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Flooring-systems and their interaction with furniture and humans

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Abstract

Flooring-system designs may be sensitive in terms of their vibrational performance due the risk that serviceability-limit-state problems may be encountered. For evaluating the vibrational performance of a flooring system at the design stage, decisions must be made by the engineer in charge of computations. Passive humans and/or furniture are often present on a floor. Typically, these masses and their way of interacting with the floor mass are ignored in predictions of vibrational behaviour of the flooring system. Utilizing a shell finite-element model, the paper explores and quantifies how non-structural mass can influence central parameters describing the dynamic behaviour of the flooring system with focus on elevated non-structural mass.

Keywords: Modal properties of floors; floor dynamics; numerical prediction; serviceability-limit-state; estimation accuracy.

1. Introduction

A simple assumption for a vibration serviceability check of a floor design would be to assume that the floor is not carrying any non-structural members and masses. However, this is seldom a correct assumption as many floors are equipped with furniture or equipment of some sort. Also the floor might be occupied by humans and it is established that these and simple masses (such as furniture) added to the floor will influence floor dynamic characteristics [1–3] and thus the basis for the vibration serviceability check. Ultimately there is the risk that the engineer in charge of the vibration serviceability check overlooks or does not account for important influences that in-service usage of the floor area might have on floor dynamic characteristics, and eventually the outcome of the serviceability-limit-state evaluation performed for the floor might not be representative for the actual in-service conditions.

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The paper has focus on the potential interaction between elevated non-structural masses attached to a floor and the natural frequencies of the floor computed on the basis of the assumed elevation of these masses above the floor. Simple added non-structural mass on a floor is most frequently considered as a mass that does not contribute with stiffness but with additional mass moving in the vertical direction together with the floor mass. Assuming this type of behaviour, a simple equation would predict decreases in floor frequencies resulting from the presence of the added mass. However, the centre of gravity of items on the floor such as bookshelves or desks would be elevated above the floor plane and the bending of the floor experienced during floor vibrations would (in some scenarios and for some modes) cause the centres of gravity of such items to move horizontally, hereby adding rotational inertia and consequently modal mass to the floor.

Hence, it is chosen to study how a set of elevated non-structural masses attached to the floor can influence floor natural frequencies. Different elevation heights of the set of non-structural masses and different sizes of the set of non-structural masses will be considered, in order to draw a picture of the basic mechanisms.

For a floor there would be a number of different types of excitations that could be problematic and could cause excessive floor vibrations disturbing human occupants on the floor or causing problems for sensitive equipment placed on the floor area. Internal action resulting from humans in motion on the floor might be the source of vibration [4], or problematic floor vibrations or noise might be due to nearby road or rail traffic, above or below ground level [5–7], nearby construction works or similar. The list of possible vibration sources could continue, but bottom line is that a quite wide range of excitation frequencies can cause unwanted vibrations of floors. Hence, it is chosen to monitor floor natural frequencies and how these change due the presence of elevated non-structural masses in a frequency range covering frequencies up to 250 Hz. Doing so ensures capturing the frequency behaviour of the floor resulting from interaction with the elevated masses for many possible types of excitation that may cause annoyance, for example, in the form of whole-body vibration or re-radiated noise.

The floor subject to investigation is described in Section 2 which also describes the finite-element (FE) model constructed for the floor and the scenarios assumed for usage of the floor. Section 3 presents and discusses the results. Finally, Section 4 gives the conclusions of the study.

2. Methodology

2.1. Computational model of the floor

For the studies of this paper, a reinforced concrete floor was assumed. The floor was assumed to be rectangular and pinned along all four sides. Side lengths of 8 m and 9 m, respectively, were assumed and the thickness of the floor was assumed to be 180 mm and the mass density was assumed at 2400 kg/m^3. Due to the dynamic behaviour of reinforced concrete concerning the prerequisites of the problem at hand, the composite material was modelled as being homogeneous, isotropic and linear elastic. For calculations, Young's modulus (E) was assumed to be 30 GPa and Poisson's ratio (ν) at 0.15. These values are fairly realistic for a reinforced concrete floor.

The next step was to create an FE model of the floor. Since inertial energy of elevated non-structural masses was to be accounted for, it was chosen to employ an FE model using shell elements [8]. Each element had nine nodes and considered five degrees of freedom per node, involving three translational displacements and two rotations associated with bending. The drilling degree of freedom was controlled by adding a small artificial stiffness. A second-order Lagrange interpolation approach was used for computing displacements and rotations, and selective integration of the stresses was employed to avoid shear locking.

Natural frequencies $f_{(k)}$ (for mode number k) were extracted from the FE model by solving the undamped eigenvalue problem. A 12-by-12-element grid for the entire floor proved sufficient in terms of providing converged estimates of frequencies of the empty floor for modes up to 250 Hz. A plate model of the floor was also tested and it gave, as expected, minor differences in floor frequencies compared to those extracted using the shell model. The code employed for computations reported in this paper was verified by comparison with an FE model created in ABAQUS [9] using Mindlin-Reissner shell elements with eight nodes and reduced integration. For scenarios in which non-structural mass was assumed to be placed on the floor, the eigenvalue problem was solved taking offset in the stiffness matrix, **K**, and the mass matrix, **M**, of the combined system that includes the non-structural masses attached to the floor. The first mode of the empty floor was found to have a frequency just over 8 Hz.

2.2. Usage of the floor

In the computational model, allowance is made for attaching non-structural mass at nodal points of the FE grid. These masses could represent furniture such as desks and/or bookshelves. For simplicity, the non-structural masses are modelled as lumped masses. Each lumped mass is assumed to take on a value of M_n.

As the masses in question normally are elevated above the floor, their vertical position will be considered. Since the masses are considered being lumped, it suffices to define the vertical distance between the lumped mass and the horizontal plane of the FE floor model. This parameter is denoted z and is referred to as the elevated position of the non-structural mass.

For simplicity each elevated non-structural mass is attached to a single node of the FE model of the floor, namely the node located right below the point of attachment. For the calculations of this paper, nine non-structural masses are placed at fixed positions in the horizontal plane of the floor. One may image the floor area subdivided into nine equal sized rectangular areas in a 3-by-3-area grid. A non-structural mass is placed in the centre of each rectangular area. Subject to change in the studies of this paper is the size of each non-structural mass, M_n, and the elevation of the masses, z. Values of M_n ranging from 0 to 200 kg and values of z ranging from 0 to 3 m are considered. Having decided on a value of M_n and a value of z, these values are assumed for all non-structural masses.

3. Results

This section focuses on computed results for the floor frequencies in the frequency range of 0 to 250 Hz for different elevated positions of the set of non-structural masses. First the masses are assumed to be located in the horizontal plane of the FE-model (at $z = 0$ m). Fig. 1 shows the floor frequencies calculated under this assumption and assuming values of M_n ranging from 0 to 200 kg. If an elevated position of the non-structural masses is not accounted for in calculations, the floor natural frequencies shown in Fig. 1 would be obtained. A value of M_n equal to zero corresponds to empty floor conditions. Increasing the value of M_n is seen to affect the natural frequencies of only a few modes and to a limited extent. Having in mind that $M_n = 75$ kg corresponds to a total floor occupancy mass of only 675 kg (equal to 9 times 75 kg), equivalent to 2.17% of the floor mass, it is not particularly surprising that the presence of the non-structural masses have limited influence on most floor natural frequencies.

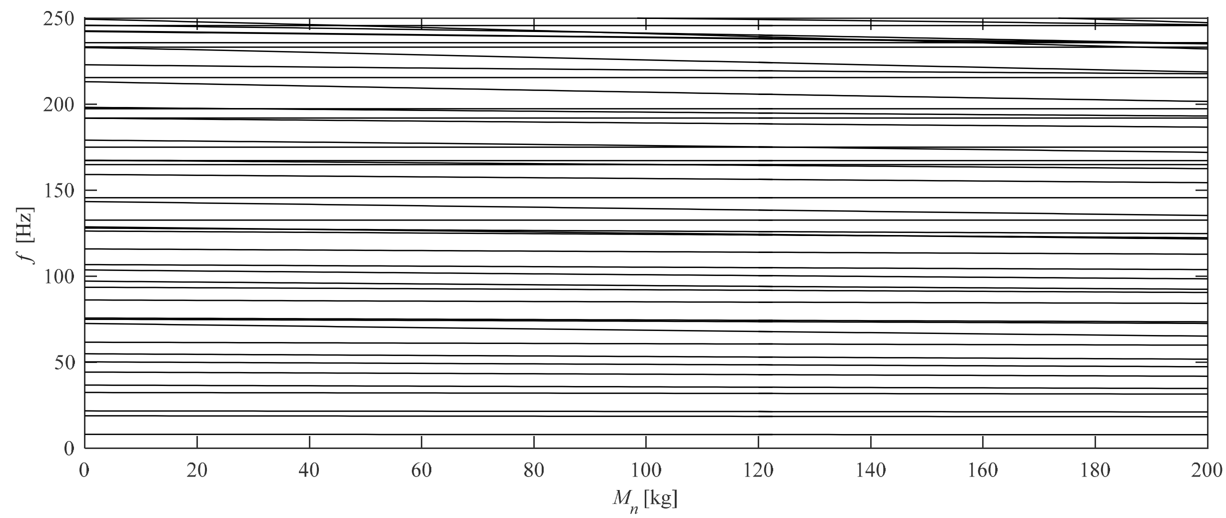

Fig. 1. Floor natural frequencies as function of M_n for non-structural masses located at $z = 0$ m.

Next, Fig. 2 illustrates computational results in terms of floor natural frequencies obtained assuming that the set of non-structural masses is elevated 1 m above the horizontal plane of the FE model. The first item to notice is that a number of the initial higher modes of vibration are influenced by elevating the non-structural masses. Even a mass of

M_n equal to only 25 kg, thus having only 9×25 kg present on the floor, results in a reduction in frequency of some of these modes of more than 50 Hz. An increasing number of modes experience a drop in frequency with further increases in the value of M_n. Noticeably, a fraction of the initial higher modes only experience a drop in frequency until they stabilize at a frequency at a lower level than the value experienced at $M_n = 0$ kg. Hereafter the frequencies of these modes are seen to be insensitive to further increases in the value of M_n. This suggests that the basic nature of these modes undergo a transformation when a certain threshold value for M_n is reached—a threshold which apparently is different from mode to mode. Another fraction of the initial higher modes continues their steady decline in frequency with increases in M_n after once having started dropping. At the same time the initial lower modes (in the frequency range below 50 Hz) hardly take any notice of the presence of the non-structural masses.

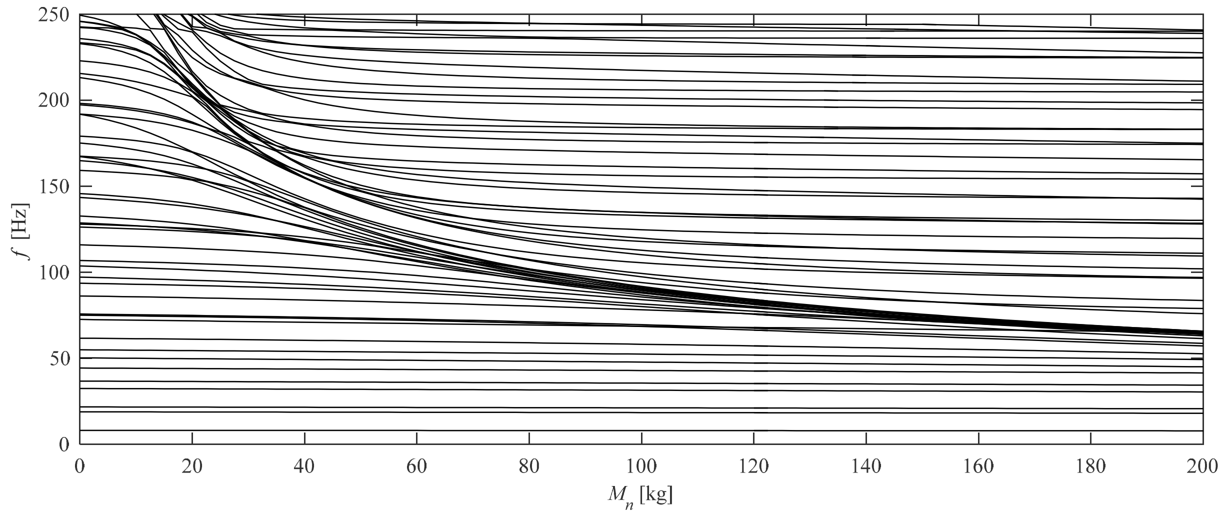

Fig. 2. Floor natural frequencies as function of M_n for non-structural masses located at $z = 1$ m.

Basically the difference in what is displayed in Fig. 1 and Fig. 2 is the result of the horizontal motion of the non-structural masses taking place during floor vibration. For the calculations presented in Fig. 1, the non-structural masses do not move in the horizontal directions as the masses are fixed in the horizontal plane of the FE model of the floor. Elevating the masses above that plane allows horizontal motion of the non-structural masses to take place, and the rotational energy involved with that motion increases the modal mass and causes drops in floor frequency.

Fig. 3 shows results assuming higher elevated positions of the non-structural masses, namely their placement at $z = 2$ m, in Fig. 3a, and at $z = 3$ m, in Fig. 3b. By comparing Fig. 3a with Fig. 2 it can be seen that the initial higher modes that experience a steady decline in frequency with increases in M_n experience a steeper decline when the non-structural masses are at $z = 2$ m compared with the case in which $z = 1$ m. If the non-structural masses are raised yet another metre (to the level $z = 3$ m, see Fig. 3b), the steepness of the decline with increases in M_n increases further.

Similar for all three scenarios ($z = 1$ m, $z = 2$ m, $z = 3$ m) is that a certain fraction of the initial higher modes at some point after having initiated a drop in frequency reaches a frequency level at which they remain regardless of further increases in M_n. For all three scenarios, the initial lower modes are hardly influenced by the presence of the non-structural masses. However, there is this fraction of the initial higher modes which are affected and experience a steady decrease in frequency with increases in the non-structural mass all the way.

Somehow these effected modes follow a similar type of pattern of frequency drop with increases in the size of M_n. This has the effect that for almost any chosen value of M_n (for a given value of z) there is a relatively high number of modes present in a well-defined and quite narrow frequency band. Probably the high-density floor frequency bands are easy to recognise in the figures presented in this section, but a mode count table is another useful tool to indicate a possible clustering of modes in certain frequency regions. Hence, for reference, Table 1 shows the results of mode counts for the scenario with nine non-structural masses of $M_n = 75$ kg with the set of masses positioned at different elevated heights. It is seen that for $z = 0$ m there is a quite even distribution of modes throughout the 0 to 250 Hz frequency range. This is not the case for values of $z > 0$ m and the frequency range with the highest number of modes gradually drops with increases in z. Furthermore the numbers in the table reveal that for $z > 0$ m there are more modes in the 0 to 250 Hz frequency range than for $z = 0$ m. This means that when the non-structural masses become elevated, some modes initially with frequencies above 250 Hz drop down into the 0 to 250 Hz range.

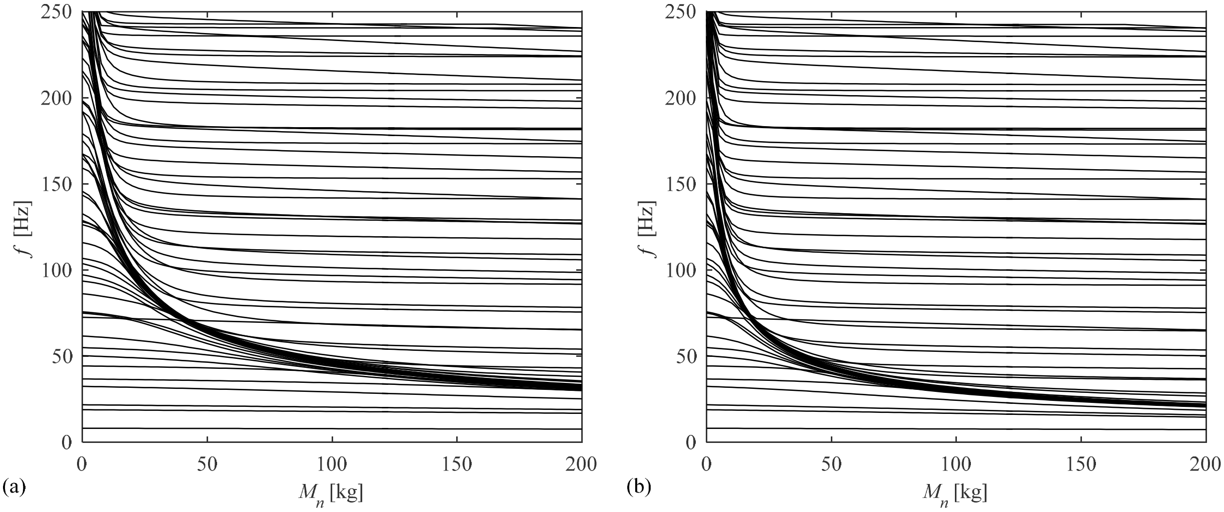

Fig. 3. Floor natural frequencies as function of M_n for non-structural masses located at: (a) $z = 2$ m; (b) $z = 3$ m.

Table 1. Mode counts for different elevated heights, z, of the set of non-structural masses.

z	0–50 Hz	50–100 Hz	100–150 Hz	150–200 Hz	200–250 Hz
0 m	7	8	9	10	11
1 m	7	13	20	9	11
2 m	10	22	9	8	11
3 m	24	8	9	8	11

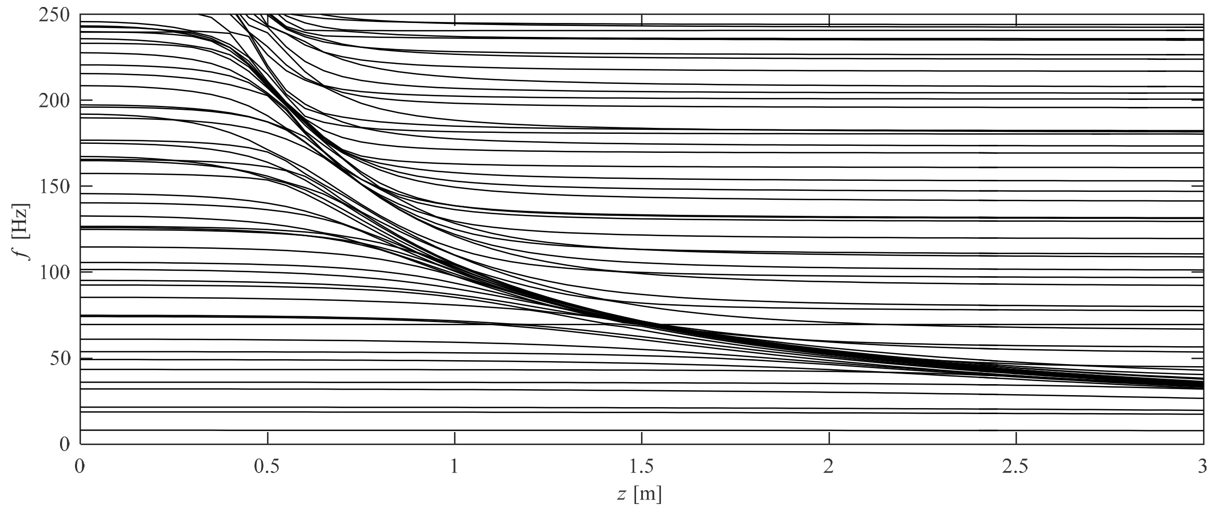

Fig. 4. Floor natural frequencies as function of z for $M_n = 75$ kg.

The calculations for the mode count results presented in Table 1 (with nine non-structural masses of M_n = 75 kg attached to the floor) were actually more extensive than Table 1 suggests. The floor frequencies were computed for a wide range of values of z in the range 0 to 3 m, resulting in the relationship between floor frequency and z shown in Fig. 4. However, it was chosen only to list the mode counts for the four discrete values of z.

In this representation of results it is apparent that whether the non-structural masses are attached at z = 0 m (*i.e.* at the mid-plane of the floor structure) or at z = 0.4 m has a minor influence on floor frequencies below 250 Hz. In practice, however, an elevated height of 0.4 m would only be a few centimetres above the top surface of the actual floor as a non-zero floor thickness is not possible. Any further elevation of the masses causes significant influences on floor frequencies in the considered frequency range and for some modes the natural frequency steadily drops with increases in z.

4. Conclusions

The numerical studies presented in the paper examined how elevated non-structural masses present on a floor might interact with the floor and cause changes in floor natural frequencies. Especially, the frequency range 0–250 Hz, relevant to whole-body vibration, sensitive equipment and low-frequency structure-borne noise, has been considered. The magnitudes and elevations of the non-structural masses could realistically represent the presence of bookshelves, desks or passive humans on the floor.

It was found that many initially higher modes of vibration might be influenced by the presence of the elevated masses—however in different ways. One key finding is that some initial higher modes would steadily drop with increases in non-structural mass and cause gathering of a large number of floor modes within a narrow frequency range. For the floor with no non-structural mass applied, the eigenmodes of the considered rectangular floor are close to being uniformly distributed in the frequency range 0–250 Hz. However, the presence of elevated non-structural mass provides a completely different behaviour—already when the centre of mass is elevated as little as 0.5–1 m above floor level. This suggests that non-structural mass in the form of furniture or passive humans present on floors should be accounted for in computational models of floors and to obtain realistic estimates of the dynamic structural response of occupied buildings.

Future research will focus on modelling furniture and humans as simple dynamic systems coupled to the floor structure, and the impact of non-structural mass on global building response will be analysed.

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