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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].

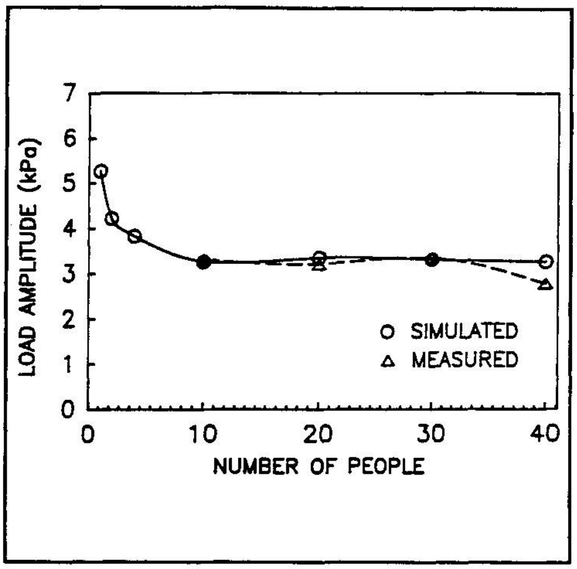

Figure 1 Simulated and Measured Load Amplitude vs. Crowd Size

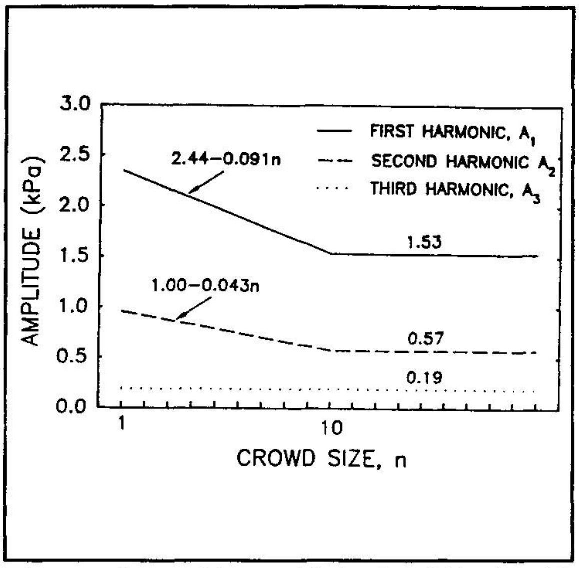

Figure 2 Sinusoidal Amplitude At Dominat Harmonics Vs. Crowd Size

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.

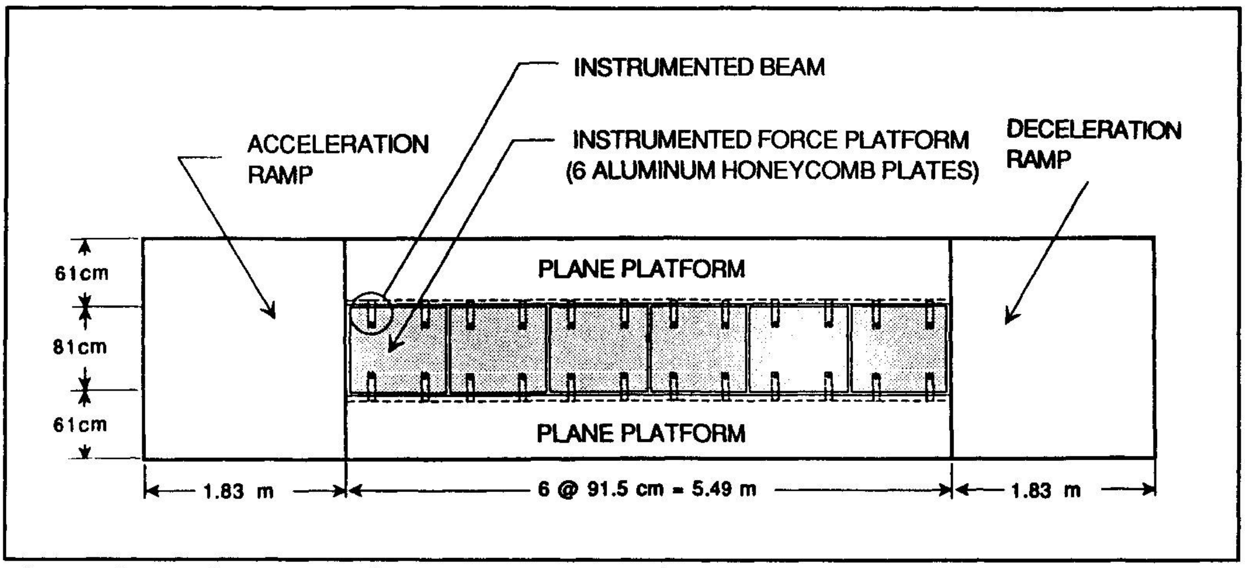

Figure 3 The Force Platform For Measuring Moving Loads

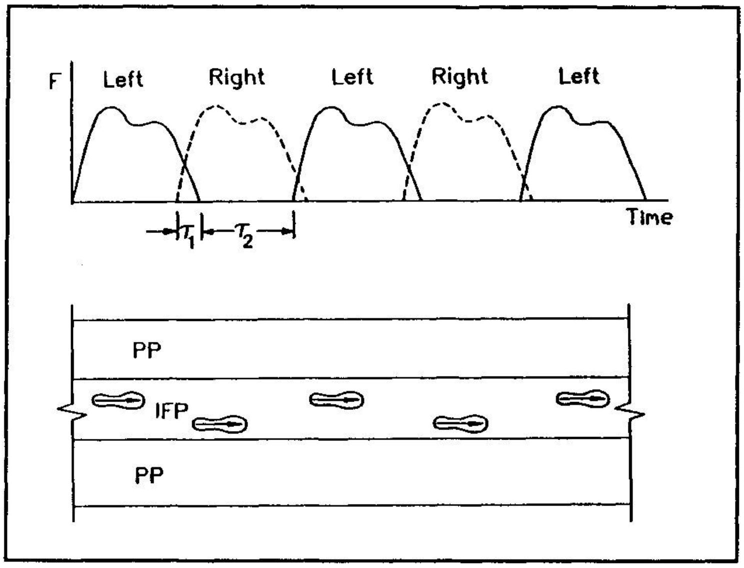

Figure 4 Force-time Plot Of A Subject Walking

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.

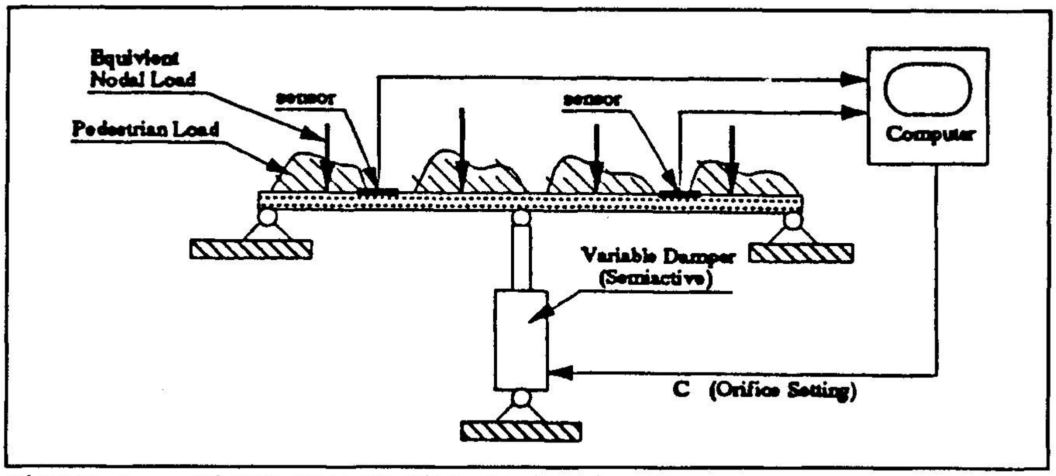

Figure 5 Floor System With Semiactive Damper

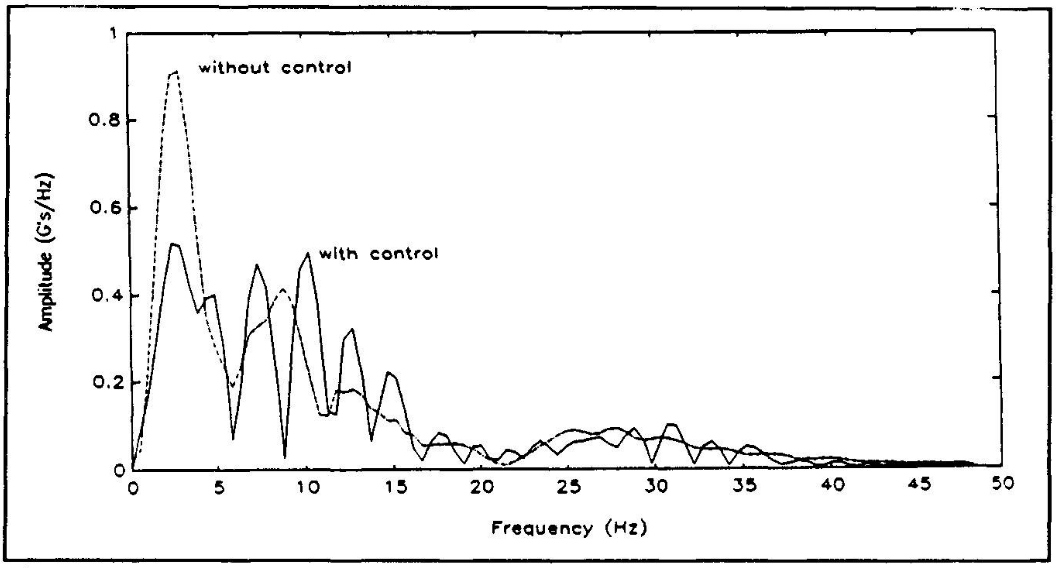

Figure 6 FFT Of The Beam Vibration

5. ACKNOWLEDGEMENTS

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