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THEME 3

SERVICE LOADS AND LOAD MODELS

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Low-Frequency Forces Caused by People: Design Force Models

Charges de basse fréquence produites par les piétons: modèle de charges

Durch Menschen induzierte Lasten mit niedrigen Frequenzen: Lastmodelle

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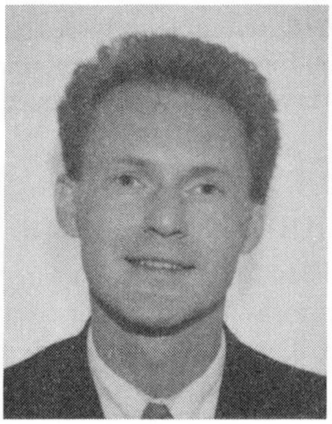

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SUMMARY

The dynamic forces from walking, running and jumping can be divided into two parts: an impulsive part of higher frequencies from the initial contact between the foot and the floor and a continuous excitation of lower frequencies from the successive footsteps. In this paper, models of the latter, low-frequency excitation based on laboratory measurements are presented. One of the options for frequency domain force models is to treat the forces as a sum of harmonic components. Another, better suited for a loading case of less coordinated pedestrian motion is a broad-band model of the force. Both these options are presented and discussed here.

RESUME

Les forces dynamiques résultant de marche, course et saut, peuvent être classées en deux groupes: un cas avec de hautes fréquences, au moment du contact initial du pied avec le plancher, et une excitation continue de fréquences basses pour les pas suivants. Des modèles pour le second groupe, à basses fréquences, ont été élaborés sur la base de mesures en laboratoire. Une des options pour les modèles de charge est de considérer les charges comme somme d'éléments harmoniques. Une autre option, mieux adaptée au cas de charges non coordonnées des piétons est un modèle à large bande. Les deux options sont présentées et discutées.

ZUSAMMENFASSUNG

Die dynamischen Kräfte, die von gehenden, laufenden oder springenden Menschen verursacht sind, können in zwei Teile aufgeteilt werden: Einen Impulsteil, von höheren Frequenzen, der vom initialen Kontakt, zwischen Fuss und Fussboden herrührt, und eine kontinuierliche Erregung niedrigerer Frequenzen von den aufeinanderfolgenden Fussschritten. In diesem Beitrag werden Modelle für die zweite Erregung, mit niedrigeren Frequenzen vorgeschlagen. Diese Modelle basieren auf Labormessungen. Eine von den Möglichkeiten für Kraftmodelle im Frequenzbereich bedeutet, dass man die Kräfte als eine Summe harmonischer Komponenten behandelt. Eine andere, die für einen Lastfall mit weniger koordinierten Fussgängerbewegungen besser geeignet ist, ist ein Breitbandmodell der Kraft. Diese beiden Möglichkeiten werden hier erläutert und diskutiert.

1. INTRODUCTION

Forces from footsteps and jumping have been studied for various reasons ranging from ergonomic considerations to prediction of floor and footbridge vibrations. Only relatively recently have the results, however, been presented in the frequency domain, which is the form most suitable for design purposes. Measurements and a model of the impulsive, high-frequency part of the forces from footsteps were presented in [1]. For low-frequency floors, where the response is dominated by resonances below 8 Hz, the steady-state forces caused by succesive footsteps are, however, most important. The main frequency components of these steady-state forces are found at the step or jump frequency and at integer multiples thereof. These are called the harmonics of the step frequency. There are few reported measurements of the *continuous* forces from walking and running. Those known by the author are [2] (these results are more extensively reported in [3]) and to some extent [4] and [5]. The latter reference does not, however, present any frequency domain models.

2. EXPERIMENTAL METHOD AND RESULTS

In order to measure the dynamic load from natural walking or running, it is necessary to use a large test floor. The technique used for measuring the force from a single step, i.e. using a "stiff, massless" platform with one (or more) force transducer is apparently not applicable here. The method chosen for this study was to determine the vertical dynamic force *indirectly* from measurements of the response of a floor structure with well-known dynamic properties to excitation from walking, running and jumping. The "semi-static" part of the response, i.e. the frequency range below the first natural frequency of the test floor, was mainly used and the measurement point was selected so that the contributions to the response from all modes except the fundamental mode could be neglected. The measured quantity was the vertical acceleration at midspan.

Measurements were made with different activity frequencies and with a varying number of participants. For the tests with *one subject* the main objective was to study the effect of various footstep frequencies f_s. f_s was kept constant by means of a metronome. All results for a single person, given below, refer to a male person weighing 740 N. Tests with *several walking subjects* were done with the subjects walking in step (1.7 or 2.0 Hz) as well as with each subject using his/her own rate, although all moved with the same speed. The largest group size used was 11 people.

In the test with <u>walking</u> the footstep frequency was varied from 1.3 up to 2.5 Hz in increments of 0.1 Hz. In Fig. 1, the spectral densities of the load from walking at four different step frequencies are given. This figure shows very clearly the peaks at each harmonic of f_s. Also, when comparing the amplitudes of the peaks of the first harmonic, a strong dependence upon the rate of walking is evident. The peaks of the higher harmonics are all of the same order of magnitude but decrease with increasing frequency. Fig. 1 also shows that the peaks at each "harmonic" has a certain width. This means that a description of the force as a sum of harmonic forces at the harmonics of the step frequency is not exactly true. The spread of the force power means that for a lightly damped structure, the fraction of the force input that will actually cause resonant vibration will depend on the damping ratio ζ_n of the structure. This variation with ζ_n may, however, not be as strong as to justify the use of a broad-band force model for the loading case "one person walking". Instead the simpler model consisting of a sum of harmonic components mentioned above may be used.

For <u>groups walking</u>, the test groups consisted of 7 and 11 people respectively and the mean weight of the subjects were 800 and 745 N respectively. Coordinated walking at the step frequencies 1.7 and 2.0 Hz and uncoordinated walking at a leisurely stride as well as at a fast stride was performed. The resulting force spectral density for the group of eleven people at f_s=1.7 Hz as well as at a leisurely stride is shown in Fig. 2. The leisurely stride seems to have corresponded to a mean step frequency of about 1.65 Hz which means that these spectral densities are comparable. As can be seen in Fig. 2 the force spectral density increases strongly with the group size as expected. At uncorrelated walking, the different walking rates within the groups have the effect of smoothing the force spectral density function. This suggests that a broad-band force model is the most appropriate for groups of pedestrians.

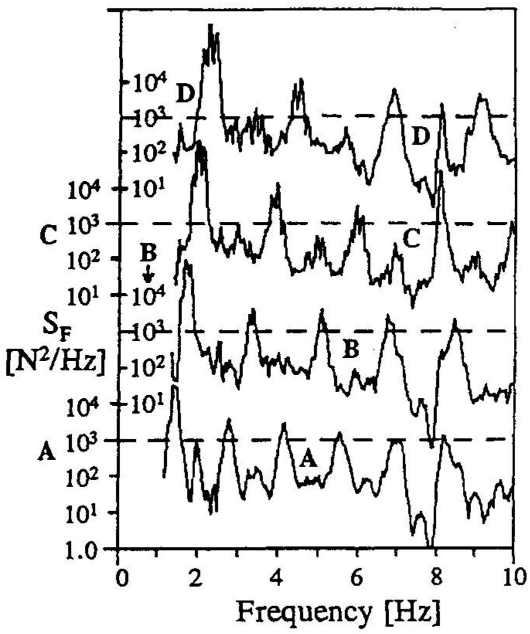

Fig. 1 Spectral densities of the force from one person walking at f_s = : A) 1.4, B) 1.7, C) 2.0 and D) 2.3 Hz respectively.

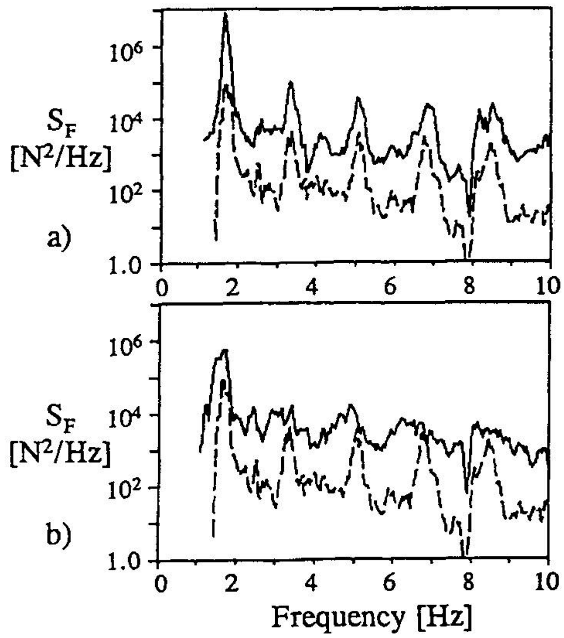

Fig. 2 The force spectral densities for a group of 11 persons at a) coordinated walking, f_s=1.7 Hz, and b) uncoordinated walking at a leisurely stride. S_F for one person at f_s=1.7 Hz, is shown with a dashed line.

In the test with one person running, the footstep frequency was varied from 2.0 up to 3.0 Hz in increments of 0.2 Hz. The resulting force spectral densities from three different footstep frequencies are shown in Fig. 3a. The shapes of the spectral density functions are very similar to those obtained for walking but their magnitudes are approximately an order higher at the first and second harmonics and somewhat less higher at the third harmonic. The spread of the force power around each harmonic is nearly identical to that for walking (one subject). This means that the same reasoning as previously applied to walking, about what kind of force model to use, will also be valid for the loading case "one person running". No measurements of the forces from groups running have been performed here.

For jumping, the frequency was varied from 1.8 up to 3.2 Hz in increments of 0.2 Hz. The resulting force spectral densities from three different jumping frequencies are shown in Fig. 3b. These are somewhat different in shape as compared to those for walking and running. The main differences are that the peaks at all the harmonics are sharper here and that the second and third harmonic peaks have higher magnitudes relative to that of the first harmonic. Compared to the magnitudes of the the peaks for running, those for jumping are 3-4 times higher at the first, 15-100 times higher at the second and 40-100 times higher at the third harmonic respectively. This means that jumping is a rather severe loading case also in the frequency range above 3 Hz. The sharpness of the peaks means that for jumping the most reasonable force model to use is one based on a sum of harmonic components.

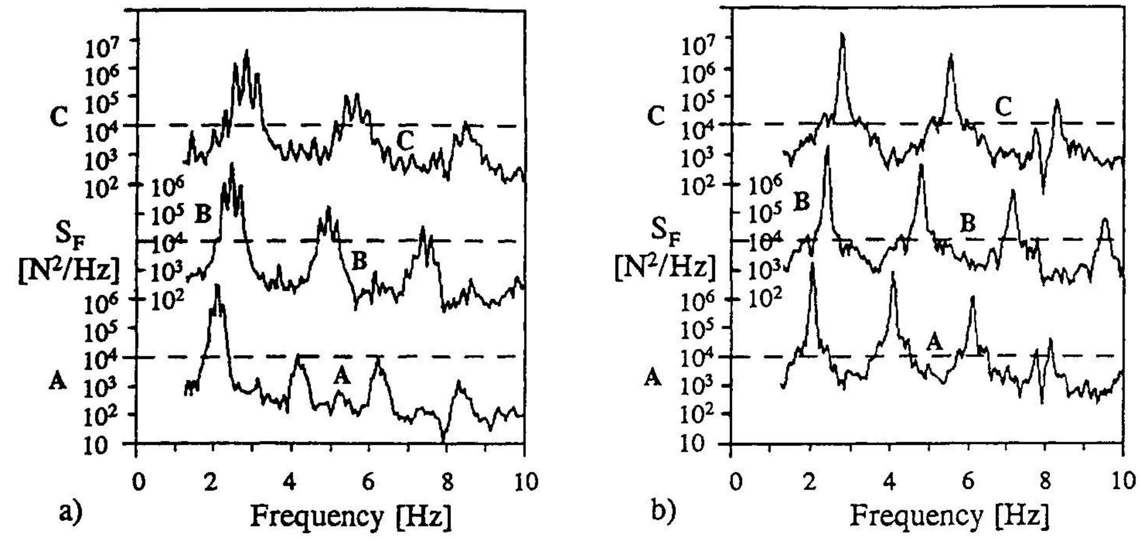

Fig. 3 Spectral densities of the force from one person a) running and b) jumping at f_s = : A) 2.0, B) 2.5 and C) 3.0 Hz respectively.

3. COMPARISON WITH RESULTS FROM THE LITERATURE

Extensive measurement series of the continuous vertical low-frequncy forces from walking, running and jumping have been reported in [3]. The results are given as "dynamic load factors" α_k, i.e. the fourier component at the k:th harmonic of the step frequency, divided by the body weight of the test persons. However, the dependence of the magnitude of the load factors on the frequency band-width they represent is not discussed. The mesurements were performed for different sets of participants, except in some group activities, and the results discussed here are the mean values. The second reference used for comparison is [4], where the forces from individual footsteps at various activity frequencies were measured and the fourier components from artificial "pulse trains" for walking and running were computed. These components were then checked against the resonant vibrations of a beam with variable resonance frequency when subjected to the same loading. The continuous forces from jumping were also measured.

In order to compare the results presented in the previous section with those referred to above, the latter are converted into root-mean-square (rms) values of the force component at each harmonic.The force rms value $F_{rms,k}$ for the k:th harmonic of the step frequency is calculated from the dynamic load factors in [3] as shown by Eq. (1). These values are compared with results from the present study, determined from the measured force spectral densities as in Eq. (2), i.e. each value for $F_{rms,k}$ is calculated over a certain bandwidth Δf around the corresponding harmonic. The bandwidth Δf is selected as an "equivalent width" of the frequency response function resonance peak of a dynamic system with $\zeta_n = 1\%$, which can be taken as $\Delta f = \pi k f_s \zeta_n = 0.0314 k f_s$, according to [6]. The factor $\sqrt{2}$ in Eq. (1) accounts for the difference between the amplitude and the root-mean-square (rms) value of a harmonic process and G is the weight of the test person in the present test (740 N).

$$F_{rms,k} = \frac{\alpha_k G}{\sqrt{2}} \quad (1)$$

$$F_{rms,k}(\Delta f) = \sqrt{F_k^2(\Delta f)} = \int_{kf_s - (\Delta f/2)}^{kf_s + (\Delta f/2)} S_F(f) df \quad (2)$$

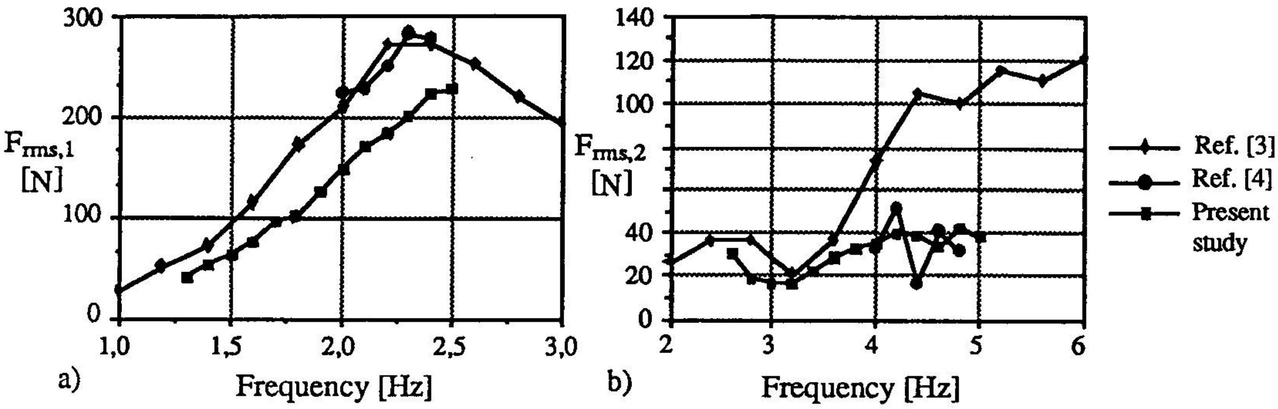

Fig. 4 Comparison of rms force components for a) the first and b) the second harmonic of the forces from walking.

The force components from walking at the first and second harmonics from the two refences above and from the present study are compared in Fig. 4. The results for the second harmonic diverge significantly. Ref. [3] reports forces at 4.4 Hz and above, that are more than twice as high as those from the present study as well as those from [4]. The differences between the three different subjects used in the former test were indeed biggest for the second harmonic but none of them gave second harmonic forces as low as those found in the present study for frequencies above 4 Hz.

The the first and second harmonics of the forces from running obtained in the present study agree very well with Ref. [3] as shown in Fig. 5a. The results from[4], presented in Fig. 5a, are not necessarily directly comparable to the other results as they were not obtained from measurements of *continuous* forces as discussed above. Neither are the forces in [4] given as a function of the step frequency. The results presented here are therefore based on those that are given in the report as the *highest* computed load factors based on the individual measured footsteps. As can be seen in the figure these are somewhat higher than the other results, especially for the second harmonic.

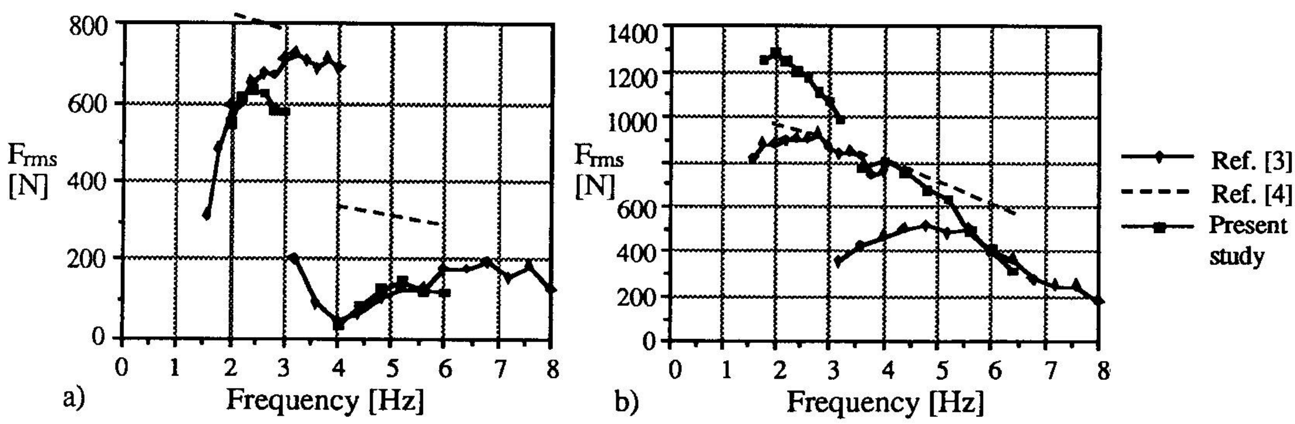

Fig. 5 Comparison of rms force components for the first two harmonics of the forces from a) running and b) jumping.

The forces from jumping measured in the present study are significantly higher than those presented in [3], at least for jumping frequencies below 3 Hz (see Fig. 5b). For the first harmonic they are also higher than those given in [4]. The explanation is partly found in the instructions given to peformers in the test. In Pernica's test [3] the subjects were asked to jump as they normally would whereas in the present study the subject was jumping relatively hard. Baumann & Bachmann [4], however, measured the forces due to different styles of jumping and the force components presented in Fig. 5 are the highest they found and they are still considerably lower than those obtained here.

4. FORCE MODELS

The *broad-band* or *spectral density model* is composed of an "envelope function" E and a "mean function" M. The E function can be regarded as a function connecting the peaks of the spectral density functions for different footstep frequencies and the M function represents the force power around each "harmonic" of the step frequency divided by the bandwidth, i.e. the step frequency. The level of the E function is chosen in such a way that it will yield the correct resonant response of a mode of vibration of the structure having a modal damping ratio $\zeta_n = 1\%$. The E(f) function of the model is therefore a curve-fit of the experimentally obtained levels $E_{exp,k}$ calculated according to Eq. (3) at each harmonic k of each step frequency f_s in the measured range. The mean square force at the k:th harmonic F_k^2 is calculated according to Eq. (2). In the same way the M(f) function of the model is a curve-fit of the experimentally obtained mean force spectral densities $M_{exp,k}$ around each harmonic, see Eq.(4).

$$E_{exp,k} = \frac{\overline{F^2}(\Delta f = 0.0314 k f_s)}{\Delta f} \tag{3}$$

$$M_{exp,k} = \frac{\overline{F^2}(\Delta f = f_s)}{f_s} \tag{4}$$

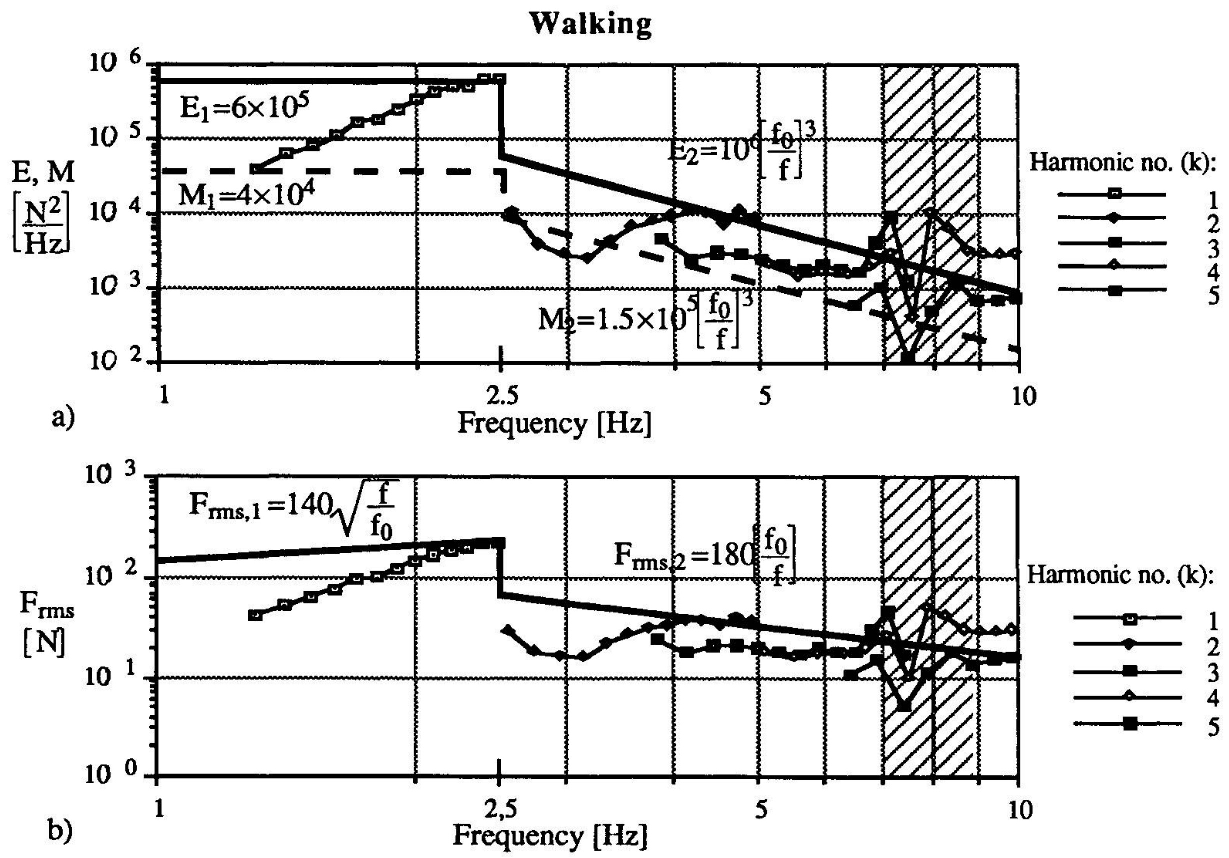

Fig. 6 Models of the forces from one person walking. a) shows the E and the M functions of the broad-band model respectively and b) the narrow-band model. f_0=1 Hz.

The *narrow-band model* of the forces used here is a model of the root-mean-square values of the forces at each harmonic F_{rms}, derived directly from the E function of the broad-band model as

$$F_{rms} = \sqrt{E(f) \times \Delta f} \quad (5)$$

where E(f) is the curve-fitted model function and $\Delta f = 0.0314f$. This means that the calculated resonant rms-response of a certain mode of vibration would be the same using either the E function or the F_{rms} function provided that the modal damping ratio ζ_n is 1%. The corresponding experimental values $F_{rms,exp}$ are obtained from the measured force spectral densities as in Eq. (2) with $\Delta f = 0.0314kf_s$, c.f. Ch. 3.

Each model consists of two different functions to take account of the drastically higher force levels at the first compared to the higher harmonics. The frequency of the shift from the first function to the second is 2.5 Hz for walking (Fig. 6), 3.0 Hz for running (Fig. 7) and 3.5 Hz for jumping (Fig. 8), which are taken as the highest occuring step frequencies. In the frequency range around the first natural frequency of the measurement platform the experimental values obtained are not reliable. In Figs. 6-8, the frequency range 7-9 Hz, which was disregarded in the curve-fitting, is therefore indicated. All these models are based on a body weight of the person that causes the vibrations of 740 N, as for the subject used in the tests. This is believed to be a fairly representative value. If another standard body weight is preferred, the F_{rms} models should be multiplied by the ratio of this body weight to 740 N and the E and M models should be multiplied by this ratio squared. For jumping, only an F_{rms} model is presented for reasons stated above. As compared to the forces from jumping measured in this study, the model gives lower forces for frequencies below 3 Hz and beteween 4 and 6 Hz. This adjustment of the model is made with respect to the comparisons made in Ch. 3.

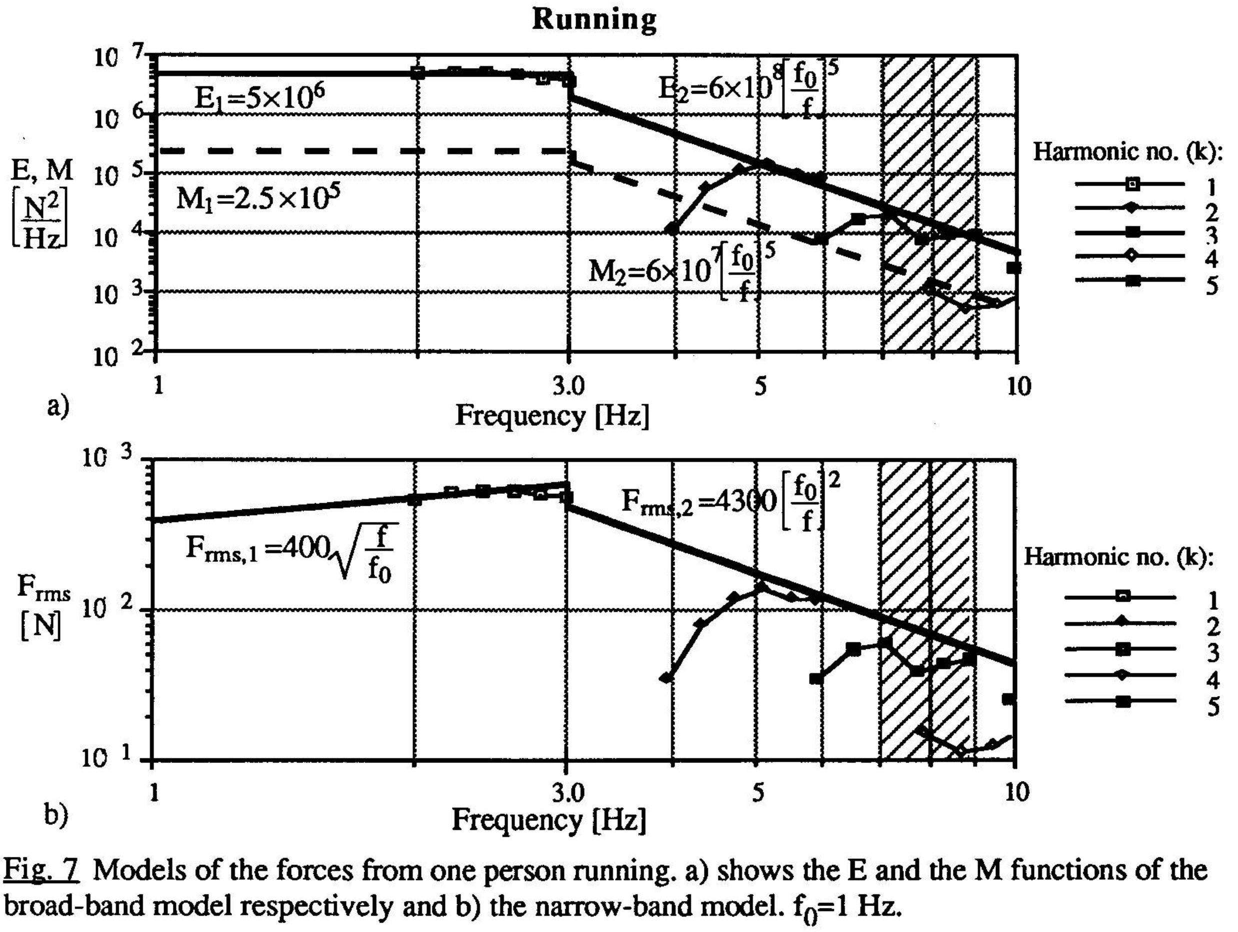

Fig. 7 Models of the forces from one person running. a) shows the E and the M functions of the broad-band model respectively and b) the narrow-band model. f_0=1 Hz.

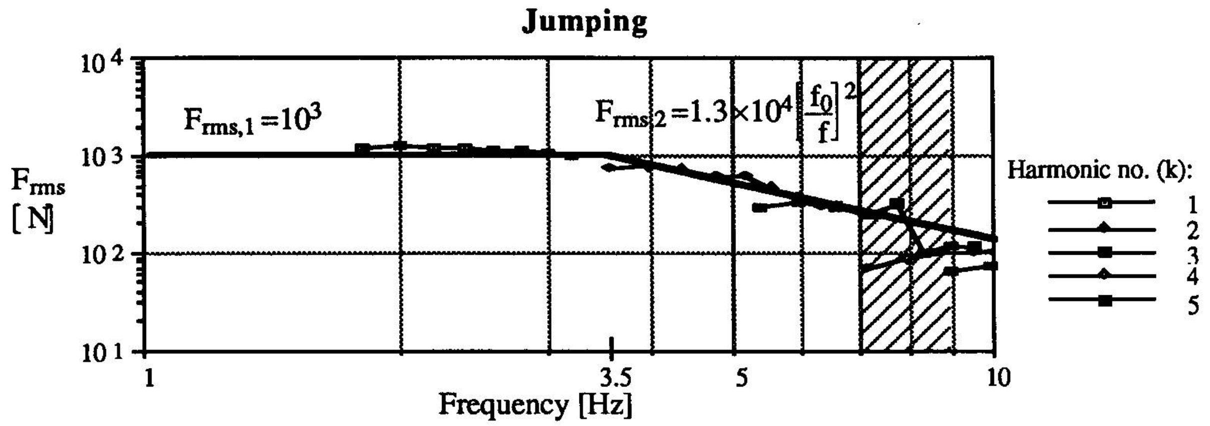

Fig. 8 Narrow-band model of the forces from one person jumping. f_0=1 Hz.

5. CONCLUDING REMARKS

The results from an experimental study of the forces from walking, running and jumping have been presented together with models to be used in the design of low-frequency floors against human-induced vibrations. A method for design calculations, using these force models, is presented in [7].

Furthermore, the experimental results presented above have been compared with results reported by other researchers. These comparisons have provided valuable information on the reliability of the various reported results as there are only a few studies covering the issue and as the measurement series, in all cases, comprise only one or a few individuals. The overall agreement between the results of the present study and those referenced has been found to be fairly good.

6. REFERENCES

1. OHLSSON S.V., Floor vibrations and Human Discomfort. PhD. thesis, Chalmers Univ. of Technology, ISBN 91-7032-077-2, Göteborg, Sweden 1982.
2. RAINER J.H. & PERNICA, G., Vertical Dynamic Forces from Footsteps. Canadian Acoustics, Vol. 14, No. 2, 1986, pp. 12-21.
3. PERNICA G., Dynamic Load Factors for Pedestrian Movements and Rythmic Exercises. Canadian Acoustics, Vol. 18, No. 2, 1990, pp.3-18.
4. BAUMANN K. & BACHMANN H., Durch Menschen verursachte dynamische Lasten und deren Auswirkungen auf Balkentragwerke. Inst. für Baustatik und Konstruktion, ETH, Bericht Nr. 7501-3, Zürich 1988 (in German).
5. EBRAHIMPOUR A. & SACK R.L., Modelling Dynamic Occupant Loads. Journ. of the Struct. Div., Proc. of ASCE, Vol. 115, No.6, 1989, pp. 1476-1496.
6. ERIKSSON P-E. & OHLSSON S., Dynamic Footfall Loading from Groups of Walking People. Proc. of Symp./Workshop on Serviceability of Buildings, Vol. 1, Ottawa 1988, pp. 497-511.
7. ERIKSSON P-E., Vibration of Low-Frequency Floors: Offices and Shopping Centres. To be published in the Proc. of the First World Conference on Structural Steel Design, Elsevier Science Publishers, England 1992.

Defining Occupant Loads and Mitigating Associated Vibrations

Définition des cas de charge des occupants et limitation des vibrations correspondantes

Lastmodelle und Reduktion menschenerregter Hochbauschwingungen

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SUMMARY

Excessive vibrations and deflections of modern flexible structures can be imposed by crowd movements. The authors have measured and modelled forces generated by small groups and crowds performing transient and periodic actions while remaining in place. Presently the authors are examining loads imposed by humans while walking, running and skipping across a structure. The research also addresses the benefits and efficiency of low power semiactive control technologies to mitigate excessive structural response due to phase-related occupant loads.

RESUME

Flexions et vibrations excessives de bâtiments modernes flexibles peuvent être imposées par des mouvements de foule. Les auteurs ont mesuré et modelé des forces produites par de petits groupes et foules qui accomplissent des actions répétées et limitées dans le temps, sur place. Ils étudient aussi les charges imposées par des personnes marchant, courant et sautant dans un bâtiment. Les recherches traitent aussi de bénéfices et de l'efficacité de technologies de faible puissance semiactive pour atténuer une réaction structurelle excessive causée par des charges variées des occupants.

ZUSAMMENFASSUNG

Menschenansammlungen können durch ihre Bewegungen übermässige Schwingungen und Durchbiegungen in modernen flexiblen Bauwerken verursachen. Kräfte wurden gemessen und modelliert, die von kleineren Gruppen und grossen Menschenansammlungen, durch temporäre und periodische Bewegungen unter Beibehaltung des Standortes, hervorgerufen werden. Zur Zeit werden Belastungen untersucht, die von Menschen ausgehen, die über ein Bauwerk gehen, rennen oder springen. Die Forschung beschäftigt sich auch mit den Vorteilen und der Leistungsfähigkeit von niederenergetischen semiaktiven Messtechniken mit der späteren Zielsetzung, übermässige Reaktionen der Bauwerke auf periodische Belastungen zu verringern.

1. INTRODUCTION

Sports stadiums, discotheques, gymnasiums, aerobic dance studios, shopping malls, and airport terminal corridors are all subjected to significant dynamic loads produced by occupants either while remaining in one location or traversing the structure. Many of the occupant actions are performed with a frequency content of 2 to 3 Hz either because the normal human gait is this frequency or music serving as the prompt for the action is played with a beat of 2 to 3 Hz.

Considering that many of today's structures are constructed with long spans and light materials, the first natural frequency tends to be in the vicinity of the excitation produced by occupants in motion. Consequently, coherent crowd harmonic movements (e.g., periodic jumping to music) can produce resonant or near-resonant structural vibrations that are uncomfortable and intolerable for some occupants.
Some of the recent structural failures, such as the Hyatt Regency Hotel in Kansas City, indicate that there can be many lives at stake when human loading is imposed. In addition, there have been serviceability problems that required costly remodeling or revision of building regulations.

In order to mitigate serviceability problems we must understand the amplitude and frequency content of the input, ensure that the natural frequency is significantly greater than the input frequency and/or retrofit existing structures to minimize the effects of the excitation.

Structural control can be used to mitigate structural response and prevent structures from reaching their limit states. Active and passive devices are becoming increasingly popular for controlling structures subjected to earthquake and wind loads. There is now mounting interest in alternate approaches to the control of structural systems. For example, smart materials (e.g., nitineol) can be embedded in structural members and selectively actuated to provide altered system stiffness on demand. The use of electro-rheological fluids to provide altered actuator and compliance characteristics is a second example of the new technologies that are being considered. Drawbacks to these proposed technologies (e.g., high power consumption and low reliability of the material properties) will have to be overcome before these alternatives can be incorporated as controller components in a structural system.

We are using adjustable hydraulic dampers as the means of mitigating the motion of a structure. This technology has been thoroughly tested by an automobile industry that has succeeded in using variable shock absorbers to improve the ride dynamics of automobiles. These computer controlled semiactive devices promise to provide an efficient and cost effective means of mitigating the effects of human dynamic loadings that are time varying and one of the primary causes of excessive vibration in assembly structures.

This paper presents our ongoing research project on loads associated with both in situ and moving human activities. It also addresses benefits of low power semiactive control technologies to mitigate excessive structural response due to phase related occupant loads.

2. IN SITU HUMAN ACTIVITIES

Between 1984 and 1988 we investigated the forces generated by occupants performing maneuvers while remaining in place. The objective of this research program was to define crowd loads for in situ activities.

2.1 Individuals and Small Groups

We designed, built and instrumented a force platform to measure dynamic loading of 1 to 5 people performing maneuvers while remaining in place. The function of the force platform was to measure the total imposed load (i.e., to act as a flat transfer function so that the imposed loads were transmitted to the sensors without distortion in the frequency range of the load).

Approximately 700 individual tests were run. The following seven loading types were chosen: periodic jumping, periodic jouncing, swaying side to side while sitting down, single jump, sitting down suddenly, standing up suddenly, and random jumping. The periodic loadings were measured for frequencies of 2, 3, and 4 Hz resulting in thirteen different test types.

Loads were classified into three major categories (i.e., periodic, transient, and random), and analytical models were used to describe each loading type. A general method of determining the descriptive parameters defining the load histories was proposed for each category. We performed multivariate regression analyses using the descriptive parameters as functions of several independent random variables (e.g., an individual's weight and sex). The regression model is a complete modeling procedure that does not ignore the dependency of the descriptive random variables.

2.2 Crowd Loads

We constructed and instrumented a floor system large enough to accommodate up to 40 people to test the accuracy of our in situ group load simulation model. The floor system (3.66 m by 4.57 m) was constructed from cold rolled steel shapes. We instrumented the floor system with strain gages and linear variable differential transformers (LVDTs), adopted the existing data acquisition system used for the smaller force platform, and calibrated the platform using both the strain gage transducers and LVDTs. The mass, stiffness, and damping matrices of the floor system were modeled as a nine degree-of-freedom system. Next we performed modal analysis and frequency testing of the floor system. Load tests were conducted with 10, 20, 30, and 40 participants for prompted jumping in place at 2 and 3 Hz. We computed group loads with the equation of motion using a combination of experimental data and analytical methods. In addition, we computed group loads using the calibration factors and base plate strain gage transducer output. The two approaches gave very similar loads. The loads obtained from the platform were compared with loads simulated using the group load model. The measured loads for 10, 20, 30, and 40 participants deviated less than 8% from those obtained from the Monte Carlo simulation approach formulated in the previous study (see Fig. 1).

2.3 Suggested Design Criteria

2.3.1 Strength Requirements

Using the results of our studies of large groups performing in situ maneuvers at 2 and 3 Hz, we believe that strength requirements will be satisfied if the structure is designed for a vertical static live load of 2.2 kN/m^2 and a dynamic component of 3.35 kN/m^2. These values are based on loading area per person of 0.325 m^2. Our sample of participants consisted of 15 females and 20 males with a mean weight of 712 N and a standard deviation of 147 N.

2.3.2 Serviceability Requirements

Based upon our investigation we suggested a design approach [2]. Using Mont Carlo simulation and transforming the load-time histories into the frequency domain, we approximated the load intensity using a sinusoidal function. The resulting load curves for three frequency ranges (i.e., 2-3 Hz, 4-6 Hz, and 6-9 Hz) are shown in Fig. 2. We suggest a simplified procedure wherein the designer: determines the fundamental natural frequency of structure (ω_0) and uses the appropriate curve in Fig. 2 to determine the design amplitude to be used with $\sin 2\pi\omega_0 t$. The design structural response is to be judged for acceptability using one of the published criteria [1,3,5,8].

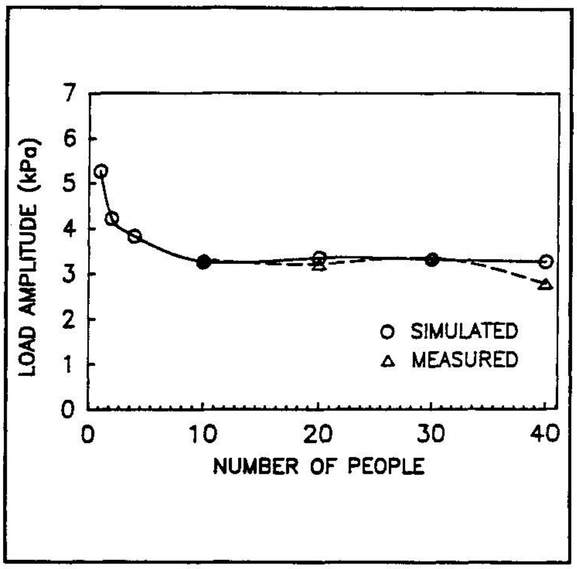

Figure 1 Simulated and Measured Load Amplitude vs. Crowd Size

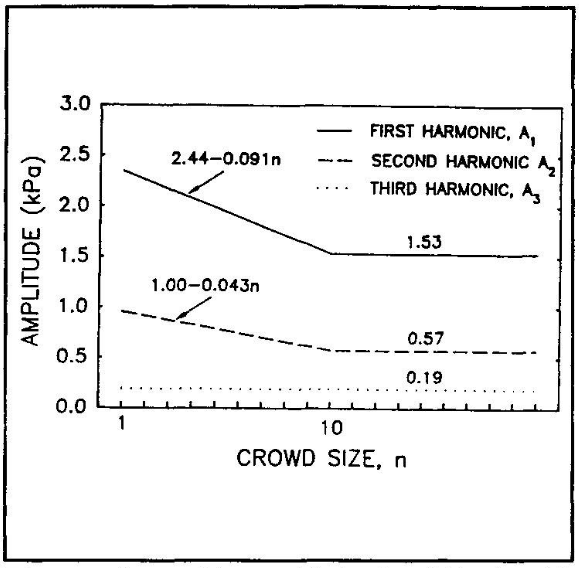

Figure 2 Sinusoidal Amplitude At Dominat Harmonics Vs. Crowd Size

3. MOVING HUMAN ACTIVITIES

Currently, we are: characterizing the loads imposed by occupants while in motion; and mitigating the effects of these dynamic loads using semiactive structural control. We constructed a force platform 9.15 m long and 2.03 m wide consisting of various modules as shown in Fig. 3. The platform is designed so that the subjects have 1.83 m of acceleration ramp to achieve their steady-state motion before encountering the instrumented module. The instrumented force platform is composed of 6 independent plates (81 cm by 91 cm) constructed of 2.5 cm aluminum honeycomb material plates supported by four short instrumented cantilever beams. The natural frequency of each panel is greater than 100 Hz.

We measure loads imposed by one and two people moving across the force platform. A typical force-time history plot with a subject walking totally on the instrumented platform is shown in Fig. 4. Each participant traverses the platform by walking (slow, medium, and fast), running and marching. Load-time histories can be mathematically described using descriptive parameters, but the inverse problem can also be posed. That is, by knowing the descriptive parameters of the load, we can produce the corresponding approximate load-time history. Using the descriptive parameters as functions of several independent variables (e.g., weight and body type, floor resilience and shoe design) we formulate a regression model for an individual's load history as follows:

$$\boldsymbol{p} = \boldsymbol{\alpha} + \boldsymbol{\beta} w + \boldsymbol{\gamma} b + \boldsymbol{\lambda} f + \boldsymbol{\mu} s + \boldsymbol{e} \tag{1}$$

where **p** = the vector of the load descriptive parameters; w = the person's weight; b = person's body type (e.g., b = 1 for ectomorph and b = 0 for endomorph); f = floor resilience (an integer variable); s = shoe type (an integer variable); and $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{\gamma}$, $\boldsymbol{\lambda}$, and $\boldsymbol{\mu}$ = regression parameter vectors; and **e** = error vector, assumed to be normally distributed with zero mean and covariance matrix $\boldsymbol{\Sigma}$. The multivariate regression model represented by Eq. (1) will not ignore the dependency of the descriptive random variables p_i (i = 1,2,3...,n = number of descriptive parameters used). This means that the error covariance matrix, $\boldsymbol{\Sigma}$, may have off diagonal non-zero terms.

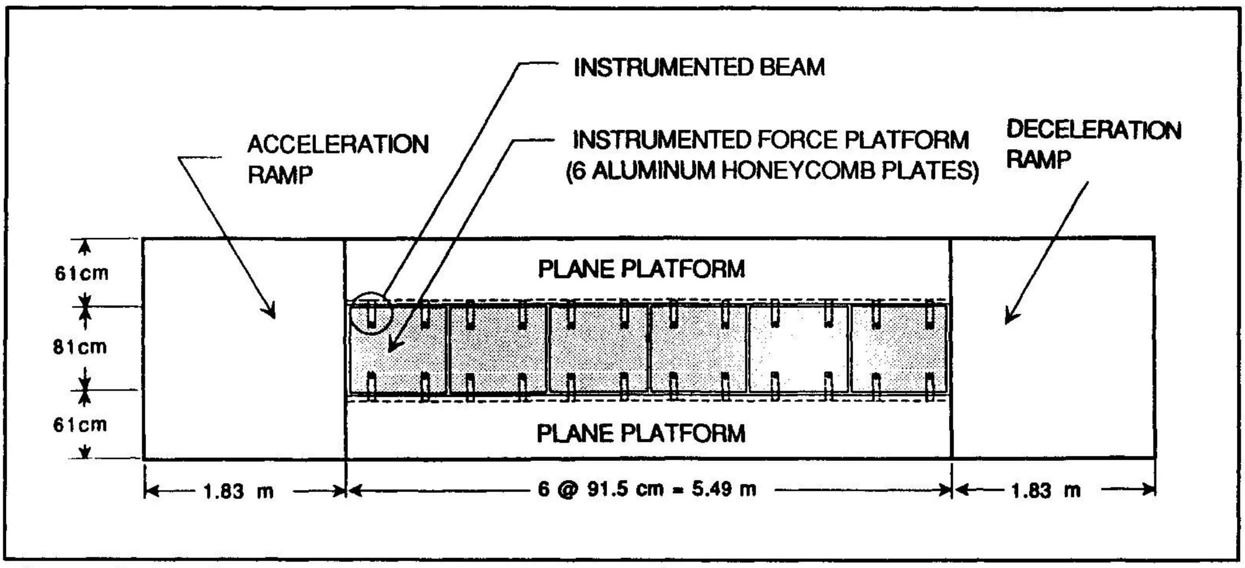

Figure 3 The Force Platform For Measuring Moving Loads

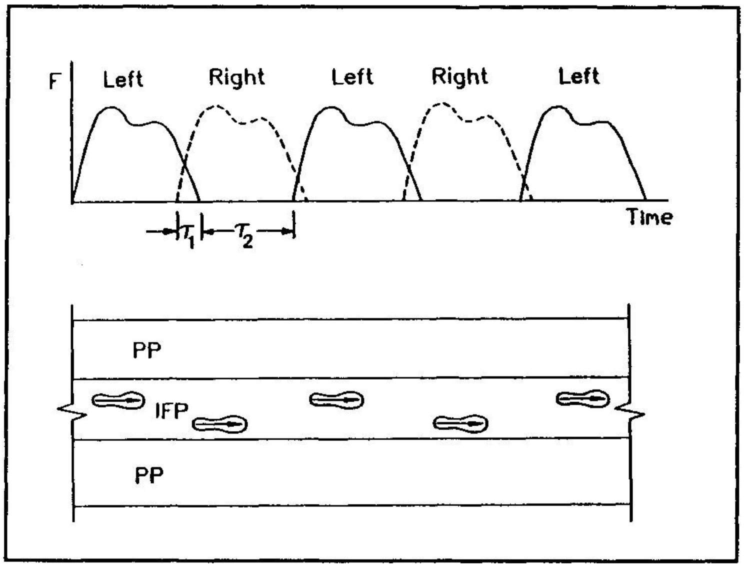

Figure 4 Force-time Plot Of A Subject Walking

Loads imposed by two people traversing the platform are also measured in the research program. If two people walk or run with no prompt, the phase lag between their foot strikes is random. But, if two people walk, march or hop across the platform in response to a prompt signal, the phase lag will be small, but will follow some statistical distribution (e.g., exponential). We found this trend to be true for subjects performing in situ movements to a prompt. We measure the phase lag between two individuals by conducting sufficient number of tests where the subjects move to a prompt.

Using temporal summation of two individual histories we can generate the load-time histories for two people. We found in our work on in situ motion that taking two individual load histories and aligning the prompts gave load-time histories that did not resemble the measured loads; the measured peak load values for two people were much larger than that given by simple superposition. The explanation is that individuals tend to synchronize their motions with respect to the prompt and movements of neighboring people. Crowd coherency is governed by auditory and visual effects.

The force platform is designed to accommodate at least four people simultaneously. The maneuvers for one and two people are also used for crowd loads. Walking and marching will be performed with and without a prompt. We will also obtain the total imposed loads by mathematically extrapolating from single foot strikes of participants moving side by side in two or more rows. The experimental information will be extrapolated for loads by large groups of various sizes using simulation, along with the descriptive parameter statistics and the phase lag distribution for two individuals. Loading spectra will be obtained for various activities.

4. STRUCTURAL CONTROL

Serviceability problems can occur in various types of floor systems such as those incorporating steel joists, lightweight concrete slabs, longspan hot-rolled steel shapes, lightweight cold-rolled steel shapes and manufactured wooden beams. We will construct a floor system with a propensity for vibrating at frequencies that are perceptible to occupants. We will identify the mass, stiffness and proportional damping matrices using both modal testing methods and time domain input-output identification methods.

Vibrations of the lightweight floor system will be mitigated using semi-active control. The controlled inputs will be provided by tunable hydraulic dampers. These low-power actuators, which resemble the common hydraulic shock absorber, typically include a motorized internal valve, or pressure actuated servo valve. The power required by the process is that necessary to position the valve.

An optimal control strategy in the frequency domain will be used to adjust the degree of required damping. The loads transmitted to the structure are phase related and the character of the correlation is detectable in real time. This approach of optimal control has been described by Lin, et al [4] and also by Patten [6] in his development of a controller design for semi-active auto suspension designs.

In order to demonstrate the concept of applying semiactive damping to structures, a preliminary experiment was conducted. A pin-roller supported walkway (4m long and .5m wide) was constructed of mild steel. The natural frequency of the structure (without the damper attached) was 4 Hz. A commercially available controllable semiactive damper was then affixed to the midspan (see Fig. 5). A small brushed DC motor was used to provide modulation of a hydraulic by pass value that was mounted internal to the damper. Bench testing revealed that the motor was able to move the valve from a full open to a full closed position in approximately 10 ms. Variation of the valve position produced variable levels of damping. The force versus velocity characteristic for the damper used was approximately linear for the range of relative velocities experienced during the experiment. Throttling of the valve essentially changes the slope of the force versus damping characteristic of the semiactive damper.

A piezoresistive accelerometer with a bandwidth of 0 to 10 KHz was mounted on the deck of the walkway to sense the dynamics of the structure. A high precision encoder was attached to the shaft of the motor to monitor the valve position. A PC based data acquisition system was utilized to acquire the amplified accelerometer output. A sample rate of 2 KHz was employed, and a single pole 1 KHz hardware filter was used to eliminate high frequency noise from the data. Updates of the actuator occurred at 1 KHz.

A test of the controlled system was conducted to demonstrate the simplicity of the design. An easy to apply instantaneous optimal control algorithm [7] was utilized. The procedure utilized the acceleration and the rate of change of the acceleration to adjust the damping. The objective of the performance index used was to reduce the acceleration transmitted to the structure when a pedestrian impact was experienced.

An individual jumped on and off the walkway to test the response of the system. Figure 6 shows the controlled and uncontrolled acceleration frequency response. The results make it clear that the activation of the damper attenuates the magnitude of the response. Also the frequency content of the controlled response is generally higher then the resonant frequency of the structure. Preliminary results indicate that a semiactive structural damper can effect a significant change in the way a structure responds to loads imposed by pedestrians.

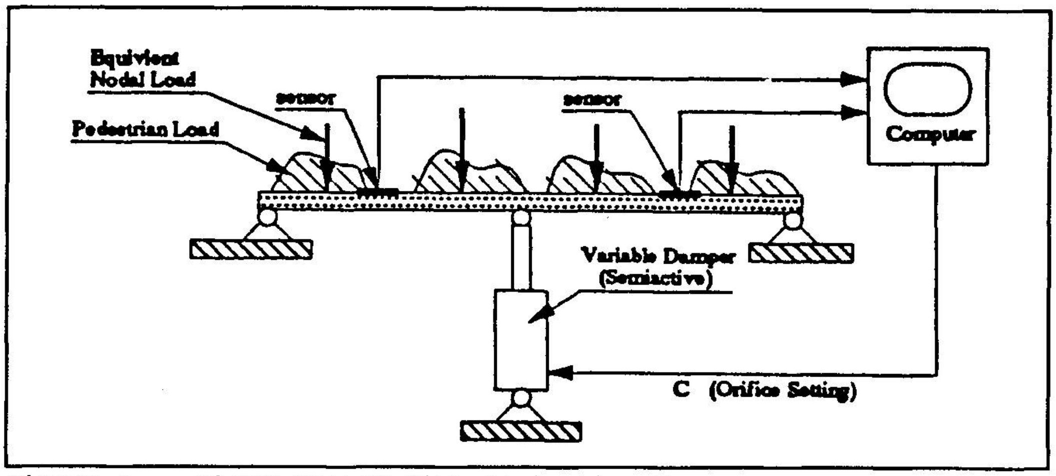

Figure 5 Floor System With Semiactive Damper

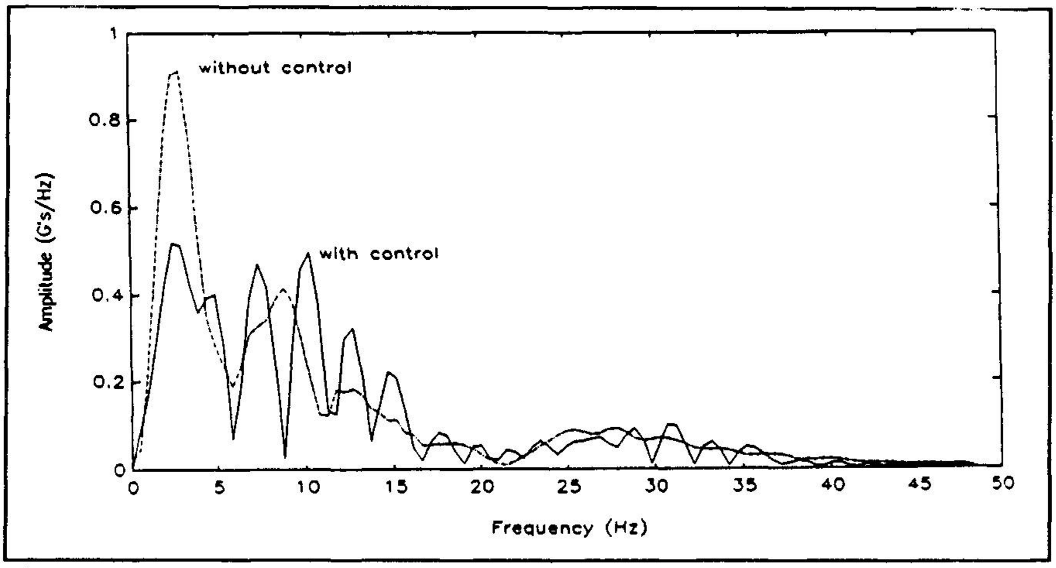

Figure 6 FFT Of The Beam Vibration

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Allen D. E., and Rainer J. H., "Vibration Criteria for Long-span Floors," *Canadian Journal of Civil Engineering*, 3(2), 1976, pp. 165-173.

2. Ebrahimpour A., and Sack, R. L., "Design Live Loads for Coherent Crowd Harmonic Movements," *Journal of Structural Engineering*, ASCE, 118(4), 1992, 1121-1136.

3. Lenzen, K. H., "Vibration of Steel Joist Concrete Slab Floors," *Engineering Journal*, AISC, 3(3), July 1966, pp. 133-136.

4. Lin, Y., Luo, W. and Zhang, Y.M., "A New Method for the Optimization of a Vibration Isolation System," *Journal of Vibration and Acoustics*, Vol. 112, July 1990, pp. 413-416.

5. Murray, T. M. , "Acceptability Criterion for Occupant-induced Floor Vibrations," *Sound Vib.* 67(4), 1979, pp. 24-30.

6. Patten, W.N., Kedar, P. and Abboud, E., "A Variable Damper Suspension Design for Phase Related Road Inputs," Presented at ASME, WAM, Dec. 1991, Atlanta, GA.

7. Yang, J.N., Akbarpour, Abbas, Ghaemmaghami, Peiman, "New Optimal Control Algorithms for Structural Control," *Journal of Engineering Mechanics*, Vol. 113, No.9, September, pp. 1369-1386.

8. Wiss, J. F. and R. A. Parmelee, "Human Perception of Transient Vibrations," *Journal of the Structural Division*, ASCE, 100(4), 1974, pp. 773-787.

Evaluation of Dynamic Crowd Effects for Dance Loads

Evaluation des effets dynamiques sur les pistes de danse

Auswertung der dynamischen Mengeneffekte bei Tanzbelastung

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SUMMARY

When a crowd of people attempt the same repetitive movement, perfect synchronism is unlikely, and the total peak load produced by the group movement is less then the individual peak loads multiplied by the number in the group, i.e. the load is attenuated due to the crowd effect. This paper provides an estimation of this effect for dance loads. The loads for individuals and for an individual in a group of people are defined. The dynamic crowd factor is defined as the ratio of the maximum dynamic response for the two types of load. Three criteria are proposed and used to evaluate this factor. It is found that the factor is not affected by boundary conditions, dance frequency, structural frequency or damping.

RESUME

Lorsqu'une foule effectue les mêmes mouvements répétitifs, il est très rare d'arriver à un synchronisme total, et la charge maximale totale produite par les mouvements de groupe est inférieure à la charge maximale produite par chaque individu multipliée par le nombre de personnes du groupe; c'est-à-dire que la charge est atténuée par l'effet de groupe. Cet exposé donne une estimation de cet effet sur les charges des pistes de danse. Y sont définies la charge de chaque individu et la charge d'un individu dans un groupe de personnes. Le facteur dynamique de foule est le rapport de la réaction dynamique maximum des deux types de charge. On propose trois critères, qui sont utilisés pour évaluer ce facteur. Les calculs ont fait apparaître que le facteur n'est pas affecté par les conditions limites, le rythme de la danse, la fréquence structurelle ou l'amortissement.

ZUSAMMENFASSUNG

Wenn eine Menschenmenge dieselbe sich wiederholende Bewegung auszuführen versucht, ist perfekte Synchronisierung unwahrscheinlich, und die von der Gruppenbewegung erzeugte Gesamtspitzenlast liegt unter dem Wert, der sich aus der Multiplikation der Einzelspitzenlasten mit der Anzahl der Gruppenmitglieder ergibt; die Belastung wird also durch den Mengeneffekt gedämpft. Der Beitrag definiert die Belastung durch einen Einzeltänzer und für das Individuum in einer Menschengruppe. Der dynamische Mengenfaktor ergibt sich aus dem Verhältnis der maximalen dynamischen Reaktion beider Lasttypen. Für die Auswertung dieses Faktors werden drei Kriterien vorgeschlagen und eingesetzt. Es stellt sich heraus, dass der Faktor von Randbedingungen, Tanzfrequenz, Baufrequenz und Dämpfung nicht beeinflusst wird.

1 Introduction

When a crowd of people attempt the same repetitive movement, perfect synchronism is unlikely, even when there is a musical beat to follow. The effect of this lack of synchronisation is that the total peak load produced by group movement is less than the individual peak loads multiplied by the number in the group, *i.e.* the load is attenuated due to the crowd effect. This effect is important in evaluating overall crowd loads and their effect for design.

The loads considered in this paper are dynamic loads induced by human movement in time with a certain rhythm, such as dancing, jumping, swaying, stamping and aerobics. These loads are herein termed dance type loads. A full description of these loads consists of four components, namely load pattern, load frequency, load intensity and dynamic crowd effect. The first three items can be determined experimentally, but it is improbable that controlled experiments will be made with very large groups of people to enable the fourth parameter to be evaluated. Research has been conducted in this area on the first three items and the results can be found in both publications[1, 2, 9] and international guides[3, 6, 8]. However, much less information is available regarding to the dynamic crowd effect, despite the fact that it is potentially quite important.

Tilden[11] observed in tests with up to seven men on an ordinary platform scale that group movements could be random, and that perfect synchronism, to get the full effect of impulsive forces from a group of people, was improbable. A laboratory test was performed by Ebrahimpour and Sack[4]based on a 4ft by 8ft force platform where they measured dynamic loads of individuals and small groups. They noticed that individual loads could not be distinguished from the response of the group as a whole; thus the phase lag between individual peak loads could not be evaluated. This experimental investigation was further developed by the same authors using a 15ft by 12ft floor system, that was able to hold up to 40 people. The measured data indicated that the load amplitude per person reduces as the number of people involved increases[5]. Rainer, Pernica and Allen[10] also found that for groups of two, four or eight people jumping to a common timing signal, the peak values of dynamic load factors would be lower than that for single person. Ebrahimpour and Sack[4] suggested that an equivalent load-time history intensity per person in the crowd was determined by a simple averaging measure, *i.e.* adding M individual loads in which the random time phase lag is considered and then dividing by M and the area.

In this paper, a dynamic crowd factor is defined, which can be incorporated into existing load models to account for the reduction in the dynamic part of the load. The solution is developed based on a previous study[7]. A random phase lag, that obeys the normal distribution law, is introduced to represent the lack of synchronisation of individuals within a group of people. This is then used to obtain a statistical estimation of the reduction of loads due to the crowd effect. The study focuses on the simple dance activity, but the idea presented can be applied to more complex situations.

2 Basic Assumptions

The following assumptions are used in this study.

1. The floor is rectangular with uniform thickness and is either simply supported or clamped along its four edges.

2. The loads are described by existing models[2, 3, 7, 9] and are uniformly distributed on the floor, *i.e.*, loads are constant in the spatial domain but vary in the time domain.

3. When a group of people attempt the same repetitive movement, the phase lag, to describe the lack of coherence, is a random variable and obeys the normal probability law.

According to the first two assumptions, the response of a floor under dance type loads can be expressed analytically and only the fundamental mode needs to be considered in the analysis[7]. The third assumption establishes the random load model, albeit the distribution of the phase lag has to be defined.

3 Load Model for Crowd

3.1 Load model for individuals

An individual dancing or jumping load can be described analytically as follows[7]

$$F(t) = G\left[1.0 + \sum_{n=1}^{\infty} r_n sin(\frac{2n\pi}{T_p}t + \phi_n)\right] \quad (1)$$

where the coefficients r_n and ϕ_n are

$$r_n = \sqrt{a_n^2 + b_n^2} \qquad \phi_n = tan^{-1}\left(\frac{a_n}{b_n}\right)$$

$$\left.\begin{array}{lll} a_n = 0.5\left[\frac{1-cos(2n\alpha+1)\pi}{2n\alpha+1} + \frac{cos(2n\alpha-1)\pi-1}{2n\alpha-1}\right] & & \\ b_n = 0.5\left[\frac{sin(2n\alpha-1)\pi}{2n\alpha-1} - \frac{sin(2n\alpha+1)\pi}{2n\alpha+1}\right] & & \\ If & 2n\alpha = 1 & n = 1,2,3,\ldots \\ then & a_n = 0 & b_n = \pi/2 \end{array}\right\} \quad (2)$$

Where T_p and α are the load period and the contact ratio. The first part of the load G is the static load and indicates the individuals weight. The second part is the dynamic load induced by human movements.

For dancing, only the first Fourier term needs to be considered while for jumping and aerobics, the first three Fourier terms should be taken into account. According to the current analysis methods, Eq.(1) is applied to every individual in the crowd. This means that the dynamic crowd effect, *i.e.* the discrepancy in phase lag, is not considered.

3.2 Load model for crowd

To consider the dynamic crowd effect for a group of people, the individual load in a group is

$$F_s(t) = G\left[1.0 + \sum_{n=1}^{\infty} r_n sin(\frac{2n\pi}{T_p}t + \phi_n + \psi_s)\right] \qquad s = 1,2,...,M \quad (3)$$

Where M is the number of people involved. Comparing Eqs.1 and 3, the only difference is the phase lag ψ_s which characterises the difference between individuals and individuals within a group. When a group of people dance at a common frequency, it is reasonable to assume that the phase lag ψ_s is a random variable and obeys the normal distribution[12] as follows

$$\Psi = \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-a)^2/2\sigma^2} \quad (4)$$

The parameter a corresponds to the central position and the parameter σ determines the spread. The area enclosed by the normal distribution Ψ (Eq. 4) and x equals one. It is worth noting that the area in the region [a-3σ, a+3σ] is 0.997. This states that it is probable that the random variable is located in this region. The phase lag ψ_s varies in the region [-π, π]. Therefore, the central position is zero, *i.e.*, $a = 0$. The standard deviation σ can be estimated by equating the above two regions $\sigma = \pi/3 = 1.0472 \doteq 1.0$. This is the typical value for σ adopted for the analysis. The selection of σ is central to the evaluation of the crowd effect. For a well co-ordinated group, may be a group of ballet

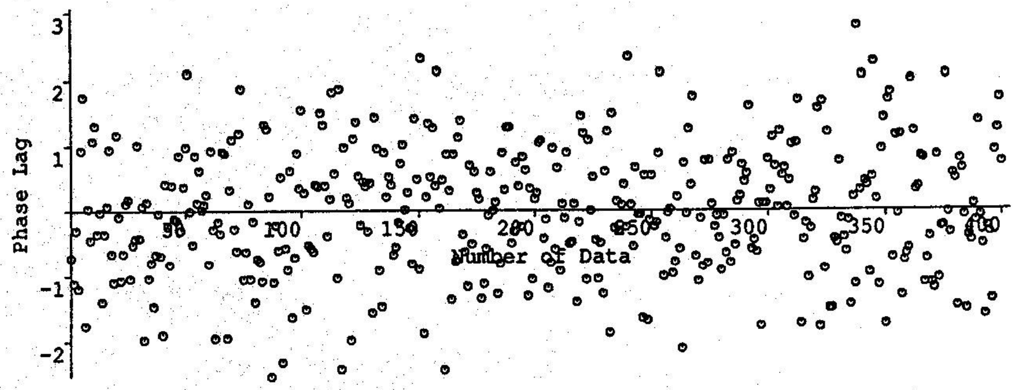

Fig.1 Computer Simulation of Random Phase Lag Obeying the Normal Distribution

dancers, σ is likely to be smaller than that for a group of disco dancers. However, for a large group, σ is likely to tend towards a specific value, which may depend on the *difficulty* of the dance; and also the difficulty of the dance may depend upon the dance frequency. Several cases will be evaluated, using various values of σ, to show the sensitivity of the crowd factor to the choice of σ.

The following summarises the method used to generate the M normally distibuted random angles in the range of $[-\pi, \pi]$.

1. For a normal distribution within the range $[-\pi, \pi]$, calculate the area within N equal bands. $(B_i, i = 1, 2, ..., N)$
2. Calculate the number of elements (MB_i) required in each band (to the nearest integer value).
3. Choose a phase angle randomly between $[-\pi, \pi]$ and accept the value if the sum of accepted values within its particular band is not greater than the total number required, otherwise discard.
4. Repeat 3 until all bands are complete.
5. Rearrange all the accepted elements in a random order to remove the effects of the selection process.

Fig.1 shows 400 generated random phase lags that follow the normal distribution.

4 Definitions of Dynamic Crowd Factor

Current methods for determining floor response are based on uniformly distributed dance loads neglecting the phase difference between individuals. It is suggested that a dynamic crowd factor can be incorporated into the current design method, as a simple modifier of the load. Several criteria can be used to define the dynamic crowd factor which is herein expressed by the symbol f_c with an additional subscript indicating the criterion adopted.

4.1 Displacement based criterion

The dynamic crowd factor is defined as the ratio of the maximum dynamic displacements induced by Eq.(3) and Eq.(1) respectively. *i.e.*

$$f_{cd} = \frac{A_{max}(\psi_s)}{A_{max}} \tag{5}$$

where A_{max} is the dynamic displacement at the centre of the floor and is the maximum absolute value during a period of steady state vibration. $A_{max}(\psi)$ has the same meaning but considers the phase discrepancy between individuals. The static displacement for both cases is the same and is not included in Eq. 5.

4.2 Acceleration based criterion

In a similar manner to the displacement based criterion, the dynamic crowd effect can be defined as follows

$$f_{ca} = \frac{\ddot{A}_{max}(\psi_s)}{\ddot{A}_{max}} \tag{6}$$

where $\ddot{A}_{max}$ indicates the acceleration at the centre of the floor and is the maximum absolute value during a period for a steady state vibration. $\ddot{A}_{max}(\psi_s)$ has the same meaning but considers the phase discrepancy between individuals.

4.3 Energy based criterion

This criterion can be represented by equating the sum of the work done by the dynamic part of the individual loads in a group (Eq.3) on the displacement $W(x, y)$ to that done by the corresponding part of the individual loads(Eq.1) multiplied by the dynamic crowd factor f_{ce}

$$f_{ce} = \frac{\sum_{s=1}^{M} W(x_s, y_s) F_{sd}(t)}{\sum_{s=1}^{M} W(x_s, y_s) F_d(t)} = \frac{\sum_{s=1}^{M} W(x_s, y_s) F_{sd}(t)}{F_d(t) \sum_{s=1}^{M} W(x_s, y_s)} \tag{7}$$

Where the displacement $W(x, y)$ could be the actual displacement or any feasible displacement that satisfies the boundary conditions.

For the first two criteria, the response of a floor should be determined in advance. For the third criterion the fundamental mode of a floor can be adopted instead of the actual response.

5 Expression of Dynamic Crowd Factor

The solution of the floor response can be determined for dancing and other human movements. However, only the dynamic crowd factors for dances, where only one Fourier term needs to be considered, are determined in this study.

5.1 Solution of floor response

A method of calculating floor vibrations induced by uniformly distributed human loads has been proposed by the authors[7]. Using this procedure, the central displacement of the floor, induced by a group of individual loads (Eq.3) can be obtained.

$$A_s(t) = \frac{G}{\omega_{11}^2 \iint mW_{11}^2(x, y) dx dy} \sum_{s=1}^{M} W_{11}(x_s, y_s) \left[1.0 + \sum_{n=1}^{\infty} \frac{r_n sin(nft - \theta_{ij} + \phi_n + \psi_s)}{\sqrt{(1 - n^2\beta_{ij}^2)^2 + (2n\zeta\beta_{ij})^2}} \right] \tag{8}$$

The displacement $A_s(t)$ is at the centre of the floor and considers the individual's contribution to the group. Eq. 8 is derived based on the first two assumptions presented in the previous section. $W_{11}(x, y)$ is the fundamental mode of vibration of the floor and depends upon boundary conditions. This solution consists of two parts, the first is the static response due to the weight of the people, while the second is the dynamic response produced by human movements. When the discrepancy in phase ψ_s is neglected, Eq. 8 is reduced to the following form

$$A(t) = \frac{G \sum_{s=1}^{M} W_{11}(x_s, y_s)}{\omega_{11}^2 \iint mW_{11}^2(x, y) dx dy} \left[1.0 + \sum_{n=1}^{\infty} \frac{r_n sin(nft - \theta_{ij} + \phi_n)}{\sqrt{(1 - n^2\beta_{ij}^2)^2 + (2n\zeta\beta_{ij})^2}} \right] \tag{9}$$

The corresponding accelerations can be obtained by double differentiation of the displacements (Eqs. 8, 9). The normalised modes for simply supported and clamped floors are respectively:

$$W_{11}(\xi, \eta) = sin(\xi) sin(\eta) \qquad 0 \le \xi \le 1, 0 \le \eta \le 1 \tag{10}$$

$$W_{11}(\xi,\eta) = (1-4\xi^2)^2(1-4\eta^2)^2 \qquad -0.5 \le \xi \le 0 - 0.5 \le \eta \le 0.5 \tag{11}$$
$$\xi = x/L_x \qquad \eta = y/L_y$$

where L_x and L_y are the dimensions of the floor.

5.2 Expression of three criteria

Taking the displacement based criterion (Eq. 5) and substituting Eqs(8, 9) into Eq. 5 gives.

$$f_{cd} = \frac{Max|\sum_{s=1}^{M} W(\xi_s,\eta_s)sin(nft - \theta_1 + \phi_1 + \psi_s)|}{Max|\sum_{s=1}^{M} W(\xi_s,\eta_s)sin(nft - \theta_1 + \phi_1)|} \tag{12}$$

Since the phase lag ψ_s follows the normal distribution law, the maximum value in the time domain is at $nft - \theta + \phi = \pi/2$ for a steady state vibration. Therefore, the above equation can be reduced to

$$f_{cd} = \frac{\sum_{s=1}^{M} W(\xi_s,\eta_s)sin(0.5\pi + \psi_s)}{\sum_{s=1}^{M} W(\xi_s,\eta_s)} \tag{13}$$

Similar procedures can be applied to the acceleration and energy based criteria. Thus it is found that

$$f_c = f_{cd} = f_{ca} = f_{ce} \tag{14}$$

Eqs. 13 and 14 indicate that for dancing

1. The dynamic crowd factors are the same for either the displacement, the acceleration or the energy base criteria and can be represented in the simple form shown in Eq. 13.
2. The dynamic crowd effect is not related to the dance frequency, the floor frequency, the damping factor and the dead and live mass involved.

6 Determination of Dynamic Crowd Factor

Before using Eq. 13 to calculate the dynamic crowd factor, the following conditions should be considered

1. ψ_s describing the phase difference between the individual action and the music beat, is a random variable that obeys the normal distribution. The more random angles involved, the closer the actual distribution of these angles to the normal distribution. Therefore, a minimum number of 100 individuals in a group is used in this study.
2. Since ψ_s is a random variable, the dynamic crowd factor is correspondingly a random variable. To ensure a reliable result, 400 samples are calculated using Eq. 13, then statistical analysis is applied to determine the mean value and standard deviation of the dynamic crowd factor.

In the determination of the dynamic crowd factor, the individuals in a group are assumed to be uniformly distributed on a rectangle floor *i.e.* NX and NY people equally distribute in the x and y directions. The following data is adopted in the analysis

$$NX = 10, 15, 20, 25, 30, 35, 40, 45, 50$$

$$NY = 10, 15, 20, 25, 30, 35, 40, 45, 50$$

Hence there are in total 81 combinations to evaluate for each set of conditions. The boundary conditions considered are either the simply supported or fully clamped along the four edges of the floor. Also three values of σ (the standard deviation for the normal distribution) are given. Tables 1 lists the mean value of the dynamic crowd factors for selected cases evaluated for simply supported and clamped floors. Comparison of the dynamic crowd factors in these two tables shows

Table 1: Dynamic Crowd Factor

Simply Supported Boundary Condition									
	$\sigma = 0.9$			$\sigma = 1.0$			$\sigma = 1.1$		
	10	30	50	10	30	50	10	30	50
10	0.712	0.696	0.686	0.680	0.641	0.626	0.605	0.577	0.574
30	0.692	0.686	0.688	0.639	0.630	0.630	0.580	0.570	0.572
50	0.686	0.688	0.685	0.626	0.630	0.625	0.573	0.573	0.566
Clamped Boundary Condition									
	$\sigma = 0.9$			$\sigma = 1.0$			$\sigma = 1.1$		
	10	30	50	10	30	50	10	30	50
10	0.720	0.694	0.688	0.687	0.646	0.627	0.610	0.580	0.576
30	0.696	0.692	0.694	0.647	0.635	0.636	0.582	0.576	0.576
50	0.689	0.694	0.691	0.626	0.636	0.630	0.577	0.577	0.571

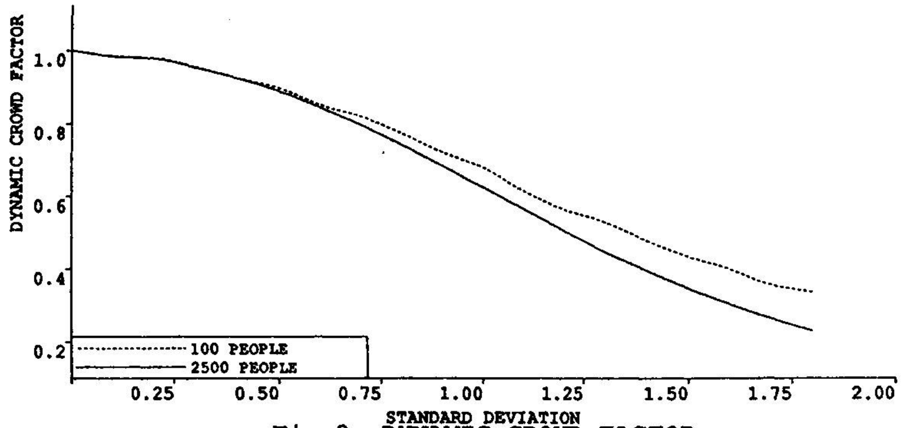

Fig.2 DYNAMIC CROWD FACTOR

1. The different boundary conditions basically do not affect the dynamic crowd factors.
2. The smaller the standard deviation (corresponding to that the distribution of the phase lag ψ_s), the higher the dynamic crowd factor.

Fig.2 gives the dynamic crowd factor f_c for a group of 100 and 2500 people and for the simply supported boundary condition as the function of the standard deviation σ. It has already been mentioned that this is central to the evaluation of the crowd effect and it's significance is shown in the figure. It is important not to overestimate σ as this would lead to an underestimation of the total load. Some experimental measurements had been made by Ebrahimpour and Sack[4], and these gave a value of about 0.55 for 40 people. This is slightly smaller than the values obtained using $\sigma = 1.0$ which are 0.68 for a group of 100 people and 0.63 for 2500 people. Hence, if the values for $\sigma = 1.0$ are adopted they are conservative with respect to the one measured value available.

7 Conclusions

In this study the dynamic crowd factor is defined which reflects the lack of synchronisation of individuals within a group. The conclusions drawn from the study for the dance activity are summarised as follows

1. The displacement, acceleration and energy based criteria give the same results.
2. The different boundary conditions basically do not affect the dynamic crowd factor

3. The dance frequency, structural frequency and damping factor do not affect the dynamic crowd factor.

4. For the proposed distribution of phase differences, the dynamic factor for a group of 100 people is 0.68 and for 2500 people it is 0.63.

The advantage of introducing the dynamic crowd factor for a group of people dancing is that it provides a better model of the loads and it also combines simply with existing analysis methods. Thus the load for a group of people and the response induced by the group of people are respectively

$$F(t) = G\left[1.0 + f_c \sum_{n=1}^{\infty} r_n sin(\frac{2n\pi}{T_p}t + \phi_n)\right] \quad (15)$$

$$A(x,y,t) = \frac{G \iint W_{11}(x,y)}{m\omega_{11}^2 \iint W_{11}^2(x,y)dxdy}\left[1.0 + f_c \sum_{n=1}^{\infty} \frac{r_n sin(nft - \theta_{ij} + \phi_n)}{\sqrt{(1-n^2\beta_{ij}^2)^2 + (2n\zeta\beta_{ij})^2}}\right] W_{11}(x,y) \quad (16)$$

Further analytical studies of the dynamic crowd effect to provide the dynamic crowd factor for other cases are required for

1. Activities where several Fourier coefficients are needed to model the loads.

2. Non-uniformly distributed load in which several modes need to be considered.

In addition, further experimental studies would be helpful.

References

[1] Allen, D. E., Vibration criteria for assembly occupancies, Canadian Journal of Civil Engineering, **12**(3), pp. 617-623, 1985

[2] Bachmann, H., Vibrations of building structures caused by human activities; case study of a gymnasium, Technical Translation No. TT-2077, National Research Council of Canada, Ottawa, 1984.

[3] Comite Euro-Internatinal de Beton, Vibration problems in Structures – Practical Guidelines, 1991.

[4] Ebrahimpour, A. and Sack, R. L., Modelling dymanic occupant loads, J. of Structural Engineering, ASCE, **115**(6), pp.1476-1496, 1989.

[5] Ebrahimpour, A., Sack, R. L. and Van Kleek, P. D., Computing crowd loads using a nonlinear equation of motion, Computer & Structures, **41**(6), pp.1313-1319, 1991.

[6] International Standard ISO 2631-1978, 1978

[7] Ji, T. and Ellis, B. R., Floor vibration induced by dance type of loads, to be published.

[8] National Building Code of Canada 1985, National Research Council of Canada, Ottawa, Canada.

[9] Pernica, G., Dynamic load factors for fedestrian movements and rhythmic exercises, Canadian Acoustics, **18**(2), pp.3-18, 1990.

[10] Rainer, J. H., Pernica, G. and Allen, D. E., Dynamic loading and response of footbridge, Canadian Journal of Civil Engineering, **15**(1), pp. 66-71, 1987.

[11] Saul, W. E. and Tuan, C. Y., Review of live loads due to human movements, J. of Structural Engineering, **112**(5), pp. 995-1004, 1986.

[12] Wetherill, G. B., Elementary Statistical Methods, Chapamn and Hall Ltd, London, 1982

Reduction Factor for Human Loads in Dancing Halls

Facteur de réduction pour les charges humaines dans les salles de danse

Ein Reduktionsfaktor für menschenerzeugte Lasten in Tanzsälen

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SUMMARY

In this paper a reduction factor for dynamic loads in dancing halls is proposed. This factor relates the computed spectral values of the structural response, considering on the one hand the actual partially-correlated loads and on the other hand deterministic, fully correlated design loads. The reduction obtained is compared with the results from measurements included in the bibliography.

RESUME

L'article propose un facteur de réduction des charges dynamiques dans les salles de danse. Ce facteur est déduit de la relation entre les valeurs spectrales de la réponse structurale, calculée pour la valeur estimée de la corrélation partielle des charges et pour la valeur unitaire de cette corrélation. La réduction ainsi calculée est comparée avec des valeurs mesurées, mentionnées dans la bibliographie.

ZUSAMMENFASSUNG

In diesem Aufsatz wird ein Reduktionsfaktor für die in Tanzsälen erzeugten dynamischen Lasten vorgeschlagen. Dieser Faktor gibt das Verhältnis zwischen den Spektralwerten der Bauwerksantwort wider, die einerseits mit den wirklichen, teilweise korrelierten Lasten und andererseits mit den deterministischen, vollkorrelierten Lasten gerechnet werden. Der Reduktionsfaktor wird anschliessend mit Messungsergebnissen aus der Literatur verglichen.

1. INTRODUCTION

Excessive vibrations of dancing halls and other structures due to dynamic loads imposed by assemblies have been noted in recent years. These vibrations were annoying to the users and, in some cases, calculations have even shown an unacceptable loss of structural safety.

The increase in the number of structures needing repair leaded to the development of different load models. These models, derived on a deterministic basis, do not take into account the correlation between the individuals which leads to an unrealistic linear increase of the dynamic load with the number of participants.

To investigate this assumption a more general, stochastic model was developed and measurements were carried out on a dance hall to evaluate the model parameters. Based on this model a reduction factor for the structural response computed by a deterministic load model can be derived.

2. STOCHASTIC LOAD MODEL

The proposed model aims to represent the physical phenomena and must, therefore, take into account the principal characteristics of this type of loads:

- They are almost periodic, characterized by narrow peaks in the frequency domain, and can be decomposed into several harmonics of the basic frequency, usually up to three, each of them owing a different degree of randomness.
- Assembly loads are made up from individual point loads, all of the same type and correlated with each other. Considering that we are interested, in the practice in a determined frequency to check the case of resonance only the correlation between individuals at the same harmonic should be investigated.

The loads are modeled as a random field of time and space. Under the assumption of homogeneity, it is described by its complex valued cross spectrum, $C(\xi, f)$, computed between any two points at a distance ξ on the load field. The coefficient $\rho_f(\xi)$, defined as follows,

$$\rho_f(\xi) = \frac{C(\xi,f)}{C(0,f)} = \frac{C(\xi,f)}{S(f)} \tag{1}$$

can be seen as a spatial correlation coefficient [6], whose square module is the coherency function and whose imaginary and real parts define a phase angle,

$$\begin{cases} |\rho_f(\xi)|^2 = \Re^2[\rho_f(\xi)] + \Im^2[\rho_f(\xi)] \\ \phi_f(\xi) = -\arctan\frac{\Im[\rho_f(\xi)]}{\Re[\rho_f(\xi)]} \end{cases} \tag{2}$$

Because only the harmonics of the load function are of interest the spatial correlation coefficient has to be computed only for these harmonics.

2.1 Time correlation

Load histories are measured from individuals at rhythmic movements (jumping, dancing, etc.) and filtered with a bandpass filter to obtain separate time functions for each harmonic. The correlation function for a harmonic is of the form:

$$R_n(\tau) = a_n(\tau)\cos(2n\pi f_0 \tau) \tag{3}$$

where nf_0 and $a_n(\tau)$ represent, respectively, the n^{th} harmonic[1] and the envelope of the correlation function.

Based on the observation of measurements, the following model is suggested for the envelope:

$$a_n(\tau) = \begin{cases} \sigma_n^2[\eta_{d,n} + (1-\eta_{d,n})\frac{\Gamma_n - \tau}{\Gamma_n}] & \text{for } 0 \leq |\tau| \leq \Gamma_n \\ \sigma_n^2 \eta_{d,n} & \text{for } |\tau| > \Gamma_n \end{cases} \tag{4}$$

According to (4), the correlation consists of a deterministic part, $\sigma_n^2\eta_{d,n}$, that is own to the rhythmic stimulus of the music, and a stochastic part given by the time-dependent fluctuation of the load amplitude and period. This random portion has a correlation length of Γ_n.

2.2 Space correlation

The space correlation coefficient defined in (1) is modelled by mutually independent functions for its module and for its phase angle:

$$\begin{aligned} |\rho_n(\xi)| &= k_{d,n} + (1-k_{d,n})e^{-k_{a,n}\xi} \\ \phi_n(\xi) &= \lim_{c\to\infty} \Phi_n(1-e^{-c\xi}) \end{aligned} \tag{5}$$

The function for the module allows the existence of a deterministic part, k_d, in accordance with the time correlation model. The phase angle is assumed to be independent of the distance ξ between individuals.

2.3 Model parameters

The identification of the parameters from the response acceleration measurements with duration length of 20 and 40 seconds on a structure during one dancing event have shown [1,2] that the coefficient k_d can be made equal to η_d. This means that the mean value arising from an increasing number of persons can indeed be estimated by building the mean on the time axis. According to this the load field can be considered isotropic.

The values of the parameter k_a were, in general, very high. Therefore the exponential decrease in the first equation of (5) can be approximated with the step function showed in fig.1, where ξ_1 is assumed to be the smallest distance between any two persons.

For the phase angle, values between 10 and 30 degrees were found. Due to its variance the identification of this parameter was more difficult than the one of the coherency.

3. LOAD REDUCTION

3.1 Reduction factor

Based on the load model presented, a structure independent reduction factor for the structural response can be derived.

The structural response, computed on a deterministic basis, which implies a full correlated load field, is then multiplied by the reduction factor, in order to take into account a realistic space correlation.

[1] Indeed, the harmonic frequency is identified with the middle frequency of the spectral peak

To derive such a factor some assumptions have to be made, which are fullfilled under most practical conditions:

1. The random load field is considered homogeneous
2. The simplification in fig.1 may be applied with $\xi_1 \cdot \mu = 2$, where μ is the density of the uniformly distributed persons, and $M = \xi \cdot \mu$ the number of persons.
3. All the load points on the structure have the same transfer function to the output point, i.e., structure dependent influences on the reduction factor are neglected[2].

The power spectral value of the response displacement at point y at the n^{th} harmonic is computed as follows:

$$S_{yy}(nf_0) = [H(nf_0)]\, S_{pp}(nf_0)\rho_n\, [H^*(nf_0)]^T \tag{6}$$

which can be simplified to:

$$S_{yy} = |H_y|^2\, S_{pp} M \left[1 + \frac{M-1}{M}(\rho_n + \rho_n^*)\right] \tag{7}$$

where the frequency was dropped out for simplicity.

In these equations the vector of the transfer functions $[H(nf_0)]$ contains M elements all of them having the same value, H_y. The power spectrum of the loads is given by the product of the spectral values at the harmonic frequency $S_{pp}(nf_0)$ multiplied by the correlation coefficient ρ_n. If the correlation coefficient follows the step function of fig.1, the model parameters according to (5) are:

$$\begin{cases} |\rho_n|^2 & = & k_{d,n}^2 \\ -\arctan\frac{\Im[\rho_n]}{\Re[\rho_n]} & = & \Phi_n \end{cases} \tag{8}$$

From (7) and (8), taking into account that the reduction factor is defined as a relation between the spectral value S_{yy} for the actual correlation and the one for a full correlated load field

$$K_\rho^2(f) = \frac{S_{yy}(f)}{S_{yy}(f)\,|_{k_d=1.0,\Phi=0.0}}, \tag{9}$$

the following expression can be derived for the load reduction factor:

$$K_{\rho,n}^2 = \frac{1}{M} + \frac{(M-1)}{M} k_{d,n} \cos\Phi_n. \tag{10}$$

For increasing M this factor tends asymptotically to the following limit:

$$\lim_{M\to\infty} K_{\rho,n}^2 = k_{d,n} \cos\Phi_n \tag{11}$$

[2]This is a common but not always a conservative assumption for load reduction factors

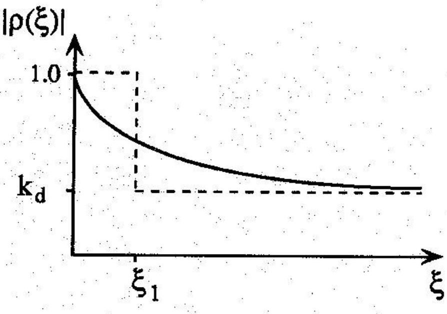

Figure 1: Correlation coefficient approximated with a step function

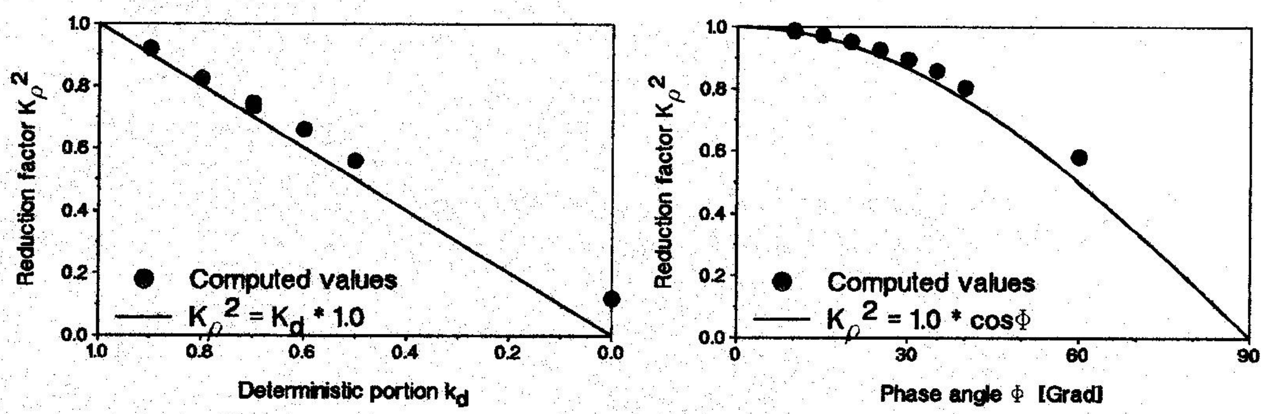

Figure 2: Comparison of the reduction factor with the computed values by means of the power spectral method.

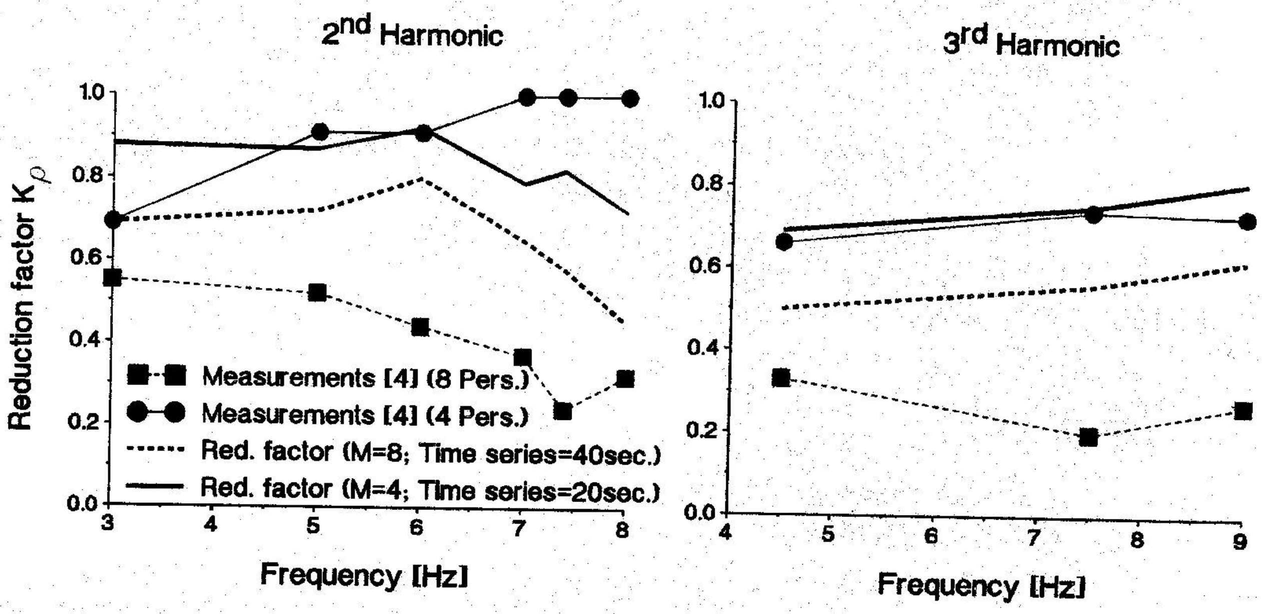

Figure 3: Comparison of the reduction factor with measurements from [4]

Equation (11) is compared with the results from the stochastic method (6) applied to a dancing hall, described in [1], for $M = 90$ and using the load model of (8). Fig.2-a and 2-b show the variation of the reduction factor as a function of $k_{d,n}$ and Φ_n respectively.

Both plots show a good agreement of eq.(11) with the computed values. However, caution should be taken when using this factor since the reduction may not lie on the safe side, as shown in the figures. The differences between computed values and eq.(11) increase when the load field becomes fully uncorrelated.

3.2 Comparison with measurements

The reduction given by (11) and the results of measurements from [4] are compared in fig.3, for the second and third harmonics of the vertical load arising from rhythmical jumping. The parameters for the reduction factor were computed from measurements made in [2] where the durations of the time series were 20 and 40 seconds respectively for the computation of the parameters for groups of 4 and 8 persons. The phase angle was assumed to be zero, a rather conservative assumption, since no reliable value was found from the measurements.

From this figure it can be concluded that, for groups of 4 persons any reduction may be unsafe, whereas for groups of 8 persons the reduction factor remains always on the safety side. The same can also be said for the first harmonic. This phenomen can be explained either by the ability of synchronisation of small groups or by the statistical bias because of small samples.

4. CONCLUSIONS

Starting from a stochastic model, a simple way was found to take into account a possible reduction of the structural response computed on a deterministic basis.

The main advantage of this analysis is that the load field can be considered isotropic and, therefore, the parameter k_d of the spatial correlation can be estimated from the load time series measured on individuals.

REFERENCES

[1] Rebelo,C., Scherer,R.J., Eibl,J. — Statistical modelling of dynamic loads imposed by occupancies, EURODYN'90, Bochum, Germany(1990).

[2] Rebelo,C. — Stochastische Modellierung menschenerzeugter Schwingungen, doctoral thesis at the university of Karlsruhe, Germany (1992).

[3] Ebrahimpour, A.— Modeling spectator induced dynamic loads, Ph.D. Thesis, University of Idaho, USA (1987)

[4] Pernica G. — Dynamic load factors for pedestrian movements and rhythmic exercises, Canadian Acoustics, 18,2, 3-18 (1990).

[5] Bachmann,H., Ammann,W. — Schwingungsprobleme bei Bauwerken, IABSE, Structural Engineering Documents,3d (1987)

[6] Vanmarcke,E. — Random fields, analysis and synthesis, MIT press (1984).