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Dynamic Model of a Structure Carrying Stationary Humans and Assessment of Its Response to Walking Excitation

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ABSTRACT

A flooring-system, e.g. a floor in a building, is excited dynamically when a person walks across the floor, and resonant excitation might bring structural vibrations to unacceptable levels. Stationary (non-moving) crowds of people might be present on the same floor and they will sense the floor vibrations, but they will also interact dynamically with the floor in a passive sense, thus altering the dynamic system excited to vibration by the walking person. Consequently, the vibration level of the floor is likely to depend on the presence and size of the stationary crowd. It is also known that different techniques (different parameters calculated from structural response time series) are proposed for assessing floor serviceability. The paper looks into the influence of the stationary crowd of people on the floor response to walking excitation and into the influence of the crowd on different parameters calculated from structural response time series for assessing the serviceability limit state. A numerical approach based on simulation of floor excitation is employed for the investigations, and the paper describes the study assumptions and the findings related to the influence of the presence a stationary crowd on the dynamic model of the flooring-system and on floor serviceability assessments.

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
f	Floor load	m_1	Empty floor modal mass	m_2	Crowd modal mass
p	Modal load	Φ	Mode shape function	a	Floor accelerations
α_n	Dynamic load factor	φ_n	Phase lag	f_m	Step frequency
L	Span length	v	Pacing speed	δ	Walkers position

1. INTRODUCTION

The locomotion of people on floors can result in unacceptable floor vibrations if integer multiples of the step frequency coincide with a floor resonant frequency. It is likely that the walking person will not sense the vibrations, but stationary people on the floor act as sensors of vibration and may perceive the vibrations as annoying. Accordingly, international and national standards, for example [1] and [2], specify procedures for analysing floor acceleration time histories for an evaluation of floor serviceability. According to the International Standards ([1] and [2]), a central parameter for calculation from the acceleration time history is the root mean square (*rms*) value, whereas according to the British Standards ([3] and [4]), a central parameter for calculation is the vibration dose value (*vdv*). The rating of floor serviceability is evaluated based on the calculated parameters, which are often derived from acceleration measurements made on the floor. The fact that different parameters are proposed in different standards seems to suggest that consensus have not yet been reached in the matter of which parameter correlates best to subjective evaluations of discomfort. Tradition and previous history regarding definition of threshold values on evaluation scales might also explain why different parameters are proposed in different standards. For the present paper, the previous history is not important. The interesting part is that there are different methods available for evaluating floor serviceability (the *rms* and the *vdv* approach). Hence, both of the approaches are considered in this paper when evaluating floor serviceability from acceleration time histories.

Another interesting item to recognize is that often an evaluation of floor serviceability is made in order to assess the state of comfort with the stationary persons on the floor in mind (and not with the person in locomotion in mind). The scenario for evaluation thus involves the presence of stationary humans atop the floor. The dynamic system excited to vibration by the walking person thus does not only include the floor, but the floor and a stationary crowd of people of some size. The crowd mass and the floor mass are known to interact [5] which means that the dynamic characteristics of the floor carrying a stationary crowd are different from those of the empty floor, and accordingly that the floor response to the action of a walking person depends on whether a stationary crowd of people is present on the floor. Recent research results presented in for instance [6] suggest procedures for modelling the interaction between the floor mass and the mass of the stationary crowd of people. This is interesting from the point of view that use of the interaction model allows predictions to be made of floor responses for the situation where stationary people are present on the floor (i.e. the situation actually to be considered for serviceability assessments).

Hence, it is the purpose of this paper to present results of numerical simulations illustrating how a stationary crowd of people influences the acceleration time series of a floor excited by a walking person. Additionally, to illustrate how various crowd sizes influences the parameters *rms* and *vdv* often used as input for floor serviceability evaluations. Particular focus is on how these parameters attenuate with increases in crowd mass and it is interesting to investigate whether the parameters *rms* and *vdv* attenuate at a similar rate.

For the numerical study a floor prone to vibrate to actions of humans in motion is selected. In situations when a crowd of stationary people is assumed to be present on the floor, the crowd is modelled as a SDOF (single-degree-of-freedom) system in accordance with findings in [6]. Section 2 describes the floor and the modelling of walking excitation. Section 3 describes the modelling of the assumed interaction between the floor and a stationary crowd of people. Section 4 describes how to compute the parameters *rms* and *vdv* from acceleration time histories, and section 5 presents and discusses the results of the simulation study.

2. THE FLOOR AND WALKING EXCITATION

2.1 The floor

The floor considered is pin-supported at both ends spanning 11 m between the supports. The dynamic characteristics of the first bending mode of the floor are listed in table 1.

Natural frequency, f_1	5.5 Hz
Damping ratio, ζ_1	0.5, 1.0, 2.0, and 3.0 %cr
Modal mass, m_1	5,700 kg

Table 1 Dynamic characteristics of the empty floor.

Four different values of the damping ratio, ζ_1, are considered so as to widen the basis for the evaluations. The lower damping value represents a floor that is quite lightly damped whereas the higher damping value represents a floor which is rather heavily damped.

2.2 Modelling of walking excitation

The excitation from a single person walking across the floor is considered and eq. (1) gives the load-time history assumed for the vertical excitation.

$$f(t) = G(1 + \sum_{n=1}^{N} \alpha_n \sin(2\pi f_m t + \varphi_n)) \tag{1}$$

G represents the static weight of the person crossing the floor at a constant step frequency, f_m. The factors α_n are dynamic load factors associated with walking excitation, and φ_n are the phase lags associated with the different harmonic components of the excitation.

For simplicity only the load harmonic that causes the floor to resonate will be considered. For the floor described in section 2.1, this would probably be the third load harmonic (i.e. n = 3) as the step frequency of human locomotion is normally in the proximity of 2 Hz [7]. Hence, for the empty foor, f_m is assumed to correspond to 5.5/3 = 1.833 Hz, and the dynamic load factor associated with the third load harmonic, α_3, is assumed to be equal to 0.10 in accordance with recommendations in [8].

The modal load *p(t)* associated with the first vertical bending mode of the floor is considered, and it is calculated by multiplying the excitation force *f(t)* with the mode shape function Φ:

$$p(t) = \Phi(\delta) f(t) \tag{2}$$

where

$$\Phi(\delta) = \sin(\frac{\delta\pi}{L}), \qquad \delta = vt \tag{3}$$

In eq. (3), δ represents the position of the walking person on the floor, which is defined in figure 1 along with some of the other fundamental parameters involved in modelling the excitation.

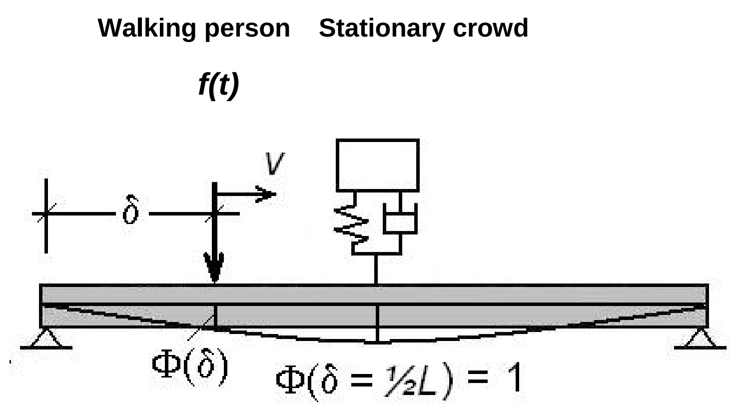

Figure 1 Fundamental parameters involved in modelling walking excitation. The SDOF system attached to the floor illustrates that a stationary crowd of people may be present on the floor.

The walking person is assumed to begin his locomotion at $\delta = 0$ and to move at a constant pace v until he reaches $\delta = L$ where he is assumed to stop. L is the distance between floor supports. For the numerical studies, a pacing speed of 1.5 m/s is assumed, which is reasonable when natural walking is considered [9]. A stationary crowd of people may be present on the floor illustrated by the SDOF model attached to the floor. The characteristics of the crowd-floor interaction and of the crowd model are described next.

3. THE CROWD-STRUCTURE INTERACTION MODEL AND THE STATIONARY CROWD

3.1 The crowd-structure interaction model

The interaction between the first bending mode of the floor and a stationary crowd is considered in situations when a stationary crowd is present on the floor and the 2DOF crowd-structure interaction model assumed is shown in figure 2.

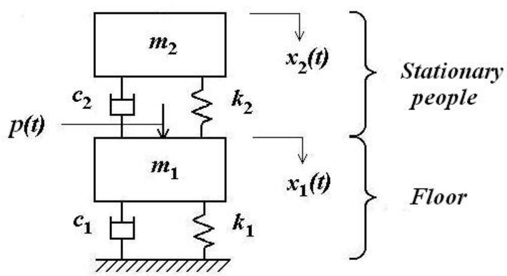

Figure 2 The interaction model assumed.

The grounded system represents the first bending mode of the floor to which a SDOF crowd model is attached. Both SDOF subsystems of the 2DOF assembly are assumed viscously damped and linear elastic.

The excitation *p(t)* applied to the floor mass is the modal load calculated using the procedures described in section 2.

For simplicity, the second time derivative of $x_1(t)$ is denoted *a(t)* and it represents the vertical floor acceleration at floor midspan to the action *p(t)*. *a(t)* is the floor response considered in floor serviceability assessments.

Time series of floor response can be calculated numerically if the dynamic system is fully described. This requires assumptions to be made with respect to the dynamic characteristics of the crowd.

3.2 The stationary crowd

For the SDOF model for the stationary crowd, the dynamic characteristics given in table 2 are assumed.

Natural frequency, f_2	5.9 Hz
Damping ratio, ζ_2	0.38
Modal mass, m_2	m_2

Table 2 Dynamic characteristics of the SDOF crowd model.

The crowd modal mass (m_2) is not defined by a specific value indicating that it is subject to variation in the numerical studies of this paper. The natural frequency and damping ratio tabulated above are those that were found to describe the interaction between a sitting crowd and a test floor quite well in the experimental investigations reported in [6]. These values might not be useful for any crowd and generally the appropriateness of the SDOF crowd model is still subject for investigation. However, for the purposes of the studies of this paper, it suffices to employ the SDOF crowd model defined in table 2.

3.3 Simulation of excitation and floor response

Time series of resonant floor accelerations *a(t)* to the action *p(t)* are obtained using a Newmark time integration scheme. Response time histories are obtained for different values of m_2 (i.e. for varying crowd sizes) and for four different values of the damping ratio of the empty floor, ζ_1. The presence of a crowd atop the floor causes a change in the resonant frequency of the system, and hence the step frequency of the walking person is modified from one scenario to the next so as to ensure simulation of resonant action. The calculated response time histories are subsequently used as a basis for identifying parameters for use in the assessment of floor serviceability.

4. METHODS EMPLOYED FOR EVALUATING THE SERVICEABILITY LIMIT STATE

As a basis for assessment of floor serviceability, the parameters *rms* and *vdv* are calculated from acceleration time histories The frequency-weighted acceleration time histories ($a_w(t)$) are to be used for the calculation. The frequency-weighting of acceleration signals is made in order to account for the fact that human perception of vibration varies with the frequency of the excitation. In the frequency region of 4-8 Hz, a frequency weighting gain of 1 applies according to [10], and since the floor resonant frequency attains a value in this range, $a_w(t)= a(t)$.

The *rms* (root-mean-square) value is calculated using the expression:

$$rms = \left[\frac{1}{T} \int_{t=0}^{t=T} a_w^2(t)dt \right]^{1/2} \tag{4}$$

where T is the measurement duration. For the studies, the measurement duration is chosen as the period during which the floor encounters vibration as a result of action of walking. More precisely T is set to be equal to the duration between t = 0 and the time T at which the amplitude of floor acceleration attenuates to values less than 1 % of the peak acceleration.

The *vdv* (vibration dose value) is calculated using the expression:

$$vdv = \left[\int_{t=0}^{t=T} a_w^4(t)dt \right]^{1/4} \tag{5}$$

It can be noted that different powers are used (2 and 4) in the two definitions. Furthermore, that “the measurement duration” T enters the expressions in two different ways.

5. RESULTS

5.1 Floor responses

Envelope curves (a_e) of the positive part of floor response time series are derived as they give an indication of the nature of the response. Figure 3 (right) compares envelope curves for empty floors having different damping ratios (ζ_1), and figure 3 (left) compares envelope curves derived on different assumptions with respect to the crowd modal mass (m_2) for a floor with a damping ratio of 0.5 %cr. All envelope curves are normalized by the peak acceleration (a_p) identified in the response of the empty floor having a damping ratio of 0.5 %cr.

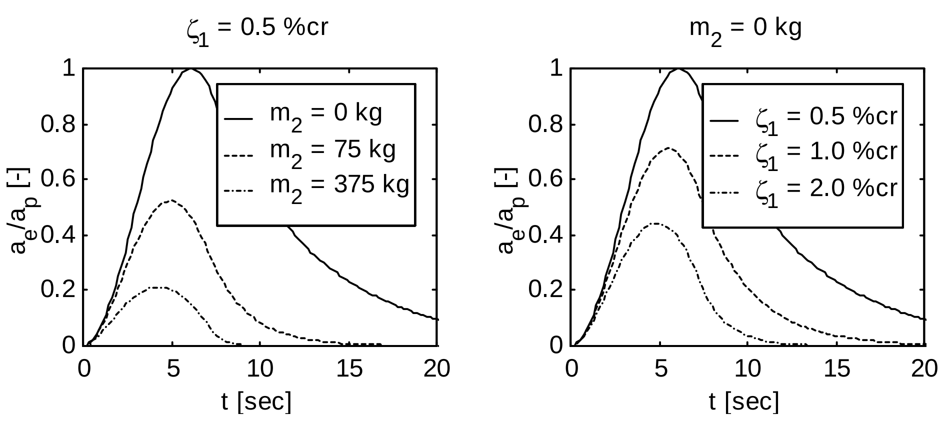

Figure 3 Envelope curves of positive floor response (normalized by a_p identified assuming ζ_1 = 0.5 %cr and m_2 = 0 kg). Influence from parameter ζ_1 (right) and m_2 (left).

As can be seen (figure 3, right), an increase in floor damping (ζ_1) has the effect that the peak value of the response reduces and that the response attenuates more rapidly after the peak response has been reached. It is instructive to note that the walking person terminates his motion (has crossed the floor) after approximately 7.3 seconds. After this point, no energy is conveyed to the floor, but vibrations persist at least for some time. The tail of the response is most significant for floors that are lightly damped.

It can also be noticed (figure 3, left) that the presence of a stationary crowd of people atop the floor influences floor vibrations set up by the walking person. A crowd modal mass (m_2) of 375 kg is suggested to reduce the peak value of the floor response by a factor of approximately 5. Considering that 375 kg corresponds to less than 10 % of the floor modal mass (m_1 = 5700 kg), the attenuation ensured by such crowd is quite significant and suggests that the crowd adds much damping to floor.

5.2 Variation of rms and vdv with crowd size

On the basis of floor response time series, the parameters *vdv* and *rms* defined in section 4 are calculated for different values of ζ_1 and m_2. For the empty floor situation (m_2 = 0 kg, i.e. no stationary crowd present), the parameters attain a value denoted Q(0), whereas they attain a value denoted Q(m_2) when a crowd with modal mass m_2 is present atop the floor. Thus, the ratio Q(m_2)/Q(0) is indicative of how a crowd with modal mass m_2 would be expected to influence the parameter Q(m_2) to be used for floor serviceability assessment. The plots in figure 4 show calculated variations of the ratio on different assumptions with respect to the empty floor damping, ζ_1. Q represents either the parameter *rms* or the parameter *vdv* as specified in figure legends.

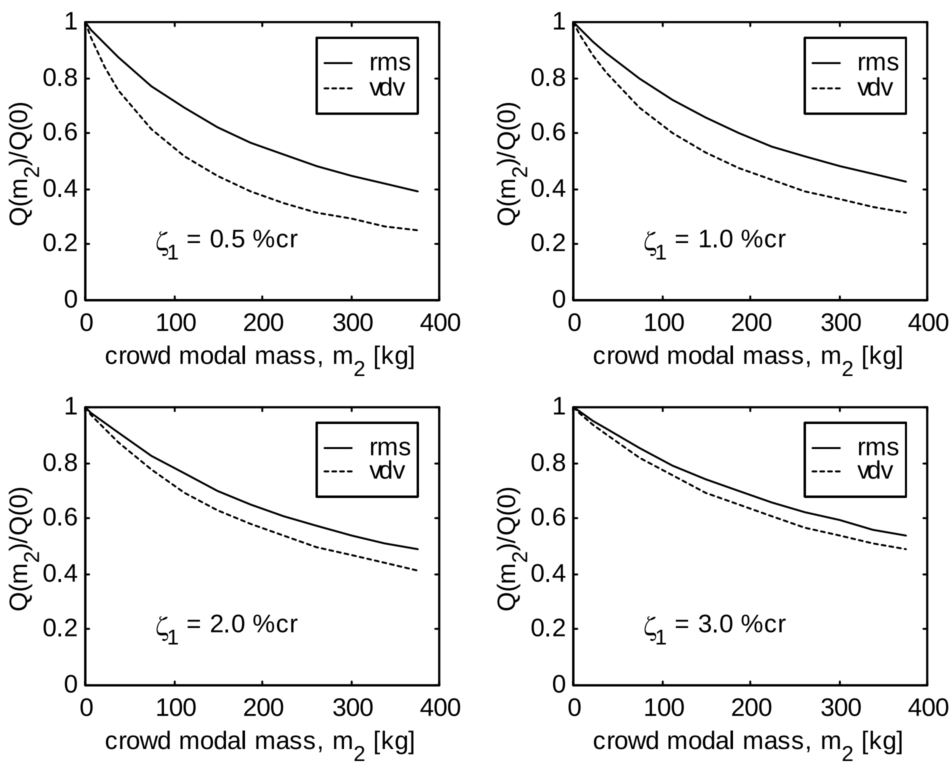

Figure 4 Variations of ratios for *rms* and *vdv* with m_2 on different assumptions with respect to empty floor damping, ζ_1.

Generally, it can be noticed that the presence of a crowd atop the floor would reduce values of the parameters to be used for serviceability assessment compared with the empty floor situation. It is a result of the damping that the stationary crowd adds to the floor. For the floor considered for this paper, the damping added by the crowd is rather significant. For instance, a crowd modal mass of 400 kg would be expected to reduce the *rms* and the *vdv* parameters by more than 50 %.

Another item to notice in figure 4 is that the parameters *rms* and *vdv* do not attenuate at a similar rate with increases in crowd size. For the lightly damped empty floor (ζ_1 = 0.5 %cr), the difference between the *rms* and *vdv* variations is most significant. With increases in the damping of the empty floor (ζ_1), the discrepancy between *rms* and *vdv* variations reduces. Generally, it would be reassuring if the parameters attenuated at a similar rate, as they both represent measures of floor serviceability and they are calculated to evaluate one and the same condition (a floor carrying a certain crowd of people). Nevertheless some discrepancy can be noted.

For the study, the most straightforward approach was adopted for defining the parameters *rms* and *vdv*. In the expressions defining the parameters (eqs. (4) and (5)), the time duration (record length) T appears, and T was set to be equal to the period during which the floor encounters vibration as a result of action of walking. It is considered a plausible approach at least for comparing how the parameters *rms* and *vdv* behave when a crowd of people assembles on the floor. As mentioned, the parameters do not behave equally when a crowd assembles, at least not for the lightly damped floors, which are the floors that are most prone to encounter excessive vibrations. Considering the nature of the vibrations, however, the definition of the value T can also explain the discrepancy between the attenuation rate of *rms* and *vdv* observed when a crowd assembles on the floor. The empty floors are relatively lightly damped and a quite long tail of vibrations appears with the result that the value of T is relatively large. This means that when calculating the normalization constant Q(0) for the parameter *rms*, a relatively low value is obtained as the factor ($1/T$) appears in the expression for the parameter *rms*. This is not the case for the parameter *vdv*. Hence, the ratio $Q(m_2)/Q(0)$ for the parameter *rms* attenuates at a higher rate than the ratio $Q(m_2)/Q(0)$ for the parameter *vdv.*

That the choice of the value of T affects the *rms* value is not a new observation, as it can be seen directly from the definition of the *rms* value. The new observation is how it affects the attenuation rate of the *rms* value when a crowd of stationary people assemble on the floor, and that the attenuation rate is not similar to that of the parameter *vdv*. Arriving at this observation was made possible by being able to model the interaction between a floor and a crowd of people.

To some extent, the observations of the paper question the reasonability of using the *rms* value as a measure of floor serviceability as different attenuation rates will be obtained by choosing other definitions of T. But there are other aspects of floor serviceability that might be questioned in light of the crowd-floor interaction model. Should floor serviceability be evaluated based on vibration levels of the floor mass, or would is be more reasonable to base evaluations on vibration levels of the human body?

6. CONCLUSIONS

The paper has investigated how a stationary crowd of people influences vibrations of a floor excited by a person walking across the floor putting the floor into resonant vibration. For the investigations a crowd-floor interaction model was assumed, and similarly a case floor was selected.

Results of a numerical study showed that the stationary crowd of people markedly influences the floor vibrations (floor acceleration response). The acceleration response is often used as basis for evaluating floor serviceability and often by computing either the root mean square (*rms*) value or the vibration dose value (*vdv*). It was found that these values attenuate when a stationary crowd of people assembles on the floor, and thus that the crowd acts as a passive damping mechanism on the floor.

It was also observed that the parameters *rms* and *vdv* do not attenuate at a similar rate with increases in the crowd size. This might indicate that the implications of the presence of the stationary crowd are evaluated differently by the *rms* and the *vdv* approach. Discrepancies between the variations of the parameters *rms* and *vdv* with crowd size were seen to depend on the damping ratio of the empty floor. For lightly damped floors, the discrepancy is most pronounced, and it reduces as the damping of the empty floor increases. Another factor that influences the attenuation rate of the *rms* value is the choice made with respect to record length to be used for calculating the *rms* value.

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