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EFFECTS OF HUMAN-STRUCTURE INTERACTIONS ON THE DYNAMIC PROPERTIES OF BUILDING FLOORS SUSCEPTIBLE TO VIBRATIONS

MEHDI SETAREH and STEPHANIE RENARD

School of Architecture and Design, Virginia Tech, Blacksburg, USA

Excessive vibrations of building floors due to human movements have become an important vibration serviceability problem for building designers and owners. A series of vibration tests on a full-scale laboratory floor with different numbers of humans in various postures were conducted. Using this data, the dynamic properties of a two-degree-of-freedom (2-DOF) dynamic system representing groups of people in different postures were computed. A 3-DOF model representing the floor and humans was developed and its dynamic properties were defined in terms of non-dimensional parameters. The dynamic properties of the floor were measured when occupied by groups of people in different postures and compared to those predicted using the 3-DOF dynamic model considering the identified human models. The results showed that the predicted properties were within the range of those found from the measurements, which validated the identified human dynamic models. This study also showed how the presence of humans can affect the natural frequency and damping ratio of a floor system.

Keywords: Human models, Simplified models, Human vibrations, Human dynamic parameters, Floor vibrations, Excessive vibrations.

1 INTRODUCTION

Structural engineers generally consider the presence of humans on building floors as added weight (live load). This is a correct assumption as long as the structure is not susceptible to vibrations. When vibration serviceability issues are considered, humans cannot simply be assumed as static weights (masses). Various research studies and design guides have recommended humans to be considered as additional masses resulting in a reduction in floor natural frequencies and/or added damping.

An accurate approach is to consider human as a dynamic system consisting of a mass (or several masses), spring(s) and damping element(s). Various lumped-mass models of human body with various degrees of freedom have been proposed and studied in the literature. A few recent studies are mentioned below:

Pedersen and Hansen (2004) considered the effects of the human-structure interaction (HSI) on floors using SDOF models to represent the humans and a specific mode of a floor to form a 2-DOF dynamic model. The human parameters were assumed to be f_H (natural frequency) = 6 Hz and ξ_H (damping ratio) = 20%. The results of the study showed that the presence of humans have different effects on the low and high frequency floors.

Sim *et al.* (2006) developed a 2-DOF crowd model using the individual human dynamic properties recommended by Wei and Griffin (1998) and Matsumoto and Griffin (2003) for the seated and standing individuals. They conducted an analytical study, which showed that passive crowd add mass and damping to the structure, resulting in a reduction in natural frequency and response compared to the empty structure.

Agu and Kasperski (2011) conducted a probabilistic study to check how random scatter of individual human dynamic properties in a group can affect the natural frequency and damping ratio *(f and ξ)* of the structure with a crowd. They concluded that due to the randomness of dynamic properties of human body, the mean values for individual human dynamic properties cannot be used for all cases to represent the human-structure dynamic interactions.

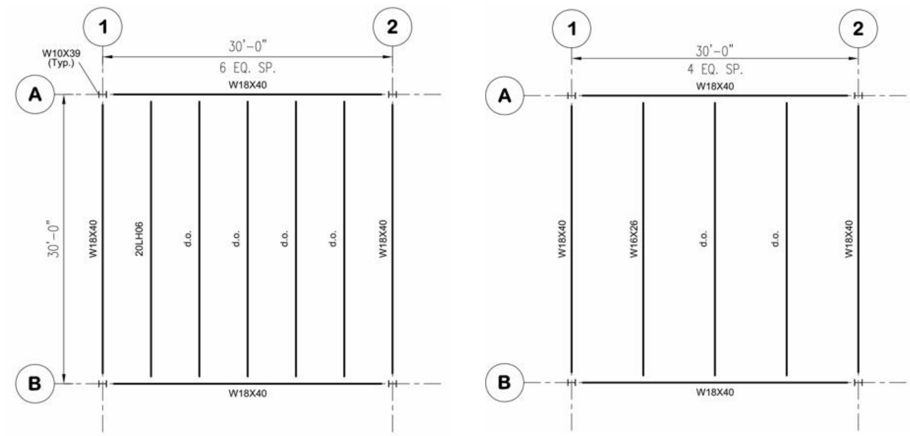
Zheng (2013) developed a continuous model of a standing human body from the available natural frequency measurements of standing subjects by Matsumoto and Griffin (2003). By incorporating the available information in biomechanics and his interaction human body model, Zheng (2013) identified parameters for a 2-DOF human model to be f_1 = 5.78 Hz and ξ_1 = 36.9%, and f_2 = 13.2 Hz and ξ_2 = 44.5%. The identified damping ratio of the human body varied from 2.5% to 38.8%, and the mean damping ratio of the four individuals were from 8.6% to 22.5%.

This paper uses the dynamic parameters for a 2-DOF model to represent groups of people measured through an extensive experimental and analytical program. The measured effects of the presence of human on the resonance frequency and damping ratio of the floor structures were compared to those found by a simplified 3-DOF system representing a particular mode of vibration of the structure and the 2-DOF human model. The results show that the proposed model provide a very good representation of the dynamic properties of groups of people in terms of their interaction with the structure and can provide a good prediction of building floors' dynamic response.

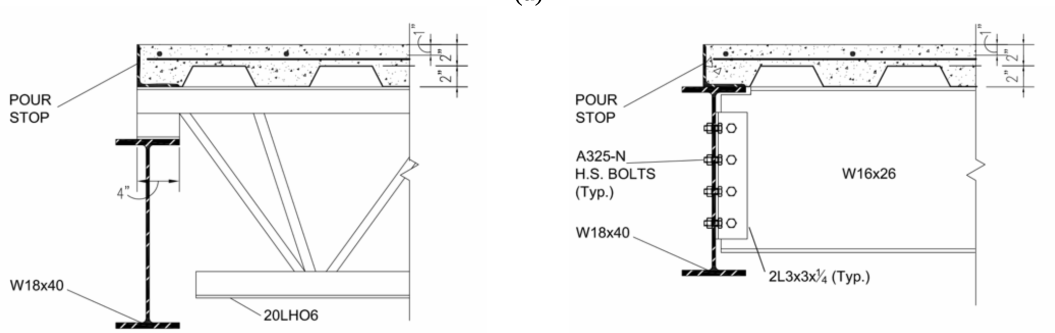
Figure 1. Test structure at the Virginia Tech Vibration Testing Laboratory.

2 DESCRIPTION OF THE TEST STRUCTURE AND DYNAMIC TESTS

The test structure is comprised of a two-story steel structure located at the Virginia Tech Vibration Testing Laboratory. The structure has a single square bay with center to center column dimensions of 30 ft. by 30 ft. as shown in Figure 1. The floor is made of a 2 in. steel deck with 2 in. of concrete topping, supported by 20LH06 steel joists on the first floor and W16x26 steel beams on the second floor as shown in Figure 2. The joists and beams are supported by W18x40 girders. The test floor did not include any non-structural elements.



(a)



(b)

(c)

Figure 2. Details of the test structure: (a) Plan views of the first and second floors first, respectively, (b) Section through the floors, (c) Views from below the floors.

Full modal tests of the floors were conducted using an APS-400 electrodynamic shaker on each floor. The shaker was placed at the quarter point from a corner column to excite several lower modes of vibration of the floor. The test on the first floor was repeated with two groups of human subjects and also after the floor was covered by 2-inch concrete blocks to reduce the floor natural frequencies. A burst chirp excitation with 30 seconds on and 15 seconds off and a frequency bandwidth of 3-20 Hz was used. The measured records were used in MEscope VES (2013) to estimate the natural frequencies, damping ratios and mode shapes of the structure. Figure 3 shows the shaker and accelerometers during one of the stages of the modal test.

(a) (b)

Figure 3. Modal test setups for the floors: (a) Without concrete blocks, (b) With concrete blocks.

The effects of a group of people on the dynamic properties of the test floors were used to estimate the crowd dynamic properties. Different groups of human subjects with various sizes were placed on the floor in three postures: sitting on chairs, standing erect, and standing with the bent knees (Setareh and Gan 2016).

PCB 393C accelerometers were placed at different locations on the floors and at the drive point and the shaker was placed at the same location as for the modal test. A burst chirp excitation with 30 seconds on and 15 seconds off and a frequency band of 3-15 Hz was used. Low levels of vibration within the range typically resulted from human movements were applied. Their magnitudes were at the lower limits of those used in the biomechanics research.

3 HUMAN DYNAMIC PARAMETERS AND MODELING

Using the results of these tests, the dynamic parameters of the 2-DOF human model were estimated by minimizing errors between the measured resonance frequencies and response of the floor and their analytical counterparts (Gan and Setareh 2015). This resulted in the human dynamic parameters with natural frequencies between 3.4 and 20.4 Hz and damping ratios between 35% to 290% for the three different postures.

A 3-DOF analytical system representing the floor and the 2-DOF human model was developed. The floor response in terms of non-dimensional dynamic parameters was computed. Using the frequency response functions, the resonance frequencies and damping ratios of the floors occupied by different numbers of human subjects were computed. These values were compared to those from the four different test measurements on the first and second floors of the test structure for the first three modes of vibrations of each floor by computing the ratios between the measured resonance frequencies and damping ratios to their counterparts predicted by the analytical models.

Figure 4 shows the variations of the floor resonance frequency ratios and ratios of damping ratio of the second mode of vibration of each tested floor as a function of mass ratio (mass of humans to the effective mass of floor), for the three different postures. The floor natural frequencies (without people) ranged from 6.7 Hz to 9.4 Hz with damping ratios between 0.15% to 0.35%. The results show that the human models and the 3-DOF dynamic representation of the effects of HSI on the floor provide excellent prediction of the variation in the floors' resonance frequencies as the frequency ratios are very close to 1 (maximum discrepancy of 3%). As expected, the variation in the damping ratios are larger. However, on average the predictions of the resonance frequencies were within 2% for all the floors. This value for damping ratios was about 25%. The results show that the human parameters found from the previous studies and the consideration of 3-DOF models to represent the human-structure interactions on building floor are accurate and provide good results for vibration serviceability analysis of building floors.

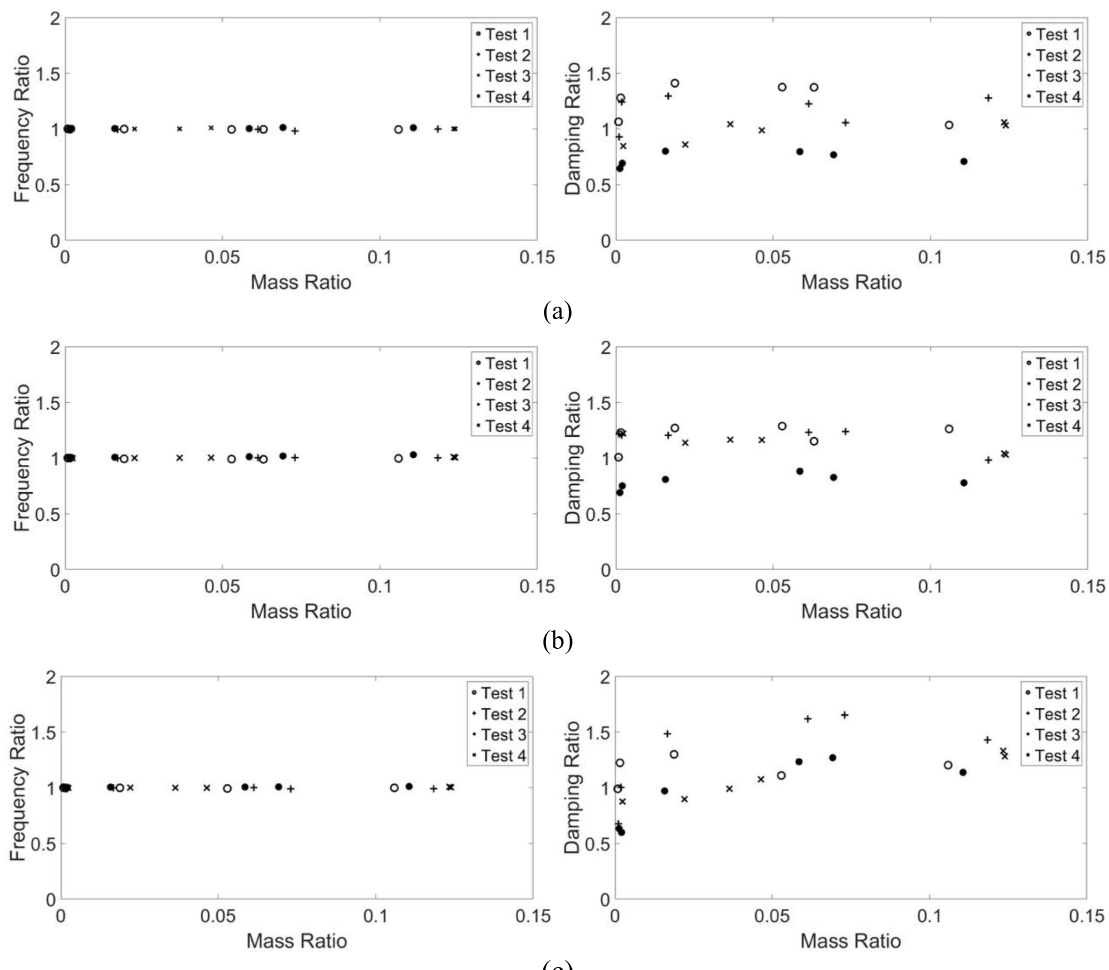


Figure 4. Variation of the resonance frequency ratios and damping ratios for the second mode of the floor versus the mass ratios for different human postures: (a) Standing; (b) Sitting; and (c) Bent-Knees.

4 CONCLUSION

This paper used a simplified 3-DOF model to check the accuracy of the dynamic parameters for the 2-DOF human model that were found through a separate study. It showed the accuracy of the modeling approaches used and the closeness in the prediction of the resonance frequency and damping ratio when human-structure interactions for floor vibration serviceability are considered.

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