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Sound and Vibrations investigations in a multi-family wooden frame building

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ABSTRACT

Lightweight constructions made of timber material have a number of advantages; they could become cost effective in future and demand relatively short production duration. One of the main drawbacks of lightweight structures is related to sound transmission and vibrations. The differences in weight, density, stiffness and repartition compared to traditional materials have repercussions on how the sound propagates in the rooms and in the structures themselves. Sound and vibration transmissions become an increasing nuisance. In order to be able to reduce theses transmissions, a better understanding of how the sound propagates through a real wood cross junction and between floors is needed. The multi-family house in this study has eight storeys and contains 34 apartments. While the ground floor is cast in concrete, all the seven floors above are made of wood, what makes this building a perfect object of study for wood building elements. In this work, it was focused solely on the propagation of sound and vibration from one room on the first floor to the adjacent room on the same floor and to the two rooms above. The investigation was further extended to comparing the former results to the transmission taking place between the fourth and fifth floors. This investigation also included measurements of induced walking vibrations with real human walking and the mobility; those were performed on a wooden floor inside the timber building. The measurements of accelerations induced by a walking person were used to evaluate existing vibration criteria. The studies that have been led put in evidence the existence of complex phenomena taking place in lightweight buildings and confirm that current evaluation methods for the acoustic quality of lightweight constructions are not adapted to those structures. Thus, a reevaluation of the methods is needed, in order to cope with the increasing demand for lightweight constructions, and in order to avoid conceptual mistakes that would degrade their future reputation. This is exactly the main objective of the Swedish project AkuLite; develop new objective measures of assessing the acoustic and vibration quality, with the expected result that the experienced sound, vibration and springiness are not dependent of structural bearing system in the building any more.

INTRODUCTION

Lightweight constructions made of timber material could become cost effective in future and can be produced quickly. However, the differences in weight, density and stiffness compared to traditional materials are often the cause of more nuisances related to sound transmission. For high-rise wooden buildings the largest acoustical challenge is to determine how sound is transmitted and to control and reduce this transmission. Flanking transmission is of particular interest since it is necessary to increase the understanding of the sound transmission through the joints to connected flanking elements in light weight building structures. If the joints are not properly designed they become the origin of disturbances for the inhabitants. A study of the transmission properties of a wood cross junction in an actual multi-storey construction build on a wooden lightweight frame has been presented previously in [1]. The seven-storey multi-family house located in Växjö (named as “Limnologen”), Sweden, has been the object of in-situ measurements of the vibrations along the floor, ceiling and wall, in response to the excitation of a tapping machine. Arrays of accelerometers have been used to capture the vibration levels simultaneously.

Whereas for the former study focused solely on the propagation within one room or between adjacent rooms of the first and second floors, this study presents the outcome of measurements conducted on the fourth and fifth floors, and compared to the initial work with the new results

BUILDING UNDER TESTS

Site

The work presented here takes place in the Swedish wooden construction project of Välle Broar in Växjö, Sweden. Välle Broar is a part of the city where wood buildings are built with modern techniques, and the project Limnologen belongs to it. The aim is to develop the industrial building technique for houses built with wood, which is considered as an environmentally friendly material. The Limnologen buildings are the highest buildings in Sweden that are constructed with a load-bearing framework made of wood.

Structure

The ground floor is cast in concrete, but the rest of the bearing framework, seven floors, is entirely made of wood. The side of the building that is facing northeast has a glue-laminated timber facade (Figure 1) while the opposite side is covered with plaster. The façade of the topmost storey is made entirely of glue-laminated timber.

Figure 1. Facade facing southwest

The floor structure stretches between the exterior walls on the two long sides of the building. The top of the structure (Figure 2) consists of cross laminated (three layers) massive timber. The top structure is connected to glue laminated T beams and those together create a stiff timber I-beam construction, and stiffen the floor structure in its longitudinal direction. The ceiling is the lower part of the floor element, consisting of massive wood beams and battens which are orthogonal to each other. Two 13 mm gypsum boards are fastened on the battens. Between the beams, mineral wool fiber insulation is placed. The structural elements are produced in a standard width of 1200 mm.

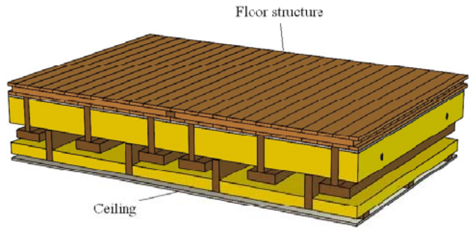

Figure 2. Floor and ceiling structures

The wall structure has been developed specially to minimize the sound transmission between two adjacent apartments, and has to fulfill the sound insulation requirements corresponding to sound class B according to SS 25267 (2004). The apartment separating wall is a part of the vertical bearing frame composed by studs with a center distance of 600 mm. A board is connected to the studs on top of which battens are fastened with a center distance of 450 mm. The outer parts facing the room consist of two gypsum boards. Between the beams, both between the studs and the battens, wool fiber insulation is applied. The wall is composed of two of those layers separated by a 20 mm air gap. This air gap prevents mechanical vibrations from transferring directly between adjacent walls [2]. Nevertheless, by statical reasons some connections exists at several points of the floor structures, hence adjacent apartments might transfer the horizontal forces in the building. As mentioned those connections are necessary from a static point of view, but normally detrimental with regard to sound insulation between apartments [3].

MEASUREMENTS SET UP

The investigated floor is situated in what will be the living-room in one of the apartments of the Limnologen buildings. This floor is the floor that most likely would have the worst vibration performance in the buildings, as the span width is 8 m. The width of the room is 3.7 m. Arrays of accelerometers were fixed tightly in place with screws on the floor that was investigated. The sensors were disposed along a line parallel to the walking direction, and with 65cm intervals between them.

In order to measure direct (1) and flanking (2) sound transmission through a wood cross junction (Figure 3), a tapping machine (illustrated on the top left room) was used as an excitation to deliver reproducible impacts while arrays of 16 accelerometers permitted the recording of the response. The accelerometers were re-located between successive measurements in order to determine the vibration pattern, at 4 different positions on the floor/wall/ceiling in each room.

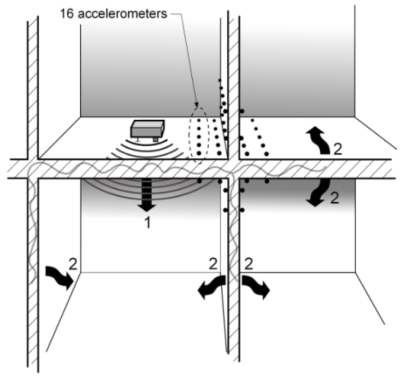

Figure 3. Measurement setup and representation of direct (1) and flanking transmission (2).

In the previous study, propagation between adjacent apartments on floors 1 and 2 has been investigated. The tapping machine is located on the second floor, on the left room. Measurements have been done in all four rooms, at the positions close to the junction under study: on the floor for the top rooms, at the ceiling for the bottom rooms, and on each side of he separating walls, either on top or bottom.

Now, floors 4 and 5 have been considered additionally. Therefore, the whole setup for the floors 1 and 2 has been reproduced identically for the floors 4 and 5, in order to compare the junction properties.

RESULTS: VIBRATIONS INDUCED BY HUMAN WALKING

Several recordings have been done with different persons walking on the floor, men and women, and of different age and weight. From each recording, the signals have been analyzed and the foot step impacts on the floor extracted and isolated. The accelerometer that has recorded the highest signal is retained and the corresponding data is further analyzed.

The third-octave frequency spectrum of the accelerometer signals has been extracted systematically for every step of the recorded sequence. The median curve of all valid steps for the chosen accelerometer has been plotted. On each graphic plot, the curve defined in the ISO 2631-2:1989 standard has been plotted for reference.

ISO 2631-2:1989 Standard

The title of the second part of ISO standard 2631 is Mechanical vibration and shock-Evaluation of human exposure to whole-body vibration- Part 2: Vibration in buildings (1 Hz to 80 Hz). This standard is applicable to the evaluation of vibration in buildings with respect to comfort and annoyance of the occupants; it is not applicable when investigating the effects of vibration on human health and safety. This former edition, though outdated, is interesting because tentative vibration limits are given in the form of base curves [7].

There is one base curve for vibration in the foot-to-head direction. This base curve represents vibration magnitudes that cause approximately the same annoyance. The second curve has the same shape, but a coefficient factor is applied, in order to take into account the different types of use. In this case, a factor of 4 has been chosen, corresponding to values typically applied for office space.

Datas

Time-domain signals

The figure 4 represents a typical recorded AC signal from an accelerometer, before it is converted to actual acceleration values. On can clearly notice the large peak, corresponding to the moment where the heel enters in contact with the floor, followed by a double peak in the opposite direction, as the foot is released from the floor, heel first, then the toe [6]. Finally, some oscillations subsist during a while after the impact, then decay.

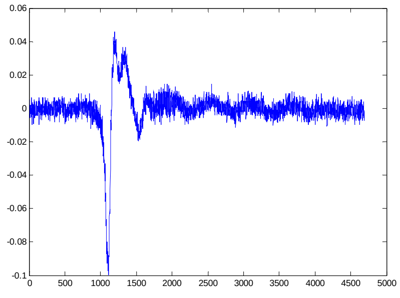

Figure 4. Time-domain signal, as recorded by an accelerometer, corresponding to the impact and release of a foot on the floor. The vertical scale represents the measured AC voltage, whereas the horizontal scale represents the sample count, with a sample rate of 9500 samples per second.

Third-octave frequency spectrum

The time-domain extract is put to the right scale, by taking into account the sensitivity of the sensor, and the signal is converted to its frequency-domain representation, using a third-octave scale. We will use the frequency range of 1Hz to 100Hz only, as the nuisances typically encountered by the inhabitants are predominantly in this range.

The first graphic (Figure 5) represents the results for the steps of the first author, Delphine, while walking along a line towards the middle of the floor. One can see that in the frequency range of 4-20Hz, the recorded acceleration levels are clearly above the ISO2631-2 shifted curve. This indicates that according to the standard the level of vibrations in this particular range will most probably be perceived as too high and disturbing by the inhabitants.

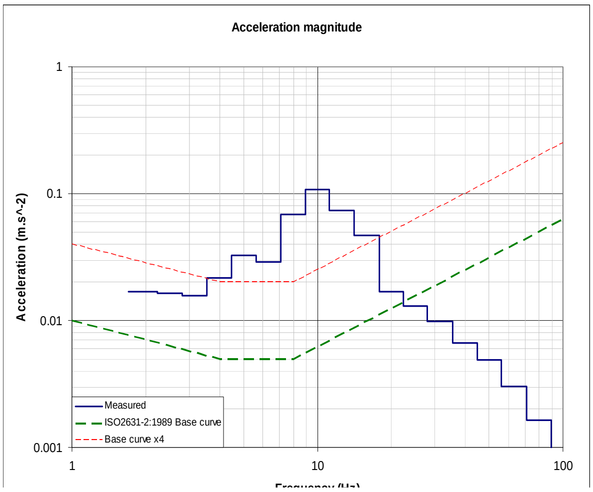

Figure 5. Delphine's acceleration magnitudes in 1/3 octave bands. The diagram also shows the base curve of ISO 2631-2:1989, and its shifted curve, with a factor of four.

The second graphic (Figure 6) originates from the same location, but this time, another female, is walking. Whereas the maximum acceleration remains almost identical, it appears that the frequency distribution is slightly different, with more energy in the lower frequencies (4-8Hz), probably reflecting a different way to put her foot on the floor and to release it. In any case, the measured levels still lay above the shifted ISO curve in the same frequency range.

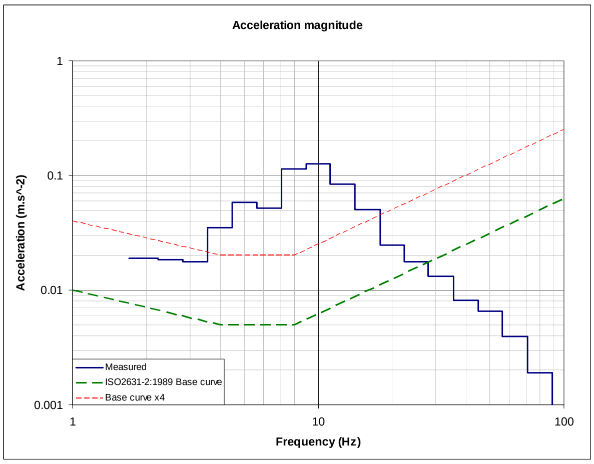

Figure 6. Second female acceleration magnitudes.

Finally, the third graphic (Figure 7) still corresponds to the same walking path, but this time, a man is walking. Whereas the maximum acceleration remains again almost identical, it appears that the peak position is slightly shifted towards the lower frequencies, probably due to the higher weight, and a different body mass distribution. Nevertheless, the previous remarks about the ISO shifted curve still apply here.

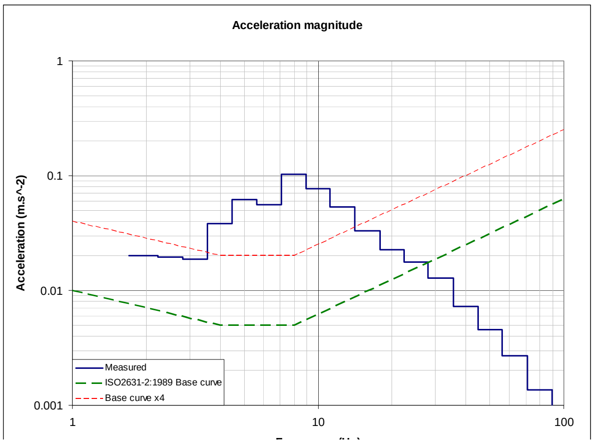

Figure 7. Man acceleration magnitudes.

RESULTS: ATTENUATION

For a more thorough analysis, the third-octave frequency spectrum of the accelerometer signals has now been extracted systematically. For each measurement, the spectra originating from the simultaneous recording of the 16 accelerometers have been analyzed statistically and the maximum, minimum, average, median, 95% and 5% percentile have been calculated for each frequency band. As a good compromise between clarity and accuracy, it has been chosen to represent on the following graphics only the median and the 5%-95% percentiles, constituting the confidence interval.

The following sections present a reference measurement, then a series of attenuation results, for different configurations, and compared between floors 1, 2 and 4, 5.

Reference

As a reference, and in order to understand the typical spectral distribution of the impact created by the tapping machine, a representation of the acceleration frequency spectrum near the tapping machine is given in figure 8. The 16 accelerometers have been placed along the wall at the second floor in the room where the tapping machine is operating, at a distance of 5cm from the wall, (labeled "A" in Figure 3).

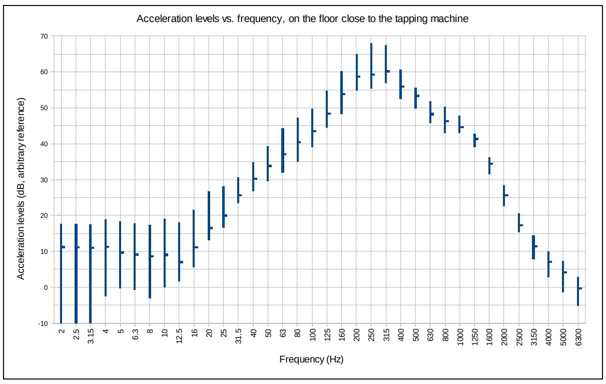

Figure 8. Frequency spectrum of the acceleration recorded by an array of 16 sensors placed on the floor, along the wall, in the same room as the tapping machine, on floor 2 (room "A"). This spectrum serves as the reference for the attenuations calculated for floors 1 and 2. The horizontal segment indicates the median value, whereas the vertical line indicates the extent of the 5%-95% confidence interval.

As it is shown in figure 8, the energy is mainly spread from a frequency of 100 Hz to 1000 Hz, with the peak around 300 Hz. This spectrum will serve as a reference for the attenuation calculations for the measurements made on floors 1 and 2. A similar reference has been extracted for floors 4 and 5, with the tapping machine located on floor 5.

Floor attenuation between adjacent rooms, same floor

The attenuation of noise level is defined as the difference in dB between the spectrum measured at a given place and the reference measurement. In this first configuration the difference between the reference room "A" (where the vibration source is located) and data measured with the accelerometers fixed on the floor (along the wall) in the adjacent room "B" is calculated. The vibration path considered is therefore horizontal, through the junction. Exactly the same configuration is repeated at the fifth floor. Both results are shown side by side on Figures 9 and 10.

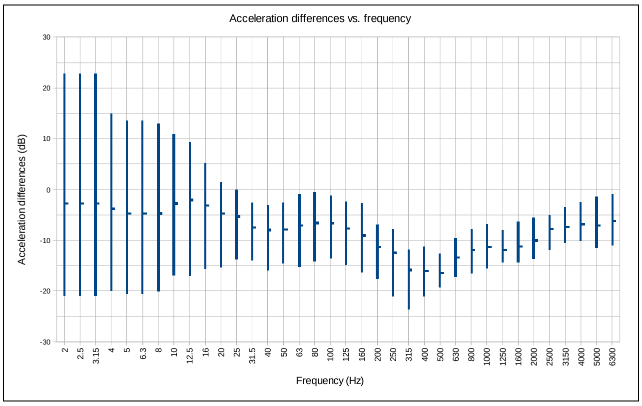

Figure 9. Median and confidence interval for the attenuation of vibrations from the room "A" to the adjacent room "B". The sensors are fixed on the floor, along the wall: Floor 2

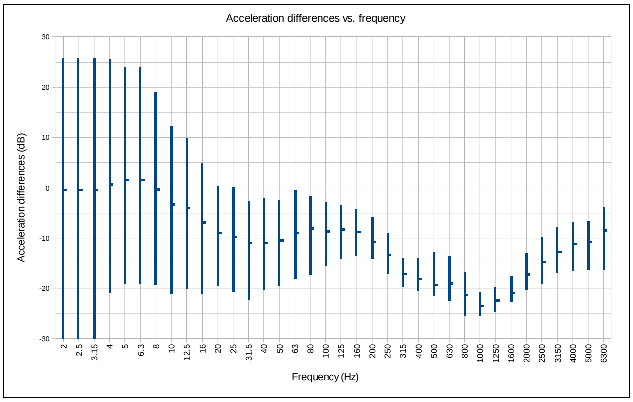

Figure 10. Median and confidence interval for the attenuation of vibrations from the room "A" to the adjacent room "B". The sensors are fixed on the floor, along the wall: Floor 5.

Differences are clearly noticed, with respect to the high frequency and the low frequency attenuation in both cases. On the fifth floor (right figure), the higher frequencies (where the energy is mainly concentrated), is very well attenuated, maximum -23 dB attenuation at a frequency of 1 kHz. At floor 2 (left figure), an attenuation of -16 dB is achieved at 500 Hz, and the attenuation at 1 kHz is not more than -12 dB. For low frequencies (around 40 Hz) the attenuation at floor level between two adjacent rooms is about 3-4 dB better on fifth floor.

At the extreme low frequency range (less than 10 Hz) the vibrations are however better attenuated on floor 2 than on floor 5. One plausible explanation for this difference is that the pressure applied on the junction, resulting from the cumulated weight of the structure situated *above* the junction, is much lower in the case of the measurement at the fifth floor than it is on the second floor. Therefore, the upper floors exhibit more the typical behavior of the lightweight structure.

Floor-ceiling attenuation

The second comparison focuses on the attenuation of the vibrations through the ceiling. Hence, the vibration levels between room "D" and the levels in the reference room, which is just above, are compared. The sensors in room "D" are fixed on the ceiling, at a distance of 5 cm from the wall, directly underneath the sensor positions of the reference room "A". The vibration path is therefore a direct path through the floor/ceiling element. The results are presented in Figures 11 & 12, where again Fig.11 view corresponds to the lower floors (1 and 2) and Fig. 12 to the upper floors (4 and 5).

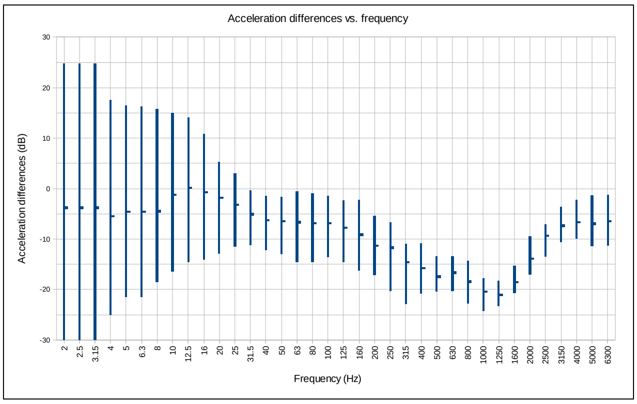

Figure 11. Median and confidence interval for the attenuation of vibrations from the room "A" to the room "D" below. The sensors are fixed on the ceiling of room "D", along the wall: Floor 1.

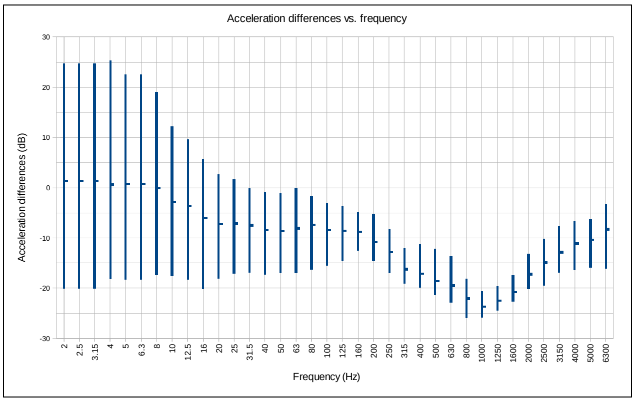

Figure 12. Median and confidence interval for the attenuation of vibrations from the room "A" to the room "D" below. The sensors are fixed on the ceiling of room "D", along the wall: Floor 4.

Here, the difference is not as dramatic as in section 4.2, but the same general tendency can be observed. The floor/ceiling building elements perform better between the fourth and fifth storeys than they do between the first and second. A difference of 2-3 dB is observed all over the frequency spectrum, except the extreme low frequency range, where again, the lower floor performs better by about 5 dB.

Attenuation versus room below, measured along the wall

This last result finally confirms what earlier was observed with the first two. Here, the reference is still the same, and still the vibration levels are measured in the room "D" below, but the accelerometers are now fixed on the wall, at a distance of 10 cm from the ceiling. This means that the same vibration path is not considered any more. Currently, the vibrations propagating horizontally from the floor to the junction, and are then transmitted vertically down to the wall below, is considered. The results are shown on Figures 13 & 14.

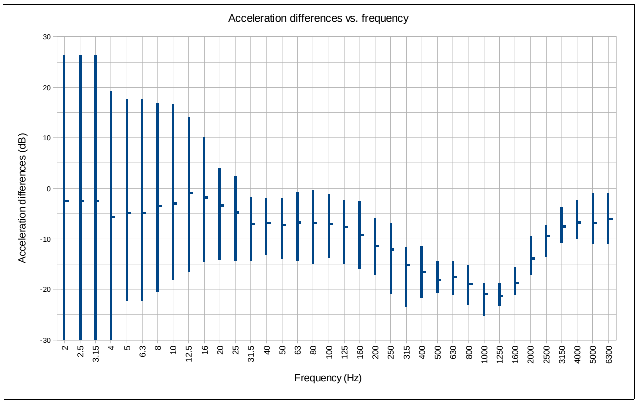

Figure 13. Median and confidence interval for the attenuation of vibrations from the room "A" to the room "D" below. The sensors are fixed on the wall of room "D", along the ceiling: Floor 1.

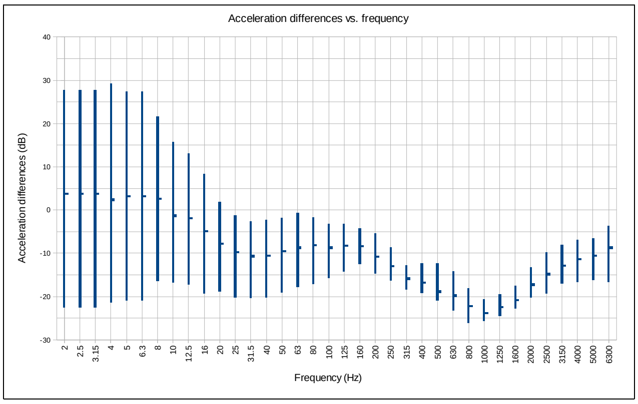

Figure 14. Median and confidence interval for the attenuation of vibrations from the room "A" to the room "D" below. The sensors are fixed on the wall of room "D", along the ceiling: Floor 4.

The extreme low frequency behavior did not change, and lower floors still perform better. From 10 Hz and above, the tendency observed earlier when measuring on the ceiling is hereby confirmed. The upper floor performs better than the lower floor in terms of vibration attenuation by up to 2-3 dB all over the frequency spectrum.

Discussion

From the vibration attenuation spectra, and even more from the comparisons that have been made between the lower and upper floors, a general observation could be made. The upper floors perform better in terms of vibration attenuation than the lower floors, except for the very low frequencies (<10Hz), where the tendency is opposite. This trend can be observed the most in the case of a horizontal vibration path through the junction (floor to floor, section 4.2). For the horizontal-vertical path through the junction (floor to wall), the difference is more moderate. The comparison presented in the section ‘’Floor-ceiling attenuation’’ shows the least difference, but in that case, the junction is not involved, as the vibration path goes directly through the floor/ceiling building element. One way to explain the differences in behavior of the wooden building junction would be to consider the accumulated weight of the building elements on top of the junction, that apply a large pressure on it. The lower the junction, the more elements it supports, and the higher the pressure. Therefore, it is reasonable to think that the junction located between floors 1 and 2 presents less elasticity than the one between the floors 4 and 5, because of the higher constraints that are applied to it.

CONCLUSIONS

A presentation of vibrations measurements induced by foot step impact on a floor in a lightweight structure building has been made. The results corresponding to several persons and along different walk paths have been presented. The measurements suggest that the frequency distribution of the vibrations varies slightly depending on the tested person. In particular, a heavier person seems to cause more vibrations in the lower frequency range (4-8Hz). On another side, the highest level of vibrations seems to be rather independent of the person or path. But above all, it is observed that in all three cases, and despite the different morphologies and physical characteristics of the “test walkers”, the recorded acceleration level lies above the limit suggested by the ISO2631-2 limit, within the frequency range of 4 to 20Hz.

An analytic presentation of extensive vibration measurements has been made, in order to compare the behavior of wooden building junctions, depending on their position in the building. It has been clearly shown that the same junction performs better in attenuating vibrations when used at higher floors, compared to lower floors. This behavior has been observed to be consistent all over the spectrum, except for extreme low frequencies, where the opposite is observed. It is suggested that the differences observed and measured could be explained by the different load that is applied on the junction, depending if it is used in lower or higher floors. It might be worthwhile to consider this relationship during the design phase of lightweight wooden frame buildings, as it has been proven that the vibration attenuation performances are affected. Junctions of different sections might for example be used throughout the building, depending on the load they have to support

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