A Contribution to Documenting and Validating Dynamic Interaction Effects

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ABSTRACT

On structures carrying humans (e.g. floors, grandstands in stadia etc.) there may be two different types of crowds present: Active and passive crowds of people. The active crowd, comprising people in motion, may generate dynamic loads causing the structure to vibrate. The passive (stationary) crowd, e.g. humans sitting or standing on the structure, interact dynamically with the structure in a passive sense and this crowd influences the dynamic characteristics of the structure such as its damping capacity. The paper looks into the dynamic interaction between the passive (stationary) crowd and a floor in vertical motion. The mechanism of crowd-structure interaction is not well understood and the primary aim of the paper is to present results of experimental investigations documenting effects of crowd-structure interaction and to exploring the validity of a crowd-structure interaction model. Controlled laboratory tests, employing a vibrating test floor carrying stationary crowds of people, are designed and carried out to investigate the dynamic interaction. The paper describes the tests and the modal identification procedures employed for the assessment of model validity. Besides from aspects of model validation, the experimental results also illustrate some of the essential implications of crowd-structure interaction.

NOMENCLATURE

f_F	Floor frequency	f_1	Empty floor frequency	f_2	Crowd frequency
ζ_F	Floor damping	ζ_1	Empty floor damping	ζ_2	Crowd damping
w_2	Weight of person	m_1	Empty floor modal mass	m_2	Crowd modal mass
k	Spring stiffness	c	Damping coefficient	λ	System root
M	Mass matrix	C	Damping matrix	K	Stiffness matrix

1. INTRODUCTION

It has been recognised that active persons (humans jumping, dancing or walking on a structure) are capable of causing structural vibrations of concern. The vibrations may be of sizes that cause either safety or serviceability problems. A great deal of research has therefore been devoted to establishing models of dynamic loads generated by single humans and crowds of humans in motion on flooring-systems, for example in [1] and [2], and load models have entered into codes for the design of structures in e.g. Canada, UK, and Denmark. However, it has also been acknowledged that a stationary crowd of people (sitting or standing) present on the structure (and put into vertical vibration together with the structure) interact dynamically with the vibrating structure, and that this crowd changes the dynamic system excited to vibration by the humans in motion. This is for instance demonstrated in [3], [4], and [5] based on field measurements made on human-occupied structures, and in [6] and

[7] on the basis of laboratory tests. The mechanism of the interaction is not well understood and it is the subject of this paper.

In biodynamics, the human whole-body is modelled as a dynamic system consisting of lumped masses interconnected by springs and dashpots (see e.g. [8], [9], and [10]), and the investigations for this paper also considers a lumped mass dynamic model for the stationary humans that occupy the floor. In biodynamics, the human whole-body would typically be represented by a set of degrees of freedom, and some biodynamic models assume a vast number of degrees of freedom of the human body. A central aim of this paper is to evaluate the appropriateness of employing a quite simplistic model of the human whole-body for modelling effects of interaction between floor and human occupants: A SDOF (single degree-of-freedom) spring-mass-damper model. In fact this model will be assumed for the entire crowd of stationary people which is represented by a single lumped mass. This naturally would be a simplification of matters considering the model complexity of the human whole-body considered in biodynamics, but nevertheless it might be a useful and sufficiently accurate simplification of matters in the context of evaluating the dynamic behaviour of the human-occupied floor. The usefulness of employing the SDOF crowd model in connection with modelling crowd-floor interaction is the subject for investigation. The investigations involve experiments made on a test floor put into vertical vibration. The floor carries a crowd of sitting people and the dynamic characteristics of the floor (frequency and damping) are extracted and it is examined whether a SDOF spring-mass-damper crowd model can explain the experimental findings.

The general methodology is outlined in section 2, and section 3 gives details about the model validation tests. Section 4 presents and discusses test results, and conclusions are provided in section 5.

2. INITIAL CONSIDERATIONS AND METHODOLOGY

2.1 The crowd-floor interaction model

When a stationary crowd of people vibrate together with a floor, the crowd and floor masses interact. Possibly, the crowd-floor interaction may be represented by the dynamic model shown in figure 1. It is the model for the interaction examined in this paper.
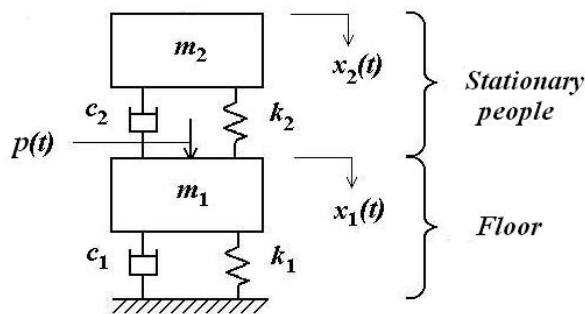

Figure 1   The dynamic model assumed.

A SDOF empty floor model is assumed (the grounded SDOF system) representing a vibration mode of the floor. The crowd of stationary people atop the floor is modelled as a SDOF system attached to the floor mass. For simplicity, both SDOF systems are assumed viscously damped and linear elastic.

Some external vertical force applied to the floor mass (indicated by $p(t)$) normally will bring the masses of the system into vibration. By comparing floor mass vibrations recorded in experiments with theoretical predictions relying on the model shown in figure 1 allows for evaluating the reasonability of the interaction model; and in particularly the reasonability of the SDOF crowd model assumption.

I real life situations, the size of the crowd may vary and for the interaction model to be viable, the model should be capable of predicting changes in floor vibrations that result from a change in crowd size. Generally, changing the conditions, in the manner discussed, corresponds to altering the crowd modal mass (m_2). In more general terms, a modal variability is introduced in the crowd-floor interaction model.

2.2 Modal variability of crowd-floor interaction model

As discussed, the crowd modal mass (m_2) is varied in tests in order to establish a basis for validating the SDOF crowd model assumption. Figure 2 shows a floor vibrating in its first bending mode. The floor carries a stationary crowd of people modelled as a SDOF attachment system to the floor.
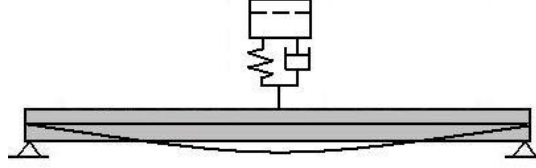
Figure 2 The crowd at floor midspan reducing in size.

Since the crowd is located at floor midspan, the modal mass of the crowd is estimated using the equation:

$$m_2 = \sum_{n=1}^{N} w_2(n) \tag{1}$$

where $w_2(n)$ represents the weight of person n, and N represents the total number of people in the crowd. In tests N is subject to changes, and this is expected to give rise to a change in the modal characteristics (frequency and damping) of the combined crowd-floor system. This change can be predicted theoretically, if the change in crowd modal mass in known, as discussed next.

2.3 Theoretical estimation of dynamic characteristics of the human-occupied floor

Assuming free decaying vibrations of the dynamic system shown in figure 1, the equation of motion is:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{2}$$

with system matrices:

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}, \quad C = \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix}, \quad K = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \tag{4}$$

The entries in the stiffness and damping matrices (K and C) are defined by the equations:

$$k_2 = m_2(2\pi f_2)^2 \qquad c_2 = 2\sqrt{m_2 k_2}\,\zeta_2 \tag{4}$$

$$k_1 = m_1(2\pi f_1)^2 \qquad c_1 = 2\sqrt{m_1 k_1}\,\zeta_1 \tag{5}$$

where the set (m_1, f_1, ζ_1) represents the dynamic characteristics associated with the first bending mode of the empty floor and the set (m_2, f_2, ζ_2) represents the dynamic characteristics of the crowd. The characteristics represent the modal mass (m), the undamped natural frequency (f), and the damping ratio (ζ), respectively.

If all entries in the system matrices are known, the dynamic characteristics (frequency and damping) of the 2DOF interaction model can be determined by solving the damped eigenvalue problem:

$$\det(\lambda^2 M + \lambda C + K) = 0 \tag{6}$$

where λ represents the roots of the system. As the interaction model is a 2DOF system, there will be two modes of vibration, and the frequencies and damping ratios associated with these modes are here denoted (f_F, ζ_F) and (f_H, ζ_H), respectively. The former characteristics are the characteristics associated with the floor mode of vibration (floor frequency and floor damping), and the latter characteristics are those associated with the human mode, i.e. the crowd. These frequencies and damping ratios can be determined from the roots of the system determined using eq. (6).

For their determination, the sets (m_1, f_1, ζ_1) and (m_2, f_2, ζ_2) need to be known, as from these characteristics the entries in the three system matrices can be calculated. The dynamic characteristics of the empty floor (the set (m_1, f_1, ζ_1)) may be estimated from modal identification tests with the empty floor. The modal mass of the crowd (m_2) can be determined from eq. (1), but generally the crowd frequency (f_2) and crowd damping (ζ_2) are not known. However, guesses as concerns values of the set (f_2, ζ_2) can be made, and for such guess, the variation of floor frequency (f_F) with crowd modal mass (m_2) and the variation of floor damping (ζ_F) with crowd modal mass (m_2) can be calculated. If these variations are in good agreement with corresponding variations determined experimentally, it indicates that the SDOF crowd model is reasonable. This is generally the approach adopted to investigate the usefulness and accuracy of the SDOF crowd model. Hence, the approach rely on experiments in which the floor frequency (f_F) and floor damping (ζ_F) are determined for changing values of the crowd modal mass.

3. THE EXPERIMENTS

3.1 The test floor and the instrumentation

The test floor is a hollow-core concrete element pin supported at both ends. The distance between the supports of the one-way spanning element is about 11 m. Tests were made to identify the dynamic characteristics of the first vertical bending mode of the floor and results are given in section 4. The dynamic characteristics were identified from free decays tests and by an instrumentation recording the decaying vertical floor response at floor midspan. The instrumentation consisted of LVTD displacement sensors which were sampled at a frequency of 2400 Hz. The modal identification was based on the logarithmic decrement method for the identification of damping, and a zero-crossing procedure was employed for identification of the frequency of the decaying vibrations.

The fundamental mode (the first vertical bending mode) of the floor is well separated from other modes of vibration because of the way in which the floor is supported.

3.2 Tests with crowds atop the floor

After testing the empty floor, decaying floor responses were measured with a stationary (sitting crowd) of people atop the floor. The floor was put into vertical vibrations by an impact load applied to the floor at midspan. In all tests the individuals sat at floor midspan, thus primarily interacting with the floor fundamental mode. No chairs or back rests were used and the individuals sat directly on the floor surface in a relaxed position with legs hanging down over the side of the concrete element. The feet of the individuals were not in contact with the floor of the laboratory, and arms were resting in the lap of the individual. The individuals assumed this position during the entire decay.

First floor decaying responses were recorded with a crowd of 5 atop the floor. Then decays were recorded with a crowd of 4, 3, 2, and 1 on the floor. In each situation, a series of floor decays were recorded, and the damping and frequency of the decaying oscillations were estimated. The estimated parameters will be referred to as floor frequency (f_F) and floor damping (ζ_F). A basis is thus established that allows relating floor frequency (f_F) and floor damping (ζ_F) with variations in m_2.

4. RESULTS

This section presents the results of experiments and evaluates whether a SDOF crowd model would be able to explain experimental observations.

From the floor decays monitored with the different crowd sizes on the floor, the mean value of estimates of floor frequency (f_F) and floor damping (ζ_F) were calculated and results are displayed in figure 3 for different values of the crowd modal mass (m_2). The experimental estimates (+) are shown together with theoretical estimates (continuous lines) obtained assuming a SDOF crowd model attached to the empty floor, i.e. assuming a 2DOF crowd-floor interaction model. For the SDOF crowd model of the 2DOF interaction model, the characteristics f_2 = 5.9 Hz and ζ_2 = 0.38 are assumed. The empty floor dynamic characteristics are those at m_2 = 0 kg.
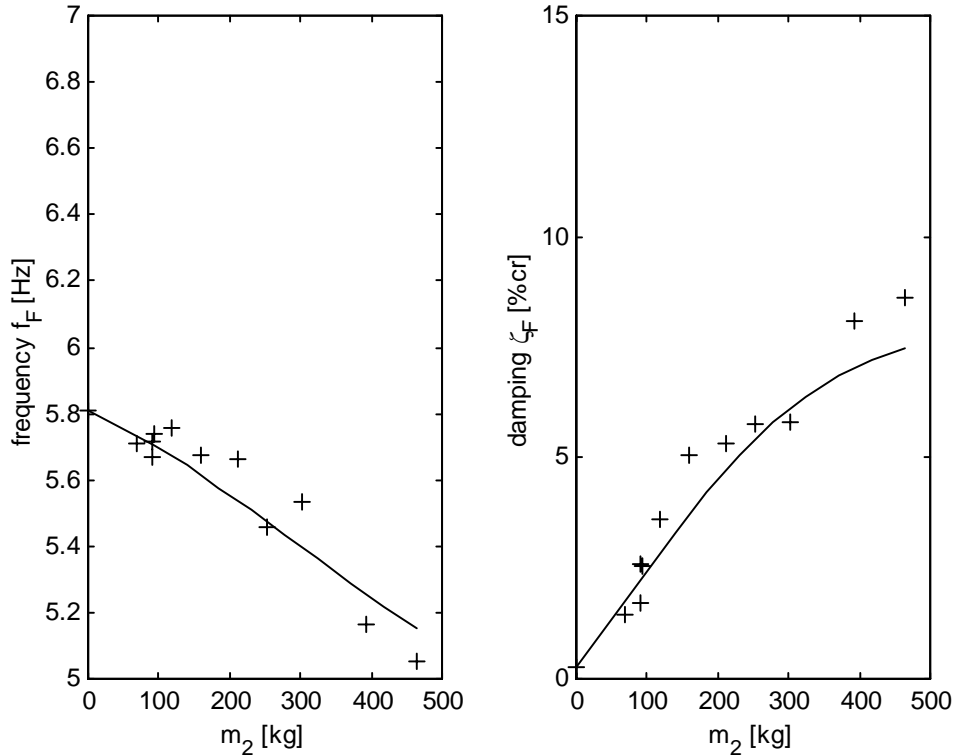

Figure 3 Variations of floor frequency and floor damping with crowd modal mass (m_2).
Experimental results (+), Theoretical predictions (continuous line).

Generally, the theoretical model that assumes a SDOF crowd model gives estimates of floor frequency and floor damping that agree quite well with corresponding experimental results. Some deviations can be noticed, but overall, the theoretical model works well, if f_2 = 5.9 Hz and ζ_2 = 0.38 are assumed. If, for instance, f_2 = 7.0 Hz and ζ_2 = 0.2 are assumed, the theoretical results would not agree well with experimental results. The SDOF crowd model characterised by (f_2, ζ_2) = (5.9 Hz, 0.38) is obtained by calibration (trial and error), but the interesting part is that a SDOF crowd model exists that predicts variations of floor frequency as well as variations of floor damping with crowd size quite well.

It is quite possible that the solution, (f_2, ζ_2) = (5.9 Hz, 0.38), would not perform well for any stationary crowd, and a standing crowd might interact differently with the floor. However, it is reassuring to find that a model seems to exist that works well in modelling floor dynamic behaviour.

Turning to the results presented above (figure 3) it can be recognized that a stationary crowd adds much damping to the floor. For example, is can be noticed that if a crowd of 5 assemble on the floor (m_2 ≈ 500 kg), the floor damping increases significantly. Indeed, the floor damping increases by a factor of approximately 35 although the mass of a crowd of 5 corresponds to less than 10% of the floor mass. The manner in which the presence of a

crowd influences the dynamic behaviour of the floor can also be seen in floor decays, and figure 4 presents floor decays recorded on the empty floor and on the floor occupied by a crowd of 3.
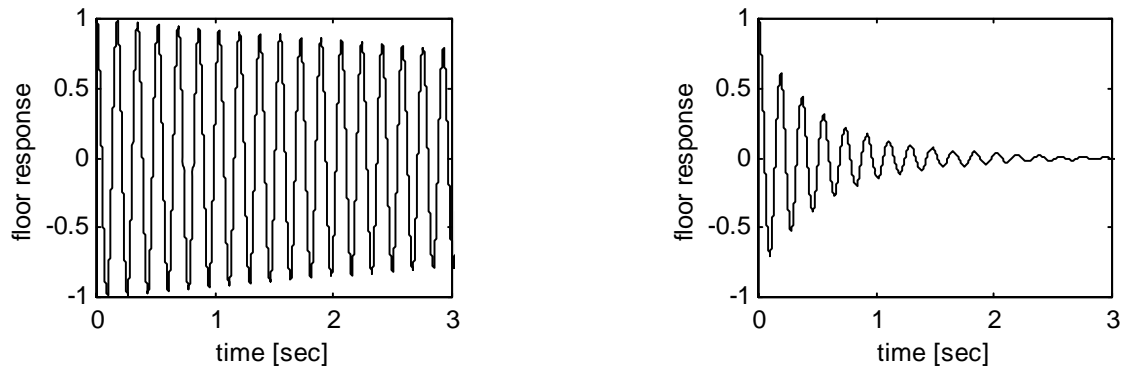

Figure 4 Floor decays recorded on the empty floor (left) and on a floor occupied by a crowd of 3 (right).

The decays illustrate that sitting crowds of people are quite efficient in attenuating floor vibrations, and thus that it may be worthwhile considering the dynamic interaction between the crowd mass and the floor mass when attempting to predict dynamic behaviour of a flooring-system.

5. CONCLUSION

The paper investigated the usefulness of modelling a stationary crowd of people on a floor as a SDOF spring-mass-damper system in connection with predicting the dynamic behaviour of floors occupied by stationary crowds of people. Tests with sitting crowds of people vibrating together with a test floor were carried out and the frequency and damping of the floor were determined for different crowd sizes.

The experimental estimates of the dynamic characteristics (frequency and damping) of the floor varied with the size of the crowd validating that the floor and crowd mass interact. The results showed that much damping is added to the floor when a crowd of people is present on the floor. For example, the damping of the test floor increased by a factor of approximately 35 when a crowd of 5 assembled on the floor although the mass of a crowd of 5 corresponds to less than 10% of the floor mass.

It was found that by modelling the crowd as a SDOF system attached to the floor, the experimentally obtained variations of floor damping with crowd size could be explained. If indeed, the frequency of the crowd is assumed to be equal to 5.9 Hz and the damping ratio of the crowd is assumed to be equal to 0.38, the SDOF model assumption for the crowd predicts variations of floor damping as well as variations of floor frequency with crowd size quite well.

Generally, the results of the investigations suggest that the approach of modelling a sitting crowd of people as a SDOF attachment system to a vibrating floor seems promising, and that the interaction between floor and human masses is a factor that is worthwhile considering when estimating dynamic behaviour of floors occupied by stationary humans.

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