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Pedersen, Lars

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Aspects of Prediction Accuracy in Human-structure Interaction

Lars Pedersen

Aalborg University
Department of Civil Engineering
Sohngaardsholmsvej 57
DK-9000 Aalborg

ABSTRACT

Structures such as grandstands in stadia and office floors in buildings are typically occupied by seated persons, and it is a challenge to predict the dynamic characteristics of these structures. This is because the structures and the seated persons interact when the structures undergo vibrations, basically with the effect that the seated persons influence the dynamic system. The mechanism of the interaction is not well understood, and there are a number of factors that might influence the mechanism of the interaction. Through experiments with a vibrating floor carrying seated humans, the paper looks into the mechanism of the interaction focusing on its effect on dynamic structural properties. It is investigated to which extent factors such as posture of the seated persons and the construction type of the seat on which the persons are sitting have a bearing on the structural frequency and damping. This provides useful insight into the uncertainties and errors that may be involved with predicting these structural properties from simple analytical models not accounting for the factors considered in this paper. The paper describes the conditions for the tests, the modal identification procedures, the test programme, and the test results are discussed.

NOMENCLATURE

f_F	Floor frequency	f_0	Empty floor frequency	τ_f	Frequency ratio
ζ_F	Floor damping	ζ_0	Empty floor damping	τ_ζ	Damping ratio
w	Weight of person/crowd	1..4	Seats	A..C	Human postures

1. INTRODUCTION

Vibrations may be induced in grandstands and in office floors by people in motion on these structures. The activity of these people (bouncing, walking, or similar) may be problematic in terms of vibration serviceability of the structures and occasionally with respect to structural integrity. However, stationary crowds of people might be present on these structures as well, and the complex problem is that these people interact with the supporting structure and change structural modal properties (such as frequency and damping). The structural response to the loading generated by people in motion is thus influenced by the stationary persons present on the structure. That the dynamic characteristics of structures carrying stationary persons are influenced by the stationary crowd of people on the structure was demonstrated, for instance, in [1], [2], and [3] based on field measurements made on human-occupied structures, and in [4] and [5] on the basis of laboratory tests. However, 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 [4] and [5]) or with humans on floors in a certain standing posture (such as in [3]). These have been useful steps in providing an understanding of the basic mechanisms of the interaction, and how humans influence dynamic characteristics (frequency and damping) 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 and a person sitting on a floor, grandstand or similar will not attain one and the same posture all the time. It is, therefore, of interest to examine whether and to which extent changes in sitting posture influence structural modal properties. This gives insight into how accurately structural modal properties can be predicted, as you may have available an analytical dynamic model of a sitting person and its interaction with the structure, but a model in which changes in posture are not modelled. In [6] results of controlled tests investigating this aspect of human-structure interaction were presented, and the present paper takes investigations a step further by also considering changes in the construction type of the seats used by persons on the structure and consequential changes in structural modal properties. Now it is not common to change seats (for instance when watching a football match), but on different structures you can expect different seat types, and it is therefore investigated whether the seat type has a bearing on the structural modal properties. In the tests for the studies of this paper, the structure (test floor) is the same in all tests and so is the persons used in tests, and the only thing which is changed in the tests is the seat and the sitting posture.

Besides from providing some idea about the influence of posture and of seat on structural modal properties, the results of the study also shed some light on which of the two parameters influence structural modal parameters the most and thus which parameter is most important to account for when in the situation where the structural modal properties are to be predicted for a structure carrying humans.

As mentioned a test floor is employed for the investigations, and they general idea is to monitor its modal characteristics (frequency and damping) 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 and different seats influence modal characteristics of the test floor. The results are discussed, and a conclusion is provided.

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.

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 in tests this mode is excited. 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. Hence, as a reference, the modal characteristics of the first bending mode of the test floor (undamped frequency f_0 [Hz], and damping ratio ζ_0 [%cr]) were determined. Since in subsequent tests, humans will be sitting on different types of seats, a reference (a value of f_0 and ζ_0) was established for each seat type by determining the floor frequency and floor damping while carrying the empty seats later to be occupied by humans. Without any seats atop the test floor its undamped frequency was at about 5.8 Hz and the damping ratio was below 0.25 %cr.

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’s 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.

2.2 Tests with crowds atop the floor

After testing the floor occupied by empty seats, decaying floor responses were measured with stationary people sitting in the seats. 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 i to iv occupied). Then decays were recorded with a crowd of 3 on the floor (seats ii, iii, and iv occupied), 2 (seat iii and iv occupied), and 1 (seat iv 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.

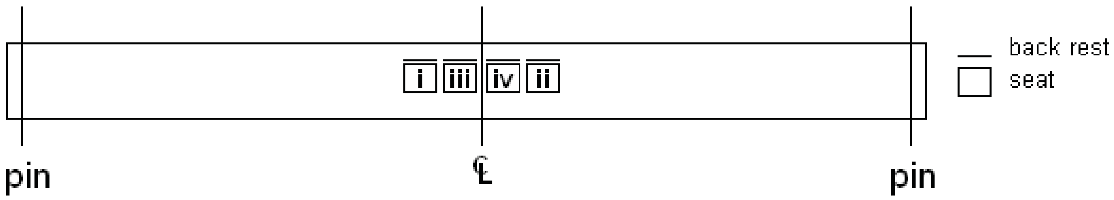

Figure 1 Top view of test floor and specification of seat numbers.

2.3 Seats and Human postures

The test sequence outlined above was carried out with humans sitting on the seats in three different postures and on four different types of seats. Figure 2 shows the four seat types used in tests. In the first tests, four type 1 seats were aligned on the floor and after testing with humans in different postures, the four type 1 seats were exchanged with four seats of type 2, etc.

Figure 1 The seats used in tests. From left: Seat type 1, 2, 3, and 4.

The heights of all seats (relative to the test floor) were 0.45m (or slightly less depending on how the height was measured).

Seat 1 is a seat type used on the grandstands of Aalborg Ice hockey Arena. Seat 2 and 3 are chairs used at Aalborg University in meeting rooms, and at working desks, respectively. Basically seat 4 is added as reference, as it constitutes a “rigid seat”.

The postures examined and seats used for the tests are presented in figure 3 (illustrating the postures by a side view of the test subject sitting on the various seats). As for human postures, the following comments:

Posture A: No use of back rest, relaxed position with hands resting on the knees of the test subject.
Posture B: Use of back rest, relaxed position with lower part of the arms resting in the lap of the test subject.
Posture C: No use of back rest, head of test subject resting in his hands and elbows resting on his knees.

The legs of test subjects were slightly spread in all postures, and in posture B, one hand rested on the other. In tests, the individuals were asked to assume the respective postures during the entire phase of decaying vibrations.

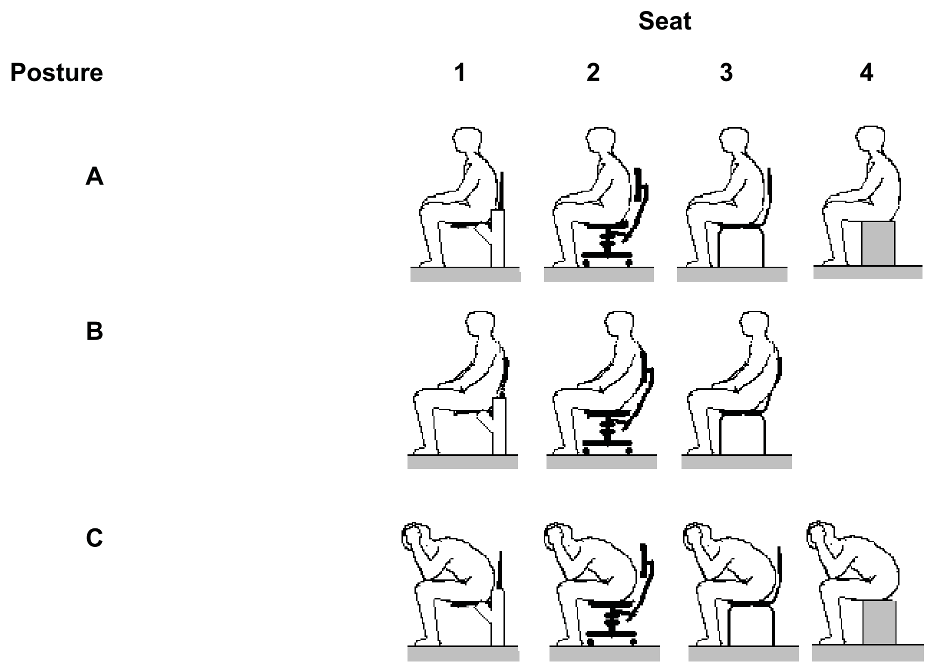

Figure 3 The three different human postures examined in tests on different seats/chairs.

As can be seen in figure 3, the human posture B was not employed in tests with seat 4 basically because the seat does not offer a backrest.

3. RESULTS

From the floor decays, 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). For the presentation of results it is useful to employ the frequency and damping ratios defined below.

$$\tau_f = \frac{f_F}{f_0}, \qquad \tau_\zeta = \frac{\zeta_F}{\zeta_0} \tag{1}$$

The frequency ratio (τ_f) relates the floor frequency monitored with a sitting crowd (with a weight of w) atop the floor to floor frequency without an occupancy in the seats (w = 0), and the damping ratio (τ_ζ) relates the floor damping monitored with a crowd atop the floor to floor damping measured without an occupancy in the seats. Values of the two ratios and their variation with *w* are derived for the four seat types and for the 3 different postures. Values of τ_f below unity suggest that the crowd reduces the floor frequency, and values of τ_ζ above unity suggest that the crowd adds damping to the floor. The results as regards how a sitting crowd influences floor frequency are addressed first.

3.1 Floor frequency, human-occupied seats

Observed variations of the frequency ratio (τ_f) with crowd mass (*w*) are shown in figure 4 for the 3 different postures (A, B, and C) and on the four different seats (1 to 4). A simple added mass (rigid mass) attached to the floor would influence floor frequency as stipulated by the added mass model (--).

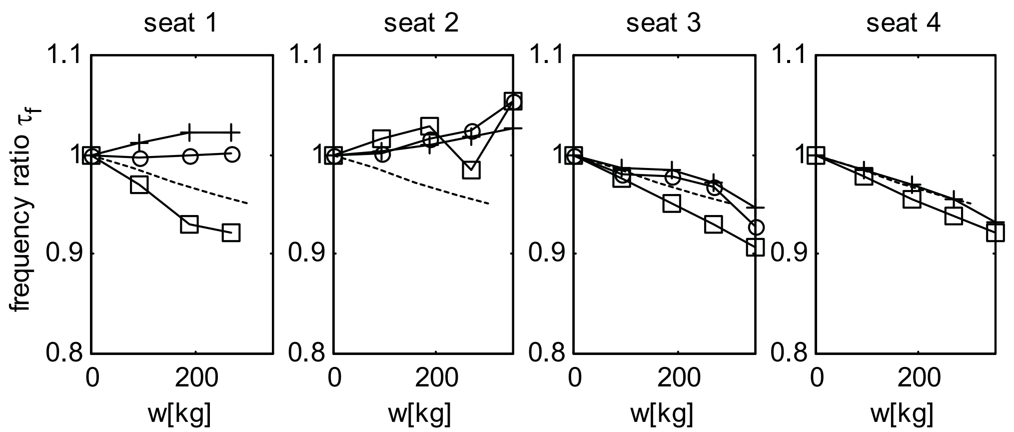

Figure 4 Variations of frequency ratio with crowd mass (*w*) for the postures A (+), B (o) and C (□) on the four different seats. The rigid mass model stipulates the variation (--).

It is noticeable that for the rigid seats (3 and 4), the floor frequency systematically declines when the size of the mass (*w*) increases. This is not observed for the swivel chair (seat 2) where, apparently, the addition of human mass to the structure (human mass in the seats) does not alter the structural frequency or slightly increase the structural frequency. This will have to do with the fact that this seat type is not rigid, and thus that a flexible mechanical system is inserted in between the human body and the floor (the swivel chair).

For the grandstand seat (seat 1), the frequency behaviour apparently depend much on posture. Disregarding the somewhat unusual posture C, there is the tendency that the floor frequency is unaffected or slightly increases when human mass is added. Hence the grandstand seat used in tests shows some similarity with the swivel chair used in tests (a not fully rigid seat). For each seat type, the frequency behaviour is quite similar for posture A and B, but it is apparent that the rigid mass model is not useful for predicting structural frequency.

3.2 Floor damping, human-occupied seats

In structural dynamics, damping mechanisms are important and the observed variations of the damping ratio (τ_ζ) with crowd mass (*w*) are shown in figure 5 for the 3 different postures (A to C). When adding rigid mass to the structure in stead of human mass practically no increase in damping is expected (as indicated by the dashed line, i.e. a value of τ_ζ equal to one).

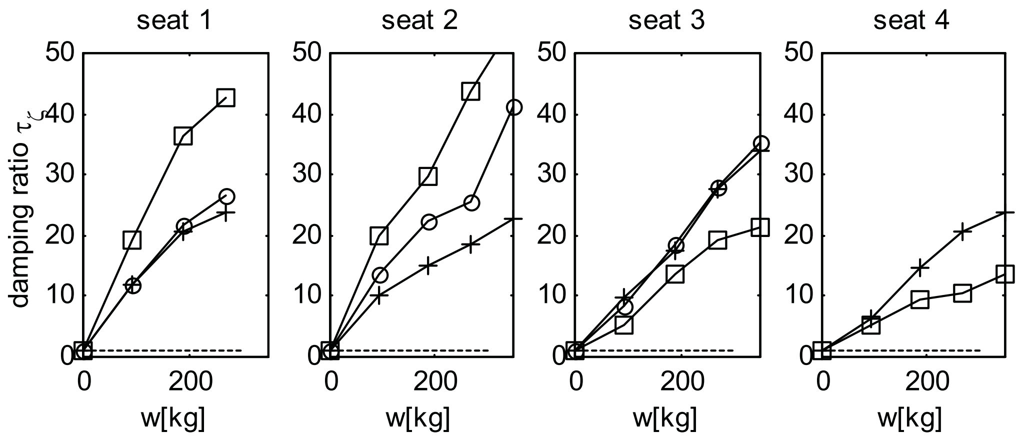

Figure 5 Variations of damping ratio with crowd mass (*w*) for the postures A (+), B (o) and C (□) on the four different seats. The rigid mass model (--).

Certainly, humans in the seats add much damping to the floor irrespective of seat type and human posture. For all seats and postures the tendency is similar, namely that as *w* increases so does floor damping.

For posture A (+), the damping added to the floor does not seem to depend that much on the seat type. For instance when seats are occupied by three persons (*w* = 270 kg), posture A resulted in an increase in damping in the range of 18 to 28 times the empty floor damping value irrespective of seat type. The damping that result when humans are seated in posture B (o) is fairly similar to that observed when human are seated in posture A (+), particularly for seat 1 and 3. Perhaps not surprising, the difference is most pronounced when the back rest is flexible (seat 2, the swivel chair) as in posture B use is made of the back rest. For posture C (head resting in the hands of the test subjects), the largest influence of seat type is observed. For the rigid seats (3 and 4) the damping observed in posture C is almost similar, but it is quite different from the damping found for the more flexible seats (1 and 2). This is probably because of the difference in vibration transmission path between human body mass and the floor when the seat is rigid and when it is not. It can be argued that posture C is not of much interest, but it constitutes a useful reference case for illustrating the variability in terms of how humans influence the modal properties of the structure that support them.

4. DISCUSSION

Considering that the postures A and B probably are the postures most often employed (regardless of whether on a grandstand or on an office floor) it is useful to recognize that they both introduce damping of a size that is of the same scale of magnitude. Differences are observed, but considering that the rigid mass model of a person would not predict an increase in damping, it seems useful to employ a model of the interaction between humans and floors that facilitates overall reasonable estimates of floor damping for these postures. In terms of floor damping, the results suggest that it is not that important which type of seat the crowd of people is sitting on. For the test floor (almost independent of seat type) almost similar damping was observed for fixed values of crowd mass. It would be interesting to investigate whether this is also the case for test floors with different modal properties.

The results with the test floor suggest that when it comes to the frequency of the human-occupied floor, the seat type does have an influence (and irrespective of the modal properties of the actual floor as this is already observed for the test floor).

For the swivel chair (often used in offices) there were no decline in floor frequency observed when the crowd mass increased. The importance of this observation relates to the fact that the frequency of the floor determines the size of dynamic excitation from persons walking across the floor. So indirectly, the frequency of the floor is important as it determines whether it is relevant to consider floor dynamic behaviour and thus whether it is relevant to consider the damping capability of the floor. If the frequency of the floor increases with humans in swivel chairs it would (to some extent) reduce the risk of serviceability problems (as the load would reduce), and as in some design codes, the floor frequency determines whether a vibration serviceability study should be launched or not, it would be useful to have an understanding of how the seat type influences floor frequency. The results of the tests of this paper have given the first indication.

Definitely, the swivel chair is not rigid, and there are indications that the grandstand seats employed for the tests of this paper are not rigid either. At least the results of the tests made with the grandstand seat show some resemblance with the behaviour of the swivel chair (on this particular floor). By construction the grandstand seat is not fully rigid as the seat is made of plastic, but it cannot be excluded that the fixation of the grandstand seat to the floor in the tested configuration is not as stiff as in in-place conditions (where the seat is bolted to a concrete mass). Furthermore, grandstand seats are different from one stadium to the next, and based on these arguments the results obtained with grandstand seats in tests probably cannot be generalised. Interestingly, however, the results suggest that some grandstand seats might be flexible and this can have an influence on the frequency of the structure on which they are fixed (when the seats are occupied by humans). The flexibility of the seat may thus to some extent determine the size (and risk) of resonant excitation induced by humans in motion on the structure.

Generally, the results of the tests suggest that 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. This is in agreement with recommendations in, for instance, [7] and [8]. 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).

Since at least the frequency behaviour of the test floor depends on seat type (as observed for the swivel chair), a rigid model for the seat is not always meaningful. Hence, in some situations the problem of predicting floor vibrations is not solely a problem of understanding human-structure interaction, but a problem of understanding human-seat-structure interaction.

5. CONCLUSION

The paper investigated the influence of different human postures and seat types on the modal characteristics of a test floor carrying human-occupied seats.

The results showed that much damping is added to the test floor when a crowd of people is present on the floor. This was the case for all human postures and for all seat types, although some difference could be noticed in the development of floor damping with crowd size. Generally the amount of damping added to the test floor where found to depend a lot on the number of people present, and less on human posture and seat type.

In terms of floor frequency it depended on the number of people present on the floor (particularly for the rigid seats where the floor frequency declined as the number of people increased). For the flexible seats, however, there was the tendency that the floor frequency slightly increased when the crowd size increased.

Generally, the results of the tests 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. But also that the flexibility (and thus mechanical characteristics) of the seat can be an item that is worth considering when aiming at estimating floor vibrations. At least the results suggest that this is important for reliable estimation of the frequency of human-occupied floors and as the frequency of the floor is a parameter that determines the size of the dynamic excitation generated by humans in motion (walking, bouncing, jumping or similar) it might in some cases be useful to be able to reliably estimate the frequency of human-occupied floors. For flexible seats this would require knowledge about their mechanical characteristics and from those a human-seat-structure interaction model could be built.

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