On force- and moment mobilities of a timber joist floor

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Introduction

In wood framed buildings, floors are formed by fastening wood sheathing to joists spaced at a regular interval. The sheathing is typically fastened to the joist using screws so the resulting system is a complicated periodic point-connected plate-rib structure. It is shown that the point force mobility varies significantly with position. A machine installation generally is close to discontinuities, such as at: floor edges, joist-screw locations, joints between the sheathing plates, and due to workmanship. In such cases, moment excitation might become important and the neglect of moments a priori can lead to inaccurate prediction of the total emission. This paper presents measured point moment mobilities with respect to the distance to discontinuities for a timber joist floor where a single layer of chipboard forms the sheathing. It is shown that the measured point moment mobility indicates infinite plate behaviour. This includes for positions above a joist. To determine the relative contribution of moments and perpendicular forces to the total structure-borne sound power, case studies of two sources, a fan unit and a whirlpool bath, are described, for various locations on a timber joist floor. To overcome the problem of incompatibility of the dimensions introduced by the components, the analysis is presented on a power basis.

Floor Set-up

The floor construction investigated, shown in Figure 1, can be considered as the basic structure for real timber joist floors with various toppings, e.g. resilient interlayer and floating floor systems. The floor selected did not have additional layers of toppings and therefore was not representative of complete floors in lightweight buildings. It was selected because it forms the simplest possible timber floor construction. This means that uncertainties related to workmanship and dynamic properties of plate and joist materials are limited to few floor components. In addition, it forms the most extreme situation in terms of likely spatial variation in the dynamic behaviour.

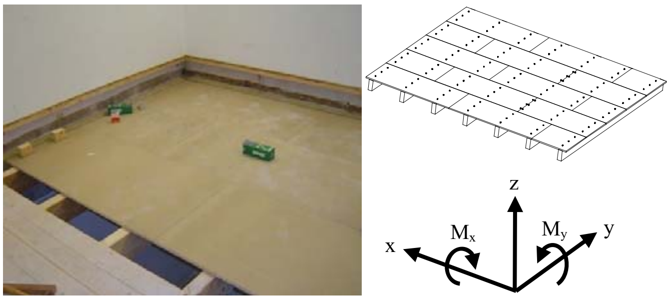

Figure 1: Timber joist floor with global orientation.

It can be assumed, that additional sheathings and toppings tend to reduce the spatial variation in mobility. The floor dimensions were 4.55 m x 4.95 m, with one layer of 21 mm chipboard sheathing supported by seven Norwegian spruce joists with dimensions 0.096 m x 0.192 m x 4.55 m. The joist spacing was a nominal 0.78 m on centre. The chipboard sheathing consisted of panels of dimensions 0.9 m x 2.05 m, joined by unglued tongue and grooves and secured to the joists by screws, spaced at 0.20 m.

Point Force Mobility

Although work has been reported by others on the measurement of point mobility on heavyweight building elements, there has been little reported on measured point mobility of timber floors [1]. In particular, information is required on the spatial variation in point mobility, relative to the nearest joist and/or the nearest fixing point.

To examine the spatial variation and the dependence of the drive point mobility on the location of excitation relative to the nearest joist, point mobilities were measured along a line perpendicular to the joists. Fig. 2(a) shows the measured point mobility normalized to that of an infinite plate and plotted as a function of distance in wavelengths. When this distance is less than one-quarter of the wavelength, beam behaviour dominates. At distances greater than one-quarter wavelength, the chipboard panel can be considered as an uncoupled infinite plate.

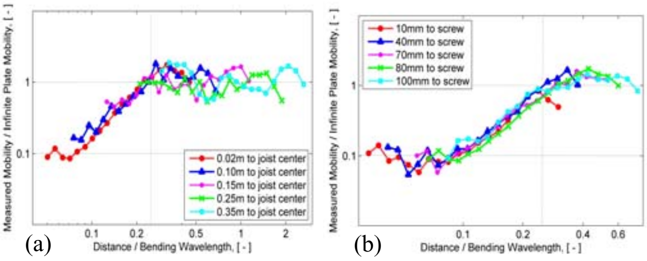

Figure 2: Normalised point mobility as function of non-dimensional distance between the drive point and (a) nearest joist; (b) nearest screw.

The fact that the chipboard panels are fastened to the joists using only screws spaced approximately 20 mm apart, leads to the chipboard being effectively point-connected to the joists at the high frequencies and line-connected at the low frequencies. Hence, in addition to the effect observed in Figure 2(a), the location relative to the nearest fixing (screw) point becomes an important factor when the drive point is located above a joist. To investigate the effect of distance to the nearest screw point, the mobility for positions above a joist was recorded above and along a joist. In Fig. 2(b) again, the measured point mobility is normalized to that of an infinite plate and plotted as a function of the distance in wavelengths to the nearest screw. These results have been reported elsewhere [2, 3]. It was concluded when the ratio of the distance to the next screw to the bending wave length is less than 1/4 the joist dominates the floor response and the mobility is considerably less than that of an uncoupled infinite plate. When the ratio is greater than 1/4 the joists have minimal effect and the chip board panel can be considered as an uncoupled infinite plate. This implies that when the fastener spacing is at least 1/2 bending wave length there will be points above the joist for which the quarter wave length condition is not satisfied and the joist will have minimal effect on the mobility at this points. This half wavelength criterion, marks the transition between line- and point connected behaviour and has been used earlier [4].

Point Moment Mobility

A finite difference technique according to [5] was applied to obtain the moment mobilities of the timber joist floor. The main advantage of this method is that moments are excited by applying a force directly to the structure at a small distance from the point of interest, hence effectively using the structure itself as a lever. It requires a force hammer and accelerometers, and only a few excitations are required to determine the force- and moment mobility together with their related cross mobilities [6].

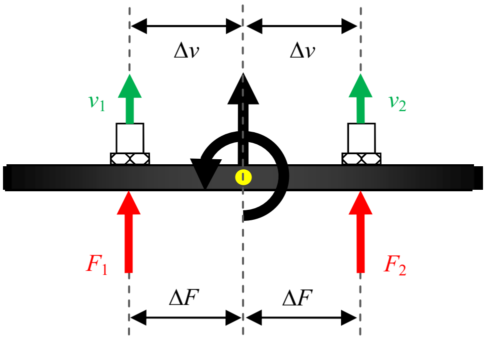

Figure 3: Sketch of force excitation and velocity response for the determination of moment mobilities.

By applying a force F_1 directly to a structure at a distance ΔF from the point of interest, a moment is generated, see Figure 3. This excitation results in an effective force and moment as well as an effective velocity and angular velocity at the point of interest. However, these excitations and responses are coupled since forces and moments cause both translational and rotational velocities. With a second excitation F_2 forces and moments can be separated and by measuring a second velocity v_2 angular and translational velocities can be extracted [6]. From Figure 3 it can be seen that applying the force F_2 will generate a positive moment and F_1 a negative moment. Thus the sum of the two will cancel the moment giving a pure force at the point of interest. The difference of the two forces on the other hand will cancel forces and giving a pure moment. Similar arguments lead to translational and rotational velocities. It is therefore possible to derive force-, moment- and cross mobilities purely from measured transfer functions, namely force- point and transfer mobilities [6]. The moment mobility then is given by the central difference equation [5]:

$$\overline{Y_{M\,x,y}} = \frac{\left(\overline{Y_{11}} - \overline{Y_{12}} - \overline{Y_{21}} + \overline{Y_{22}}\right)}{4\,\Delta F\,\Delta v} \qquad (1)$$

Referring to Figure 3, as an example, the transfer mobility $\overline{Y_{21}}$ corresponds to the response v_1 to the applied force F_2.

Practical difficulties arise due to the contradicting requirements for quality measures. On the one hand, the purity of the data is dependent upon ΔF and Δv much smaller than the bending wave length. Whilst on the other hand, experimental errors such as noise dictate that ΔF and Δv are sufficiently large to provide differences which are incorruptible. Both requirements are case specific. For the moment mobility measurements on the timber joist floor construction, it was found that the best results were obtained for ΔF and Δv with an accelerometer spacing of 0.1 m. This spacing corresponds with the bending wavelength in the chipboard sheathing at 5000 Hz.

In order to investigate the dependence of the moment mobility on location, relative to the nearest joist and / or screw, seven points on the floor were considered. Figure 4 shows measured point moment mobilities about the y-axis of the floor, i.e. parallel to the long axis of the joists, with respect to distance to the nearest joist. Additionally, for positions located above the joist, the two extreme cases (midway between two screws and directly on a screw) are presented. Further, the calculated moment mobility about the x- and y-axis of an infinite plate, according to [7], is given for comparison.

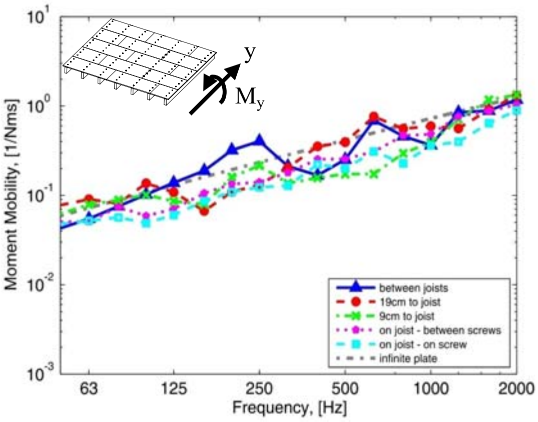

Figure 4: Measured moment mobility about y-axis as a function of location.

As shown in Figure 4, the measured moment mobility obtained midway between two joists fluctuates about the infinite plate moment mobility, between about 150 Hz and 2000 Hz. Below and above this frequency range, the infinite plate mobility provides good approximation. For positions closer to or on a joist, the measured moment mobilities tend to slightly lower values without systematic deviation between each other. The lowest values are obtained for the measurement position located above a joist directly at a screw. For moment mobilities about the y-axis of the floor, i.e. perpendicular to the joist direction, a change in the dynamic behaviour due to the presence of a joist is not evident. It is assumed that, even for positions above a joist, the sheathing plate can more or less freely rotate about the long axis of the joist.

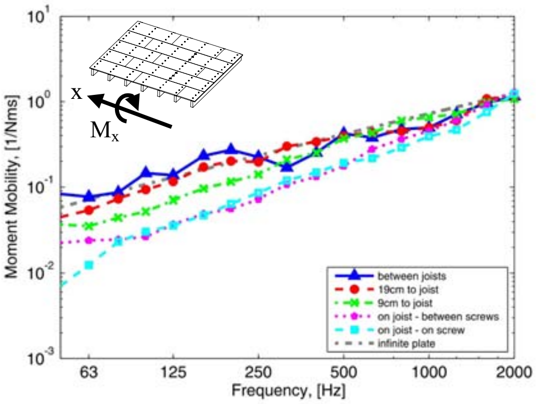

Figure 5: Measured moment mobility about x-axis as a function of location.

Different observations can be made from the measured moment mobilities about the x-axis of the floor, given in Figure 5. These results clearly reveal a systematic effect associated with distance to the joist. For the moment mobility obtained midway between two joists again a fluctuation about the infinite plate moment mobility can be observed. With decreasing distance to the joist, the magnitude of the moment mobilities decreases with growing deviation towards lower frequencies. Measurements above the joist indicate similar moment mobilities about the x-axis for positions midway between two screws and directly at a screw location for frequencies above 80 Hz. This is expected because of ΔF and Δv is 50 mm leading to the accelerometers being approximately 50 mm apart from the next screw in both cases (since the screw spacing is about 200 mm). Again, it is the distance to the nearest screw which is determining the rotational response about the x-axis of the floor. The reasons for the discrepancies below 80 Hz are not obvious. With increasing frequency the dependence on the distance decreases. At 2000 Hz the measured moment mobilities about the x-axis coincide and agree with that of an infinite plate.

Case Studies - Component Contribution

Bending wave fields couple most efficiently with the surrounding air, whereas quasi-longitudinal waves and transverse waves do not contribute significantly to acoustic radiation [8]. It is therefore required to know which component of excitation contributes to the bending wave field of the excited plate. In [9] all components (except in-plane moment) were investigated on a power basis for selected source-receiver combinations with the aim to eliminate insignificant components. For thin plates, where the wavelength of the longitudinal, transverse and bending waves are much greater than the thickness of the plate, it was concluded, that in-plane excitation does not contribute to the total bending of the plate and therefore can be neglected. Hence, the main excitation components are forces perpendicular to the plate surface and moments about the x- and y-axes, indicated in Figure 1.

To determine the relative contribution of force and moment components to the vibrational energy transmission, the power of each component was calculated using:

$$P = \frac{\left|\overline{v}_{Sf}\right|^2}{\left|\overline{Y}_S + \overline{Y}_R\right|^2} \cdot \mathrm{Re}\left(\overline{Y}_R\right) \qquad (2)$$

The investigation was conducted for one contact point of two different sources, a whirlpool bath and a medium size fan unit, with the timber joist chipboard floor construction. Existing measures of source mobilities and free velocities, both translational and rotational, were used. The whirlpool bath data was measured by Späh [10] at the Stuttgart University of Applied Sciences. The fan unit data was measured at the University of Liverpool [11, 12].

The component powers at all contacts are presented in the form of the ratio of moment to perpendicular force induced power.

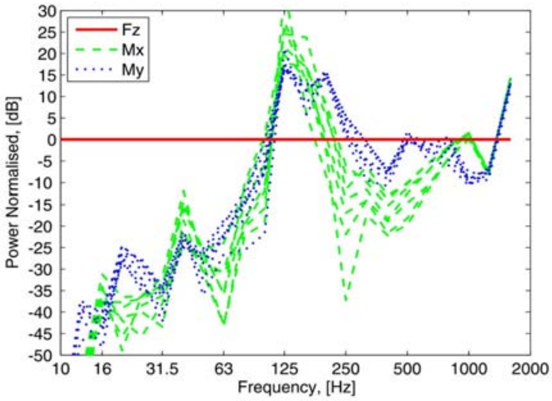

Figure 6: Normalised power of the different components of the whirlpool bath; all contact locations.

For the whirlpool bath, Figure 6, all contact situations reveal comparable results with low moment contribution below 100 Hz. Between approximately 100 Hz and 250 Hz the moment induced power of both rotational components exceed that of the translational force. Differences of up to 30 dB at 125 Hz are obtained. Above this frequency range the force component dominates by trend up to 1300 Hz approximately. However, narrow band frequency analysis reveal strong moment coupling at numerous single frequencies. Above 1300 Hz higher values for the power due to the rotational components of excitation are indicated.

The variation associated with the contact location is approximately 5 -10 dB for the rotational component about the y-axis and up to 25 dB about the x-axis at 250 Hz. The somewhat greater variation in power for the moment component about the x-axis was expected from the moment mobility measurements of the receiver structure, see Figure 5. A preliminary conclusion would appear to be that moments cannot be neglected for the case of the whirlpool bath. However, further consideration of the whirlpool bath identifies an anomalous assumption in processing the source and receiver data. The assumption is that the source and receiver are rigidly connected, i.e. the ends of the frame structure are rigidly glued or bolted to the floor. In reality, whirlpool baths are installed with relatively few location screws and often with a resilient rubber/plastic end to the vertical square sections of the frame. Therefore, although a worst-case condition has been assumed, it is arguable this is unlikely.

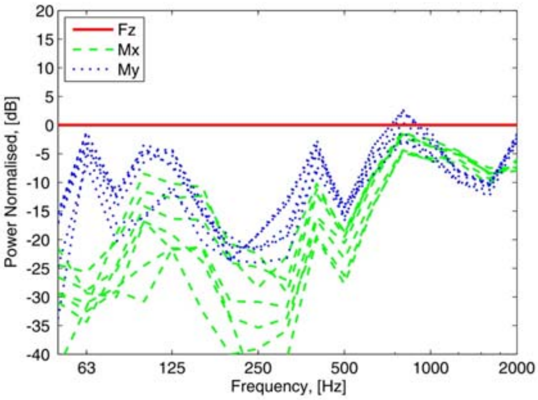

Figure 7: Normalised power of the different components of the medium size fan unit; all contact locations.

For the medium size fan unit, Figure 7, the rotational powers are comparably low at low frequencies with values on average 10-30 dB lower than for the translational force. Between about 600 Hz and 1000 Hz the moment induced power is of the same order as the force induced power. Above this frequency range, moment induced power is approximately 5-10 dB lower than that of the force.

The results show that in general it is possible to restrict the calculation of the total structure-borne sound power of both the whirlpool bath and the medium size fan unit to the translational force component. For the whirlpool bath such a restriction would lead to an underestimation of the power at the frequencies between 100 Hz and 250 Hz and presumably also above 1300 Hz. For the medium size fan unit the neglect of moment components is reasonable and will lead to fair approximation of the total power.

Conclusions

A point-connected timber joist chipboard floor construction was chosen to investigate the dynamic behaviour of lightweight building elements. This construction can be considered as the basic structure for real timber joist floors. Results show that the perpendicular force point mobility is strongly affected by the location of the excitation point relative to the joists. The mobility can be approximated by that of an uncoupled infinite plate of the same material and thickness, when the drive point is more than 1/4 bending wavelengths from the joist. For positions directly above a joist, the mobility is a similar function of distance to the nearest screw and the general conclusion is that distance from a screw position is the dominant factor, independent of angle to joist direction.

A finite difference measurement method was used for moment mobility. Results indicate infinite plate behaviour independent of location. This includes for positions between joists and above a joist for the y-direction of the floor. Moments about the x-direction of the floor indicate a systematic effect associated with distance to the joist / screw. Decreasing magnitudes can be observed for decreasing distances.

The normalised component powers for seven locations of the whirlpool bath revealed that moments are important in the frequency range between 100 Hz and 250 Hz as well as above 1300 Hz. At these frequencies the neglect of moment components would lead to an underestimate of the total power. However, the assumption has been that the source and receiver are rigidly connected, i.e. the ends of the frame structure are rigidly glued or bolted to the floor. Therefore, although a worst-case condition has been assumed, it is arguable this is unlikely. The power due to moments of the medium size fan unit in the x- and y-direction only reaches comparable values with the power due to the translational force at about 800 Hz. For this source, the neglect of moment components therefore is reasonable to approximate the total power.

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