Human footsteps induced floor vibration

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The generation of the impact sound by the act of the human walk involves two factors, the characters of the footfall and the shape of the induced floor deflection. The footfall noise is created by the impact excitation where the character of the footfall depends on the foot-ware: the heels and the frequencies of the footfall. The shape of the floor deflection depends rather on the geometrical walking pattern and the construction of the floor structure. In this investigation, the vibration pattern of the light-weight construction floor is created by the same walking object, a male with common height. The excitation from the person to the floor in the FE simulations is a function of the length of the foot and the weight of the walking object. The geometrical time history of the foot step allows it to have different directions in the room. Since the excitation is assumed to be deterministic, differences between the excitation frequencies are estimated from video recordings. The goal of this investigation is to determine the difference of the floor structure deflections between two different walking paths: one is perpendicular to the bearing beams and the other is the diagonal path.

1 Introduction

Timber framed buildings have become a more and more popular choice for many countries with rich forest resources since the late seventies, especially when the modern computerized numeric control machinery (CNC) have been adopted to accomplish many heavy and labor demanded manufacturing tasks, for example the cutting process with high precision. But there are still disadvantages for modern timber framed structures as compared with concrete structures: the noise from the footsteps in adjacent rooms both above and on the same floor in such buildings can be audible. The numerical predictions of the human footsteps induced structure vibration and acoustic wave propagation on the floor structure depends on many factors, the time history of the interaction between the impact source by the human body and the floor structure as the receiver, the foot-ware of the person, the angle of the impact excitation, the construction of the light-weight floor and ceiling structure and the geometrical walking pattern, [1, 2, 3, 6]. Even all the factors that have been listed above are important and many details are not fully understood yet, the main focus of this study is to investigate if there is a relationship between the floor deflection and the walking paths. The first question is if the spatially regular footstep excitation history can be assumed in the numerical calculations. If the spatial distribution of the impact loads in one case will follow a real human walking pattern, and in the other case can be assumed to have the same periodic walking pattern, if the difference between the excitation location is small in comparison to the dimension of the floor, how will the difference affects the final calculation results of the vibration displacement calculations. The second question concerns the orientation of the bearing beams and the walking pattern itself in the fluid structure interaction calculations.

2 Measurements

The field's measurements are provided for a male with a common body. The body weight is 75 kilogram. To be able to provide meaningful information for the excitation locations, the walking person has been walking on a check paper with painting color under his feet.

3 Footsteps/Gait

To be able to locate the spatial distribution of the footsteps effectively with an acceptable correction, a roll of check paper has been used. The length for each side of the square is 10 mm. In this fashion, the relatively exact walking trace can be captured. The walking trace is shown on figure 1.

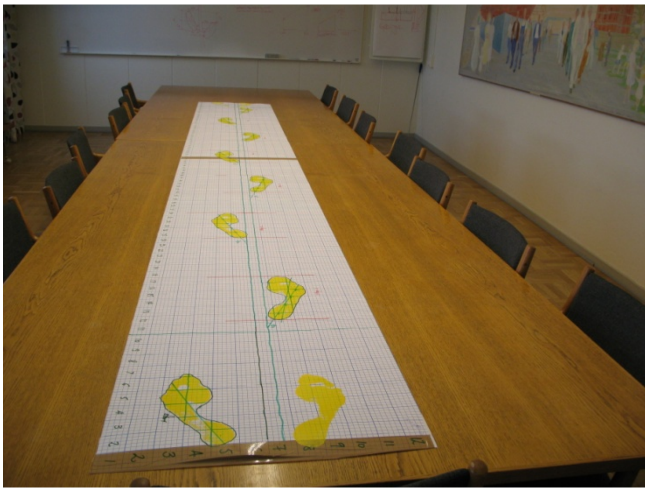

Fig. 1: Walking foot steps

The length of the paper roll is 4.6 meters and the width is 0.6 meter. In the measurements, the first and the final steps are not included they act only as reference for the other steps. All together, seven footsteps are recorded in this distance and are analyzed. To be able to investigate how to reproduce the walking pattern numerically, several parameters have been documented for each step, among others the distance between the main point of the foot and the dividing line, the distance between two steps and the angle of the foot, all the important parameters are shown in figure 2.

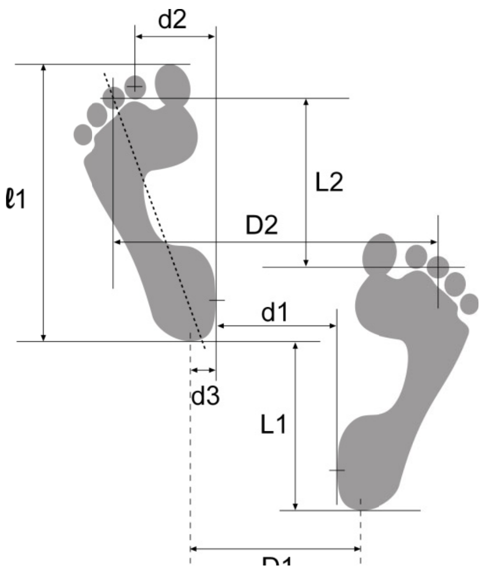

Fig. 2: Different parameters used for the calculation.

Measurement data of the parameters indicated in figure 2 can be found in table 1.

Foot step	Position	d_1 (cm)	d_2 (cm)	l_1 (cm)	l_2 (cm)
Step1	Right	3	7.5	65	28
Step2	Left	2	9	114	29
Step3	Right	2.5	7	173	30
Step4	Left	1.5	10	231	29
Step5	Right	2	8	281	28
Step6	Left	3	9	357	28
Step7	Right	3	7.5	427	28

Table 1: Measurements of gait parameters

4 Finite elements simulations

4.1 Light-weight floor studied

The modern light-weight timber framed construction contains many different components with various material characteristics. The aim of the structure borne-sound investigation is focused on the complicated junctions which gives a number of difficulties in the prediction calculations with traditional statistical energy analysis (SEA).

A finite element analysis of the vibration response from gait loading on a light weight floor structure was performed. The floor structure was assumed to be built up from seven wood beams with a cross section of 45x220 mm^2 at a spacing of 600 mm. The beams was assumed to be covered with a 22 mm thick particle board and two 12.5 mm plasterboards underneath the beams according to figure 3. The floor cavities were assumed to be open, so the air was not included in these simulations. If the cavities are closed or semi-open, the air will have a crucial impact on the vibrations levels and must then be included in the models. Moreover, if the cavities are filled with insulation this may complicate the model even further. The total size of the floor was 3x4 m^2 and it was assumed to be simply supported along the entire edge of the plasterboard. Analyses were performed for two gait patterns. The first was along the centre axis of the floor in the length direction and the second along a diagonal axis of the floor.

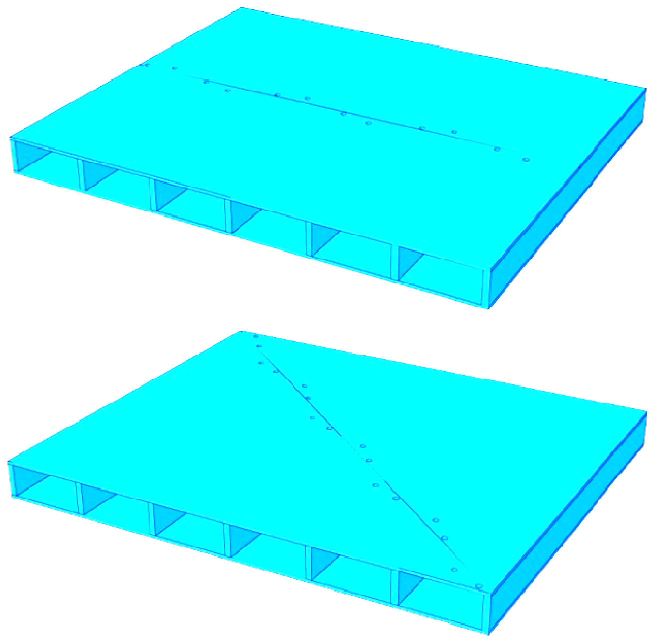

Fig. 3: The 3x4m2 floor structure. The circles indicate the position of the gait loading along the centre axis, above and along the diagonal axis, bottom.

The particle board and the plasterboard were modelled as linear elastic isotropic materials whereas the beams were modelled as a transversely isotropic linear elastic material with the third material axis in the longitudinal beam direction. The material properties and the densities of the various materials in the floor are given in table 2.

	Wood	Plasterboard	Particle board
E_{11} [MPa]	800	2000	3000
E_{33} [MPa]	13000	-	-
ν_{12}	0.21	0.2	0.35
ν_{23}	0.02	-	-
G_{13} [MPa]	750	-	-
ρ [kg/m^3]	470	720	600

Table 2: Material properties and densities for the various materials of the floor.

The two models were modelled with three-dimensional linear eight-node elements with an average size of approximately 10 mm. In total, the models contained about 360000 degrees of freedom. Damping of the floor was accounted for via a mass- and stiffness-proportional Rayleigh damping formulation where the damping ratio related to the first two eigenmodes was assumed to be 1%.

4.2 Gait loading

The time-history of the reaction forces from gait have been measured by several authors, [4, 5]. Based on those measurements, the loading from each foot was modelled by applying certain force amplitudes on two discrete circles

representing the heel and the forefoot. In figure 4 and 5, the time histories of complete gait cycles at a gait speed of 1.3 m/s for the left and right feet as well as the cycle for one foot subdivided into the time histories for the heel and forefoot are shown. In the simulations, the loads were applied at the discrete circles, representing the heel or forefoot, as forces on surfaces in the normal direction to the floor where the amplitude was calculated as a time history as shown in figure 5 times the bodyweight. A bodyweight of 75 kg was assumed in the simulations. Since the person walking on the floor was modelled as forces on surfaces, the influence of the mass and the damping of the person was not accounted for, a fact that might be of importance for a light-weight floor structure.
Full transient analyses were performed with a time-step of 0.002s. The analysis for the gait along the centre axis of the floor was performed for the duration of four seconds and for five seconds for the analysis along the diagonal axis of the floor.

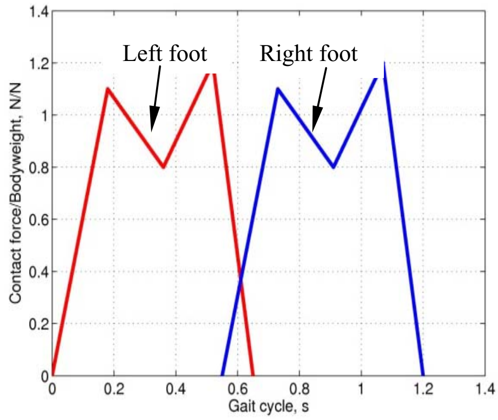

Fig. 4: The reaction force of a gait cycle for two steps

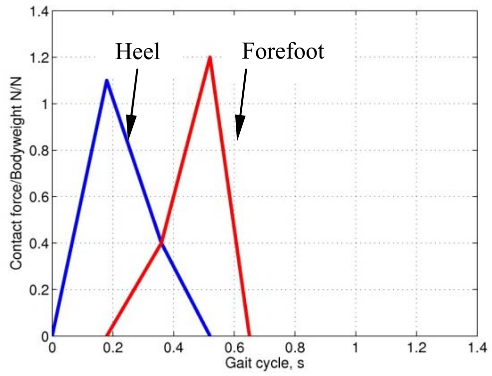

Fig. 5: The reaction force time-history for a step divided into separate time-histories for the heel and the forefoot.

5 Results

The mean velocities, $\langle v^2 \rangle$, in the direction normal to the floor were calculated for the two floor structures. For the two gait patterns, they are shown in figure 6 and 7, respectively. The graphics show that there is some difference in the partial energy distribution depending on how people are walking for instance in the middle of the floor or in the diagonal. For the diagonal gait pattern, the obtained mean velocity is markedly lower close to the corners of the floor, as expected, but at the centre the velocity is higher than for the gait pattern along the centre axis. The mean velocity obtained from the gait pattern along the centre axis is more even in amplitude.

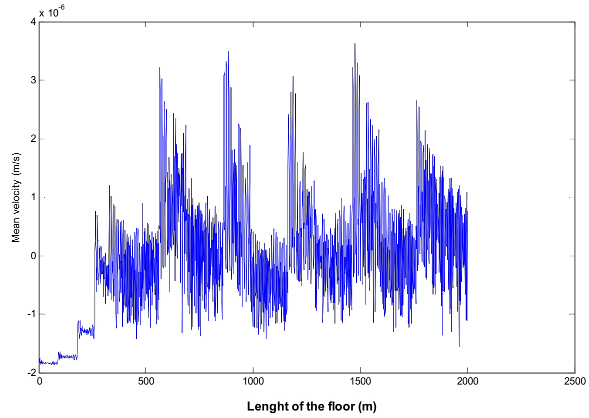

Fig. 6: Mean velocity of the floor from the gait loading along the centre axis of the floor.

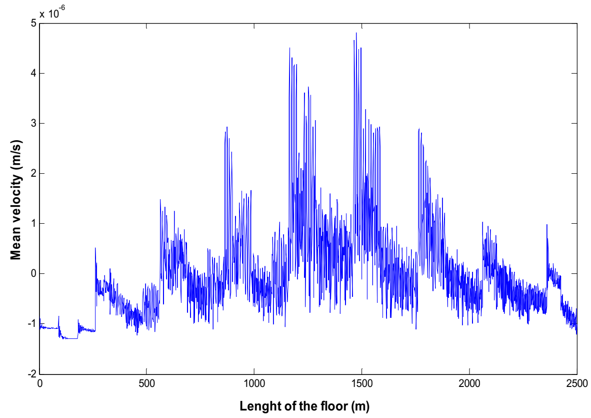

Fig. 7: Mean velocity of the floor obtained from the gait loading along the diagonal axis of the floor.

The acceleration induced by the footfall over the floor was calculated from the FEM simulations. The vibration level of the floor can be formulated by

$$R = 10 \log \frac{\langle v^2 \rangle}{v_{ref}^2} \qquad (1)$$

where $v_{ref} = 5 \cdot 10^{-8}$ is the reference velocity.

The vibration levels are plotted on third octave band for the two gait patterns as shown in figures 8 and 9.

The vibration level curves show that the energy distribution is more important at low frequency along the centre axis. The energy amplitude decreases with increasing frequency. This phenomenon illustrates the problems related to the flanking transmission.

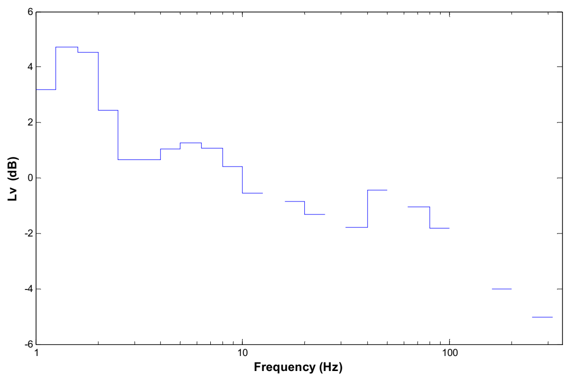

Fig. 8: Vibration level of the floor obtained from the gait loading along the centre axis of the floor.

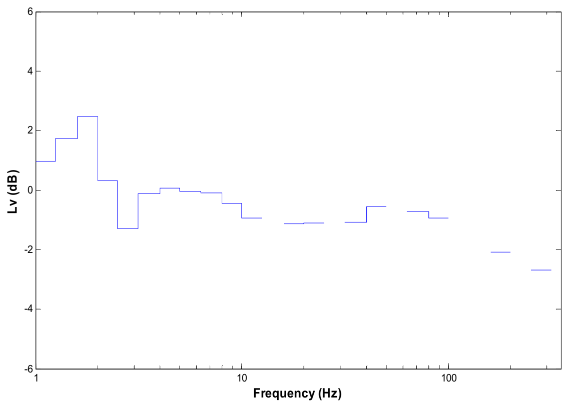

Fig. 9: Vibration level of the floor obtained from the gait loading along the diagonal axis of the floor.

Along the diagonal, the vibration level has an energy peak at low frequency too, but not so high. The slope of the vibration level is smoother also.

Due to the limited frequency coverage of the FE calculation some frequency bands are not taken into account and result in holes in the stairs graphics.

6 Conclusions

The analysis techniques presented in this paper show that how we walk in a room have a direct impact on the energy distribution. When we walk in the middle of the room the vibration level is higher as compared to walking along the diagonal. The main goal, however, is to be able to improve the sound insulation of light-weight structures built today. In such improvement work it is importance to have tools that are able to take into account as many factors as possible. By employing FE-modeling techniques together with evaluation procedures as those presented in this paper it is possible to take into account general loadings, geometries and material properties.

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