ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

EFFECTIVENESS OF STATIONARY HUMANS AND TUNED MASS DAMPERS IN CONTROLLING FLOOR VIBRATIONS

Lars Pedersen

Department of Civil Engineering, Aalborg University
Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark
lpe@bt.aau.dk(e-mail address of lead author)

Abstract

Floor vibrations can be annoying to stationary humans (sitting or standing) on a floor, and therefore codes and standards specify threshold values for floor acceleration levels. For very responsive floors if can be necessary to fit the floor with a passive damping source (such as a tuned mass damper) so as to ensure compliance with requirements related to human tolerance to vertical vibrations. However, the paper demonstrates that stationary humans themselves can provide a significant passive damping source due to dynamic interaction between the masses of the stationary humans and the vibrating floor. The paper presents results of controlled tests made with a vibrating test floor carrying stationary crowds of people and how these results are employed in the context of formulating a model for the passive damping mechanism generated by stationary humans.

The paper illustrates the implications of the passive damping mechanism by predicting the damping added to a set of floor systems where floor vibration is frequently of concern: on a grandstand, an office floor and a footbridge. Floor vibration levels with and without a stationary crowd atop these structures are calculated assuming a dynamic excitation generated by humans in motion. The vibration levels are compared with those expected if the else wise empty structures were fitted with a tuned mass damper so as to illustrate the effectiveness of the crowd in mitigating floor vibrations. Since a stationary crowd of people changes the dynamic characteristics of the floor which they occupy, the effectiveness of a potential tuned mass damper installation would also be influenced by the crowd's presence, and the paper quantifies the changes in damper effectiveness introduced in this way. From the results presented in the paper is would seem obvious that it can be relevant to model the passive damping mechanism brought about by stationary humans.

INTRODUCTION

Some flooring systems are built so flexible that dynamic floor performance is a matter of concern. Footbridges and grandstands in sports arenas serve as examples of flooring systems where resonant excitation brought about by humans in motion (walking or jumping) may cause structural vibrations annoying to the residual crowd of people, which may be people sitting or standing on the flooring system. A large open-space office environment without partitions is also a type of system which may experience excessive vibrations due to the actions of humans in motion. Codes and standards, e.g. [9], specify threshold values for acceleration levels of flooring systems and assisted by guidance on the damping of flooring systems, floor acceleration levels can be assessed. However, guidance on damping does not consider that a stationary crowd of people (e.g. sitting or standing) atop the floor will add damping to the floor, but this will be the case as identified in [2] and [5].

Understanding this mechanism (the damping added to floors by humans) is essential for realistic prediction of floor acceleration levels, and therefore this paper presents results of laboratory tests designed to provide data useful for understanding the mechanism and for evaluating the applicability of models aiming at describing the phenomenon. In biodynamics, the human whole-body is modelled as a series of lumped masses interconnected by springs and dashpots, [7], and inspired by this modelling approach it is examined whether modelling a stationary crowd of people as a linear elastic and viscously damped single-degree-of-freedom (herein after SDOF) system attached to the floor can explain the damping measured in the laboratory tests.

For flooring systems prone to excessive vibration, the fitting of a tuned mass damper (herein after TMD) to the floor might be considered (as done in e.g. [1], [4] and [8]). If, however, the floor carries stationary humans, the TMD is fitted to a combined human-floor system with dynamic characteristics different from those of the empty floor. It is therefore considered interesting to examine how this influences the effectiveness of the TMD, and a numerical investigation studying effectiveness of TMDs on human-occupied floors is therefore carried out.

First results of the experimental investigations of the passive damping mechanism brought about by stationary humans are presented. A model for the mechanism is derived and employed for a numerical study of dynamic response of three different flooring systems (a footbridge, an office floor and a grandstand) occupied by stationary crowds of people. The numerical study is followed by an investigation of the effectiveness of a TMD installed on floors occupied by stationary humans. Finally, the paper sums up on the findings in the concluding section.

EXPERIMENTAL STUDY OF PASSIVE DAMPING MECHANISM

This section describes results of controlled tests made on a test floor to examine the changes in its dynamic characteristics occurring when sitting crowds of people assemble on the floor. The test floor, a prestressed hollow-core concrete element, is pin supported at both ends, and the empty floor frequency of the first vertical bending mode is 5.85 Hz. The empty floor damping of this mode is 0.25 %cr, and this mode will dominate the vibrations in tests also when a crowd assembles at floor midspan. The empty floor is thus considered a SDOF system and a central purpose of the tests is to explore the variation of floor frequency (f_F) and floor damping (ζ_F) with crowd mass (m_2). The crowd mass is gradually increased by adding more people, and f_F and ζ_F are derived for the different values of m_2 using modal identification techniques.

Along with experimental estimates of the set (f_F, ζ_F), corresponding analytical estimates were also established assuming the two models for the combined human-floor system shown in figure 1. The model A assumes that the human crowd can be represented by a dynamic system; overall in line with the modelling approach used in biodynamics. The model B assumes a crowd mass rigidly attached to the floor mass, corresponding to the assumption often used for static calculus in civil engineering.

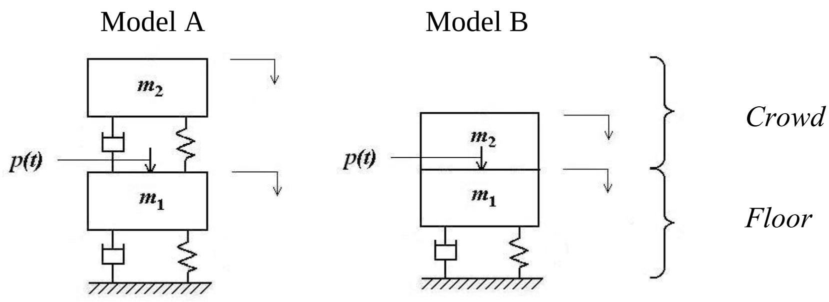

Figure 1 - The two models considered for analytic estimates of floor frequency and floor damping for a human-occupied floor.

For the model B, what is needed for estimating the set (f_F, ζ_F) is knowledge about the crowd mass (m_2) and about the empty floor dynamic characteristics (m_1, f_1, ζ_1), where m_1 represents empty floor modal mass, f_1 the empty floor frequency, and ζ_1 empty floor damping. Hence, these parameters were measured as part of the test programme.

In model A, the floor and crowd mass is assumed to interact dynamically due to the spring and dashpot interconnecting the two masses. In order to establish an estimate of floor frequency and damping (f_F, ζ_F) on the basis of model A, knowledge is required also about the frequency of the crowd (f_2) and the damping of the crowd (ζ_2), as else the system would not be fully described. However, these two parameters are not known, but by trail and error (guessing (f_2, ζ_2)-combinations) it is investigated whether the predictions of the set (f_F, ζ_F) established by model A can fit the recorded variations of f_F and ζ_F with crowd mass m_2.

Figure 2 presents experimentally obtained variations of f_F and ζ_F with crowd mass m_2, and the variations are compared with those derived analytically assuming the models A and B, respectively. For model A, the variations represent those that are calculated assuming a crowd frequency (f_2) of 6.5 Hz, and a crowd damping (ζ_2) of 38 %cr. These values are indicated using the symbol o at m_2 = 0.

As can be seen, the model B (that assumes a rigid attachment of the crowd to the floor) appears to be inappropriate for predicting floor frequency and damping when the floor carries a stationary crowd of people. The model B frequency estimate is seen to systematically differ from the experimental estimate, but perhaps most importantly, the floor damping is highly underestimated by model B.

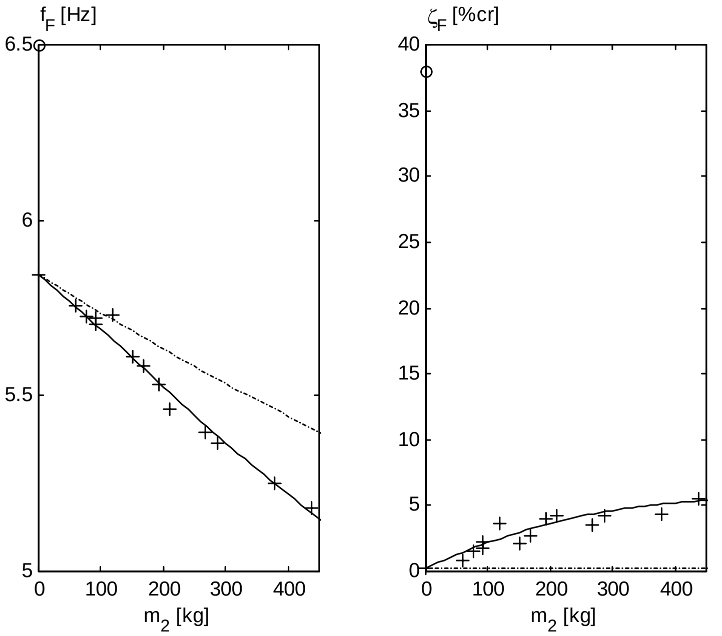

Figure 2 - Floor frequency (f_F) and floor damping (ζ_F) as functions of crowd mass (m_2). Experimental results (+) and variations derived using model A (solid lines) and using model B (dashed lines).

As can be seen, the floor damping measured in tests steadily increases with increases in crowd mass, and for a crowd mass of some 400 kg, the floor damping reaches a level of about 20 times the empty floor damping. The model A (that assumes a SDOF model for the crowd) is seen to capture the measured variations of floor frequency as well as floor damping quite well.

Hence, model A appears to be quite appropriate in describing the passive damping mechanism that is present when a sitting crowd of people occupies a floor.

Naturally, it would be important to carry out additional tests to further examine the accuracy of this modelling approach, and to validate that the values identified for the crowd frequency and damping (f_2 = 6.5 Hz, ζ_2 = 0.38) are generally representative for a crowd. In that context, it should be noted that it cannot be ruled out that the crowd frequency and damping might be different from one crowd to the next (and be different from the crowd used in the tests described in more detail in [11]). Human posture might also be of importance, and tests reported in [12] suggest slightly different values for the frequency and damping of a standing crowd.

These notes aside, it seems that the approach of modelling a crowd as a SDOF attachment system to a floor is useful in getting a general idea of floor frequency and levels of floor damping for a floor occupied by a stationary crowd of people. Hence, this crowd model is used in the next section to study the dynamic behaviour and performance of three flooring systems for which dynamic behaviour is often a matter of concern: a footbridge, an office floor and a grandstand.

PREDICTION OF RESPONSE OF HUMAN-OCCUPIED FLOORS

This section studies the dynamic behaviour of three different floors assuming the crowd model derived from the experimental investigations described above.

The floors studied

The dynamic characteristics of the flooring systems employed for the numerical study are given in table 1.

Table 1 – Empty floor dynamic characteristics of the three floors considered.

Dynamic characteristic	Office floor	Footbridge	Grandstand
Natural frequency f_1 [Hz]	8.5	4.4	7.0
Damping ratio ζ_1 [%cr]	1.60	1.25	1.0
Modal mass m_1 [kg]	6,800	18,000	30,000

The dynamic characteristics of the footbridge represent those for the fundamental mode of the pin supported footbridge described in [3], and for the office floor, the dynamic characteristics represent those of the floor described in [6].

It should be noted that the dynamic characteristics tabulated above cannot be claimed to be representative for footbridges, office floors, and grandstands in general due to a large variability in designs of such systems. Also, and as opposed to the floors above, more than a SDOF might be required to obtain a reasonable representation of the empty floor, but it is useful to consider the floors introduced above to illustrate the influence of a stationary crowd on floor dynamic behaviour.

Floor response to dynamic excitation

This section presents results of calculations of floor response to the action of humans in motion. The vertical load exerted on a floor by a single jumping person moving at a frequency of f_l is considered. Such excitation, *p(t)*, involves a number of harmonic load components exerting the floor at the frequencies nf_l, where n = 1, 2, 3,… , since jumping loads are often modelled by a Fourier series expansion. Eq. (1), representing a load approximation introduced in [10], defines the amplitudes, P_n, assumed for the various harmonics of the expansion in which the first 5 harmonics are considered.

$$P_n = \begin{cases} 2G & \text{if } nf_l < 3\text{ Hz} \\ (-0.19nf_l + 2.57)G & \text{if } 3\text{ Hz} \le nf_l < 13\text{ Hz} \\ 0.1G & \text{if } nf_l \ge 13\text{ Hz.} \end{cases} \tag{1}$$

G represents the static weight of the jumper, and jumping frequencies, f_l, in the 2-3 Hz range are assumed, thereby considering any possible action of natural jumping. It is not immediately possible in advance to foresee which jumping frequency within this range causes the most severe resonant excitation and floor response. The floor response considered is the rms acceleration response as this parameter is often used for evaluating floor serviceability and human tolerance to vibrations. To facilitate identification of the most severe (maximum) rms acceleration response, floor response is calculated for jumping frequencies of 2, 2.01, 2.02, … , 3 Hz. The maximum rms response is identified for the empty floor, i.e. the floor without stationary humans atop, (and is denoted a_{emp}) as well as for the floor occupied by a stationary crowd modal mass of m_2 (and is denoted $a_{occ}(m_2)$). By these parameters the ratio:

$$\varepsilon_H(m_2) = \frac{a_{occ}(m_2)}{a_{emp}} \tag{2}$$

is calculated and ε_H indicates how effective a stationary crowd (of modal mass m_2) is in mitigating floor rms acceleration response. The lower the value of ε_H, the more effective the crowd is in attenuating floor vibrations. Figure 3 presents $\varepsilon_H(m_2)$ calculated for the three different floors.

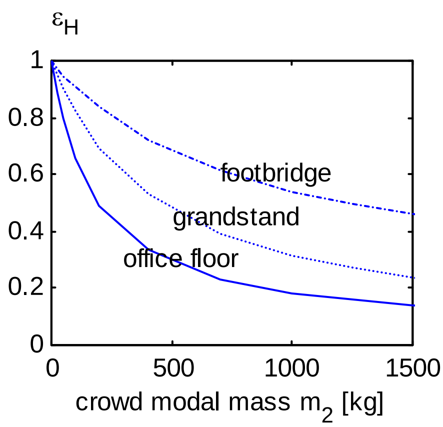

Figure 3 - Effectiveness of stationary crowds of people in mitigating floor vibrations.

As can be seen, the presence of a crowd atop the floor causes floor vibration levels to reduce, and it can further be seen that the attenuating effect of the crowd is different on the three floors. For instance on the office floor, the floor vibrations reduce rather significantly as a crowd starts assembling atop the floor. For the sake of comparison, it can be noted that on this 49 m^2 floor, a crowd modal mass of about 750 kg would attenuate floor vibrations as effectively as the TMD designed in the next section.

On the other floors it would require a larger crowd to attenuate floor vibrations to a corresponding level, but recalling that the empty floor modal masses amount to 6,800 kg (office floor), 18,000 kg (footbridge) and 30,000 kg (grandstand), respectively, it is seen that a stationary crowd markedly affect floor vibration levels even for relatively small crowd-to-floor mass ratios.

TMD EFFECTIVENESS ON HUMAN-OCCUPIED FLOORS

With a TMD fitted to a floor occupied by a stationary crowd of people, the dynamic system excited to vibration would be a 3DOF system, if assuming a SDOF floor and a SDOF crowd model. The 3DOF model is shown in figure 4, and the TMD is assumed fitted to the point on the floor experiencing the most severe response.

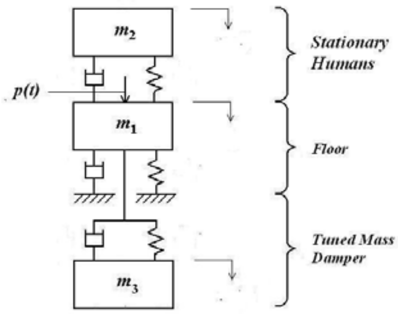

Figure 4 - Dynamic model

For a study of the effectiveness of the TMD in attenuating floor vibrations on floors occupied by stationary crowds of people, TMD dynamic characteristics corresponding to:

$$f_3 = \frac{f_1}{1+\mu}\ ;\ \zeta_3 = \sqrt{\frac{3\mu}{8(1+\mu)}}\ ;\ \mu = \frac{m_3}{m_1} = 0.03 \qquad (3)$$

are assumed. For the study, the ratio ε_{tmd}:

$$\varepsilon_{tmd}(m_2) = \frac{a_{occ,tmd}(m_2)}{a_{occ}(m_2)} \qquad (4)$$

is introduced as a measure of TMD effectiveness.

In eq. (4), the parameter $a_{occ,tmd}(m_2)$ represents the maximum floor rms acceleration response calculated for the human-occupied floor with a TMD whereas $a_{occ}(m_2)$ represents the maximum floor rms acceleration response calculated for the human-occupied floor without a TMD. As can be inferred, the lower the value of ε_{tmd}, the more effective the TMD is in attenuating floor vibrations. For the study, the floor excitation is modelled as described in the previous section. The variations of ε_{tmd} with modal mass of the stationary crowd, m_2, were calculated for the three floors and results are presented in figure 5.

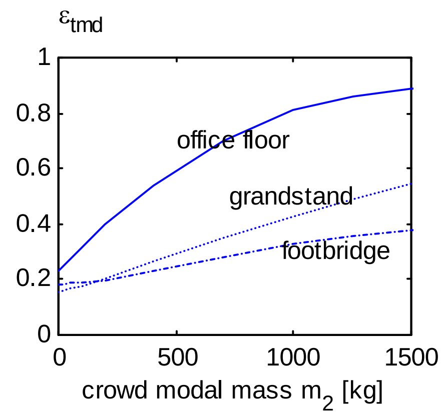

Figure 5 - TMD effectiveness as function of crowd modal mass, m_2.

The effectiveness of the TMD for the empty floors corresponds to the values of ε_{tmd} at $m_2 = 0$. A reduction of floor vibration levels of about a factor 5 would thus be expected for the three floors as a result of fitting a TMD. However, it can be seen in figure 5 that if a stationary crowd assembles atop any of the three floors, the effectiveness of the TMD would decline. It can be recognized that $\varepsilon_{tmd} = 1$ corresponds to a TMD that is ineffective in attenuating floor vibrations, and as can be seen, this condition would almost be reached on the office floor for a crowd mass of 1500 kg.

Clearly, assuming the identified passive damping mechanism of stationary humans, the TMD effectiveness is influenced by the size of the stationary crowd (even for crowd sizes corresponding to likely floor operational conditions), and the influence would vary from one floor to the next.

SUMMARY

The paper has illustrated that it might be sensible to model a stationary crowd of people as a SDOF attachment system to a floor in vertical vibration. Based on dynamic characteristics of the SDOF crowd model derived from experimental investigations, numerical studies were carried out exploring the dynamic response of three different floors carrying stationary crowds of people (a footbridge, an office floor, and a grandstand) to an excitation from a jumping person.

It was seen that a stationary crowd influences the response of the three floors differently, as different amounts of damping is added to the three floors by the crowd. Generally, even rather small crowd sizes showed capable of significantly attenuating floor vibrations, and in some cases to levels at which the attenuating effect is comparable to that of a tuned mass damper. The effectiveness of tuned mass dampers on floors carrying stationary crowds of people were investigated numerically, and results suggest that the effectiveness of the dampers in attenuating floor vibrations can significantly reduce as a result of the presence of a stationary crowd.

Generally, the results and studies presented in this paper suggest that it can be of importance to account for the passive damping mechanism brought about by stationary humans when estimating floor vibrations levels and TMD performance.

REFERENCES

[1] Bastita R.C., C. Magluta, "Spectator-induced Vibration of Maracana Football Stadium", Structural Dynamics, EURODYN' 93, 985-992 (1993)

[2] Brownjohn J.M.W., "Energy dissipation from vibrating floors due to human-structure interaction", Shock and Vibration, **8** (6), 315-323, (2001)

[3] Brownjohn J.M.W., C.J. Middletown, "Economical Dynamic Assessment of a Footbridge using AVT and FEM Updating", Proc. of IMAC XXIV, paper no. 21, (2006)

[4] Dallard P., A.J. Fitzpatrick, A. Flint, S. Le Bourva, A. Low, R. M. Ridsdill, M. Willford, "The London Millennium Bridge", The Structural Engineer, **79** (2), 17-33, (2001)

[5] Ellis B.R., T. Ji, "Human-Structure Interaction in Vertical Vibrations", Proc. of the ICE: Structures and Buildings, **122** (1), 1-9, (1997)

[6] Ellis B.R., T. Ji, "Loads generated by jumping crowds: experimental assessment", Information Paper IP4/02, Building Research Establishment, Watford, UK (2002)

[7] Griffin M.J., *Handbook of human vibrations*, (Academic Press, London, 1990)

[8] Hatanaka A., M. Nanjo, T. Yokatani, A. Hirose, "Vibration Control of a Footbridge using a Tuned Mass Damper", Proc. of Sec. World Congr. on Struct. Control", **2**, 981-990, (1999)

[9] ISO, International Standards ISO 10137, "Basis for the design of structures – serviceability of buildings against vibration", International Standards Organization, 41-43, (1992)

[10] Pedersen L., "Human damping and its capacity to control floor vibrations", in Smart Structures and Materials 2004: Damping and Isolation, Proc. of SPIE, **5386**, 141-152, (2004)

[11] Pedersen L., "Damping added to floors by seated crowds of people", in Smart Structures and Materials 2006: Damping and Isolation, Proc. of SPIE, **6169**, (2006)

[12] Pedersen L., "Updating of The Dynamic Model of Floors carrying Stationary Humans", Proc. of the 1st IOMAC, 421-428, (2005)