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# Assessments of level of comfort on a vibrating structure

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## ABSTRACT

The serviceability limit state of structures is subject to increasing attention. Flooring-systems may encounter vertical vibrations that may be perceived as annoying by stationary persons sitting or standing on the structure. This can happen on office floors, on grand stands etc. where humans in motion (for instance people walking or jumping) can bring the structure into vibration. The paper looks into human perception of decaying oscillations of floors by doing experiments with a test floor with stationary humans atop. An impulsive load is directed to the floor, and after the decay, the persons on the floor are asked to rate the level of discomfort on a scale from 1 to 10, and to assess the size of floor displacement (the initial amplitude of the decay). Tests are carried out with different numbers of people present on the test floor, and with different initial amplitudes of the decay. The paper presents tendencies in results and seeks to explain some of the observed relationships with offset in an analytical model describing the dynamic behaviour of the human-floor system.

## NOMENCLATURE

| | | | | | |
|---|---|---|---|---|---|
| $c_1$ | Damping coefficient of floor | $k_1$ | Spring stiffness of floor | $m_1$ | Empty floor modal mass |
| $c_2$ | Damping coefficient of crowd | $k_2$ | Spring stiffness of crowd | $m_2$ | Crowd mass |

## 1. INTRODUCTION

In civil engineering increasing focus is oriented towards the vibration serviceability of structures. On flooring-systems, actions of humans in motion may induce vibrations. The vibrations may develop as a result of impulsive or continuous forces directed to the floor mass in practice by heel impacts, pedestrian traffic, jumping, or similar, and the structural vibrations may be annoying to persons occupying the structure. Basically, those who might perceive the vibrations as annoying would either be the active persons on the flooring-system (the persons inducing structural vibrations) or the persons passively sitting or standing on the structure. This paper considers the passive (stationary) persons on the structure and their perception of structural vibration. The studies for the paper are based on experiments in which a stationary crowd of people occupies a floor put into vertical decaying vibration by an impact load.

Human perception of decaying vibrations has been studied previously, for example in [1]. In that reference it is argued that human perception of decaying vibration is a function of *initial amplitude* of vibrations, the *frequency* of the vibrations, and the *duration* of the vibrations. The duration of the vibrations is correlated with the damping of the system, in that high damping results in rapidly decaying vibrations and thus a short duration of the vibrations. Methods as to how to perform a vibration serviceability check of a floor are given in, for example, [2] and [3].

The studies for this paper are in some way a continuation of previous works on human sensation of decaying vibrations. But different from previous studies on this subject, the studies for this paper take off-set in an every-day-situation on a flooring-system; namely that the size of the stationary crowd atop the floor can vary during the day or even within minutes. This will change the dynamic characteristics of the floor (its frequency and damping characteristics) as demonstrated in, for example, [4], [5] and [6], and hence how the floor responds to dynamic actions (for example the duration of vibrations to impact loads). The variability in the current usage of the floor (the current crowd size) might thus also influence how stationary humans on the floor perceive floor responses, and this is a central item for investigation in this paper.

For the studies, a test floor is used. The variability in terms of crowd size is implemented in tests basically by varying the number of people present on the floor and for examining how the current usage of the floor (the crowd size) influences assessments of floor vibration serviceability, the test subjects (stationary persons) atop the floor are asked to rate the level of discomfort of decaying vibrations on the various test conditions examined.

Choosing a specific floor for the tests generally means that human perception of decaying vibrations is not examined on a *frequency* scale of vibrations, as the frequency of oscillations are generally restrained to be close to the frequency of the test floor only slightly drooping when a crowd of stationary people assembles on the floor. In tests, the *initial amplitudes* of the decaying vibration are varied so as to investigate the influence of the initial amplitude on human perception of vibrations. Also the *duration* of vibrations are varied in tests, basically by changing the crowd size from one test to the next.

Another aspect examined is how test subjects judge the size of floor vibrations in quantitative terms. The controlled tests provide a mean for comparing the actual size of vibrations with actual assessments made by test subjects on the floor. Hence, the investigations provide a mean for evaluating whether judgements from humans on vibrating structures on the subject of actual vibration levels can be considered as being reliable indicators of actual levels of structural vibrations.

The amount of data acquired in the test series is many, and for the present paper only a subset of the data has been examined, but it is believed that results presented in the paper are quite representative for the general tendencies.

The general methodology of the studies is outlined in section 2, and in section 3 results are presented and discussed. A conclusion is provided in section 4.

## 2. METHODOLOGY

### 2.1. Rating of floor vibrations

The general methodology was to have individuals rate the sensation of decaying vibrations experienced on a floor while either standing or sitting on the floor. Tests subjects were asked to assume that they were “working on the floor” and “on a floor on which they had never worked before”. Prior to the tests, the test subjects were generally unaware of vibration serviceability problems of structures, but they had knowledge about serviceability checks of structures subjected to static loads, as they were students at the Department of Civil Engineering at Aalborg University. Some had attended a course on general vibrations theory at the time of the tests.

On this basis and on the basis of experienced vibrations, each individual rated the vibrations on the scale shown is table 1.

| Rating | Description |
|---|---|
| 1 or 2 | Vibrations are not disturbing |
| 3 or 4 | Vibrations are noticeable but I would keep working |
| 5 or 6 | Would perhaps keep working |
| 7 or 8 | Would not keep on working without more information about the source of vibrations |
| 9 or 10 | Would leave the floor |

**Table 1.** Rating options

The higher the rating, the more disturbing is the sensation of vibrations. The rating scale is different from other rating scales found in the literature on vibration serviceability; primarily by the descriptions associated with the different ratings. For the present works, the primary item was to have a rating scale available, so as to allow examining possible changes in ratings given on different test conditions. Specifically, the different conditions covered different initial amplitudes of decaying vibrations and different numbers of people present on the floor during the decaying vibrations.

Test subjects rated the vibrations when being the sole person on the floor, and while a crowd of 2, 3, 4, and 5 persons was present on the floor. When in a crowd, the test subjects were asked not to inform other test subjects about their rating of vibrations. The test subject was initially the sole person on the floor, and then the crowd of stationary people present on the floor gradually increased. This procedure was adopted for different groups of 5 persons, and paper gives some of the results.

**2.2. The test floor and supplementary conditions**

The tests were made using a pin supported one-way spanning structure atop which test subjects were present at midspan during vibrations. Decaying vibrations were enforced by an impulsive vertical and external force directed to the floor at midspan (by a person not present on the floor, but impacting the floor by one of his feet). The amplitude of the impulsive load was varied so as to facilitate investigating the influence of the initial amplitude of floor motion on the rating of vibration serviceability. Figure 1 illustrates the floor and the parameters that are varied in the present study.

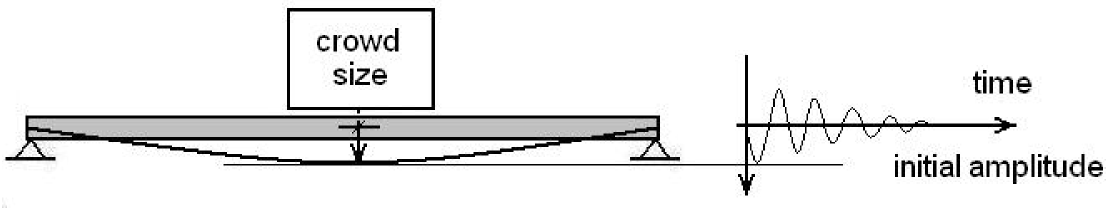



**Figure 1.** The test floor and the parameters varied in tests (initial amplitude of floor motion and size of the stationary crowd.

When sitting on the floor, the test subjects sad directly on the floor surface with legs hanging down freely over the side of the 1.2 m wide concrete element and with arms resting in their laps. When standing in upright position, the test subjects had arms hanging down freely, and in both postures, the test subject attained a posture natural to him.

During the decay phase of the vibrations, the test subjects were asked not to move besides from participating in the vertical vibrations, and the test subjects were asked to give their rating after vibrations had faded away. They were also asked to give an estimate of the initial amplitude of floor motion at midspan (in the unit [mm]).

The test floor was a hollow-core concrete element. During the floor vibration its midspan vertical motion was recorded using a LVTD displacement sensor sampled at a rate of 2400 Hz. Before tests with test subjects atop the floor, decay tests were made with the empty floor. This facilitated modal identification of the fundamental mode of the floor (first mode of vertical bending), which generally is the mode predominating the vibrations. Using the logarithmic decrement method for identifying damping, and a zero-crossing procedure for identifying the frequency of the decaying vibrations, the frequency of the empty floor was found to be of about 5.8 Hz and the damping ratio of that mode was found to be in the range of 0.2 – 0.3 %cr.

## 3. RESULTS

The ratings given by the test subjects that participated in the investigations are presented in this section.

### 3.1 Rating of vibrations and influence of initial amplitude

It is of interest to relate ratings to the initial amplitude of floor vibrations so as to explore the influence of the initial amplitude on the sensation of discomfort of decaying vibrations. Figure 2 gives the observed relationship.

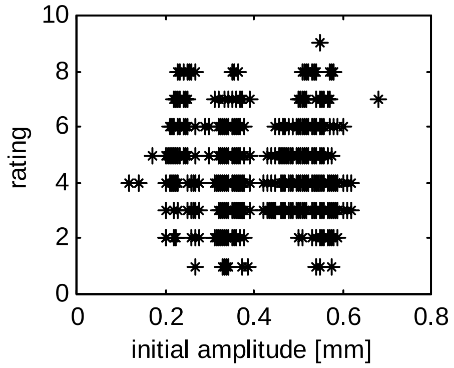



**Figure 2.** Ratings versus actual initial amplitude of the decay.

As can be seen, generally, there is no apparent correlation between the rating and the initial amplitude suggesting that the initial amplitude of the vibrations does not have much influence on the sensation of the decaying oscillations. Another item to notice is that ratings range from 1 to 9, which is a quite wide range that basically involves both ends of the 10-point scale. For completeness, it is here mentioned that “1” corresponds to “vibrations are not disturbing” and that “9” corresponds to “would leave the floor”. It can be appreciated that stationary humans are excellent sensors of vibration, as some of the test subjects might actually choose to leave a floor experiencing motion amplitudes of less than 1 mm. For reference, up to 50 mm static deflection at midspan would, according to many codes of practice, be accepted for the test floor in a static serviceability check.

### 3.2 Estimates of amplitudes of vibration

As mentioned, the persons that participated in the tests were asked to give an estimate of the initial amplitude of floor vibrations. Figure 3 relates these estimates to the ratings giving for one of the groups used in tests.

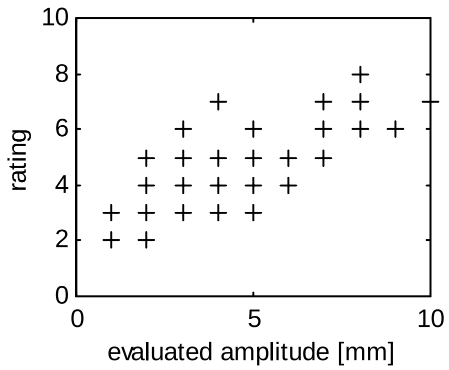



**Figure 3.** Ratings versus evaluated initial amplitude of the floor decay.

It is seen that there seems to be a correlation between the rating and the evaluated initial amplitude, in the sense that a higher rating goes hand in hand with higher estimates of initial vibration amplitudes.

Although some discrepancy is noticed, the test subjects intuitively and separately seem to have adopted the linear scale that an increase in rating by 1 grade is associated with an increase in initial amplitude of 1 mm. The adopted scale and reasoning, however, is based on a misconception, as basically the initial amplitude remained close to unchanged in all experiments (for the particular group is was in the range of 0.4 – 0.6 mm in all tests). Certainly, the judgements of initial amplitudes overestimate actual amplitudes.

Also, as it was shown in figure 2, the actual initial amplitudes and the rating did not show much correlation, supporting that the sensation of vibration and estimates given about the initial amplitude are actually not founded on the actual initial amplitude of vibrations, but on another sensation, and these recognitions generally suggest that humans are not that good sensors for judging actual initial amplitudes of decaying structural vibration.

A closer study of the estimated initial amplitude, not reported here, shows that the highest estimates (7 – 10 mm) are obtained for test conditions where the test subject is the sole person atop the floor, and the general tendency is that the estimate reduces as the number of persons in the stationary crowd increases. Only for the most densely packed crowds employed in tests (4 and 5 people), the estimate of the initial amplitude becomes close to be accurate although also in these cases, the test subjects overestimate the actual initial amplitude. These observations suggest that the number of people present on the test floor when it is vibrating have a stronger effect on the sensation of the decaying vibrations than the initial amplitude hereof. The observed influence of the crowd size on ratings are presented and discussed next.

### 3.3 Rating of vibrations and influence of crowd size

Examples of the observed relationships between ratings and the number of stationary persons present on the floor are provided in figure 4. They represent results obtained for two different groups of 5 people participating in the tests (one plot per group each of which gradually changed in size during tests).

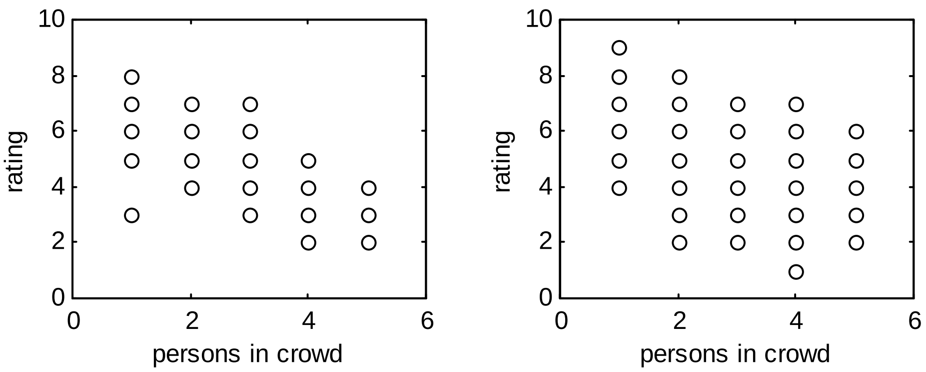


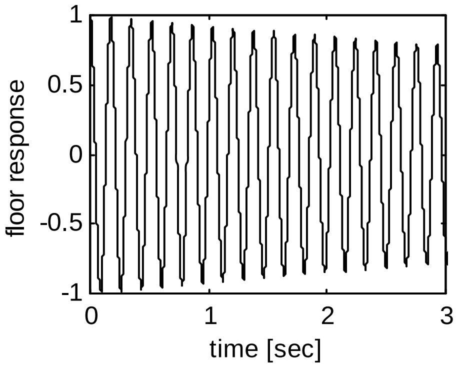

**Figure 4.** Ratings as a function of the number of passive persons atop the floor for two different test groups.

It is seen that there is a wide scatter in ratings, suggesting that people sense discomfort of vibrations differently. However, for both groups, the tendency is the same, namely that the sensation of discomfort of the vibrations takes off as the number of persons present on the floor increases. The tendency is that for each additional person on the floor, the rating is improved (decreased) by a little less than 1 grade. When the test subject is the sole person on the floor there are ratings so high that test subjects “would leave the floor” (ratings 9 - 10) whereas when there are 5 test subjects atop the floor, there are ratings so low that tests subjects find that the “vibrations are not disturbing” (ratings 1 - 2). So on the test floor, the number of people in the stationary crowd markedly influences the assessment of vibration serviceability of the floor. This subject is addressed further in the next section.

### 3.4 Rating and duration and damping of vibrations

Figure 5 shows examples of floor decays measured on the empty floor and on the floor occupied by a crowd of 3, respectively.

It is seen that the duration of vibrations significantly takes off when the number of stationary persons atop the floor increases, as the stationary crowd of people basically absorbs increasing amounts of vibration energy from the floor when the crowd increases in size. This corresponds to an increase in floor damping and the recorded data facilitated calculation of mean values of floor damping for crowds of 1 - 5 persons, respectively, and figure 6 relates ratings to the identified damping for one of the groups that participated in tests.



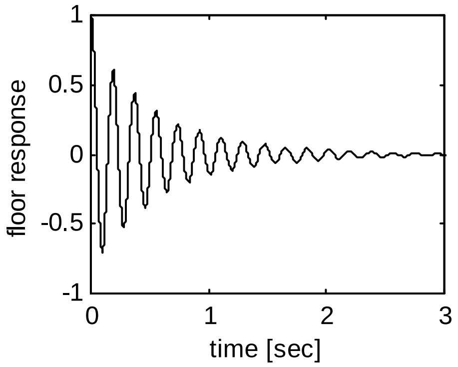




**Figure 5.** Floor decays recorded on the empty floor (left) and on the floor with 3 persons atop (right).

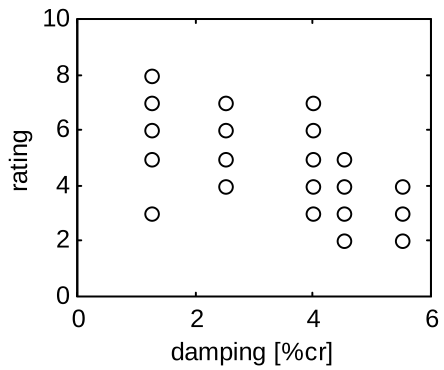



**Figure 6.** Ratings vs. floor damping.

The results presented in figure 6, and the experimental studies of the paper suggest that floor damping is strongly correlated with the sensation of discomfort of decaying floor vibrations induced by an impact load, and on the test floor it was found to be more important than the initial amplitude of decaying oscillations.

It is interesting to notice that when adding just 4 more people on the test floor weighting more than 6,000 kg, a test subject which initially was the sole person on the floor, for example, can change his rating from 7 (would not keep on working without more information about the source of vibrations) to 2 (vibrations are not disturbing). The observation emphasizes that a floor is not just a floor, and that interaction mechanisms between the floor mass and the mass of the stationary crowd of people can be useful to consider when evaluating vibration serviceability of floors (especially by considering the damping added by stationary humans on the floor).

One of the implications of the mechanism is that it can be questioned how it is appropriate to evaluate vibration serviceability of a floor design. An evaluation might be based on a prediction of floor vibration levels by calculation for comparison with threshold values found in codes or standards, and for the calculation, the engineer would need to specify sets of dynamic characteristics for the floor. For the calculation, the engineer might choose to employ damping characteristics recommended for the adopted floor material and structural type. In this case he might end up calculating vibration levels that would rate the floor inappropriate. However, if the sensation of stationary persons on a floor is of concern they would need to be present and they might by their bare presence on the floor alter the dynamic characteristics of the floor. They might add damping to the floor, and if this was accounted for, then the results presented in this paper show that it will have an improving effect on the sensation of vibrations.

Basically, there is not much guidance in codes and standards on how to address the subject of the mechanism of interaction between the floor and the stationary humans, although it is a phenomenon known to exist. But works in, for example [7], [8], and [9], have suggested that there would be much reasoning in adapting an interaction model as shown in figure 7, for estimating floor dynamic characteristics with a stationary crowd atop the floor.

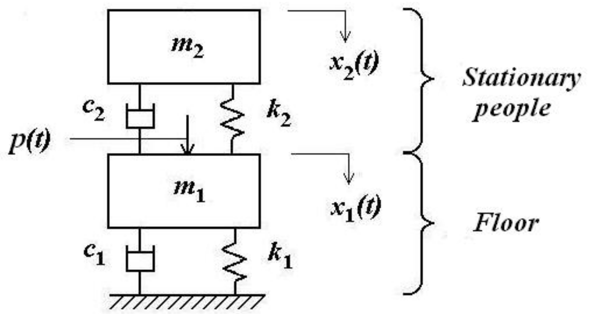



**Figure 7** The dynamic model assumed.

It is a fairly simple model that accounts for the presence of a crowd of stationary people by its mass ($m_2$) considering this mass to be hooked up to the floor mass ($m_1$) by springs and dashpots. Modelling the human body as a mechanical system is much in line with how the human body is modelled in biodynamics, see for example [9].

The model in figure 7 models the entire crowd as a single mechanical system and although the model is simplistic, it is believed that it is capable of providing a reasonable picture of the dynamic behaviour of floors carrying stationary crowds of people.

It is not shown in this paper, but the model predicts floor damping that is fairly consistent with measured damping values for any of the studied crowd sizes.

And as floor damping is found to be a quite influential parameter on the sensation of decaying floor vibrations, the model might thus be useful in predicting floor dynamic behaviour in vibration serviceability checks of human-occupied floors.

**4. CONCLUSION**

The paper investigated how stationary humans on a test floor sensed vibrations when the floor was subjected to decaying vibrations as a result of an impulsive load. Each test subject rated the annoying effect of the vibrations on a scale ranging from 1 to 10. Tests were carried out with different levels of excitation (corresponding to different initial amplitudes of vibration) and with different numbers of stationary people present on the floor (from 1 to 5 stationary persons).

It was found that ratings of floor vibrations were almost independent of the initial amplitude of the decaying vibrations. Rather the rating was influenced by the number of stationary persons on the floor during the decaying vibrations, and generally the vibrations were felt more comfortable as the size of the crowd increased. It was seen that even the presence of a small crowd on the floor had a significant influence on the rating of floor vibration serviceability (it improved) primarily because it altered (decreased) the duration of the decaying oscillations.

The results demonstrate that in vibration serviceability checks of floors, it is not always useful just to adopt the thinking that a floor is a floor with dynamic characteristics determined by floor material characteristics (stiffness and damping features). The dynamic interaction between the mass of stationary humans and the mass of the floor can have a substantial influence on floor damping features, and as shown in the paper on the sensation of floor vibrations.

The effect that the number of stationary people present on the floor has an influence on assessments of floor serviceability is not implemented in guidelines for evaluating floor serviceability. However, a model is proposed that accounts for the interaction phenomenon known to exist between stationary crowds of people and the structure which they occupy.

Furthermore, the results indicate that stationary humans are excellent sensors of vibration as they are capable of sensing very small amplitudes of vibration and judging them as annoying. But at the same time, stationary humans can be poor sensors of vibration in the sense that they tend to overestimate amplitudes of the floor motion.

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