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Chapter 25
Flooring-Systems and Their Interaction with Usage of the Floor

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Abstract Some flooring-system designs might be sensitive to their vibrational performance, as there might be the risk that serviceability-limit-state problems may be encountered. For evaluating the vibrational performance of the flooring-system at the design stage, decisions need to be made by the engineer in charge of computations. On a flooring-system often passive humans and/or furniture are present. Often these masses and their way of interacting with the floor mass are ignored in predictions of vibrational behavior of the flooring-system. The paper explores and quantifies how these masses can influence central parameters describing the dynamic behavior of the flooring-system.

Keywords Modal properties of floors • Floor dynamics • Numerical prediction • Serviceability-limit-state • Estimation accuracy

Nomenclature

$f_{(k)}$	Natural frequency
$M_{(k)}$	Modal mass
E	Young's modulus
$\mathbf{M}$	Mass matrix
$\zeta_{(k)}$	Damping ratio
k	Mode number
ν	Poisson's ratio
$\mathbf{K}$	Stiffness matrix
$\omega_{(k)}$	Circular natural frequency
n	Scenario
$\mathbf{\Phi}^{(k)}$	Mode shape vector
$\mathbf{C}$	Damping matrix

25.1 Introduction

When designing flooring systems in buildings, the main focus often is on assuring that ultimate-limit state requirements are satisfied. For flooring systems this often relates to ensuring that a specified static load is acceptable. However there can be other issues apart from the static problem that can be problematic. This paper addresses vibration issues.

For a floor, vibration problems can occur as a result of internal or external action. Internal actions may originate from humans in motion on the floor (persons walking), or from machinery placed on the floor area. This issue is addressed in [1]. External actions that can cause floor vibrations could be those arising as a result of nearby activities. This could be pile driving, trains running in a nearby metro system [2], road traffic [3] or similarly where structural and/or ground born vibrations end up bringing a floor of a building into vibration.

In any case, the problem can be that humans on the floor can perceive vibration levels as annoying or sensitive equipment on the floor can be exposed to excessive vibrations.

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The simplest possible basis for a vibration serviceability check by calculation would be to assume that the floor model is constant in time and is represented by the empty floor dynamic characteristics. This approach would rely on the assumption that the floor occupancy (which could be furniture or passive humans) does not influence the floor dynamic characteristics or at least that the influence of floor occupancy masses is neglected for the evaluation. However, it is a known fact that adding humans or non-structural mass will influence modal properties of a floor [4, 5].

The problem matter is that at the design stage often usage of the floor area is only known by the size of the specified life load. The distribution of the masses later to occupy the floor during its service life is generally unknown.

This paper examines different distributions of masses on a floor and how this would influence modal properties of the floor. More specifically, the paper examines the changes occurring in modal properties of a floor when gradually increasing the density of mass added to the floor. Additionally, the paper examines the influence on modal properties occurring when the center of added mass is elevated above the floor midplane. Bookshelves and desks serves as examples of items where the center of mass it elevated above floor midplane. It is assumed that these masses are rigidly attached to the floor. (Some might choose to consider a human mass as a mass rigidly attached to the floor for calculations of floor dynamic behavior. However this might not be appropriate as the human body is not a rigid system [6]).

The influences listed above are examined by numerical calculations and it is chosen to monitor changes in natural frequencies and damping ratios of the first nine modes of floor vibration.

For the investigations, a case study floor is selected. The floor is described in Sect. 25.2 which also describes the finite-element (FE) model of the floor. It is a simple floor in terms of geometry and support conditions in order to keep focus on effects of floor occupancy influences. Scenarios considered for usage of the floor is also outlined in Sect. 25.2 along with methods employed for extracting modal parameters of the floor. Section 25.3 presents and discusses the results. Finally, Sect. 25.4 gives the conclusions of the study.

25.2 Methodology

25.2.1 Computational Model of the Floor

The case study concerns a floor with the characteristics described below.

The floor area is assumed rectangular with side lengths of 8 and 9 m. It is assumed that the floor is pinned along all four sides. The floor is made of reinforced concrete with the material characteristics $E = 30$ GPa (Young's modulus), and $v = 0.15$ (Poisson's ratio). Based on a brief review of literature these values are considered to be fairly realistic for reinforced concrete, simplifying the composite material consisting of concrete and rebar into a homogeneous, isotropic and linear elastic material. The thickness of the floor is 180 mm and the mass density is 2400 kg/m^3. It has been checked that, with these assumptions, it is possible to meet static ultimate-limit-state requirements as well as static serviceability-limit-state requirements, assuming usage as an office floor area.

A FE model of the floor has been constructed using shell elements [7] with five degrees of freedom (d.o.f.) per node, i.e. three displacements and two rotations associated with bending. The element has nine nodes leading to second-order Lagrange interpolation of the displacements and rotations. A small artificial stiffness has been implemented to control the drilling degree of freedom, and selective integration of the stresses has been employed to avoid shear locking.

A 12-by-12-element grid has been employed to model the entire floor. Although not shown here, it has been confirmed by calculation that the model of the empty floor has converged, i.e. decreasing the mesh size will not cause significant improvements in the estimates of frequency and damping characteristics of the empty floor for modes up to 70 Hz. A plate model has also been tested for the empty floor and it gave, as expected, minor differences in floor frequencies compared to those extracted using the shell model. Finally, the MATLAB code has been verified by comparison with an ABAQUS [8] model based on Mindlin-Reissner shell elements with eight nodes and reduced integration. However, a shell model is used for the present study, as the attached masses will be elevated above the horizontal mid plane of the floor, thus influencing the inplane displacement d.o.f.'s of the shell.

The first mode of the floor is found to have a frequency slightly above 8 Hz. Empty floor frequency and damping values for all modes considered in this paper are listed in a later section.

In terms of damping characteristics, a Rayleigh damping model is assumed:

$$\mathbf{C}_f = a\mathbf{M}_f + b\mathbf{K}_f \tag{25.1}$$

$\mathbf{M}_f$ is the mass matrix and $\mathbf{K}_f$ is the stiffness matrix of the empty floor. The damping matrix $\mathbf{C}_f$ of the empty floor depends on the parameters a and b, and these parameters are tuned such that the minimum damping occurs at the frequency associated with the first mode of the empty floor. A minimum damping equivalent to a logarithmic decrement of 0.1 is assumed. This is considered representative for a reinforced concrete floor and entails that the damping ratio of the empty floor, ζ, assumes a value of approximately 0.016.

In the computational model, allowance is made for attaching floor occupancy mass at nodal points of the FE grid.

25.2.2 *Usage of the Floor*

Usage of the floor area will involve adding masses to the floor. For the studies of this paper, added masses are assumed rigidly attached to the floor and modelled as lumped masses, although this is likely to be a simplification of real-life floor occupancy conditions. Attaching each lumped mass to a single node of the model of the floor is also a simplification of matters. However, the approach is considered reasonable for the purposes of the study.

The scenarios considered for the floor occupancy are outlined in Fig. 25.1. They are denoted by the integer n taking on values of 1, 4, 9 or 16. The figure represents the number of masses placed on the floor in the particular scenario. Each individual mass is of 75 kg. The scenario $n = 0$ represent the empty floor. Lines are added on the floor area in Fig. 25.1 to provide an understanding of the exact positioning of the masses assumed for calculations. The strategy used for placing masses has been to gradually divide the floor into increasing numbers of squares (1, 4, 9, 16) and to place a mass of 75 kg in the center of each square.

As can be seen, the scenarios are arranged such that the floor occupancy mass gradually increases (when moving from scenario $n = 1$ up to $n = 16$).

Initially, the occupancy masses are assumed connected to the floor at the midplane of the floor (in the FE model of the floor at $z = 0$ m defining the horizontal plane of the floor model). For this scenario, the masses are fixed to (only influencing) translational degrees of freedom at nodal points of the FE model of the empty floor.

In order to consider scenarios in which an added mass is elevated above the floor, study scenarios are arranged assuming values of z above zero, were the value of z defines the vertical distance between the horizontal midplane of the floor and the position of the added masses. In the FE model of the floor, the influence of the added mass is modelled such that its contribution to floor dynamics mimics that of an elevated lumped mass attached to a node in the floor model by an interconnecting massless element with infinite axial and bending stiffness. This corresponds, approximately, to the influence of desks, bookshelves or similar furniture where the center of mass is placed at a finite height above the floor.

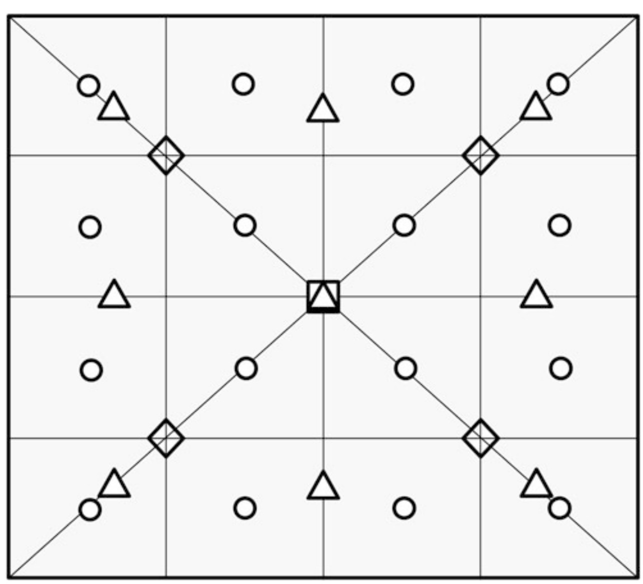

Fig. 25.1 Layout plan for floor occupancy scenarios. $n = 1$ (*open square*), $n = 4$ (*open diamond*), $n = 9$ (*open triangle*), $n = 16$ (*open circle*)

Values of z of 0, 1, and 2 m are considered in the paper in order to cover a wide range of values of z. Although values of z above 2 m are possible they are not considered in the paper. It is emphasized that in the scenarios considered it is assumed that all masses on the floor are elevated to the same height above the midplane of the floor and that the mases are equal in size (75 kg). This will for some floor applications be a simplification of matters. However, it is a useful assumption for providing an overview of the dynamic mechanisms occurring when added masses vibrate together with the floor mass.

25.2.3 *Extraction of Modal Properties*

For each floor occupancy scenario, natural frequencies $f_{(k)}$ (for mode number k) are extracted from the FE model by solving the undamped eigenvalue problem. The problem is solved taking offset in the stiffness matrix, **K**, and the mass matrix, **M**, of the combined system that includes the masses attached to the floor.

Damping ratios, $\zeta_{(k)}$, of the flooring system are extracted as

$$\zeta_{(k)} = \frac{\mathbf{\Phi}^{(k)T}\mathbf{C}\mathbf{\Phi}^{(k)}}{2\omega_{(k)}M_{(k)}}, \quad \omega_{(k)} = 2\pi f_{(k)} \tag{25.2}$$

where $\mathbf{\Phi}^{(k)}$ is the mode shape and $M_{(k)}$ is the modal mass for mode number k, and where **C** is the mass matrix.

An eigenvalue solver built into MATLAB was employed for computing natural frequencies, and a sparse approach was used in order to reduce computation time.

25.3 Results

This section presents results for floor frequencies (Sect. 25.3.1) and floor damping (Sect. 25.3.2).

25.3.1 *Floor Frequencies*

For this parameter, the presentation of results is divided into a discussion of results obtained for scenarios in which added masses are attached at floor midplane ($z = 0$ m) not assumed elevated above floor midplane and a discussion of results for scenarios in which elevated positions of added masses are assumed ($z > 0$ m). This is followed by a comparison of results.

25.3.1.1 Masses Attached at Floor Midplane

Results of calculations of floor frequencies are shown in Table 25.1. It displays calculation results obtained assuming the occupancy masses attached at $z = 0$ for the first nine modes of vibration. In the table empty floor frequencies (scenario $n = 0$) are represented by their values in Hz. When masses are attached, scenarios $n = 1$, 4, 9 and 16, the frequencies are normalized by the natural frequency computed for the empty floor, in this particular mode.

Table 25.1 Floor frequencies $f_{(k)}$ in Hz for the empty floor ($n = 0$) and normalized frequencies for other scenarios ($n > 0$)

	Mode number (k)								
n	1	2	3	4	5	6	7	8	9
0	8.149	18.909	21.761	32.464	36.773	44.331	50.239	54.946	61.678
1	0.995	1.000	1.000	1.000	0.995	0.995	1.000	1.000	1.000
4	0.995	0.990	0.990	0.981	0.995	0.995	0.991	0.991	1.000
9	0.989	0.989	0.989	0.989	0.979	0.979	0.979	0.978	0.989
16	0.981	0.981	0.981	0.981	0.981	0.981	0.981	0.981	0.963

Floor occupancy masses are attached at $z = 0$ m

First item to mention is that a wide range of modes of vibration are monitored in this study (the first 9 modes of vibration of the floor are included in the table). The quite broad interest in modes of vibration set out above is motivated by the fact that for a floor, the types of excitation may range from low frequency excitation (for instance those caused by pedestrians) to types of excitation were much higher modes of floor vibration might be excited. For instance [2] considered building vibration response to underground train traffic at frequencies up to 110 Hz and evaluated re-radiated noise in the frequency range up to 250 Hz. In a similar manner, [9] assessed the vibroacoustic response of a building to surface rail traffic in the frequency range up to 150 Hz. In the present work modes with frequencies up to 62 Hz are considered.

Looking at Table 25.1, the overall conclusion is that floor frequencies will change when mass is added to the floor. Generally, a decline in frequency is observed when adding occupancy mass (as for scenarios $n > 0$ normalized frequencies attain values less than unity). There are exceptions to this tendency in that some normalized frequencies in the table have values of 1.0, indicating that no change occurs relatively to the unoccupied floor. An inspection of the mode shapes derived by the FE model (not shown in the paper) reveals that the additional masses in these cases are placed at nodes of the associated modes, i.e. at neutral lines of vertical floor vibration. This, combined with the fact that the masses are lumped and placed at floor midplane, i.e. at $z = 0$ m, entails that the masses do not contribute with any inertia in calculations of the floor dynamic behavior.

Returning to the modes in which a decline in frequency is observed, it is found to reduce, at maximum, by a factor of 0.963 for the studied floor-occupancy scenarios (i.e. a reduction of about 4% at maximum). This corresponds to an added mass of $16 \times 75 = 1200$ kg and 3.9% of the mass of the empty floor.

25.3.1.2 Masses Attached at Elevated Positions

The scenario in which masses are attached to the floor at elevated positions is addressed here. Table 25.2 shows results of calculations of floor frequencies for which the lumped masses are placed 2.0 m above floor midplane. The results are presented similarly to Table 25.1.

As in the case of mass attachments at $z = 0$ m, there are scenarios in which a reduction in frequency will not occur when adding a mass; in this case at $z = 2$ m. Such result is observed for mode 4 with a single floor occupancy mass positioned 2 m above the floor midplane, i.e. for the scenario $n = 1$, $k = 4$ (resulting in a normalized frequency of unity). An inspection of floor mode shapes derived by the FE model reveals that the elevated added mass in question is not expected to experience any horizontal translational movements in this mode of vibration (as the mass is placed right above the intersection point of two perpendicular neutral lines for vertical vibration). Since at the same time the mass is not expected to move vertically in this mode of vibration, the mass would not be expected to provide inertia into the system, which explains why the attachment of the mass does not have any influence on floor dynamics.

In some of the other modes (for instance in modes 2 and 3), the elevated mass in question is attached to only a single neutral line of vertical vibration, which would not prevent the elevated mass from vibrating horizontally. The allowance of horizontal vibration of the mass when placed at elevated positions will cause a decline in floor frequency compared to the situation where it cannot move horizontally, as result of rotational inertia of the elevated mass.

Focusing on the maximum influence of adding elevated mass, some scenarios result in a floor-frequency decline by a factor of 0.768, i.e. a reduction of about 23%. This is corresponding to an added mass of $4 \times 75 = 300$ kg and only 1% of the total mass of the floor. Although not shown here, a small number of modes above the ninth mode enter into the 0–62 Hz frequency range for the scenarios studied here.

Table 25.2 Floor frequencies $f_{(k)}$ in Hz for the empty floor ($n = 0$) and normalized frequencies for other scenarios ($n > 0$)

	Mode number (k)								
n	1	2	3	4	5	6	7	8	9
0	8.149	18.909	21.761	32.464	36.773	44.331	50.239	54.946	61.678
1	0.995	0.989	0.986	1.000	0.995	0.995	0.946	0.835	0.897
4	0.990	0.984	0.985	0.981	0.954	0.936	0.883	0.846	0.768
9	0.978	0.960	0.955	0.929	0.958	0.954	0.862	0.842	0.768
16	0.962	0.936	0.930	0.904	0.890	0.868	0.854	0.838	0.917

Floor occupancy masses are attached at $z = 2$ m

Table 25.3 Floor frequency $f_{(9)}$ in Hz for different values of z

n	0	1	4	9	16
$f_{(9)}$ ($z = 0$ m)	61.678	61.678	61.678	61.019	59.420
$f_{(9)}$ ($z = 1$ m)	61.678	60.885	60.071	59.212	59.079
$f_{(9)}$ ($z = 2$ m)	61.678	55.330	47.367	47.379	56.550

Table 25.4 Floor damping $\zeta_{(k)}$ in Hz for the empty floor ($n = 0$) and normalized damping ratios for other scenarios ($n > 0$)

	Mode number (k)								
n	1	2	3	4	5	6	7	8	9
0	0.016	0.022	0.024	0.034	0.038	0.045	0.051	0.055	0.066
1	1.000	1.000	1.000	1.000	0.966	0.966	1.000	1.000	1.000
4	1.000	0.993	0.993	0.983	0.996	0.996	1.000	1.000	1.000
9	1.000	0.993	0.992	0.990	0.981	0.980	0.980	0.979	0.990
16	1.000	0.987	0.986	0.983	0.983	0.982	0.982	0.982	0.965

Floor occupancy masses are attached at $z = 0$ m

25.3.1.3 Comparisons and Supplementary Discussion

Table 25.3 presents floor frequencies computed for mode 9 assuming different elevations of attachment of the floor occupancy masses. Results are also presented for the empty floor ($n = 0$) to be able to follow the change in floor frequency when gradually placing more mass on to the floor.

Noticeably, the frequency drops when the number of masses attached to the floor increases. Exceptions are when floor occupancy mass is attached at floor midplane ($z = 0$ m) when mowing from scenario 0 (empty floor) to scenario 1 (a single mass on the floor), and when moving from scenario 1 to scenario 4 (four masses on the floor). This is explained by the fact that in scenarios 1 and 4, the masses are placed in neutral lines of vertical vibration for these particular modes. On the other hand, in scenarios 9 and 16 the masses are not attached at neutral lines.

Further, for elevated masses positioned 2 m above floor midplane, scenario 16 results in higher floor frequency than scenario 9 (were fewer masses are attached to the floor). This follows from the fact that the masses in scenario 16 mainly move vertically (as attached distant from neutral lines of vertical vibration), whereas masses are attached close to or directly at neutral lines of vertical floor vibration within scenarios 4 and 9. Apparently, this is of more significance in relation to estimating floor frequencies, suggesting that there is a balance point where the rotational inertia associated with the added masses becomes more significant than their contribution to inertia in vertical motion.

Interestingly, when attaching the masses at $z = 1$ m instead of at $z = 0$ m, the frequency drops, however, by far as much as when changing the position of the masses from $z = 1$ m to $z = 2$ m. It might be that it is not that common to see a mass of 75 kg placed at a height of 2 m above floor midplane. However, the results seem to suggest that the rather steep decline in frequency starts somewhere between elevated heights of 1 and 2 m, and the center of mass of a high bookshelf could easily be placed more than 1 m above the floor.

It might be expected that for a low-mass floor (and not the heavy concrete floor considered for this work), the rotational inertia of a bookshelf would contribute even more to floor dynamics. Hence, for such floors, the rather steep decline in floor frequency might start at an elevated height even lower than that found for the concrete floor considered here. Further discussions of results are given in the concluding section of this paper.

Table 25.3 showed how the elevation of the masses attached to the floor influence floor frequency for mode number 9. An inspection of frequency results obtained for the other modes (1–8) reveals that a similar type of frequency decline is found also to occur for mode 6, 7, and 8. The modes 1–5 experience less severe drops in frequency when the value of z increases. It is such the floor modes with frequencies above 40 Hz that are influenced the most by elevating masses to elevations above 1 m.

25.3.2 Floor Damping

This section focuses on damping ratios derived for the various scenarios. The first results to show are those obtained for the scenarios for which the occupancy masses are attached at floor midplane ($z = 0$ m). These results are listed in Table 25.4.

For scenarios $n > 0$ the damping ratios are normalized by the damping ratio of the empty floor of that particular mode.

The damping ratio is 0.016 for the first mode of the empty floor. As the mode number increases so does the damping ratio (see scenario $n = 0$). For some of the modes a slight decline in damping is observed when n increases. The maximum reduction corresponds to about 3.5%. For the scenario where masses are placed at an elevated height of 2 m, the maximum reduction corresponds to about 23%. Results for damping for the scenarios $z = 1$ m and $z = 2$ m will not be shown in the paper. However, it can be mentioned that the relative variations in floor damping follow the overall tendencies observed for the relative variations of floor frequency.

25.4 Conclusion

The numerical studies of this paper explored how sensitive modal properties of a 8 × 9 m concrete floor are to the usage of the floor area. Simplified assumptions in terms of floor usage were made to provide an initial understanding of the dynamics of the floor occupied by masses rigidly attached to the floor.

As the studies covered monitoring 9 modes of floor vibration, only overall findings are summarized below.

Frequency declines of up to about 4% were observed when adding masses at floor midplane. When masses were attached to the floor at an elevated position corresponding to 2 m above the floor, frequency drops of up to about 23% were observed. Hence, the vertical positioning of the masses can have a significant impact on some of the floor frequencies. For the studied floor a step decline in frequency started when masses reached elevated positions of slightly above 1 m.

Overall the declines in damping ratios perform much like the declines found for frequency.

It would be of interest to examine to which degree the findings would impact serviceability-limit-state evaluations of floors. This step is not taken in the paper. The degree of impact would probably depend on the problem matter and source generating floor vibrations and the frequency range excitations.

Further it would be of interest to study floor occupancy scenarios of less deterministic nature than considered in this paper.

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References

1. Bachmann, H., Ammann, W.: Vibrations in structures—induced by man and machines, IABSE Structural Engineering Documents 3e, Zürich, Switzerland, 1987
2. Nagy, A.B., Fiala, P., Márki, F., Augusztinovicz, F., Degrande, G., Jacobs, S., Brassenx, D.: Prediction of interior noise in buildings generated by underground rail traffic. J. Sound Vib. **293**, 680–690 (2006)
3. Lombaert, G., Degrande, G., Cloutaeu, D.: Road traffic induced free field vibrations: numerical modelling and in situ measurements. In: Proceedings of the International Workshop Wave, Bochum, Germany, pp. 195–207. Taylor & Francis, Oxfordshire, UK (2000)
4. Ellis, B.R., Ji, T.: Human-structure interaction in vertical vibrations. In: Proceedings of the ICE: Structures and Buildings, vol. 122, pp. 1–9. ICE Publishing, London, UK (1997)
5. Andersen, L.V., Kirkegaard, P.H.: Vibrations in a multi-storey lightweight building structure: influence of connections and nonstructural mass. In: Proceedings of the Fifth International Conference on Structural Engineering, Mechanics and Computation, pp. 131–136. CRC Press LLC, London (2013)
6. Griffin, M.J.: Handbook of Human Vibration. Academic Press, London (1990)
7. Ahmad, S., Irons, B., Zienkiewicz, O.: Analysis of thick and thin shell structures by curved finite elements. Int. J. Numer. Methods Eng. **2**, 419–451 (1970)
8. Abaqus 6.14. Dassault Systèmes Simulia Corporation, Providence, RI, USA: Dassault Systèmes, 2014
9. Fiala, P., Degrande, G., Augusztinovicz, F.: Numerical modelling of ground-borne noise and vibration in buildings due to surface rail traffic. J. Sound Vib. **301**, 718–738 (2007)