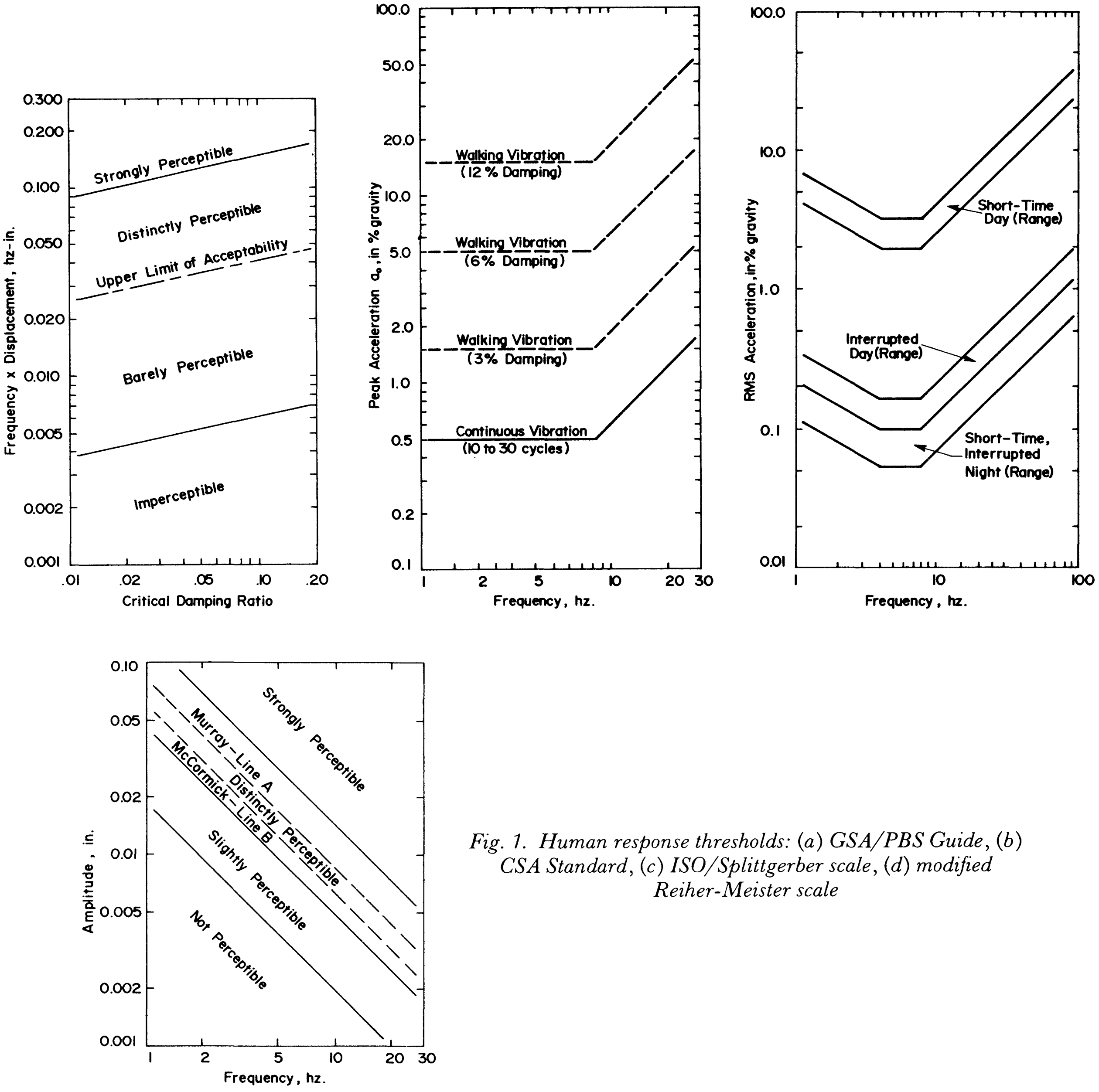

Fig. 1. Human response thresholds: (a) GSA/PBS Guide, (b) CSA Standard, (c) ISO/Splittgerber scale, (d) modified Reiher-Meister scale

variety of unsuspecting subjects indulge in a variety of activities" and the subjective reaction recorded.[11]

The understanding of human response to floor motion is so lacking that the authors of Ref. 7 state, in what almost seems despair, "In fact, not really enough is known to be able to make definitive suggestions to the designers and builders of structures." Still, standards and regulations are being developed to provide guidelines so that lightweight flexible floors can be designed with confidence that future occupants will not complain of annoying vibrations. The U.S. Department of Housing and Urban Development has proposed standards for "Operation Breakthrough," [3] the Canadian Standards Association has included vibration standards in its specification for limit states design,[26] and the International Organization for Standardization has produced a guide for whole body vibration.[8] Each of these standards includes a scale relating subjective human perception to floor motion. In addition, the modified Reiher-Meister scale[25] has been widely used to estimate human reaction to floor vibration. A description and evaluation of the scales currently in use follows.

GSA/PBS Guide—Amendment 4 to Ref. 3 established criteria for the acceptability of floor systems in "Operation Breakthrough" structural systems. The scale is shown in Fig. 1a. A heel-drop impact is to be used to determine frequency and damping, and amplitude is to be determined from an approximately 200 lb man walking at a normal pace (approximately 2 steps per second) along two perpendicular axes across the floor. The heel-drop impact is accomplished by assuming a natural stance with the knees straight, then shifting the weight to the balls of the feet, lifting the heels approximately 2½ in. off the floor, relaxing and allowing the body to fall essentially free to the floor, terminating in an impact. For both tests the motion is to be recorded by using transducers.

The criterion is based on the work of Wiss and Parmelee, who have conducted the only known laboratory study to determine human perception of transient floor vibration.[27] In their study, a total of 40 humans were subjected to a wave-form "designed to simulate vibrations caused in floor systems by one footfall." 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:

$$R = 5.08\,[fA_0/D^{0.217}]^{0.265} \qquad (1)$$

in which R = the mean response rating ($R = 1$ is imperceptible vibration, $R = 2$ is barely perceptible vibration, $R = 3$ is distinctly perceptible vibration, $R = 4$ is strongly perceptible vibration, and $R = 5$ is severe vibration); f = frequency, Hz; A_0 = maximum amplitude, in.; and D = damping ratio. The GSA/PBS criterion is the Wiss-Parmelee mean response rating in graphic form with the limit of acceptability set at $R = 2.5$.

CSA Scale—A human response scale, based on the work of Allen and Rainer,[2] is presented in Appendix G of the Canadian Standards Association Standard, CSA S16, to quantify the annoyance threshold for floor vibrations in residential, school, and office occupancies due to "footstep." The scale is shown in Fig. 1b. Walking test data are to be compared to the annoyance threshold for continuous vibration and heel-drop test data to the remaining thresholds.

Allen and Rainer developed the scale, using data from tests on 42 long span floor systems. Test data for each floor system included initial amplitude from a heel-drop impact, frequency and damping ratio. In addition, a satisfactory or unsatisfactory rating was assigned each system, based on subjective evaluation by occupants or researchers. The systems were grouped with respect to damping: less than 4%, 4% to 8%, and greater than 8%. Each group was plotted, an upper limit of acceptability determined, and the results combined.

Adjusted ISO Scale—The International Organization for Standardization's standard, "Guide for the Evaluation of Human Exposure to Whole-Body Vibration," ISO/OIS 2631 is written to cover many vibration environments.[8] The Guide presents, in graphic form, acceleration limits as a function of exposure time and frequency for both longitudinal and transverse directions for standing, sitting, and lying positions, for mechanical vibrations influencing humans. However, the Guide states: "These limits may not be very powerful in the evaluation of disturbance due to building vibration (for example, caused by traffic or footfall) in private homes, offices or similar situations in which the socio-psychological and economic factors related to human disturbance are more subtle or complex."

Splittgerber in Ref. 4 has proposed adjustments to the Guide to account for building use, type of excitation, and time of day. Splittgerber defines four occupancy classifications, adjusts for night or day occupancy, and considers steady-state, interrupted (less than 2 hours without pause), and short time (1 to 3 vibrations in a 24-hour period) vibrations. The Splittgerber recommendations as interpreted in Ref. 7 are shown in Fig. 1c. Neither Splittgerber nor the ISO Guide provides test methods to be used to excite the floor system for comparison with the threshold recommendations. However, the definitions of "short-time" and "interrupted" seem to apply in a general sense to heel-drop and walking excitations, respectively.

Modified Reiher-Meister Scale—Reiher and Meister in the early 1930's subjected a group of standing people to steady-state vibrations with frequencies of 3 to 100 Hz and amplitudes of 0.0004 to 0.40 in. and recorded their subjective reactions.[25] The results were assessed in varying levels of sensitivity from barely perceptible to intolerable severity and the perception scale developed. After studying a number of steel joist-concrete slab floor systems, Lenzen[12] suggested that the original Reiher-Meister scale is applicable to floor systems with less than 5% critical damping if the amplitude scale is increased by a factor of ten, Fig. 1d. Lenzen did not suggest limits on frequency or amplitude to assure acceptable floors. Murray[17] after testing and analyzing numerous steel beam-concrete slab floors has suggested that systems 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" (line A in Fig. 1d). Both Lenzen and Murray used a single impact to excite the floor systems: Lenzen used both a mechanical impactor and a heel-drop impact. Murray used only the heel-drop impact. The recommendations of Murray are based on the heel-drop impact and cannot be used with any other type of impact.

In 1974 McCormick of the Melbourne Research Laboratories presented a study[14] of design criteria and tests for office floor vibrations. This study was aimed at developing criteria to be used in design of two new steel-framed office towers. After reviewing some literature and performing tests on mockups for the proposed buildings, McCormick concluded that floor systems in which damping exceeds 3% should prove acceptable if below line B in Fig. 1d, although vibrations caused by normal use may be perceptible to the occupants. McCormick also suggests that if damping exceeds about 10%, a higher limit should be possible.

Although the modified Reiher-Meister scale has not been adopted by any code writing body, it is recommended for floor vibration analysis.[6]

Comparison of Scales—The four human response scales are not consistent in units; however, criteria in terms of deflection can be converted to rms acceleration using

$$a_{rms} = a_{peak}/\sqrt{2} = 4/\sqrt{2}\,\pi^2 f^2 \Delta \qquad (2)$$

in which a_{rms} = root mean square acceleration; a_{peak} = peak acceleration; f = frequency, Hz, Δ = deflection amplitude. Conversely, root mean square acceleration can be converted to deflection by

$$\Delta = \sqrt{2}\, a_{rms}/4\pi^2 f^2 \qquad (3)$$

The four scales are compared in Figs. 2a and 2b using root mean square acceleration (rms) and deflection criteria, respectively. The tremendous disparity in threshold levels from the four scales is evident. Floor systems that are acceptable by one scale are rated as intolerable by other scales; consistency is completely lacking.

COMPARISON OF SCALE RATING WITH SUBJECTIVE REACTION

To demonstrate the contradictory results from the various criteria, data recorded on five floor systems are used to obtain human response ratings from each of the scales. The rating is then compared to the subjective response of the building owners, designers, and occupants. The field measurements were obtained by exciting the floor system with a "heel-drop" impact and recording the motion together with timing lines on light-sensitive paper, using an engineering seismograph. A summary of the measurements for the five systems is shown in Table 1.

System 1 (Building 2 in Ref. 22) is a modern three-story office building completed in 1973. The floor system is a concrete slab over a cellular deck supported by welded steel beams and girders fabricated from 50 ksi yield plates. The interior space is completely free of permanent attached partitions. A hung acoustical ceiling was used and there was very little ductwork, resulting in low damping.

Two days after the building was occupied, the writer was asked to make measurements in the building, since secretarial efficiency was very low because of concern caused by floor motion induced by the occupants. Obviously, the subjective reaction to this floor system is "unacceptable"; yet from Fig. 2a or 2b the system is acceptable by the ISO standard, marginally acceptable by GSA/PBS rules, and unacceptable according to CSA. Had the design engineer used the ISO standard he would have assumed that the system was completely satisfactory from a vibration standpoint.

System 2 (Building 5 in Ref. 10) is a large midwestern shopping mall completed in 1975. The floor system is $1\frac{1}{2}$-in. clay tile laid over a $2\frac{1}{2}$-in. concrete slab on metal deck supported by hot-rolled wide flange sections. During construction it was noticed that a portion of the second level floor system exhibited annoying vibrations caused by walking. The owner indicated he would not accept the building unless the situation was corrected, and thus the

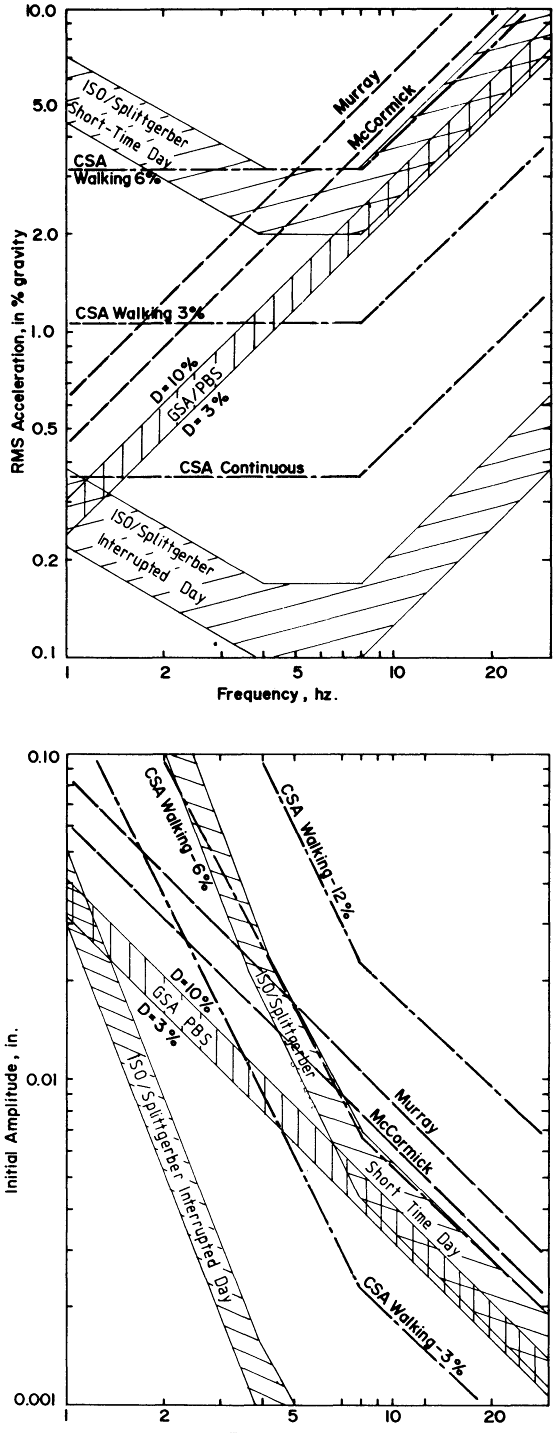

Fig. 2. Comparison of scale thresholds: (a) rms acceleration vs. frequency, (b) initial amplitude vs. frequency

Table 1. Measured data and scale ratings

System	f (Hz)	A_0 (in.)	D % critical	GSA/PBS*	CSA	ISO Splittgerber	Murray	McCormick	Remarks
1	4.0	0.007	2.0	Marginally acceptable	Unacceptable	Acceptable	Not applicable	Not applicable	Vibration resulted in numerous complaints. Structural modification was required.
2	4.7	0.029	1.4	Unacceptable	Unacceptable	Unacceptable	Not applicable	Not applicable	Floor system was unacceptable to building owner and modifications were made.
3	10.6	0.040	10.4	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Floor system is acceptable to owner. No complaints.
4	8.3	0.0038	12.3	Acceptable	Acceptable	Acceptable	Not applicable	Not applicable	Acceptable to owner/ occupants.
5	12.5	0.0046	4.1	Unacceptable	Marginally acceptable	Marginally unacceptable	Acceptable	Acceptable	Acceptable to owner/ occupants.

* GSA/PBS criterion is based on walking amplitude.

floor system must be judged unacceptable. From the measured data in Table 1 and Figs. 2a and 2b, the floor system is rated unacceptable by the GSA/PBS, CSA and ISO criteria. Because of low damping the criteria of Murray and McCormick is not applicable.

System 3 is actually a laboratory mockup of a proprietary dry floor system for use in pre-engineered multi-story office buildings. In spite of the unacceptable ratings from all the criteria included in Table 1, the system was judged satisfactory by the owner and has been placed in production.[17]

System 4 (Building 17 in Ref. 13) is a conventional high-rise office building in a large metropolitan area. The floor slab is 5 in. of lightweight concrete supported by W16x31 A36 steel beams at 9 ft-4 in. o.c. and spanning 28 ft. The occupants had not complained of annoying vibrations prior to the time of testing. Because of high damping, only the GSA/PBS, CSA and ISO scales are applicable, and the system is overdesigned, a typical situation when the design engineer is aware of potential vibration problems but is unaware of how to analyze a proposed floor system.

System 5 (Building 5 in Ref. 13) is similar to System 4. A $4\frac{1}{2}$-in. lightweight concrete slab is supported by W16x36 A36 steel beams at 10 ft-4 in. o.c. and spanning 31 ft. Complaints were not received prior to testing. The floor system is rated acceptable by Murray and McCormick, unacceptable by GSA/PBS, and marginally acceptable by CSA and ISO.

The five floor systems were chosen to demonstrate inconsistencies in the discussed criteria and to serve as a warning to designers who are using the various criteria. Clearly, further research is needed to develop a suitable standard for predicting human response to occupant-induced floor motion. One approach might be an objective evaluation of efficiency in performing a task while subjected to vibration. In the interim, a criterion based on test results of 91 floor systems is proposed.

COMPARISON OF SCALES TO TEST RESULTS

Table 2 is a summary of tests made on 91 steel joist- or steel beam-concrete slab floor systems. In each case the system was excited by a person weighing between 170 lbs and 190 lbs executing a heel-drop impact. The motion of the system was recorded and the initial amplitude A_0 and frequency f obtained from the record. The data were accumulated from several sources and, based on reported subjective evaluation by owners, occupants, and researchers, a rating of either acceptable (A) or unacceptable (U) was assigned to each system. The data shown represent a wide range of floor systems: spans from 23 ft to 95 ft, beam or joist spacing from 2 ft to 24 ft, and concrete slab thicknesses from 2 in. to $7\frac{1}{2}$ in. Tests of cantilever systems, Ref. 10, are also included.

Examination of the data shows a strong dependence of acceptable amplitude on damping. This dependence was first observed by Lenzen[12] in 1963, and confirmed by Murray[17] and Allen and Rainer.[2] Wiss and Parmelee[27] found a much weaker dependence on damping for an isolated transient vibration. Allen and Rainer offer the explanation that Wiss and Parmelee were investigating response due to walking, and at low damping walking vibrations propagate readily and merge to produce a nearly continuous motion which is very annoying to those in quiet situations.

Because of the strong dependence on damping, Figs. 2a and 2b are not suitable for determining trends. For a more clear comparison of the various criteria to test results, the data are shown in Fig. 3: damping D as a percent of critical

Table 2. Test data and subjective evaluations

System	Reference	Span (ft)	Beam Spacing (ft)	Concrete Thickness (in.)	Frequency (Hz)	Initial Amplitude (in.)	Damping (% of critical)	Rating
1	5	24.0	2.0	2.5	5.6	1.0150	9.4	A
2	5	24.0	2.0	2.5	5.9	0.0155	10.9	A
3	5	28.0	2.0	2.5	6.0	1.0100	9.2	A
4	5	24.0	2.0	2.5	9.0	0.0150	8.0	A
5	5	24.0	3.0	3.0	10.0	0.0117	10.2	A
6	5	24.0	3.0	3.0	10.0	0.0120	10.8	A
7	5	24.0	3.0	3.0	9.3	0.0133	8.7	A
8	5	24.0	3.0	3.0	9.8	0.0120	7.1	A
9	5	24.0	3.0	3.0	9.1	0.0050	9.2	A
10	5	24.0	3.0	3.0	11.1	0.0190	10.9	A
11	5	24.0	2.0	3.0	5.9	0.0150	8.3	A
12	5	24.0	2.0	3.0	5.6	0.0140	10.5	A
13	5	24.0	2.0	3.0	5.6	0.0160	9.4	A
14	5	24.0	2.0	3.0	9.1	0.0105	7.3	A
15	5	24.0	2.0	3.0	8.3	0.0105	10.2	A
16	15*	72.8	6.4	3.0	3.6	0.0083	13.0	A
17	15*	30.0	2.0	3.0	4.9	0.0200	5–10	U
18	15*	33.1	2.5	3.0	7.5	0.0087	3.0	U
19	15*	33.1	2.0	3.0	7.5	0.0122	8–15	A
20	15*	28.7	2.0	3.5	8.8	0.0177	3–4	U
21	15*	56.0	3.0	4.0	6.0	0.0136	6.0	U
22	15*	29.3	2.0	4.0	9.0	0.0145	5.0	U
23	15*	38.8	2.0	2.5	5.5	0.0184	6.0	U
24	15*	95.0	7.5	—	2.7	0.0168	2.5	A
25	15*	35.0	2.0	3.0	8.0	0.0110	7.0	U
26	13	30.0	—	5.0	7.7	0.0070	9.4	A
27	13	40.0	10.0	4.5	6.3	0.0072	11.7	A
28	13	54.0	10.0	4.5	4.6	0.0059	8.0	A
29	13	30.0	10.0	5.0	9.9	0.0052	7.9	A
30	13	40.0	10.0	5.0	7.5	0.0052	8.2	A
31	13	54.0	10.0	5.0	7.1	0.0040	8.9	A
32	13	30.0	10.0	4.5	7.5	0.0054	11.1	A
33	13	31.0	10.3	4.5	12.5	0.0060	4.1	A
34	13	25.0	8.5	4.0	7.5	0.0090	9.0	A
35	13	28.5	10.0	4.5	10.8	0.0062	8.0	A
36	13	28.0	7.0	3.0	13.4	0.0050	>14	A
37	13	30.0	7.5	3.0	12.5	0.0068	7.1	A
38	13	25.5	8.5	2.5	15.2	0.0088	7.6	A
39	13	47.6	8.0	5.0	8.0	0.0044	4.1	A
40	13	28.0	9.3	5.0	8.3	0.0038	12.8	A
41	13	30.2	5.9	7.5	9.8	0.0046	6.8	A
42	13	40.5	10.1	7.5	7.2	0.0038	10.1	A
43	13	40.5	10.1	7.5	6.9	0.0036	6.4	A
44	13	32.0	8.0	3.5	6.7	0.0200	2–4	U
45	13	36.0	12.0	5.0	5.0	0.0091	2–4	U
46	20	70.0	—	4.0	4.2	0.0022	13.0	A
47	20	23.0	—	4.5	5.1	0.0041	2.0	U
48	23*	35.0	—	3.0	6.0	0.0136	8.0	U
49	24*	48.0	—	3.0	5.5	0.0103	3.9	A
50	24*	48.0	—	3.0	6.0	0.0122	3.9	A
51	2	45.0	—	3.0	5.0	0.0176	4–8	U
52	2	60.0	—	3.0	5.3	0.0056	1.7	U
53	2	73.3	—	4.5	6.0	0.0019	11–14	A
54	2	45.0	—	5.0	7.5	0.0016	8–11	A
55	2	50.0	—	3.0	6.0	0.0043	5–7	A
56	2	70.7	—	4.5	4.5	0.0024	3.0	A
57	2	61.0	—	2.5	5.0	0.0039	3.0	U
58	22	39.8	10.9	6.3	5.6	0.0088	0	U
59	22	35.9	10.3	6.3	5.2	0.0061	0.7	U
60	22	24.0	10.0	6.3	4.1	0.0068	2.1	U
61	22	24.0	10.0	6.3	4.0	0.0073	1.7	U
62	22	24.0	10.0	6.3	4.1	0.0086	0.4	U
63	22	24.0	10.0	6.3	4.1	0.0062	0.9	U
64	22	40.0	24.0	6.3	4.2	0.0078	4.0	U
65	22	33.3	8.6	—	7.9	0.0101	0.4	U
66	22	25.7	8.6	—	10.4	0.0069	1.6	U
67	22	25.7	8.6	—	11.9	0.0078	0	U
68	22	33.3	8.6	—	8.5	0.0088	0	U
69	22	33.3	8.6	—	7.9	0.0060	0.5	U
70	22	33.3	8.5	—	7.6	0.0095	2.7	U
71	22	33.3	8.6	—	7.8	0.0090	0.8	U
72	22	49.0	12.3	5.5	5.7	0.0041	1.5	U
73	22	49.0	12.3	5.5	5.6	0.0051	1.2	U
74	22	32.9	8.0	5.5	7.4	0.0064	5.3	A
75	22	32.9	8.0	5.5	7.4	0.0070	0.8	U
76	22	32.9	8.0	5.5	7.3	0.0052	0	U
77	22	32.9	6.0	5.5	8.1	0.0077	2.6	U
78	10	10.4**	24.0	Risers	5.5	0.022	2.3	U
79	10	10.4**	24.0	Risers	5.4	0.027	2.9	U
80	10	16.3**	—	Risers	5.9	0.021	3.5	U
81	10	8.5**	—	2.5	9.7	0.023	4.2	U
82	10	9.8**	15.5	Risers	7.9	0.055	6.8	U
83	10	9.8**	15.5	Risers	9.1	0.059	5.5	U
84	10	11.4**	—	Risers	6.6	0.025	2.7	U
85	10	11.4**	—	Risers	6.8	0.025	0	U
86	10	13.2**	—	Risers	6.8	0.018	2.3	U
87	10	16.0**	—	Risers	6.9	0.013	2.4	U
88	10	14.0**	2.6	4.0	4.7	0.029	1.4	U
89	10	8.0**	2.6	4.0	6.3	0.025	5.2	U
90	10	27.7**	7.0	5.3	10.6	0.018	4.5	A
91	10	27.7**	7.0	5.3	10.6	0.009	4.6	A

* As reported in Reference 2

** Length of cantilever

A = acceptable, U = unacceptable

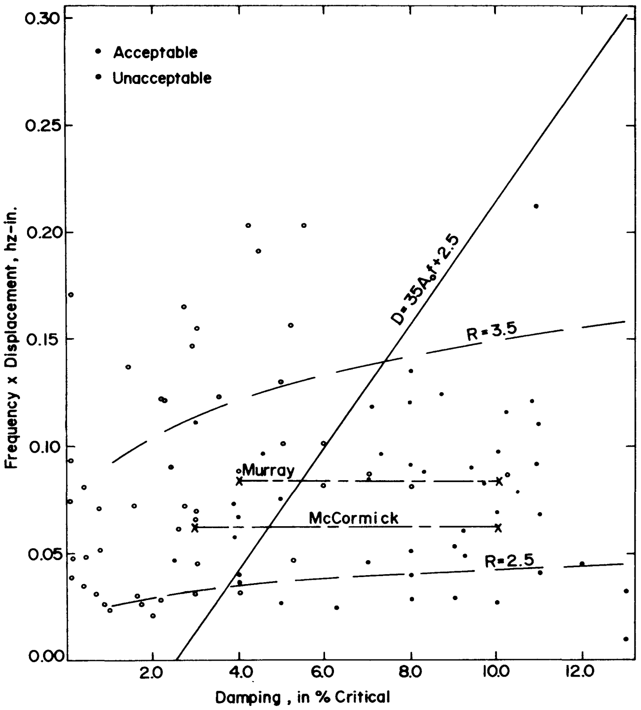

Fig. 3. Comparison of scale ratings with subjective reaction

damping versus the product A_0f. The acceptability criteria proposed by Murray[17] and McCormick[14] and the limits of the distinctly perceptible range of the Wiss-Parmelee formula,[27] and the lower limit $R = 2.5$ of the GSA/PBS criterion for accepitibility for walking amplitudes, are also shown. The CSA acceptability lines cannot be converted to this plot and damping is not a parameter in the ISO/Splittgerber criterion.

It is obvious that none of the three criteria give acceptable results over the entire data range. It appears that Murray's criterion is valid for damping only between 4 and 6% of critical, not 4 to 10% as was suggested in Ref. 17, although it is conservative for damping above 6%. McCormick's criterion is very conservative for damping above 4%, but not conservative between 3 and 4%. As previously mentioned, the Wiss-Parmelee regression formula does not appear to be sufficiently sensitive to damping.

PROPOSED CRITERION AND APPLICATION

It is clear from Fig. 3 that the damping parameter D tends to separate the acceptable from unacceptable systems; acceptability has a very strong dependence on damping. In fact, it may be stated that systems with greater than 5.5 to 6% damping will be acceptable and those with less will be unacceptable. It is noted that this is basically the same as found by Lenzen in 1963 when he stated[12]: "If the floor was damped to a small amplitude prior to five cycles of oscillation, the occupant felt only the initial impact, no vibration." Small amplitude was defined to be less than 20% of the initial amplitude and corresponds to greater than 5% damping.

A more accurate division of acceptable and unacceptable floor systems is given by

$$D = 35\,A_0 f + 2.5 \tag{4}$$

where D = percent of critical damping, A_0 = initial amplitude from a heel-drop impact, in. and f = first natural frequency of the floor system, Hz. The line defined by Eq. (4) was determined by a manual best fit of the data and has a strong dependence on damping (Fig. 3). (An attempt was made to fit the line using the statistical technique of discriminant analysis for two groups. This analysis requires multivariate normal distributions within the two populations, which is not satisfied by the data in Table 2. Most of the data presented were obtained from floor systems that could be used to develop an acceptable/unacceptable criterion; very stiff systems or systems with high damping, greater than 12%, were not tested.)

Figure 4 shows Eq. (4) plotted for constant damping against frequency versus initial amplitude. Lines for constant damping are parallel with the Murray and McCormick criteria, indicating that those criteria are valid only for specific damping values. There is significant difference between Eq. (4) and the CSA criteria. The break in the CSA lines results from Allen and Rainer's assumption that criteria for transient vibrations should parallel criteria steady-state vibration.[2]

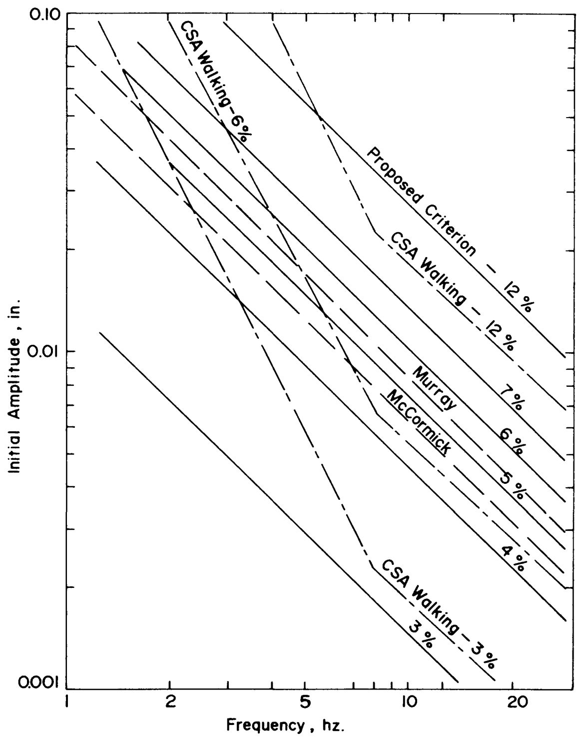

Fig. 4. Comparison of proposed and existing human response thresholds

Based on the results presented here, it is proposed that the criterion for acceptable steel beam- or steel joist-concrete slab floor systems subject to occupant induced floor vibrations be

$$D \geqslant 35\, A_0 f + 2.5 \qquad (5)$$

Methods for estimating the three parameters are available in the literature: frequency of supported systems in Refs. 6 and 17 and cantilevered systems in Ref. 18, initial amplitude due to a heel-drop impact of steel joist systems in Ref. 6 and steel beam systems in Refs. 17 and 26, and damping in Refs. 17 and 26. Cantilevered systems are discussed in Ref. 18.

SUMMARY AND CONCLUSIONS

Various scales for determining the acceptability of steel beam- and steel joist-concrete slab floor systems subject to occupant-induced floor vibrations have been reviewed and compared. The scales were shown to be inconsistent and, in general, to underestimate the strong dependence of acceptability on damping. A new criterion, based on experimental results from 91 floor systems, was presented. The proposed criterion is strongly dependent on damping and is suitable for design office use for evaluating the acceptability of steel beam or joist-concrete slab floor systems subject to occupant-induced vibrations.

The proposed criterion is strictly applicable to steel beam- or steel joist-concrete slab floor systems and is not necessarily applicable to other types of construction, particularly wood systems. Other systems may cause completely different psychological responses because of long-time conditioning or expected feel.*

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* *For example: Most residential floor systems constructed of wood probably do not satisfy the proposed criteria, yet are completely acceptable. One explanation is that wood systems are expected to vibrate and are therefore acceptable, whereas, concrete slab systems are not expected to move noticeably and may be unacceptable.*

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