Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 69 (1993)

Artikel: Minimizing floor vibration caused by building occupants

Autor: Mouring, Sarah E. / Ellingwood, Bruce R.

DOI: https://doi.org/10.5169/seals-52554

Minimizing Floor Vibration Caused by Building Occupants

Minimalisation des vibrations de planchers provoquées par la foule

Minderung von menschenverursachten Deckenschwingungen

Sarah E. MOURING
Assistant Professor
United States Naval Academy
Annapolis, MD, USA

Sarah E. Mouring received her Ph.D. degree from The Johns Hopkins University, Baltimore, MD, in 1992. Currently, she is an assistant professor at the United States Naval Academy, Annapolis, MD.

Bruce R. ELLINGWOOD
Prof. Dr.
The Johns Hopkins University
Baltimore, MD, USA

Bruce R. Ellingwood received all Civil Engineering degrees at the University of Illinois in Urbana-Champaign. He was Head of Structural Engineering at the U.S. National Bureau of Standards before coming to Hopkins in 1986.

SUMMARY

One major serviceability consideration in modern buildings is excessive floor vibration due to occupant activities. Methods for accurate prediction of these vibrations and evaluation of floor systems are not readily available to the design community. An investigation is made into the characteristics of crowd-induced loads. The load characteristics are incorporated into simplified but realistic load models. Analytical procedures are developed to determine the influence of each load characteristic on the dynamic response of floor systems. Design guidelines are developed for systems subjected to crowd-induced loads.

RESUME

Les très fortes vibrations engendrées par les activités des occupants représentent l'un des aspects essentiels dans la détermination de l'aptitude au service des immeubles modernes. Il n'y a pas de méthodes servant à pronostiquer avec exactitude de telles vibrations et à évaluer le comportement des systèmes de planchers. Les auteurs examinent les caractéristiques des charges provoquées par la foule, puis les traduisent par des modèles de charge. Ils développent des méthodes analytiques pour la détermination de l'effet de chaque caractéristique de charge sur la réponse dynamique des systèmes de planchers. Ils en tirent finalement des directives de calcul pour les systèmes de dalles sous charges dues à la foule.

ZUSAMMENFASSUNG

Einer der wichtigsten Aspekte für die Gebrauchstauglichkeit moderner Gebäude sind starke, durch die Benützer verursachte Schwingungen. Methoden zu ihrer genauen Vorhersage und der Bewertung von Deckensystemen stehen der Berufswelt nicht ohne weiteres zur Verfügung. Eine Untersuchung betrifft die Charakteristiken der Einwirkung von Menschenmassen, die in einfache aber realitätsnahe Lastmodelle umgesetzt werden. Ferner werden analytische Verfahren zur Bestimmung des Einflusses jeder Kenngrösse auf die dynamische Deckenantwort bestimmt. Daraus resultieren Entwurfsrichtlinien für Deckensysteme.

1 INTRODUCTION

Floor vibrations have become a major serviceability consideration with the increasing use of high-strength, light-weight materials in modern building construction and the demand for open-space areas in office and commercial retail buildings. Floor systems in modern buildings have longer spans and are more flexible than in the past, and may have natural frequencies of vibration that fall within the range of rhythmic human activities. Floors in a number of different buildings built in the last few decades have experienced objectionable vibrations due to human activity [2,7]. Current design guidelines may not enable the structural engineer to deal with the floor vibration serviceability limit state effectively in designing floor systems. In particular, improved serviceability criteria and design guidelines need to be developed for floor systems in shopping malls, pedestrian walkways and concourses, and gymnasiums. These systems often are relatively light and are susceptible to vibration problems due to crowd-induced loading.

This paper presents the results of an investigation into characteristics of crowd-induced loads and dynamic response of floor systems [5]. These characteristics, many of which have been neglected in prior load modeling studies, include the density of the crowd, randomness of crowd movement, crowd activity, and temporal interaction between individuals. Simplified but realistic models of the crowd-induced loads are developed. Guidelines which can be used in the design and evaluation of malls, gymnasiums, and walkways are developed using these load models and dynamic analysis procedures.

2 FORCE MODELS AND DYNAMIC ANALYSIS

The starting point in developing accurate force models of human activities is the representation of the force due to an individual human footfall. Footfall force functions of several different activities, including slow walking, normal walking, brisk walking, running, and aerobics, were evaluated by Fourier analysis [1,5] (see Fig. 1). It was found that the forces could be represented by Fourier sine series with from 3 to 10 terms, depending on the pacing frequency of the individual. Using these force models, two techniques were developed to predict vibrations due to occupant-induced loads. The first technique was based on the simulation of forces due to individuals and groups of people on floor systems in the time domain and used the finite element analysis (FEA) package ABAQUS to calculate the response of the floor system due to dynamic loading. A second and simpler method involved the development of a frequency-domain solution using random vibration theory.

2.1 Time-Domain Method

The data needed to describe the activities (walking and/or running), movement, and physical make-up of the crowd include group size, individual weights, starting locations, directions of movement, coherency of movement, and pacing frequencies. The stride length, step duration, and type of footfall function for each individual are functions of the pacing frequency [5].

When simulating a group walking or running across a two-way floor system, first it was assumed that the probability of an individual entering the floor system at any location along any of the floor edges was described by a uniform probability distribution function (PDF). The starting direction of motion for each individual was given by the angle, α, with respect to the floor edge, which also was assumed to be uniformly distributed between 0 and 180°. The loading due to an individual was represented by a moving point load-time history and was multiplied by interpolation functions to determine the equivalent nodal moment- and point load-time histories for use in the dynamic FEA. After this procedure was completed for each individual in the crowd, the individual forces were shifted in time to account for randomness in the pedestrian arrival times and the nodal time histories of each individual were superposed to create nodal time histories for the group.

For a group engaging in aerobic exercise, the general approach is the same as above; however, the loading is different. One difference is that aerobic exercise is usually performed to music

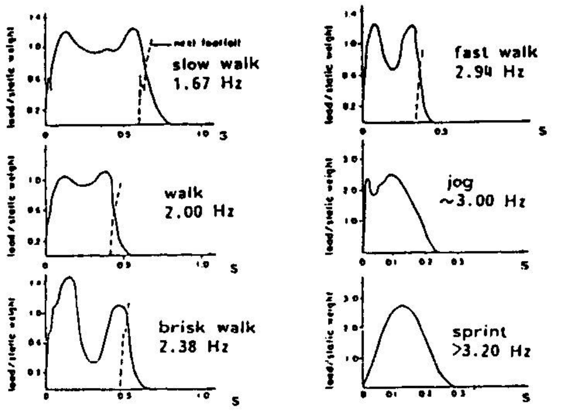

Fig. 1: Footfall Force Functions [2]

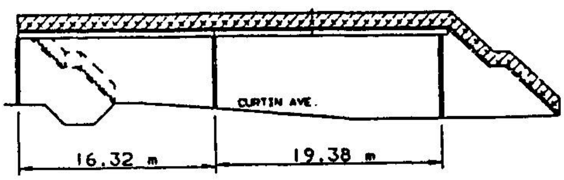

Fig. 2: Curtin Ave. Footbridge [8]

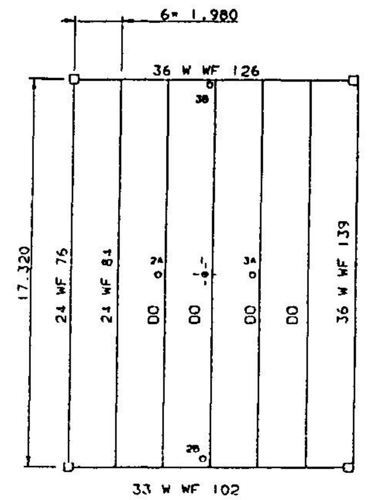

Fig. 3: Shopping Mall Floor [7]

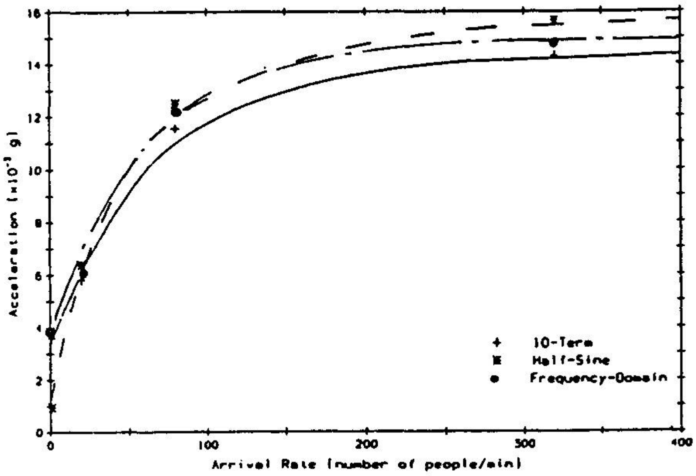

Fig. 4: Floor Accelerations: Groups Walking

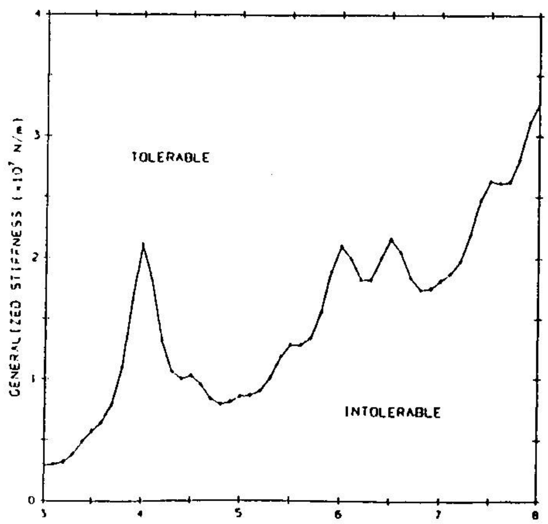

Fig. 5: Design Limits for Reference Walkway

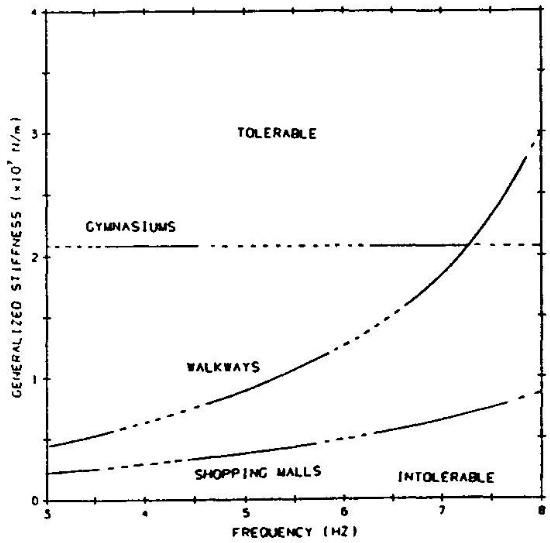

Fig. 6: Design Guidelines

in a class setting where the participants remain in place and their locations can be modeled as uniformly distributed over the floor system [5]. A second difference is that individual phase lags within a group exercising are better described by an exponential distribution due to auditory cuing from the music [3].

2.2 Frequency-Domain Method

The simulation of an individual walking or exercising was the same as described in Sec. 2.1. However, a generalized force-time history for the dominant modes was calculated for each individual instead of nodal force- and moment-time histories. This procedure was repeated for all the individuals in the crowd. The generalized force-time history, $F_g(t)$, of the crowd-induced loading then was produced by superposing the individual generalized force-time histories using the individual random phase lags. The one-sided PSD of the generalized force, $S_{f_g}(\bar{f})$, was calculated from this time history using Fast Fourier Transforms. With the determination of $S_{f_g}(\bar{f})$, the variance of the acceleration response of a floor system can be calculated in the frequency domain using standard random vibration methods [9]:

$$\sigma_a^2 = \int_0^\infty \mid H_a(\bar{f}) \mid^2 S_{f_g}(\bar{f}) d\bar{f} \qquad (1)$$

where $H_a(\bar{f})$ is the system transfer function, defined by the acceleration response of a SDOF oscillator to the excitation, $\exp(i2\pi\bar{f}t)$.

3 ANALYSES OF FLOOR SYSTEMS

Several structures were analyzed as a part of a sensitivity study to test the validity of modeling assumptions made in this study and to determine those factors that most influenced the dynamic response of floors [5].

3.1 Simple Floor Systems

Two simply supported floor systems subjected to one-way, randomly phased crowd motion were analyzed. First, the significance of random pacing frequencies was investigated by selecting the pacing frequencies for the members of the crowd from a uniform PDF (uniform between 1.7 and 2.3 Hz). (See Fig. 1.) The dynamic displacements of two 16m floor systems (5 and 10Hz) subjected to a randomly paced group were approximately 15% larger than the displacements of the same systems subjected to a group pacing with the common frequency of 2.0 Hz. Second, the total peak displacement response at midspan of a floor system (16m, 5Hz) subjected to a crowd with a common pedestrian weight of 700N was found to be 7% less than the response of the same floor system subjected to a crowd with pedestrian weights normally distributed with mean 700N and standard deviation 145N. Therefore, assumptions of a common pacing frequency and pedestrian weight were made in subsequent analyses, since they do not appear to affect the response of the floor system significantly and greatly simplify the force modeling.

3.2 Footbridge

The Curtin Ave. footbridge is one of 21 footbridges in Perth, Australia used in an experimental and analytical study by Wheeler [8] of objectionable vibrations of pedestrian walkways. It is a two-span steel structure with the main span having a length of 19 m (see Fig. 2). Wheeler calculated the first and second frequencies of vibration as $f_{1_{calc}} = 3.7$ Hz and $f_{2_{calc}} = 4.3$ Hz, respectively, and the responses of the footbridge due to a person traversing the structure at pacing frequencies equal to 2.0 Hz and natural frequency (3.7 Hz). The load model used was a "half sine pedestrian model" and the weight of the test pedestrian was equal to 700N.

The fundamental frequency calculated in this study was 3.28 Hz. The second calculated frequency of 4.29 Hz could only be compared to Wheeler's calculated value of 4.3 Hz, since he did not provide the experimental frequency for the second mode in his paper. The experimental and calculated responses of the footbridge subjected to a 768N pedestrian pacing at 2.0 Hz and f_1 are compared in Table 1. It should be noted that the first mode represented 92% of the total displacement response. The responses calculated by Wheeler did not compare as well to the experimental results, most likely because of his approximations in the force model.

3.3 Floor System in a Shopping Mall

The floor system analyzed is located on the second story of a mall in Canada, and reportedly had noticeable floor vibration due to pedestrian-induced loads [7]. The floor is of composite construction (see Fig. 3). In-situ measurements of accelerations were taken at designated locations noted on Fig. 3. The floor system was excited by a 935N person performing heel-drop impacts at each accelerometer location, and by the same person walking past and between specific accelerometers at a normal pacing frequency of approximately 2.0 Hz. The fundamental frequency measured was $f_{1_{exp}} = 4.0$ Hz, while the fundamental damping value determined by the log decrement method was 3.3%.

The fundamental frequency of the floor system was calculated in this study to be 4.26 Hz. A comparison of predicted and measured accelerations is given in Table 2. The first mode represented 96% of the total acceleration response. A sensitivity study on group activity revealed that [5]:

- The assumption in a floor system evaluation that an individual treads in place at midspan rather than walks across the floor overestimates the calculated peak acceleration by 28%.
- The floor acceleration and the pedestrian arrival rate are related by a factor $\sqrt{N}$, where N is the number of randomly phased people walking on the floor at a given time (see Fig. 4).
- The half-sine shape approximation of the individual footfall function is adequate for group loading but not for individual loading (see Fig. 4).
- The total acceleration of the floor system subjected to a group of people exercising with exponentially distributed phase lags is less than 50% of the response when the same group exercises completely in phase.

The accelerations calculated by the frequency-domain method considering only the first mode compared very well to the responses calculated by the time-domain method for both groups exercising and groups walking. The time-domain and frequency-domain response values due to groups of individuals with a common body weight (935N), common walking frequency (2.0 Hz), and random individual arrival times were within 15% of each other (see Fig. 4).

4 GENERAL DESIGN GUIDELINES

Serviceability of floors traditionally has been addressed by requiring that the deflection of the floor system due to live load be less than some fraction, typically 1/360, of the span length. Other important factors governing dynamic response, including the mass and damping of the floor system, are not reflected in this requirement. It has been suggested recently that the static deflection of the floor system under a 2KN force applied at midspan should be less than 1mm to provide sufficient static stiffness against walking vibration [4]. Limiting absolute static deflection is tantamount to limiting the fundamental frequency, but does not directly deal with the dynamic component of the load. It also has been suggested that excessive vibrations often can be avoided by designing floor systems to have fundamental frequencies above a certain value (typically about 8 Hz) [1,6]. However, this alternative may not always be economical. Designers ought to have other methods that deal with directly the dynamic nature of the loads and are relatively easy to implement in practice.

4.1 Development of General Design Guidelines for Walkways

The development of design guidelines for walkways was based on the results summarized in Sec. 3 [5]. The first step was to perform a FEA of a walkway subjected to crowd loading. A simply supported, one-span reference system with length L (18.36m) and damping value of 3% was designed to specification and modeled using finite elements. It was assumed that the maximum arrival rate of people was 120 people per minute, that each pedestrian weighed 700N, had a common pacing frequency (2.0 Hz) and forward speed, and a random arrival time. The loading was calculated using the method described in Section 2.1. The natural frequency, generalized mass, and acceleration-time history at the center node were calculated for the first mode. The power spectral density (PSD) of acceleration, $S_a(\bar{f})$, for the first mode was calculated from the acceleration-time history using Fast Fourier Transforms. After calculating the system transfer function, the PSD of the generalized force at the center node for the first mode was determined by:

$$S_f(\bar{f}) = \frac{S_a(\bar{f})}{\mid H_{a_{ref}}(\bar{f}) \mid^2} \tag{2}$$

in which $H_{a_{ref}}(\bar{f})$=system transfer function for the reference floor.

Any simply supported floor systems of length L subjected to the same crowd behavior has a PSD of the generalized force of the first mode equal to $S_f(\bar{f})$. If acceleration, $a(t)$, can be assumed to be a stationary process [5,9], then the rms acceleration can be calculated from Eqns. 1 and 2. The peak acceleration is related to the rms acceleration by a peak factor, found to be equal to approximately 3.0 for the floor systems considered herein by inspecting outputs from the time-domain analyses [5]. Therefore, the peak acceleration is calculated by:

$$a_p = 3.0\sqrt{\int_0^\infty \mid H_a(\bar{f}) \mid^2 S_f(\bar{f}) d\bar{f}} \tag{3}$$

in which $H_a(\bar{f})$=system transfer function for the floor considered.

A design chart for walkways can be developed for the reference system mentioned above. The recommended peak acceleration limit for walking vibration on walkways is 5% g [2]. By varying the fundamental frequency, values of the generalized stiffness can be determined for which the peak acceleration is 5% g. These specific systems also must satisfy strength and static deflection requirements. A curve was developed in this manner which identifies systems as being either tolerable or intolerable (see Fig. 5). Figure 6, where a smooth curve has been fitted, is proposed for design purposes. The dotted lines in Fig. 6 represent the zones of resonance and should be avoided.

Figure 6 cannot be used directly with simply supported floor systems with span lengths other than L, since a floor system of length L/N has 1/N times the number of pedestrians on the system at one time due to the constant pedestrian arrival rate assumed for all systems. However, the generalized stiffness in Fig. 6 can be scaled by the factor $\sqrt{N}$ for use with other span lengths. Thus if the floor system has span length, l, the generalized stiffness is scaled by $\sqrt{L/l}$ where L=18.36m and K_1^*=scaled generalized stiffness. Finally, the point (f_1, K_1^*) is plotted to see if it lies in the tolerable or intolerable area of the chart. Figure 6 also can be used for floor systems of length L with different arrival rates by scaling the generalized stiffness by the square-root of the ratio of 120 people/min to the given arrival rate.

4.2 Evaluations of Walkways

Six simply supported, one-span walkways were evaluated after first being designed to meet strength and traditional (static) serviceability requirements. By plotting the scaled generalized stiffness, K_1^*, and fundamental frequency, f_1, on the design chart, only Walkway 4 was found to have tolerable accelerations (see column 7 of Table 3). To validate the proposed design chart, these results are checked with results calculated using simulated force-time histories and FEA to compute dynamic responses (see column 8 of Table 3). In every case, peak accelerations above 5%g corresponded to intolerable ratings given in column 7 of Table 3. Therefore, the design chart identified those walkways that had unacceptable vibrations due to heavy crowd loading.

Other serviceability criteria considered included limiting the maximum deflection under a uniformly distributed design live load to be less than L/360, and limiting maximum deflection under 2KN point load located at midspan be less than 1mm [4]. Deflections under a 2.9kPa uniformly distributed nominal live load and under a 2KN point load are given in columns 9 and 10 of Table 3. Both criteria were satisfied for all six walkways; however, Walkway 4 was the only system to have a tolerable rating when dynamic response was considered. Therefore, walkway designs that satisfy the static deflection criteria may vibrate objectionably when heavily trafficked.

4.3 Summary of Design Guidelines for Other Occupancies

Design guidelines for shopping malls and gymnasiums also were developed as part of this study (see Fig. 6) [5]. However, the zones of resonance for the gymnasium guidelines are very wide. Therefore, there is only a relatively small range of fundamental frequencies in which a gymnasium floor can be designed using the proposed design guidelines. It is recommended that floor systems in buildings where exercise classes are regularly scheduled be designed to have fundamental frequencies above 10 Hz. This value is greater than the third harmonic of the forcing frequency most likely to be encountered on the floor.

5 CONCLUSIONS

General design guidelines were developed to evaluate simply supported floor systems where the occupants walk or exercise in groups. These may be used as screening tools for floor systems with different boundary conditions. The design guidelines are limited to a few common activities and building occupancies. Other guidelines need to be developed for floor systems subjected to different activities.

6 ACKNOWLEDGEMENTS

Computional support from the Pittsburgh Supercomputer Center through Grant No. MSM910013P is greatly appreciated. Assistance in this study by J.E. Wheeler in providing working drawings and other documentation also is appreciated.

	Total Peak Response (mm)		
	Calculated (Wheeler)	Experimental (Wheeler)	This study
Pacing = 2.0 Hz	0.70	0.60	0.59
Pacing = f_1	9.9	7.5	7.0

Table 1: Comparison of Results of Curtin Ave. Footbridge

Transducer Setup	Type of Test	Peak Acceleration (x10e-3g) at Transducer Location					
		Experimental			Calculated		
		1	2	3	1	2	3
A	Heel Impact at (1)	7.0	8.7	9.2	10.2	8.4	9.5
A	Walking Past (1,2,3)	2.6	3.0	3.2	3.6	3.7	3.0
B	Heel Impact at (1)	7.7	3.1	1.5	10.2	3.6	3.1
B	Walking Past (1,2,3)	2.8	2.0	1.4	3.7	1.3	1.1

Table 2: Comparison of Results of Shopping Mall Floor

Walkway (1)	L (m) (2)	f_1 (Hz) (3)	M_1 (kg) (4)	K_1 (N/m) (5)	K_1^* (N/m) (6)	Chart Eval. (7)	$a_{P,calc}$ (%g) (8)	L/Δ_{LL} (9)	$\Delta_{P=2Kn}$ (mm) (10)
1	18.36	3.41	4.66e3	2.14e6	2.14e6	INTOL.	11.0	595	0.94
2	18.36	4.95	5.68e3	5.49e6	5.49e6	INTOL.	7.5	1529	0.36
3	18.36	5.70	6.35e3	8.13e6	8.13e6	INTOL.	8.4	2260	0.25
4	18.36	7.46	1.06e4	2.33e7	2.33e7	TOL.	5.0	6397	0.09
5	13.77	6.59	4.21e3	7.20e6	8.31e6	INTOL.	12.0	1978	0.28
6	9.16	7.10	2.37e3	4.75e6	6.71e6	INTOL.	14.0	1295	0.43

Table 3: Comparison of Methods to Evaluate Footbridges

References

[1] ALLEN, D.E., and RAINER, J.H. and PERNICA, G. "Vibration Criteria for Assembly Occupancies." Canadian Journal of Civil Engineering, 1985, 12(3): 617-623.

[2] BACHMANN, H. and AMMANN, W. *Vibrations in Structures*, IABSE, Zurich, Switzerland, 1987.

[3] EBRAHIMPOUR, A. and SACK, R.L. "Crowd-Induced Dynamic Loads." Proceedings of Symposium/Workshop on Serviceability of Buildings, Ottawa, Canada, 1988, 451-464.

[4] ELLINGWOOD, B. and TALLIN, A. "Structural Serviceability : Floor Vibration." Journal of Structural Engineering, ASCE, 1984, 110(2): 401-418.

[5] MOURING, S.E. "Dynamic Response of Floor Systems to Building Occupant Activities" Thesis presented to The Johns Hopkins University, Baltimore, MD, in partial fulfillment of the requirements for the degree of Doctor of Philosophy, 1992.

[6] MURRAY, T.M. "Building Floor Vibrations." Engineering Journal, AISC, 1991, 28(3): 102-109.

[7] PERNICA, G., and ALLEN, D.E. "Floor Vibration Measurements in a Shopping Centre." Canadian Journal of Civil Engineering, 1982, 9(2): 149-155.

[8] WHEELER, J.E. "Prediction and Control of Pedestrian-Induced Vibrations of Footbridges." Journal of Structural Engineering, ASCE, 1982, 108(9): 2045-2065.

[9] YANG, C.Y. *Random Vibration of Structures*, John Wiley and Sons, New York, N.Y, 1986.