NRC Publications Archive
Archives des publications du CNRC

Vibration criteria for long-span floors

Allen, D. E.; Rainer, J. H.

This publication could be one of several versions: author’s original, accepted manuscript or the publisher’s version. / La version de cette publication peut être l’une des suivantes : la version prépublication de l’auteur, la version acceptée du manuscrit ou la version de l’éditeur.

Publisher’s version / Version de l'éditeur:

Canadian Journal of Civil Engineering, 3, 2, pp. 165-173, 1976-06

NRC Publications Record / Notice d'Archives des publications de CNRC:
https://nrc-publications.canada.ca/eng/view/object/?id=cda03e19-8250-4ac2-8e1c-587ec3ef030f
https://publications-cnrc.canada.ca/fra/voir/objet/?id=cda03e19-8250-4ac2-8e1c-587ec3ef030f

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L’accès à ce site Web et l’utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D’UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n’arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada
Conseil national de recherches Canada

5275

ANALYZED

NATIONAL RESEARCH COUNCIL OF CANADA
CONSEIL NATIONAL DE RECHERCHES DU CANADA

VIBRATION CRITERIA FOR LONG-SPAN FLOORS

BY D. E. ALLEN AND J. H. RAINER

Reprinted from
CANADIAN JOURNAL OF CIVIL ENGINEERING
Vol. 3, No. 2, June 1976
9 p.

DBR Paper No. 668
DIVISION OF BUILDING RESEARCH

Price 25 cents OTTAWA NRCC 15207

Canadian Journal of Civil Engineering
Published by
THE NATIONAL RESEARCH COUNCIL OF CANADA

Revue canadienne de génie civil
Publiée par
LE CONSEIL NATIONAL DE RECHERCHES DU CANADA

Volume 3 Number 2 June 1976
Volume 3 numéro 2 juin 1976

Vibration criteria for long-span floors

D. E. ALLEN[1] AND J. H. RAINER[2]
Division of Building Research, National Research Council of Canada, Ottawa, Canada K1A 0R6

Received July 30, 1975
Accepted December 23, 1975

Annoyance criteria are derived for walking vibrations of long-span floors. The criteria are developed primarily for steel beam or joist construction with concrete deck, spans greater than about 25 ft (8 m) and natural frequencies less than about 10 Hz. The criteria are expressed in terms of the dynamic properties of a floor as measured by a heel impact test. The advantage of the heel impact test is that it provides a tool for design calculation.

Les auteurs obtiennent des critères de nuisance pour les vibrations dues aux pas dans les planchers de grande portée. Les critères se rapportent surtout aux constructions de poutres ou de solives d'acier avec un tablier de béton, des travées de plus de 25 pieds (8 m) environ et des fréquences naturelles de moins de 10 Hz environ. Les critères sont exprimés en fonction des caractéristiques dynamiques d'un plancher mesurées par un essai d'impact de talon, qui offre l'avantage d'être un instrument de calcul.

Can. J. Civ. Eng., 3, 165 (1976)

Introduction

Floors vibrate when people walk on them. These vibrations have been controlled in the past for conventional building floors by well-known stiffness criteria such as limiting the deflection under live load to span/360 or limiting the ratio of span to depth of a supporting steel beam to 20. Recently, however, excessive footstep vibrations have occurred for long-span steel beam or joist floors with a concrete deck used in conjunction with open floor plans, free of partitions. The traditional stiffness criteria have been found inapplicable to these floors because they are not related to the motion of the floor which a person feels. Existing criteria also neglect damping—a structural property that has been found to be the most significant one affecting the performance of long-span floors to walking vibrations.

This paper presents annoyance criteria for walking vibrations for long-span floors in terms of floor acceleration and damping. The criteria were developed for CSA Standard S16.1–1974 (Steel Structures for Buildings—Limit States Design) and are contained in Appendix G to the standard. The suggested criteria, which are an extension to those presented by Lenzen (1966), are based on the experience of various investigators with long-span floors. Because of limited data the criteria are proposed only on an interim basis.

The criteria for acceptable floor vibrations presented here are intended for normal 'quiet' human occupancies, *i.e.* residences, offices, and schoolrooms. More stringent criteria may be required for sensitive occupancies such as hospital operating rooms and laboratories, and

---

[1] Building Structures Section.
[2] Noise and Vibration Section.

3436045

less stringent criteria for manufacturing work areas, footbridges, dance halls, gymnasia, and similar occupancies.

Criterion for Continuous Vibrations

Continuous vibrations considered here are those that persist at a reasonably constant amplitude and frequency for a short duration, approximately 10 to 30 cycles. Such vibrations can arise from dancing, regular jumping, or street traffic. Continuous vibration for hours caused by machinery will require a more severe criterion for the same type of occupancy.

Figure 1 shows ranges of perception and criteria for continuous vibration presented by various investigators: (a) the 'distinctly perceptible' range for vibrations of 5 min duration by Reiher and Meister (1931); (b) the 'distinctly perceptible' range for vibrations of 5 s duration by Wiss and Parmelee (1974); (c) 'perceptible' level of building vibrations given in the German Standard DIN 4150; (d) criterion suggested by Splittgerber based on a modification of International Standard ISO 2631 curve for an 8 h exposure (Galambos *et al.* 1973). Also shown in Fig. 1 is the authors' proposed annoyance criterion for residences, offices and schoolrooms (10 to 30 cycles), which is based primarily on the data points for three case studies.

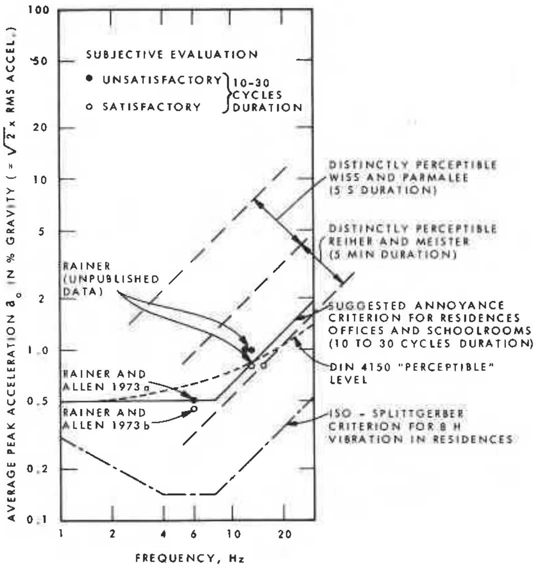

FIG. 1. Human response criteria for continuous vibration.

A comparison of the various levels of perception and criteria in Fig. 1 shows the same general trend, but little agreement among the various sources. These differences can be attributed to: different vibration durations (10 cycles to 8 h); different occupancies (*e.g.* office *vs.* manufacturing); and different methods of testing and evaluating the results. It has been the authors' experience that continuous vibrations in 'quiet' human occupancies cause annoyance when they begin to be distinctly perceptible. The proposed annoyance criterion approaches the lower bound of the Reiher and Meister 'distinctly perceptible' range.

Criteria for Walking Vibrations

If a person walks across a floor, vibrations are initiated at approximately $\frac{1}{2}$ s intervals. Experience with long-span floors has shown that the higher modes of vibration need not be considered because they die out quickly and do not cause discomfort. If the floor vibrating in one or more of its lower modes has little damping, the induced vibrations merge together resulting in an almost continuous motion. The resulting degree of discomfort can be estimated by comparing peak accelerations due to walking with those corresponding to the proposed annoyance criterion in Fig. 1. There are, however, two shortcomings in this approach. The first is that the damping is usually sufficient to prevent continuity of motion. The second, that although such a procedure could be used in a performance test of a built floor system, it is not amenable to design calculation.

In order to overcome these difficulties the heel impact test will be used to evaluate the dynamic properties of long-span floors. These properties will then be correlated with subjective evaluations from which performance criteria will subsequently be derived. The heel impact test not only provides a means of evaluating floor performance but can also be modelled analytically to provide a loading function for design. The test is as follows:

A person weighing approximately 170 lb (760 N) supports his weight on the balls of his feet with the heels raised about 2.5 in. (64 mm), then suddenly drops his weight on his heels to the floor.

A typical acceleration trace of the resulting floor response is shown in Fig. 2. The signal has been filtered so that only the vibrations of the fundamental mode are retained, since, as stated above, the higher modes die out quickly and do not cause discomfort.

The following parameters, shown in Fig. 2, can be determined from the response curve: natural frequency (f), damping ratio (β), and initial peak acceleration (a_0). While the response curve is usually quite regular, some floors will produce a more irregular response, and their interpretation will require some judgement.

Table 1 gives field data from various investigators on the response of long-span steel and concrete floors to heel impact as well as their subjective evaluation for walking vibrations. The floors have been grouped according to the damping ratios measured during heel impact tests as follows: $\beta < 4\%$; $4\% \leqslant \beta \leqslant 8\%$; $\beta > 8\%$. For each group, measured peak accelerations from heel impact are plotted in Figs. 3, 4, and 5 along with subjective evaluation of the floors to walking vibration. The data are also plotted in terms of peak accelerations calculated by a method described later.

The data in Figs. 3, 4, and 5 indicate: (1) a good correlation between initial peak acceleration from heel impact and acceptability to footstep vibrations within a range of damping; and (2) a strong dependence of acceptability to footstep vibrations on damping. Criteria for 3, 6, and 12% damping, shown by the dashed lines, were estimated by shifting the curve for continuous vibration in Fig. 1 up to fit the data; the peak accelerations associated with the criteria are respectively 3, 10, and 30 times the level for continuous vibrations. The criterion for 6% damping agrees with the criterion of Lenzen (1966), who multiplied the Reiher and Meister curves for continuous vibration by 10 to obtain curves for finished floor systems without partitions (where $\beta \simeq 6\%$ above) when using the heel impact test.

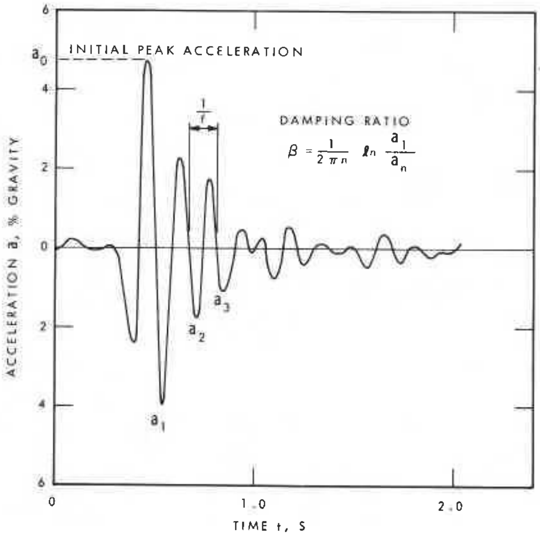

FIG. 2. Typical floor response to heel impact (high frequencies filtered out).

The strong dependence of acceptable floor acceleration on damping, first shown by Lenzen (1966), does not at first appear to be borne out by human response to isolated transient vibrations. Wiss and Parmelee (1974) found a much weaker dependence of acceptable peak acceleration on damping for an isolated transient vibration. The reason for this, however, may be due to the fact that for low damping, the vibrations from walking propagate readily and merge together to produce a nearly continuous motion, which is very annoying to those in quiet situations. 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.

The suggested criteria for long-span floors do not apply to lighter short-span floors. For short-span floors the persons involved, both the one causing and the one feeling the vibration, interact with the floor to damp out the vibration quickly. For these floors, the motion due to static deflections of the walker has more effect on human response than the transient vibrations in the fundamental mode; static deflection criteria under concentrated load therefore appear to be more appropriate in these cases.

The criteria for continuous vibration and for walking, which apply to long-span floors in 'quiet' occupancies, are summarized in Fig. 6.

Prediction of Performance by Design Calculation

Performance of a long-span floor subject to

TABLE 1. Floor test data

Item No.	Source	Type of construction	Span L (ft)	Span / Joist depth	Effective concrete thickness t_c (in.)	Measured frequency f (Hz)	Measured damping from heel impact β (% critical)	Peak acceleration from heel impact a_o, (%g)		Subjective evaluation of floor performance
								Measured	Calculated [3]	
1	Rainer and Allen (1973*a*)	Joist	35	21	3	6	8	5	5	U
2	Rainer and Allen (1973*b*)	Joist	48	18	3	5.5	3.9	3.2	3.3	S
3	Rainer and Allen (1973*b*)	Joist	48	18	3	6	3.9	4.5	3.6	S
4	Allen, D. L. (private comm.)	Joist on girders	45	15	3	5	4–8	3–6	3.3	U
5	Allen, D. L. (private comm.)	Joist–Composite	60	20	3	5.3	1.7	1.4–1.7	2.6	U
6	Allen, D. L. (private comm.)	Lin-T's	73.3	21	4.5	6	11–14	0.7	1.2	S
7	Allen, D. L. (private comm.)	Beam–Composite	45	22	5	7.5	8–11	0.9	1.9	S
8	Allen, D. L. (private comm.)	Joist	50	17	3	6	5–7	1.6	3.5	S
9	Allen, D. L. (private comm.)	Beam–Composite	70.7	35	4.5	4.5	3	0.5	0.9	S
10	Allen, D. L. (private comm.)	Joist	61	17	2.5	5	3	1.0	3.3	U
11	Nelson (1970)	Beam on girder (floating floor)	70	23	4	4.2	≃13	0.4	<1	S
12	Nelson (1970)	Beam	23	4	4.5	5.1	2	1.1	1.5	U
13	Moderow (1970, A)	Joist	72.8	21	3	3.6	4	1.1	1.4	S
14	Moderow (1970, B)	Joist on girders	30	16	3	4.9	5–10	5	5.6	U
15	Moderow (1970, C)	Joist on girders	33.1	15	3	7.5	3	5	6.6	U*
16	Moderow (1970, D)	Joist on girders	33.1	15	3	7.5	8–15	7	6.6	S*
17	Moderow (1970, E)	Joist composite	28.7	17	3.5	8.8	3–4	14	7	U
18	Moderow (1970, E)	Joist	56	17	4	6	6	5	2	B*
19	Moderow (1970, F)	Joist	29.3	20	4	9	5	12	7	U*
20	Moderow (1970, G)	Joist on girders	38.8	21	2.5	5.5	6	5.7	5.7	U
21	Moderow (1970, H)	Joist	95			2.75	2.5	1.3		S
22	Moderow (1970, I)	Joist	35	21	3	8	7	7.2	6.7	U*
23	Lenzen and Murray (1969, 1)	Beam–Composite	30	23	5 LW	7.7	9	4.2	3.9	S
24	Lenzen and Murray (1969, 3-1)	Beam–Composite	54	21	4	4.6	8	1.3	1.5	S
25	Lenzen and Murray (1969, 3-2)	Beam–Composite	40	30	4	6.3	12	2.9	2.9	S
26	Lenzen and Murray (1969, 3-4)	Beam–Composite	30	23	4	9.9	8	5.2	5.8	S
27	Lenzen and Murray (1969, 3-6)	Beam–Composite	40	27	4	7.5	8	3.0	3.3	S
28	Lenzen and Murray (1969, 3-7)	Beam–Composite	54	21	4	7.1	9	2.1	2.3	S
29	Lenzen and Murray (1969, 4)	Beam–Composite	30	23	4.5 LW	7.5	11	3.1	4.5	S
30	Lenzen and Murray (1969, 5)	Beam–Composite	31	23	4.5 LW	12.5	>5	9.6	7.3	S
31	Lenzen and Murray (1969, 6)	Beam–Composite	25	25	4 LW	7.5	11	5.2	6.7	S
32	Lenzen and Murray (1969, 8)	Beam–Composite	28.5	21	4.5 LW	10.8	>4	7.4	6.9	S
33	Lenzen and Murray (1969, 10)	Beam–non Composite	30	20	3 LW	12.5	7	11	16	S
34	Lenzen and Murray (1969, 11)	Beam–non Composite	28	21	3 LW	13	>10	9	17	S
35	Lenzen and Murray (1969, 15)	Beam–non Composite	23.3	17	3 LW	16	>10	16	26	S
36	Lenzen and Murray (1969, 16)	Beam–Composite	47.6	27	5	8.2	4	3	2	S
37	Lenzen and Murray (1969, 17)	Beam–Composite	28	21	5 LW	8.3	13	2.7	4.4	S
38	Lenzen and Murray (1969, 18-4)	Beam–Composite	30.3	30	6.5	9.8	7	4.5	2.3	S
39	Lenzen and Murray (1969, 18-10)	Beam–Composite	40.5	27	6.5	7.2	10	2.0	1.3	S
40	Lenzen and Murray (1969, 18-12)	Beam–Composite	40.5	27	6.5	6.9	6.5	1.7	1.2	S
41	Lenzen and Murray (1969, 19)	Beam–Composite	32		3.5	6.7C	2–4		4.6	U
42	Lenzen and Murray (1969, 20)	Beam–Composite	36	27	5 LW	5.0	2–4	2.3	2.1	U

NOTES: U = unsatisfactory, S = satisfactory, B = borderline, * = subjective evaluation inferred from test report, LW = lightweight concrete, and C = calculated.

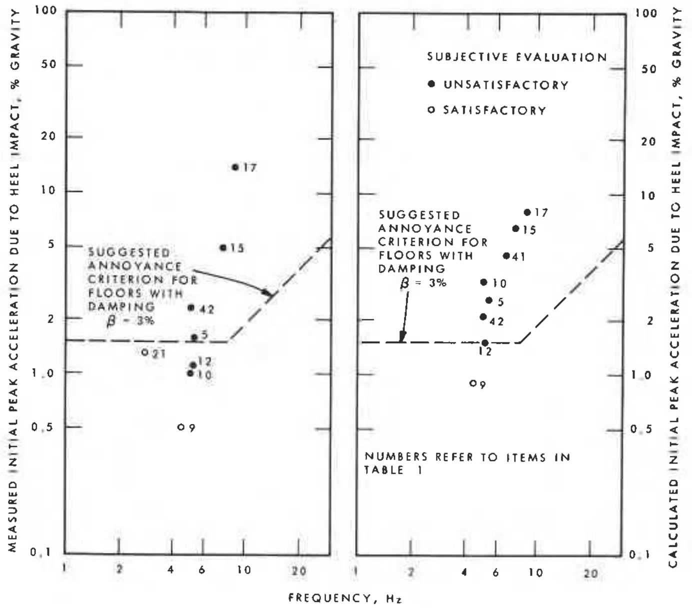

FIG. 3. Heel impact tests of floors: damping $\beta < 4\%$.

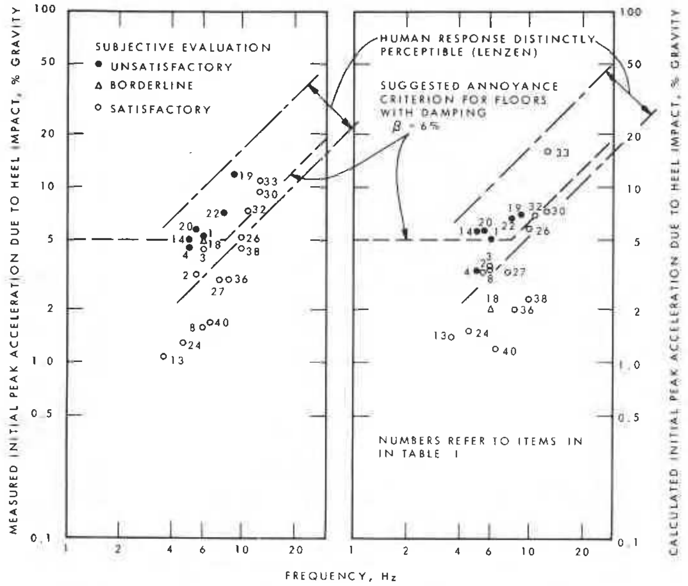

FIG. 4. Heel impact tests of floors: damping $\beta = 4$ to 8%.

walking vibrations can be predicted using Fig. 6 in terms of frequency, damping, and initial peak acceleration due to heel impact. For design these parameters are estimated as follows. They are derived for concrete deck floors on steel beams or joists but the same approach can also be used for other types of construction.

(a) The natural *frequency* f (Hz) of simply-supported, one-way steel and concrete

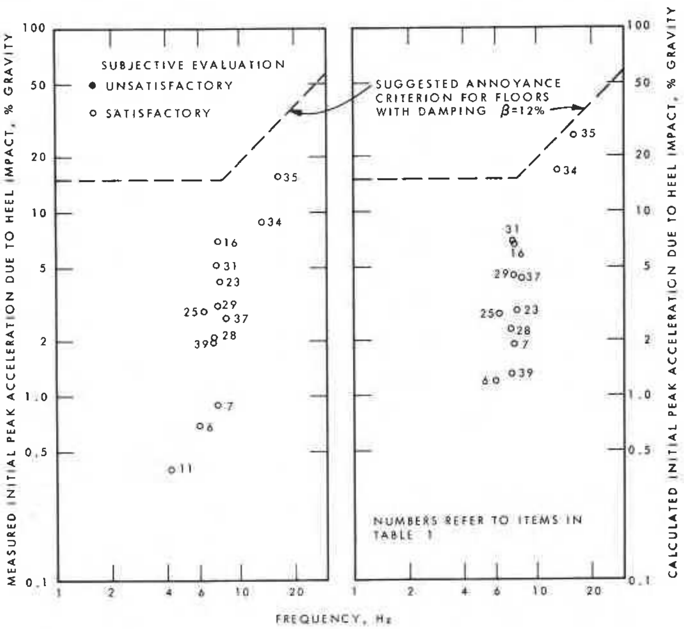

FIG. 5. Heel impact tests of floors: damping $\beta > 8\%$.

floors can be calculated from

$$[1]\quad f = 31\sqrt{\frac{EI}{wL^4}}$$

$$\left(= 0.0049\sqrt{\frac{EI}{wL^4}}\ \text{in SI units}\right)$$

where E = modulus of elasticity of steel, psi (kN/mm^2), I = moment of inertia, in.^{4} (mm^4), w = dead weight, lb/in. (kN/m), L = span, in. (m).

Experience has shown that the steel and concrete deck usually acts compositely under dynamic loading, even for construction not structurally designed for composite action: I in [1] is usually determined, therefore, on the basis of full composite action. Special considerations are required in determining the frequency of more complex floor systems, *e.g.*, one-way systems supported on girders.

(b) *Damping* of a floor system must be estimated. The following values, based on experience with existing long-span concrete deck floors on steel beams or joists, are suggested: bare floor, $\beta = 3\%$; finished floor—with ceilings, ducts, flooring, and furniture, $\beta = 6\%$; and finished floor with partitions, $\beta = 12\%$. Further guidance for the estimation of damping is given by Allen (1974).

Human beings also contribute to the damping, especially for light floors as discussed previously, or when there are many persons on a long-span floor.

(c) One of the advantages of the heel impact test is that it provides a loading function for calculating floor response; *initial peak acceleration* can be estimated as follows.

Figure 7 shows the measured force–time relationship for heel impact (Lenzen and Murray 1969). This relationship can be approximated by a triangular loading function with initial peak load of 600 lb (2.67 kN) lasting 1/20 s. For a floor system vibrating in its fundamental mode the loading function can further be approximated by an impulse I of 15 lb-s (67 kN-s), provided the floor frequency is less than about 10 Hz. The resulting velocity $\dot{x}$ of an equivalent simple oscillator of mass M is given by

$$\dot{x} = \frac{I}{M}e^{-2\pi f t\beta}\cdot\sin 2\pi f t$$

For small values of damping the initial peak acceleration, which occurs at $2\pi ft = \pi/2$, is

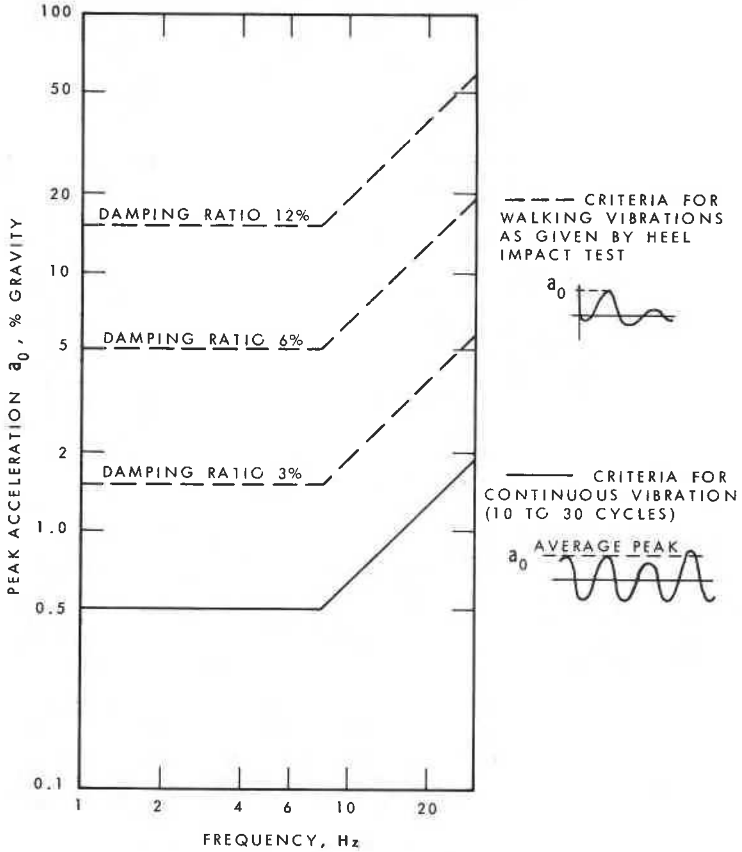

FIG. 6. Annoyance criteria for floor vibrations: residences, offices, and schoolrooms.

closely approximated by

$$[2] \qquad a_0 \simeq \frac{2\pi f I}{M}(0.9)$$

The mass M is determined by assuming an isolated vibrating floor panel whose dimensions correspond to the nodal lines of vibration in the fundamental mode. The width of such a panel can be approximated by[3] 60 t_c, where t_c is the effective thickness[4] of the concrete slab in inches. The weight of the steel beam or joist, ceiling, and flooring is estimated to be 12 psf. For a deck of normal concrete, this gives a total mass of floor panel per ft of span of $(12t_c + 12)\ ((60/12)\ t_c)/g$ lb, where g is the acceleration due to gravity. If the response of the floor panel in the fundamental mode is approximated by a double sine wave, the lumped mass of an equivalent simple oscillator is 0.4 times the total distributed mass of the floor panel.

Thus

$$M = 0.4L\ 60\ (t_c + 1)\ t_c/g$$

where L is span length in ft. Substitution in [2] gives

$$[3a] \qquad a_0 \text{ (in \% } g) = \frac{350f}{Lt_c(t_c + 1)}$$

$$\left(= \frac{69\,000f}{Lt_c(t_c + 25)} \text{ in SI units}[5] \right)$$

for a deck of normal weight concrete. For

---

[3] For a more accurate determination, see Galambos (1973).

[4] For concrete on a ribbed deck the effective thickness is determined from the average weight of concrete, including ribs.

[5] L in metres and t_c in millimetres.

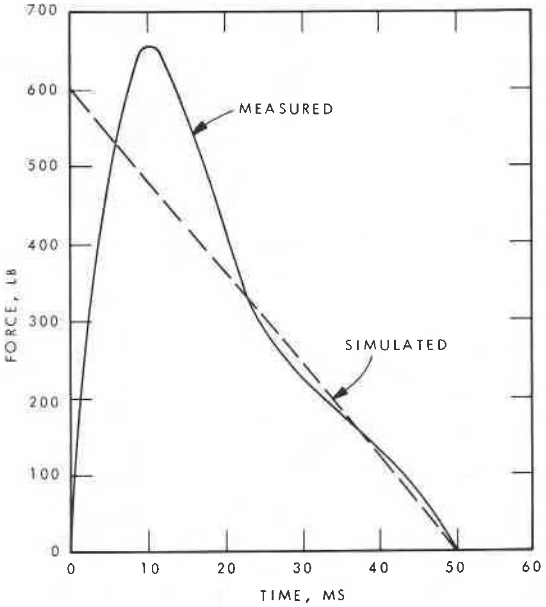

FIG. 7. Average plot of force *vs.* time for heel impact (from Lenzen and Murray 1969).

lightweight concrete deck, assumed to weigh 105 lb/ft^3 (16.5 kN/m^3), the following can be used

$$[3b] \quad a_0\,(\text{in }\%\ g) = \frac{450f}{Lt_c(t_c + 1)}$$

$$\left(= \frac{88\,000f}{Lt_c(t_c + 25)} \text{ in SI units}^3\right)$$

Table 1 compares peak accelerations computed by [3] with those measured in the field by various investigators. The comparison is generally quite reasonable considering that the concrete thickness t_c was often not accurately known and that the intensity of heel impact varies from one tester to another.

Using the estimated values for natural frequency, damping, and initial peak acceleration due to heel impact, the response is compared with the suggested annoyance criteria shown in Fig. 6. If the floor is found to be unsuitable, then the designer can either increase the damping (*e.g.* by specifying partitions or damper posts) thereby moving up the annoyance criterion in Fig. 6 or by altering the floor properties so as to move the peak acceleration into the acceptable region. Equation [3] shows that concrete thickness is very effective in reducing peak acceleration. For reasons given earlier, however, [3] used in conjunction with Fig. 6 should not be applied to floors that are light (spans less than about 25 ft) or that have frequencies greater than about 10 Hz.

Summary and Conclusions

Annoyance criteria, shown in Fig. 6, are derived for floor vibrations for normal 'quiet' human occupancies—residences, offices, and schoolrooms. The criterion in Fig. 6 for continuous vibrations is judged to be generally applicable, whereas the criteria for walking vibrations, the dashed lines in Fig. 6, are to be used only for evaluating long-span floors by means of the heel impact test or its calculated equivalent. The criteria are based on the experience of various investigators with long-span steel and concrete floors.

The performance of long-span floors to walking vibrations can be estimated from a knowledge of damping and initial peak acceleration due to heel impact for the floor vibrating in the fundamental mode. For design of concrete deck floors on steel beams or joists, peak acceleration can be estimated by an impulse formula, [3], provided the span is greater than about 25 ft (8 m) and the frequency is less than about 10 Hz.

An evaluation of the proposed criteria for long-span floors indicates that damping and slab thickness are effective in reducing annoying walking vibrations, whereas stiffness is not. The proposed criteria are based on limited information and simplifying assumptions, however, and they will not guarantee satisfactory floor performance in all situations.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

ALLEN, D. L. 1974. Vibrational behavior of long-span floor slabs. Can. J. Civ. Eng. **1** (1), pp. 108–115.

GALAMBOS, T. V. 1973. Vibration of steel joist-concrete slab floors. Techn. Dig. No. 5, Steel Joist Inst., Arlington, Va.

GALAMBOS, T. V., GOULD, P. L., RAVINDRA, M. K., SURYOUTOMO, H., and CRIST, R. A. 1973. Structural deflections. A Literature and State-of-the-Art Survey. Build. Sci. Ser. 47, Nat. Bureau Stand., U.S. Dep. Commer.

LENZEN, K. H. 1966. Vibration of steel joists. AISC Eng. J. 3(3) p. 133.

LENZEN, K. H. and MURRAY, T. M. 1969. Vibration of steel beam concrete slab floor systems. Rep. No. 29, Univ. Kansas, Lawrence, Kan.

MODEROW, R. R. 1970. Vibration characteristics of steel joist-concrete slab floor systems. MSc thesis, Univ. Kansas Lawrence, Kan.

NELSON, F. C., 1970. Human awareness of transient floor vibration and reduction of this awareness by constrained viscoelastic damping layers. Dynatech Rep. No. 920. Prepared for Am. Inst. Steel Constr. and Am. Iron Steel Inst.

RAINER, J. H. and ALLEN, D. E. 1973*a*. Vibration measurements on a steel joist floor—Montreal. Tech. Note No. 573, Div. Build. Res., Nat. Res. Counc. Can., Ottawa, Can.

——— 1973*b*. Vibration characteristics of a dance floor. Tech. Note No. 576, Div. Build. Res., Nat. Res. Counc. Can., Ottawa, Can., (limited distribution).

REIHER, H. and MEISTER, F. J. 1931. The effect of vibration on people. (*in German*) Forschung (VDI-Berlin), **2**(11), pp. 381–386 (transl.—Rep. No. F-TS-616-RE, Headquarters Air Mater. Command, Wright Field, Ohio, 1946).

WISS, J. F. and PARMELEE, R. A. 1974. Human perception of transient vibrations. ASCE, J. Struct. Div. **100**(ST4), pp. 773–787.