Modeling and simulation of human-floor system under vertical vibration

Xiahua Zheng, James M. W. Brownjohn
School of Civil & Structural Engineering
Nanyang Technological University, Singapore 639798

ABSTRACT

With the trend towards longer span and thus lower frequency floors, human induced vibration and human-structure interaction has received more and more concern about structural serviceability. When subjected to vertical vibration, a human behaves as a mass-spring-damper system rather than solely as a mass on the structure. The interaction between the human body and the structure results in a significant increase in the damping of the human-structure system. In order to study human-structure interaction, mathematical model for this system is established. The human body and the slab are simulated as a SDOF model respectively.

Through laboratory experiment with 30 human samples, the parameters of the SDOF human model were obtained. The result shows that the human resonant frequency is 5.24 ± 0.40Hz, and damping ratio is 39% ± 0.05.

By combining experimental data and simulation, the human body's damping effect on vibrating floor was quantified in terms of energy absorption. During vibration, human absorbed most of the input energy.

Keywords: Human-structure interaction, energy dissipation, biomechanics, resonant frequency

1. INTRODUCTION

In recent years, with the development of pre and post-stressing techniques and the availability of light but high strength materials, long span structures can be built to accommodate static loads and thereby provide clear space and viewing, such as gymnastics and dance hall. This leads to structures that have relatively low natural frequencies, low damping capacity and therefore are dynamically more sensitive.

Normally, structural safety and integrity of such long span structures can be met if properly engineered. However, an existing vibration level, although far from endangering the structural safety, may be unacceptable from a user's point of view. According to the study of Mallock (1), when a vibration produces an acceleration range of 0.04g to 0.05g, it is considered unpleasant.

The important thing is that human not only perceives the vibration, he also interacts with the floor during the vibration. It has occasionally been assumed that the effect of a human on a floor is simply that of added mass on it. However, both site and laboratory tests have demonstrated that human bodies do not act solely as mass but a mass-spring-damper system.

In order to study the interaction between the human and the floor when under vertical vibration, a mathematical model for the human-floor system is established. Through experimental and analytical work, the modal parameters can be determined. Based on this mathematical modal, the human body's damping effect on a vibrating floor can be quantified by simulation.

2. MATHEMATICAL MODEL

In this study, a 4-meter-long reinforced concrete plank was used in the experiment. In the mathematical model, the plank is assumed to be a single degree of freedom system. For this SDOF system, the mass, stiffness and damping can be obtained from dynamic experiment with ease.

Compared with the plank, the human body is more complicated. Various kinds of human body modals were proposed in many studies. The degree of freedom of those modals can range from 2 to 16, such as the 4 DOF human body model proposed by

ISO [2]. If the modal has more DOF, it is easier to describe the movement of the human body. However, it is in the mean time a heavy task to solve the undetermined parameters that define the MDOF modals.

In this paper, the human body is simplified as a SDOF modal. By solving the parameters of this human modal, human body's dynamics properties are determined which is necessary in the study of the human-floor interaction under vertical vibration.

The modeling of the human-floor system is shown in Figure 1.

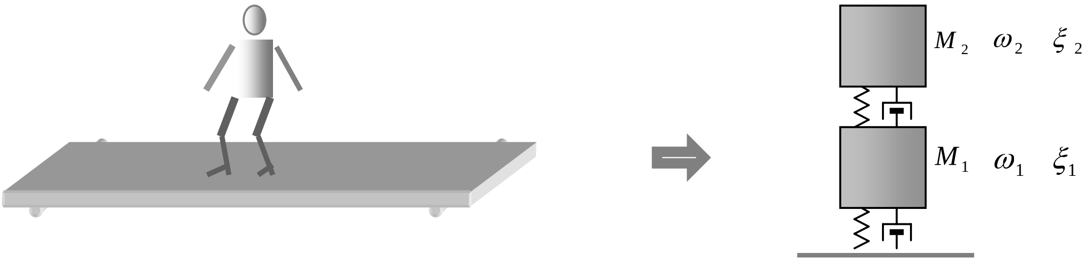

Figure1 Modeling of human-floor system

In which, $M_{1,}\omega_{1,}\xi_1$ and M_2, ω_2, ξ_2 refer to the modal mass, natural frequency and damping ratio of the beam and the human body respectively.

3. HUMAN MODAL PARAMETER DETERMINATION

3.1 Methodology and Experimental setup

Indirect method was used to determine the human modal parameters. The plank supported at the ends was vibrated in its fundamental mode by a shaker located on the beam surface at one-third of the span.

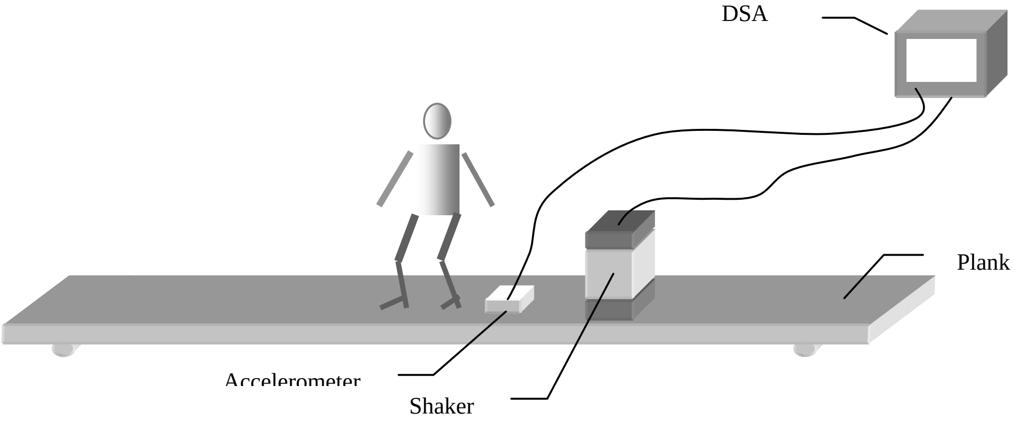

Figure 2 Experimental setup for human parameter determination

The process was repeated with a human subject standing at the center of the beam (figure 2). In both cases the resonant frequency f and the damping ratio ξ of the plank or the human-plank system was recorded, from which the resonant frequency of the human can be deduced by solving the 2DOF motion equation (1) in the state space (2).

$$M\ddot{X} + C\dot{X} + KX = U \tag{1}$$

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{2}$$

A program called ‘reverse’ in MATLAB was written to solve the above equations. With the input, M_1, M_2, ω_1, ξ_1 and the ω, ξ of the human-plank system, which can all be obtained from the experiment, ‘reverse’ will solve out the human modal parameter ω_2 and ξ_2.

3.2 Results

To obtain a statistical human modal parameter, 30 persons, including 9 females and 21males, of different age, weight were tested. The result is as shown in table 1.

Table1 Human modal parameters

	Female	Male	Overall
Frequency ($\omega_2/2\pi$)	5.35 ± 0.18	5.19 ± 0.35	5.24 ± 0.40
Damping (ξ_2)	0.36 ± 0.02	0.40 ± 0.05	0.39 ± 0.05

From table1, it can be seen that the human resonant frequency is around 5.24 Hz, and the damping ratio is around 39%. The result is consistent with the eigenvalue solution of the ISO model for the human alone (3).

The resonant frequencies of all 30 males and females are shown against their mass (figure 3a), against their height (figure 3b) and their mass to height ratio (figure 3c). From these three figures, there is no evidence to suggest that either of these factors is significant.

In addition, the tolerance of the human natural frequency in this study is 7.6% and that of the damping ratio is 12.8%. Therefore, the 2DOF modal of the human-floor system is considered to be reasonable.

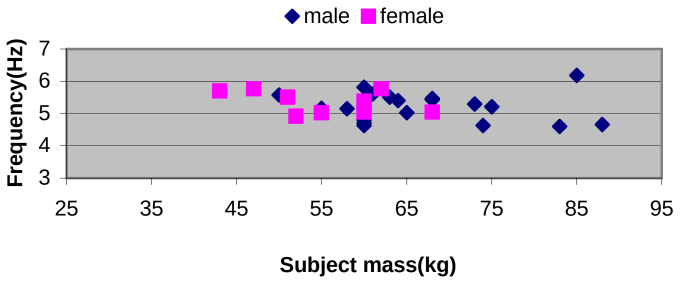

Figure3a Frequency against mass

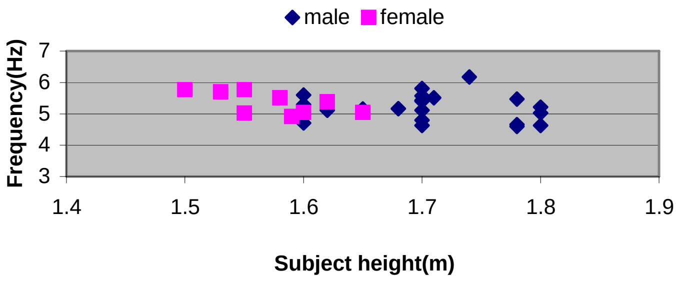

Figure3b Frequency against height

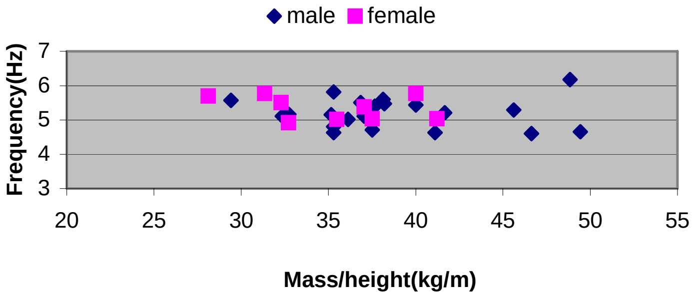

Figure3c Frequency against mass/height

4. SIMULATION ON ENERGY DISSIPATION

4.1 Introduction

When subjected to vertical vibration, human interacts with the floor, absorbs part of the transmitted energy and significantly increases the damping of the human-floor system. In the case of Twickenham grandstand, Ellis and Ji (4) observed that a significant increase in damping was noted when the crowd was present. Comparing with unoccupied plank, Brownjohn (3) figured out the obvious increase in system damping of an occupied plank by a human with different postures.

To quantify the dampening effects of a human body on a floor, Brownjohn (3) studied the flow of energy through a vibrating concrete plank with a human present. Chirp signal was used; force and acceleration at the vibration power source and the human/plank interface were recorded. The results suggested that the human absorption capacity was much greater than that of the heavy plank. When passing through system resonance, the energy loss via internal damping and by the human subject was greatest and energy dissipated by the human subject was several times larger than due to the plank, accounting for the damping increase.

However, since chirp signal is not providing enough time duration for each certain frequency to get full amplitude, it might not be able to give exact and obvious response of each frequency. This study substitutes chirp signal with steady state sine wave signal of discrete frequencies covering the system resonant frequencies.

4.2 Methodology

The basic principle in analysing is the conservation of energy. In general, the energy of the entire system is given by the equation shown below:

Energy input = Energy output

Then the energy balance for the plank system was given:

Energy supplied by shaker

= energy loss due to plank internal damping

+ energy loss due to human damping

+ energy stored in plank

Power supplied by the shaker is computed as shaker force × plank velocity. Shaker force is obtained from acceleration of known armature mass, and velocity is integrated (high-pass filtered) plank acceleration data. Energy is integrated power supplied. Similarly energy dissipated by the human subject is computed as the integration of the contact force × velocity.

Energy dissipation rate for the plank is $4\xi\omega\times\text{KE}$ where ξ is the fraction of critical damping for the bare plank, ω is plank natural frequency and KE is instantaneous kinetic energy.

Based on the 2DOF human-plank system modal, the process of simulation is demonstrated in figure 4.

4.3 Experimental set-up

Figure 5 shows the experimental setup for the energy study. Two accelerometers are used. One is placed next to the shaker to record the movement of the shaker; the other is on the force plate to record that of the human body. The shaker will feed back the input force and the force plate will provide the vertical contact force between the human and the force plate.

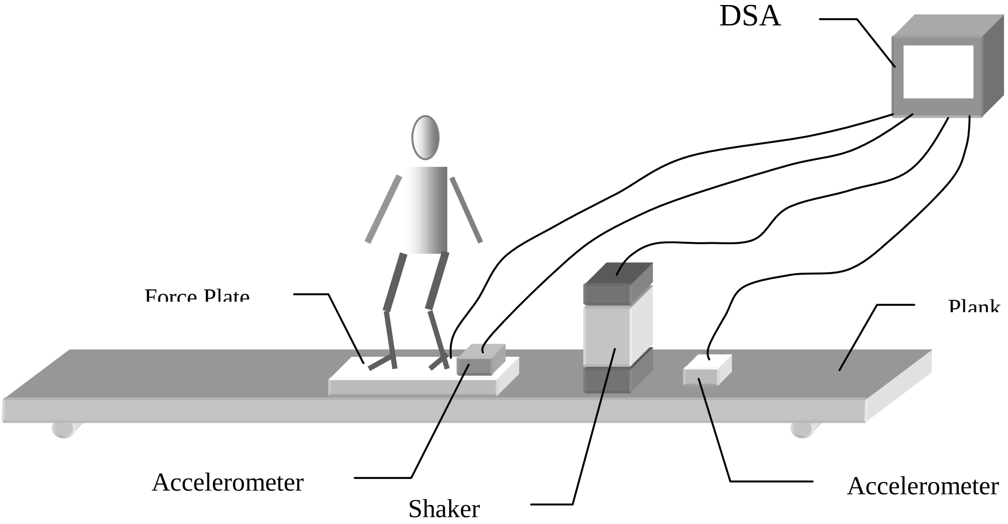

Figure5 Experimental setup for study of energy dissipation

Before studying the energy dissipation, the modal mass and the damping ratio of the plank with all the devices on it (but no human subject) were measured.

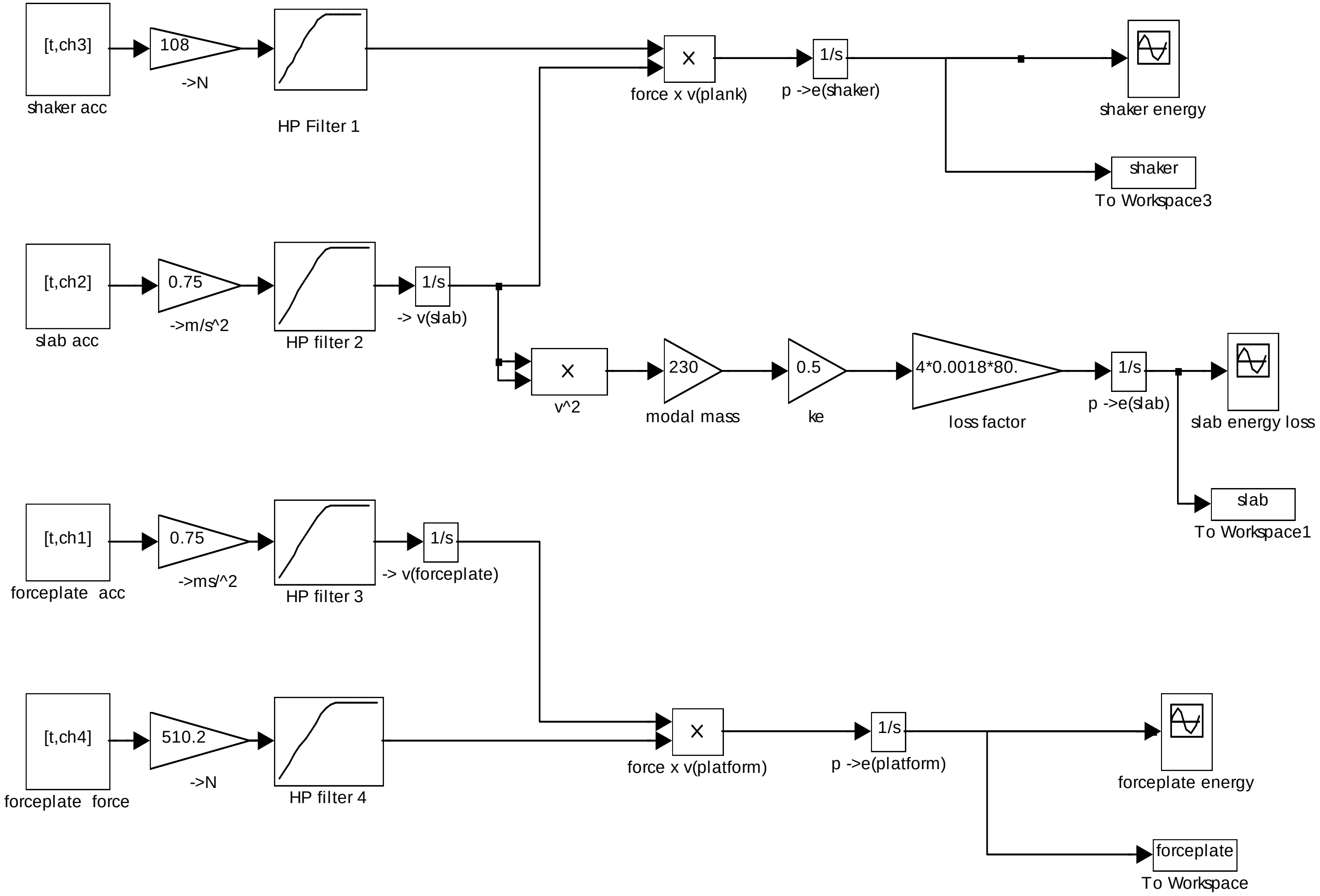

Figure4 Energy dissipation simulation

Then the plank was vibrated at 12.8 Hz, which is approximately its resonant frequency.

4.4 Results

The energy dissipation and conservation for each case is demonstrated in figure 6a and 6b respectively.

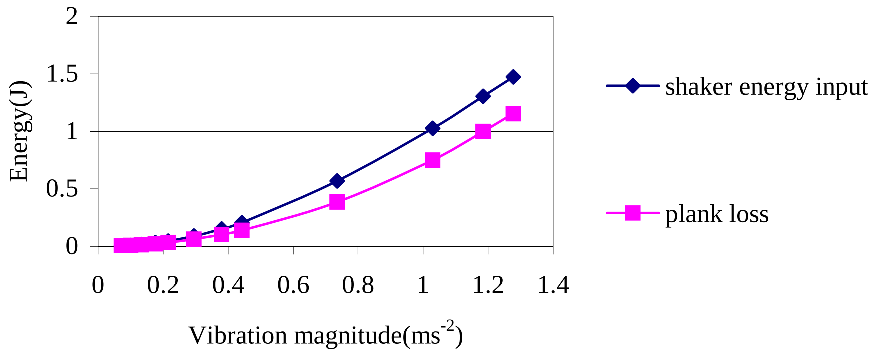

Figure 6a Energy dissipation for the bare slab

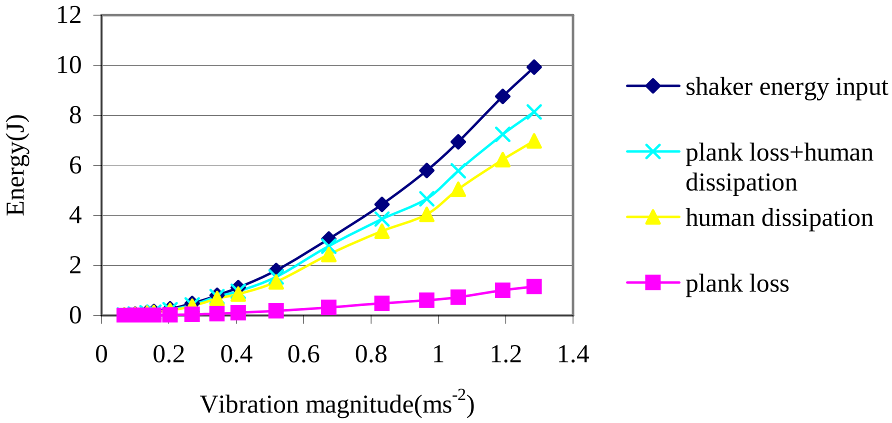

Figure 6b Energy flow for the slab with standing human

From these three figures, it can be confirmed that the shaker input energy is the square of the slab acceleration magnitude. The energy input and output agrees well. For the bare plank, figure 6a, the energy output is mainly the slab loss. The force plate itself also dissipated a fraction of energy. For the other two cases, the output is the plank loss plus human dissipation. There is a minor gap between the energy input and output which is due to some other kinds of energy losses such as the force plate dissipation, supports energy loss, and noise etc..

Figure 6a shows that, for the bare plank, most of the input energy was consumed by the plank internal damping. The damping loss increases when the vibration magnitude increases. However, when the plank is occupied by a human subject (figure 6b), most of the energy is dissipated by the human body. The human energy dissipation is several times larger than the slab internal damping loss.

To illustrate the human effect more clearly, the shaker energy inputs for maintaining a certain vibration level are plotted for each case (figure 6c).

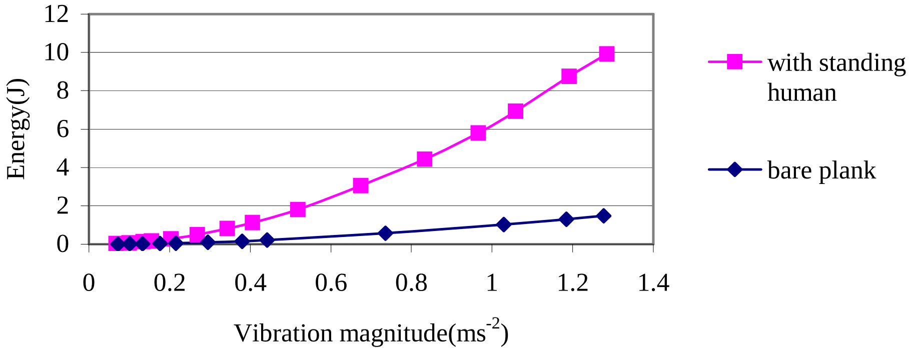

Figure 6c Shaker energy input of the two cases

If a vertical line is drawn in the plot, it can be easily seen that, to maintain a certain vibration level, much more shaker input energy is needed for the cases with human occupation than for the bare slab. For example, to obtain the vibration magnitude of 1.3 m/s^2, only 1.5 J is needed for the bare slab, however, for the case with a standing human the input energy rises up to 10 J.

This phenomenon can also be explained using a horizontal line through the two curves. That means if there is a certain energy input, it will result in a much smaller vibration level for the human occupied case than for the bare slab. Thus the human damping effect is obvious.

5. CONCLUSIONS

By modeling the human-plank system under vertical vibration as a 2 DOF system, the human body's dynamic properties were obtained. The human natural frequency is 5.24 ± 0.40Hz, and damping ratio is 39% ± 0.05.

In the study of energy flow, the energy balance was found to be satisfactory for each set of data collected for a certain vibration magnitude. The human energy dissipation showed that a stationary human can dissipate most of the input energy and further reinforces the fact that a human can act as a mass-spring damper system.

REFERENCES

1. Mallock, H., 'Vibration produced by the working of the traffic on the Central London Railway', Board of Trade Report 951, England, 1902
2. Mechanical vibration and shock - Mechanical transmissibility of the human body in the z direction. ISO 7962. International Standards Organization, 1987
3. Brownjohn J M W, 'Energy dissipation in one-way slabs with human participation.' Asia-Pacific Vibration Conference, Singapore, December 1999
4. Ellis B R, Ji T, 'Human-structure interaction in vertical vibrations', Structures and Building, Proceedings ICE, 122, Feb 1997,1-19