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An Aspect of Dynamic Human-structure Interaction

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ABSTRACT

It is known that humans and structures interact. Humans can cause structures to vibrate, and excessive vibrations may occur if the motion frequency of humans coincides with a resonant frequency of the structural system. It is also known that stationary humans (such as humans sitting or standing on the structure) influence the dynamic behaviour and modal characteristics of the structure carrying them, whether being a grandstand, an office floor or similar. However, the interaction between the stationary humans and the structure is generally not well understood, and the paper addresses this interaction. Focus is on how modal characteristics of the structure, i.e. its frequency and damping, are influenced by the presence of stationary humans. Vertical vibrations are considered, and particular focus is given the influence of human posture on modal characteristics of the supporting structure. Insight into this area is obtained by carrying out experiments with a test floor carrying humans. The paper describes the conditions for the tests, the modal identification procedures, the test programme, and the results.

NOMENCLATURE

f_F	Floor frequency	α	Dynamic load factor	g	Acceleration of gravity
ζ_F	Floor damping	m	Mass of jumper	t	Time
w	Weight of person/crowd	F	Load on structure	A..F	Human postures

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. 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.

Some research efforts have investigated the interaction phenomenon by carrying out tests with humans on floors in a certain sitting posture (such as works in [6] and [7]) or with humans on floors in a certain standing posture (such as in [5]). These have been useful steps in providing an understanding of the basic mechanisms of the interaction, and how humans influence dynamic characteristics of the structure supporting them, but at the same

time it must be recognised that there is no universal consensus of what a sitting posture is. Each individual is likely to find its own sitting posture and this posture is likely to change over time. For instance spectators seated on a grandstand in stadia structures are not likely to assume one and the same posture throughout the entire game, and definitely different spectators will assume different sitting postures. But the posture of the spectators might have a bearing on the how the structure supporting them will behave dynamically when exposed to dynamic loads from humans in vertical motion (for example jumping).

To the knowledge of this author, results of controlled tests examining how humans in different sitting postures effect the modal characteristics of the structure supporting them have not previously been published in literature, although it would seem to be a reasonable study approach for gaining insight into the variability of the dynamic interaction known to exist between the mass of stationary (for example sitting) humans and the vibrating structural mass.

The purpose of the investigations for this paper is to examine a number of different sitting postures (postures that are likely on grandstands) and particularly to quantify how humans in the different postures influence modal characteristics of the structure supporting them. For the investigations a test floor is employed, and its modal characteristics (frequency and damping) are determined in situations with and without a sitting crowd atop the floor. In tests, the crowd size is varied so as to investigate mechanisms hereof and generally to provide a wider basis for understanding the mechanisms of the interaction.

The experimental efforts and the general approach are outlined in section 2, and section 3 presents results of how different postures influence modal characteristics of the test floor. The results are discussed, some implications are presented in section 4, and a conclusion is provided in section 5.

2. THE EXPERIMENTS

2.1 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, and the width of the element is about 1.2 m. The weight of the element amounts to more than 6,000 kg.

Tests were made to identify the modal characteristics of the first vertical bending mode of the floor and results are presented in section 3. The modal characteristics were identified from free decays tests and by an instrumentation recording the decaying vertical floor response at floor midspan. The instrumentation consisted of LVDT 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.

Due to the floor support conditions, the fundamental mode (the first vertical bending mode) of the floor is well separated from other modes of vibration, and as humans in subsequent tests will be positioned close to floor midspan, it is their influence on modal characteristics of the first bending mode of the floor that is examined in tests. The empty floor tests actually were carried out with four chairs on top the floor at midspan, as these chairs were later to be used by individuals grouping on the floor, as explained next.

2.2 Tests with crowds atop the floor

After testing the floor occupied by empty chairs, decaying floor responses were measured with stationary people sitting on the chairs. The floor was put into vertical vibrations by an impact load applied to the floor at midspan. In all tests the individuals (test subjects) sat close to floor midspan in the arrangement shown in figure 1.

First, floor decaying responses were recorded with a crowd of 4 atop the floor (seats 1 to 4 occupied). Then decays were recorded with a crowd of 3 on the floor (seats 2, 3, and 4 occupied), 2 (seat 3 and 4 occupied), and 1 (seat 4 occupied). 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 w , where w represents the crowd mass present on the floor. This mass is known as each individual was weighted prior to the tests.

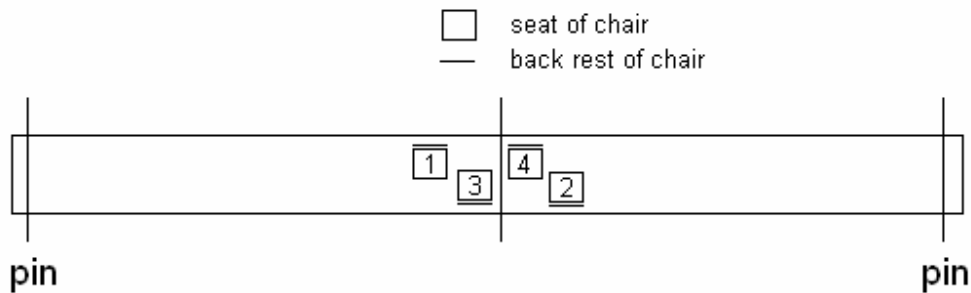


Figure 1 Upper: Top view of test floor and specification of seat numbers, Lower: View of the test subjects 2, 3 and 4 sitting on the test floor in one of the studied postures.

2.3 Human postures

The test sequence outlined above was carried out with humans sitting on the chairs in different postures. Figure 1 illustrated one of the postures examined. All the postures examined are presented in figure 2, illustrating the postures by a front view and a side view of the test subject. The postures encompass a variety of postures that one might choose when present on a grandstand with seating capacity.

It is useful to supplement figure 2 by the following comments:

Posture A:

No use of back rest, the spine of the test subject is fairly straight, straight arms with elbows and shoulders locked and hands firmly resting on the knees as arms are slightly prestressed and capable of transferring compressive axial forces between knee and shoulder.

Posture B:

No use of back rest, relaxed position in upper part of the body with hands resting on the knees of the test subject.

Posture C:

Use of back rest, relaxed position in the upper part of the body with lower part of the arms resting in the lap of the test subject.

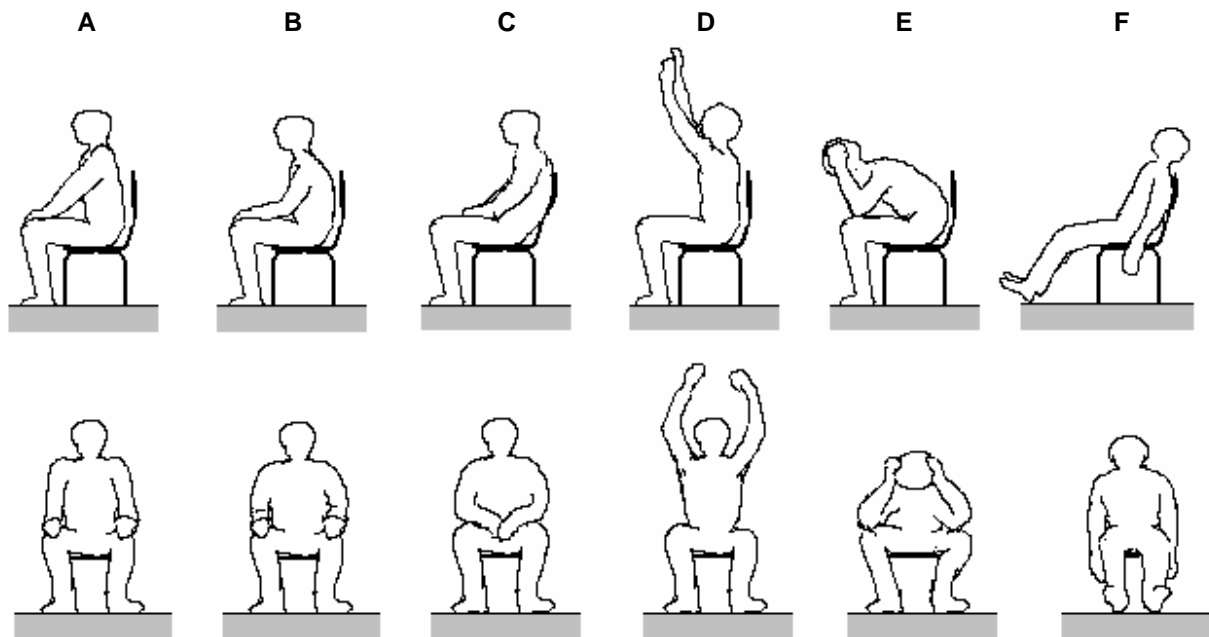


Figure 2 The six different human postures examined in tests.

Posture D:

No use of back rest, fairly straight spine, and hands above the head of the test subject.

Posture E:

No use of back rest, head of test subject resting in his hands and elbows resting on his knees.

Posture F:

Use of back rest, head of test subject back and feet in front of the test subject. Relaxed position with arms hanging down loose.

In tests, the individuals were asked to assume the respective postures during the entire phase of decaying vibrations. All test subjects assumed the same postures when going through the sequence outlined in section 2.2; starting with posture A and ending with posture F. As a reference case, floor decays were monitored with sandbags in place of humans on chairs. For the reference case, sandbags of 80 kg were placed on the chairs else occupied by humans. The bags were then removed one by one.

3. RESULTS

This section presents the results of the experiments. 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 for different values of the crowd mass (w). This was done for each of the six different postures examined.

The variations of mean values of floor frequency (f_F) with crowd mass (w) are shown in figure 3 for the 6 different postures (A to F). The empty floor modal characteristics are those at $w = 0$ kg.

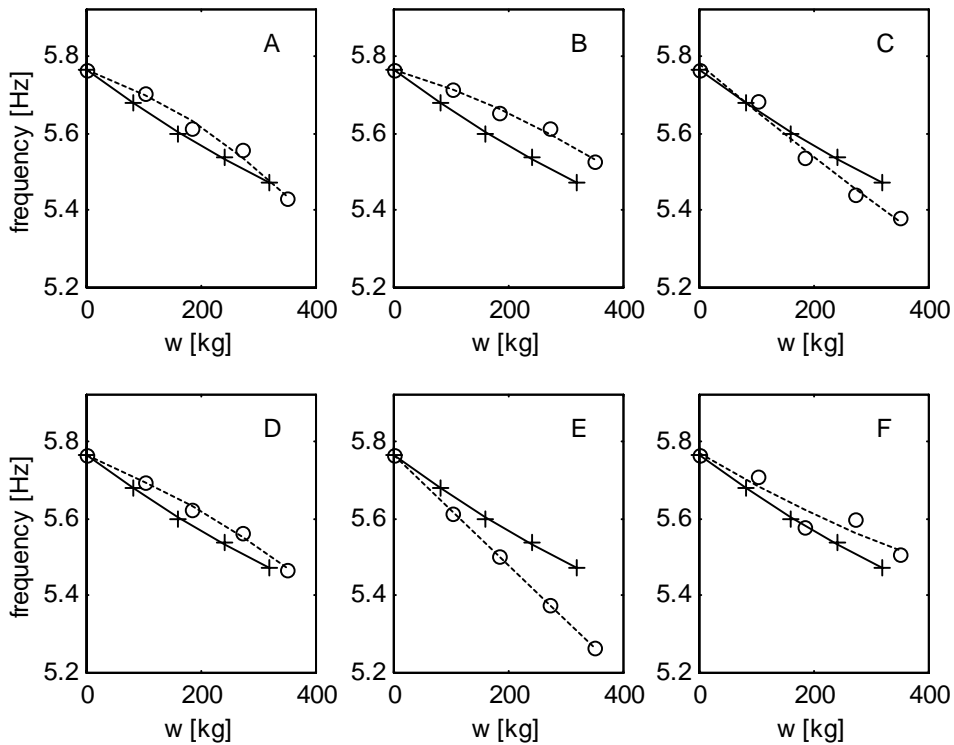


Figure 3 Variations of floor frequency with crowd mass (w) for the postures A to F (o) compared with results obtained in sandbag tests (+). Polynomial fits to variations are also shown.

It can be recognised that all results suggest a general decrease in floor frequency with the size of the mass added to the structure. For most postures, the decline of frequency fits fairly well with the decline observed in tests where sandbags were used in place of humans. Some deviation can be noticed in the decline from one posture to the next. An item to notice is that posture E (the posture in which test subjects were bending forward and where their heads were supported by their hands) resulted in a variation, where there is a quite systematic deviation from the reference case (the sandbag tests).

In structural dynamics, damping mechanisms are important and variations of mean values of floor damping (ζ_F) with crowd mass (w) are shown in figure 4 for the 6 different postures (A to F). Again, the empty floor dynamic characteristics are those at $w = 0$ kg.

It can be noticed that the reference tests (with sandbags on chairs) gave variations that markedly deviate from those obtained in tests with people sitting on the chairs. The most pronounced difference is the amount of damping added to the floor by sandbags and by humans. The sandbags hardly add any damping whereas the human body adds quite substantial amounts of damping and it increases with the number of people present on the floor. The postures A, B, and C represent postures that are quite realistic and postures that one would possibly attain for most of the time when seated. It can be seen that these postures resulted in almost similar floor damping. The postures D, E, and F are also likely postures on seats in stadia structures; although perhaps only for a short period of time. As can be seen, human bodies in these postures also add substantial amounts of damping to the supporting structure, and postures D and F add close to as much damping as postures A, B, and C. As was also seen in variations of floor frequency, posture E resulted in variations somewhat different from the variations found for the other postures.

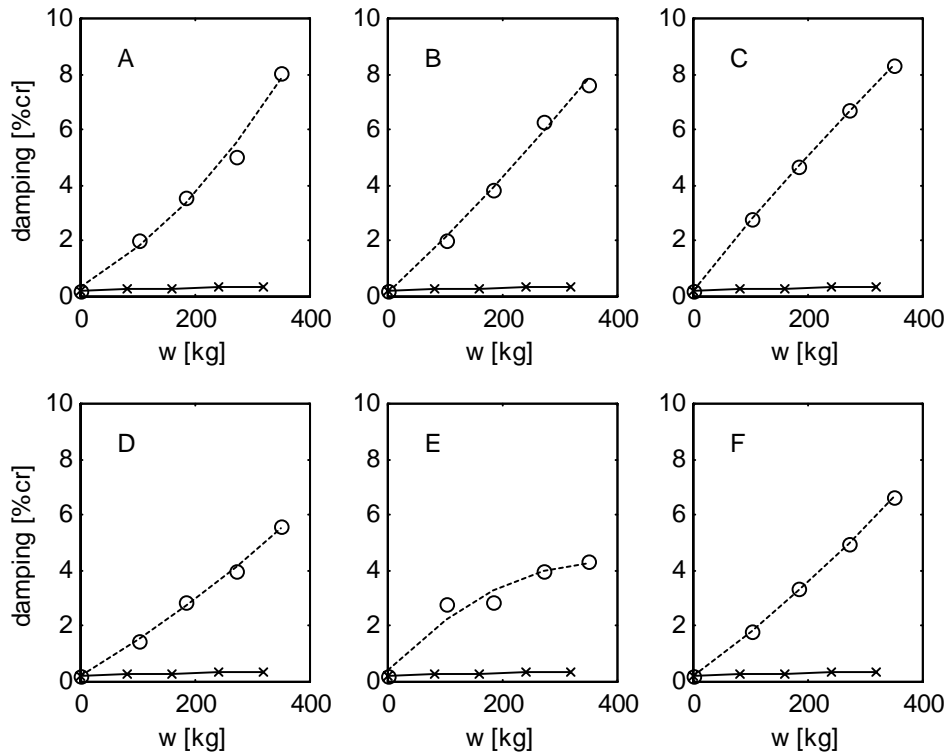


Figure 4 Variations of floor damping with crowd mass (w) for the postures A to F (o) compared with results obtained in sandbag tests (+). Polynomial fits to variations are also shown.

The frequency variation observed using sandbags in tests agreed fairly well the variations found in tests with humans, although there were some differences. But the fact that floor damping features with human bodies in chairs by far matched the floor damping features seen in tests with sandbags substantiates that it is not reasonable to model the human body or a crowd of human bodies on a floor as a rigid mass attached to the floor in cases where the floor dynamic behaviour is subject for investigation. This is in agreement with conclusions drawn in for example [3], [4], and [5].

Instead, and as proposed in the references mentioned above, the human body should be modelled as a mechanical system with masses hooked up by springs and damping elements; a system attached to the vibrating floor mass, and vibrating together with the floor mass. Adapting this approach assists in explaining the general dynamic behaviour of the human occupied floor and in explaining some of the observed differences and similarities in floor dynamic characteristics from one posture to the next. First of all such model of the human body explains that humans absorb vibration energy from the floor and adds damping when present atop the floor (as was observed). Next, one can find (from figures 3 and 4) that the postures A, B, and C influenced floor modal characteristics almost similarly, which probably can be explained by the fact that in these postures, the body mass above the pelvis is positioned close to right above the pelvis. This results in a type of dynamic interaction with the floor that is somewhat different from that observed for posture E, where the torso is positioned in front of the pelvis of the test subject. Hence, the human body forms a different mechanical system in this posture, and it probably explains why this posture influenced floor modal characteristics somewhat differently than other postures.

Although in some cases it can be a simple matter to foresee that one posture will result in a different type of interaction with the floor than another posture, it is similarly difficult to predict (in quantitative terms) the influence of the posture on floor modal characteristics. This requires controlled tests as those carried out for this paper. Generally, the results presented in figures 3 and 4 suggest that there is some variability in how different human postures influence the modal characteristics of the structure supporting them. If the influence of a large seated

crowd on the modal characteristics of a stand is to be estimated, it would seem reasonable to consider the likelihood of different postures as different spectators probably would assume different postures (a mixed crowd with different postures). Also it could be relevant to address the time aspect, as postures would possibly to some degree synchronize during certain events on the pitch. For instance postures D, E, and F might only be likely postures when the home or visiting team scores a goal.

But, irrespective of human posture, there is the tendency that a human crowd adds damping orders of magnitudes from the damping added, if humans are modelled as simple added mass (sandbags, i.e. rigid mass). In order to be able to reliably predict floor vibration levels in situations where a sitting crowd is present on the floor, it may thus be useful to construct an analytical model of the human-floor dynamic system that accounts for the existence of the phenomenon of the dynamic interaction between humans and floors observed in tests. In such a model it would be useful to model the mass of the crowd of people on the floor, as in the present tests it can be observed that the mass of the crowd has at least as much influence on the floor modal characteristics as the variability of human postures examined in tests.

Depending on the use of the model it may or may not be relevant to account for the potential variability in postures. However, just by accounting for the human-structure interaction would significantly improve model reliability, and whether it would be relevant to model postures as D, E, and F, would depend, for example, on the usage of the floor. These postures might be relevant to consider when examining vibrations of grandstands in stadia structures, but when examining vibrations of office floors, the postures might be irrelevant.

Overall, the results suggest that despite differences in sitting postures, the difference in terms of their influence on modal characteristics of the floor is not that far apart, especially when compared with the influence observed and predicted by the simple rigid mass model for the stationary crowd. Hence, it would seem realistic and reasonable to construct a dynamic model for structures carrying humans (that accounts for human-structure interaction) that is fairly representative for stationary crowds even though different individuals in the crowd might attain different postures. The model could be a single-degree-of-freedom model for the crowd (attached to the floor) as proposed in, for example, [3] and [5].

4. IMPLICATIONS

To add some perspective to the findings, the stationary resonant displacement response of the fundamental mode of the test floor to the vertical load:

$$F(t) = \alpha m g \sin(2\pi f_F t) \quad (1)$$

acting at floor midspan was calculated for the floor carrying 80 kg sandbags on each of the four chairs, and for the floor carrying four sitting persons in posture A. This load model is fairly representative for a single person jumping at floor midspan, if the properties $\alpha = 1.1$, $m = 75$ kg, $g = 9.82$ m/s² are employed. The calculations showed that the stationary amplitude of test floor response was more than 20 times higher if the crowd was modelled as sandbags (rigid mass attached to the floor) than if the floor modal characteristics found for posture A was assumed for the calculations. Hence, the presence of sitting crowds of humans on the floor can influence floor behaviour quite significantly.

5. CONCLUSION

The paper investigated the influence of different human postures (sitting positions) on the modal characteristics of the structure (test floor) supporting them. Tests with sitting crowds of people vibrating together with a test floor and positioned close to its midspan were carried out and the frequency and damping of the floor were determined for different crowd sizes and with the crowd in six different postures.

The results showed that much damping is added to the test floor when a crowd of people is present on the floor. Generally the amount of damping added to the test floor where found to depend a lot on the number of people present, but the sitting posture assumed by the test subjects also influenced floor damping to some degree.

The pattern of variation of floor damping with the mass of the crowd present on the floor was found to be fairly identical for most of the postures, although at least for one posture, the pattern was somewhat different, which can be explained by the fact that human posture determines how the human body reacts as a mechanical system to floor vibrations. The results of the paper also suggest that it is useful to adopt the thinking that the human body is not a rigid mass attached to the floor, but a mass supported by springs and dashpots attached to the floor.

Generally, the results indicate that it would seem realistic and reasonable to construct a dynamic model for structures carrying humans (that accounts for human-structure interaction) that at the same time is fairly representative for stationary crowds even though humans in the crowd may attain different postures. Such model would be a significant improvement compared with the rigid mass model for the crowd regardless of whether specific human postures are accounted for in the model.

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