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SUBJECTIVE EVALUATION OF IMPACT SOUND FROM FOOTSTEPS

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ABSTRACT

Low-frequency impact sound caused by upstairs neighbors walking on the floor is a key acoustic challenge regarding lightweight floors and a major source of disturbance particularly in wooden buildings. To investigate the effect of floor design on the perceived walking sound, a virtual design tool has been developed, which allows for auralising the impact sounds containing low frequencies down to 20 Hz. Using this tool, footstep sounds on 10 different lightweight floors were auralised by a loudspeaker grid mounted in the ceiling of an acoustically controlled lab, which is furnished as a common living room. The walking sounds were subjectively evaluated through listening tests while the subjects were sitting freely on a sofa without needing to use any extra listening equipment. The listening test results suggest that loudness, thumpiness and reverberation are correlated with the perceived annoyance. The results also indicate a correlation between annoyance and age as well as the individual experience of earlier exposure to noise.

Keywords: *impact sound, footsteps, lightweight floor, annoyance*

1. INTRODUCTION

The building sector is globally known as one of the major sources of greenhouse gas emissions by accounting for almost 40% of global CO2 emissions [1]. In recent years, there has been an increasing focus on using wood as a main building material for building frames and components due to its renewability and carbon-neutrality. In Sweden, building mid and high-rise buildings in wood has been identified as one of the effective solutions to reduce the carbon emissions of the building industry while meeting the sustainable development needs of cities and communities [2].

However, ever since 90s when multistorey wooden buildings became permitted in Sweden, the noise issues, especially footstep noise from neighbors, have been the cause of many residents' complaints and a source of concern for the wooden building industry. A series of survey-based studies were conducted in Sweden between years 2010 and 2022, which investigated the perceived acoustic performance of a variety of modern residential buildings, including 28 wooden buildings [3]. The results show that in half of the studied wooden buildings, 30 % up to 67 % of the residents who participated in the study, were moderately to highly annoyed by the footstep noise from their neighbors. This is while all these buildings had fulfilled the minimum requirement or higher sound classes according to the Swedish national building regulations, and the minimum requirements in Sweden are designed to ensure that more than 80 % of the building residents are not disturbed by noise [4].

Today, the wooden building industry pays high costs for preventing the low-frequency impact noise problems in multi-family wooden buildings. These costs are in different forms such as over-dimensioning the thickness of the floor, building prototypes for testing or spending large amounts of money to fix the floors installed in a finalized building. Apart from the economic costs, these solutions require

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using extra materials and resources, which makes the solutions less sustainable.

An extensive interview series with various stakeholders in the Swedish wooden building industry, including property owners, building element manufacturers, consultants, and researchers, highlighted two of the most pressing acoustic challenges for the industry: impact sound insulation at low frequencies and lack of reliable prediction tools for sound insulation at low frequencies. In addition, the weak link between residents' complaints and fulfilling building requirements was identified as another significant problem that the industry is facing with [5]. Even when the most recent proposal for the single number rating of impact sound, tailored to adapt to the performance of lightweight floors, is used, no more than 60 % correlation between resident's responses and standard evaluations has been achieved [3]. A major source of such low correlation can be the reliance of these single number rating proposals to survey evaluations as the background information such as living habits of neighbors, timing and duration of exposure to noise, survey timing, and room dimensions are not taken into account in the surveys. These factors may significantly affect participants' responses, making it difficult to determine which factors dominate each participant's answer.

To address the challenges that wooden building industry faces in mitigating low-frequency impact sound, the virtual design tool developed in [6] offers a potential solution. This tool allows for investigating subjective response to impact sound of different floors under controlled conditions and already in the design phase. In this study, the virtual design tool has been used to examine how different design parameters of 10 model floors influence subjective responses to walking sound. Subjective evaluations have been conducted by listening tests in an acoustically controlled living room laboratory, using the same walking sound samples. As a result, any variations in subjective responses can be attributed solely to the differences in floor design and the range of perceptions among the subjects.

2. METHOD

The virtual design tool developed for low frequency impact sound is based on using a loudspeaker grid which reproduces the same volume velocity as of a vibrating floor excited by impact forces. The design tool consists of four parts:

- Impact force description

To simulate the impact sound on a floor structure, the first step is to obtain the impact force signals. For walking sound simulations, the walking force data were obtained using measurements of a real walker on a lightweight floor structure built according to the reference floor No. 2 in ISO 10140-5:2010. The force signals were measured using an inverse measurement method based on LMS algorithm in the time domain. The measurement method development procedure and examples of different walking forces are presented in [7, 8].

- Floor model

The virtual design tool allows for using both analytical and numerical floor models. In this study, the floor models are generated using a modal approach for a prestressed, simply supported, orthotropic plate (see [9]).

- Auralisation technique

The low-frequency impact sound is auralised by simulating the volume velocity of the vibrating floor structure using a combination of twenty mid-to-high frequency loudspeakers and four subwoofers mounted in the ceiling of the listening room. The Genelec 8020B loudspeakers have a frequency range of 66 – 21000 Hz and are arranged in a 5×4 grid, and the Neumann KH805 active subwoofers have a frequency range of 18 – 350 Hz and are mounted in the four corners of the ceiling. A digital crossover filter with a cut-off frequency of 70 Hz was used to separate the signals from the two types of loudspeakers.

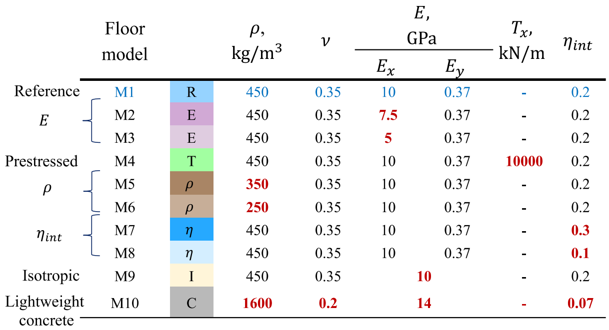
- Listening room

The listening room has the dimensions L×W×H=4.8m×3.73m×3.6m. Aiming to create a more realistic impression, the room is furnished as a common living room.

More details about the auralisation method and the listening room construction can be found in [6, 9].

3. STUDIED CASES

To investigate the relationship between the floor properties and perception of walking sound, 10 different floors were investigated. The floors had all the same dimensions l×w×h=4800mm×3730mm×100mm, but their structural parameters such as density, Poisson's ratio, Young's modulus, tensile prestress and damping were varied to generate different structures. The material data of the floors are shown in Figure 1. Floor sample M1 is the reference floor having the material properties of a typical 3-ply CLT plate with rather low impact sound insulation.



	Floor model		ρ, kg/m^3	ν	E, GPa		T_x, kN/m	η_{int}
					E_x	E_y		
Reference	M1	R	450	0.35	10	0.37	-	0.2
E	M2	E	450	0.35	**7.5**	0.37	-	0.2
	M3	E	450	0.35	**5**	0.37	-	0.2
Prestressed	M4	T	450	0.35	10	0.37	**10000**	0.2
ρ	M5	ρ	**350**	0.35	10	0.37	-	0.2
	M6	ρ	**250**	0.35	10	0.37	-	0.2
η_{int}	M7	η	450	0.35	10	0.37	-	**0.3**
	M8	η	450	0.35	10	0.37	-	**0.1**
Isotropic	M9	I	450	0.35	**10**		-	0.2
Lightweight concrete	M10	C	**1600**	**0.2**	**14**		-	**0.07**

Figure 1. Material data of the floor models

To generate floor samples M2 and M3, the Young's modulus in the stiffer direction of the reference floor was reduced, and floors M5 and M6 were made lighter in comparison with the M1 by reducing the density. For floors M7 and M8, the damping was increased and decreased respectively. The remaining three floor samples were not generated by systematic material parameter variations as the other floors. For M4, prestress was added to the reference floor along its length, while M9 was modelled as an isotropic floor with high stiffness in both directions, and M10 was given the material properties of a lightweight concrete floor. Figure 2 shows the calculated driving point mobility of the 10 floor samples in the frequency range of 10-150 Hz. For comparison, an example of measured driving point mobility for a lightweight wooden joist floor, with the same length and width dimensions as the model floors, is also demonstrated in Figure 2.

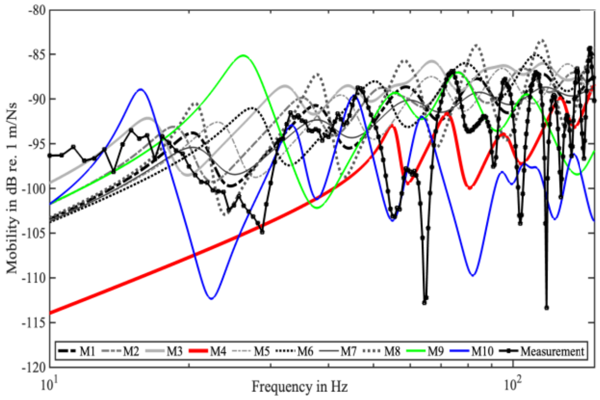


Figure 2. Driving point mobility at position (x,y)=(0.8,3) m.

For exciting the floors, a walking scenario consisting of 5 walking paths and a sequence of 21 steps were generated, see Figure 3. Footstep force signals for a barefoot walker were used as excitation, because barefoot walking has shown to have more audible low-frequency content and has often been reported as the main source of disturbance in wooden buildings [10]. The heel impact contains the main part of the excitation energy and is dominated by frequencies below 100 Hz.

The sequence of force signals that are used for exciting the floor samples is shown in Figure 4.

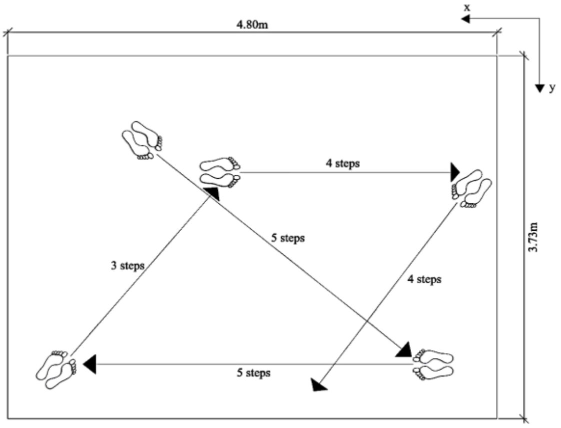


Figure 3. Walking path used for exciting the model floors

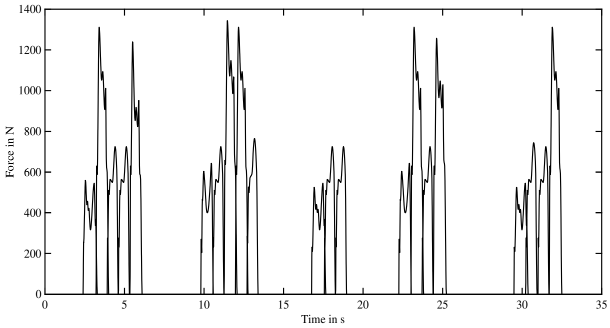


Figure 4. A sequence of 21 footstep forces used for exciting the floors

To generate the input signals for loudspeakers in order to auralise walking sounds, a multi-step method was applied. Initially, the force signals were transformed into the frequency domain, and using the modal approach, the vibrational response of the dense grid of the floor was calculated. Subsequently, the velocity signal of the floor was obtained by transforming back into the time domain. To determine the required volume velocity for each loudspeaker, the floor was divided into 20 subareas, each corresponding to a specific loudspeaker, and the mesh grids within each subarea were integrated. The result of this integration yielded the necessary volume velocity for each loudspeaker. Similarly, for the subwoofers the floor was segmented into four subareas, and the low-frequency volume velocity of the floor was mapped to the corresponding subwoofers using the same approach. In this way the radiation of the floor is captured as along as the spatial resolution given by the loudspeakers is sufficient to represent the modes involved in the vibration of the floor.

4. LISTENING TESTS

4.1 Design of the listening test

The auralised walking sounds for the ten floor samples were used in a listening test conducted at Chalmers living room lab. The subjective response to walking sounds from different floors was studied using semantic differentials. Adjectives used in the semantic scales were chosen to reflect various characteristics of the sample floors as well as the general perception of the walking sound. In the test, both bipolar and artificial bipolar semantic scales were used. For example, to evaluate loudness a bipolar scale featuring the adjectives ‘Low’ and ‘High’ was applied, whereas for assessing annoyance, an artificial bipolar scale ranging from ‘Not annoying’ to ‘Very annoying’ was used. The rating scales consisted of 7 equidistant steps, with a range of 1 to 7. A list of the attributes and their range are presented in Table 1.

Table 1. List of attributes used in the listening test and their range

Attribute	*Range*	
Loudness	Low	High
Distinctness	Not distinct	Very distinct
Thumping	Not thumping	Very thumping
Reverberation	Not reverberant	Very reverberant
Annoyance	Not annoying	Very annoying
Naturalness (plausibility)	Artificial	Natural

The auralisation method applied in this study is not limited to any particular listening position. However, due to the large variations of the sound field at low frequencies, it was necessary to select a sitting position for the listeners to ensure the comparability of the responses. The selected position was on the sofa in front of the TV, and it was chosen to represent a real-life case at home. The only consideration for the sitting position was to be away from the center and the corners of the room, where the probability of exposure to the minimum or the maximum sound pressure levels in the room is higher.

The sound samples were played in random order twice, and the subjects answered to the questions using a computer interface. The subjects had control over the playback of the sounds, including the possibility to pause the sound or go to the next sample, via the controls in the computer interface.

4.2 Test subjects

The test involved fifty participants, consisting of 20 females and 30 males, with an age distribution as shown in Figure 5. The participants had different backgrounds regarding their experience of wooden buildings and earlier exposure to walking sound. Nineteen of the participants were living in wooden buildings or had lived in such buildings earlier in their life, while 31 participants had only lived in concrete buildings. Out of all the participants, 42 reported having experienced disturbance by walking sound at some point in their lives, whereas only 8 participants stated that they had never been disturbed by walking sound.

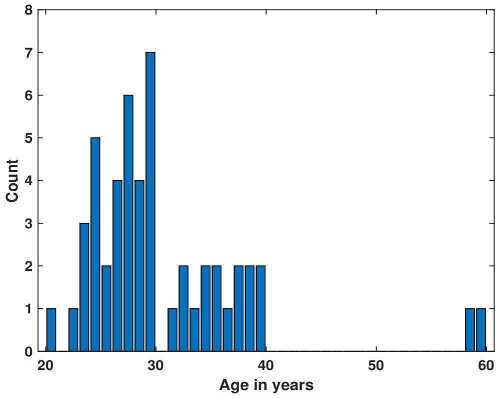


Figure 5. Age distribution among the test subjects

4.3 Listening test results

The perceived annoyance by the walking sound shows strong correlation with loudness, thumping and reverberation, while distinctness does not seem to have the same influence on the annoyance. The coefficient of determination R^2 for the different attributes is given in Table 2.

Table 2. Correlation between annoyance and different walking sound attributes

R^2
(p-values)

	Loudness	Thumping	Reverberation	Distinctness
Annoyance	**97 %** ($2.3e^{-7}$)	**98 %** ($3.4e^{-8}$)	**80 %** ($3e^{-4}$)	**57 %** ($7e^{-3}$)

Figure 6 shows how judgement of annoyance varies with respect to the perceived loudness, thumping and reverberation. The correlation, however, does not necessarily mean that the annoyance can be explained by these three attributes, but rather that e.g. loudness could be used to predict annoyance.

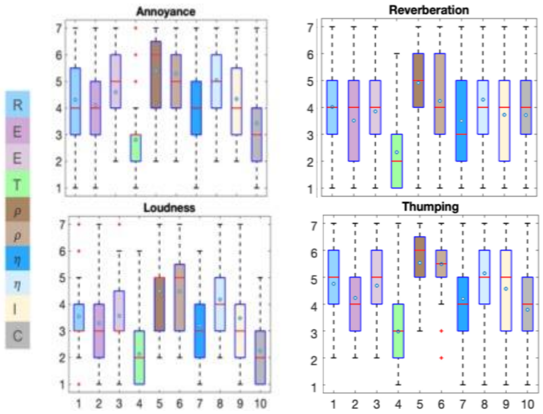


Figure 6. Annoyance, loudness, thumping and reverberation judgements for the investigated floors

The lightweight concrete floor (M10) and the prestressed floor (M4) have the lowest average ratings in loudness and annoyance. M4 also has the lowest average ratings in reverberation and thumping. The low subjective ratings of the concrete floor can be explained by its high mass and bending stiffness, which result in a generally lower vibrational response compared to the lightweight wooden floor samples. The lower annoyance rating for the prestressed floor could be due to the first eigenfrequency of the floor which is shifted up to about 60 Hz, while the first resonance for all the other floor samples is around 20 Hz, as shown in Figure 2.

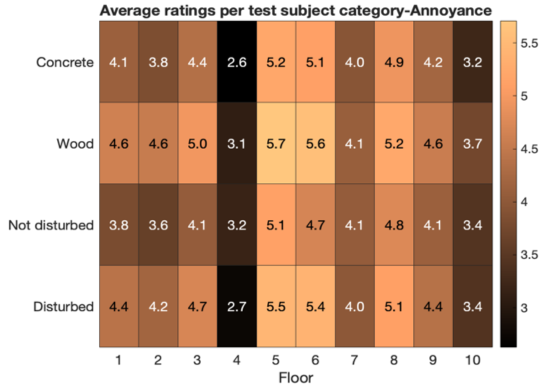
Among the investigated structural parameters, the mass and the damping show a more noticeable effect on the perceived attributes of the floors. For floors M5 and M6, reducing the mass resulted in an increase in the average ratings of loudness, thumping and annoyance, while for floor sample M7, a drastic increase of damping reduced the perceived loudness and annoyance, and vice versa for M8.

The judgement of distinctness did not seem to be influenced by the variations in the floor structure parameters, nor did it show any correlation with the other subjective attributes. Therefore, distinctness is no further discussed in the analysis of the listening test results in this paper.

Despite the identified effects of density and damping on the perceived walking sounds, to make a more general judgement about the influence of floor design parameters on the perceived qualities of the impact sound, more floor samples and a more thorough parameter study is required, which is outside the scope of this study.

To study the potential impact of individual differences and background of the participants on the results, the subjects were categorized into different groups based on their gender, age and experience with different buildings and walking noise, and the collected data were analysed accordingly.

According to the evaluations, the subjects who had prior experience of living in wooden buildings, had higher loudness and annoyance ratings for all the sounds compared to those who had only lived in concrete buildings, as depicted in Figure 7 and Figure 8. The former group also tended to judge the sounds as more natural as shown in Figure 9. However, the individuals with experience from concrete houses found the sounds from prestressed floor (M4), concrete floor (M10) and the highly damped floor (M7) more natural compared to those with experience of living in wooden buildings.



	1	2	3	4	5	6	7	8	9	10
Concrete	4.1	3.8	4.4	2.6	5.2	5.1	4.0	4.9	4.2	3.2
Wood	4.6	4.6	5.0	3.1	5.7	5.6	4.1	5.2	4.6	3.7
Not disturbed	3.8	3.6	4.1	3.2	5.1	4.7	4.1	4.8	4.1	3.4
Disturbed	4.4	4.2	4.7	2.7	5.5	5.4	4.0	5.1	4.4	3.4

Figure 7. Annoyance judged by different groups with different experience of floor type and disturbance by walking sound

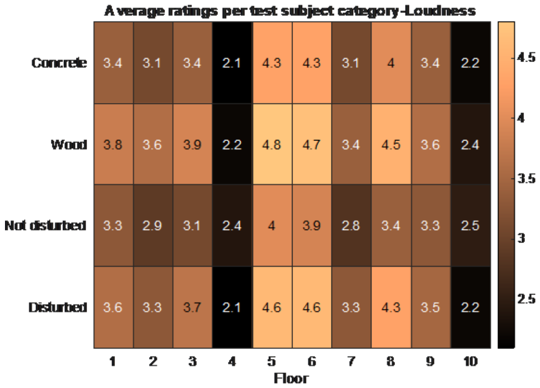


Figure 8. Loudness judged by different groups with different experience of floor type and disturbance by walking sound

Among the two groups with different backgrounds of familiarity with the walking sound, the paticipants who had previously experienced disturbance from walking sound, had the tendency to rate the walking sounds as more natural and more annoying compared to those who had never been disturbed by walking sound, as illustrated in Figure 7 and Figure 9. However, the former group found the prestressed, concrete and highly damped floors to be less annoying compared with the latter group. Interestingly, the differences in judgements between these two groups were minimal for the concrete floor. The prestressed floor was judged as significantly more natural and less loud and annoying by the previously disturbed listeners than the other floors. It was in fact the only floor sample that received a lower annoyance rating from the experienced subjects than from the unexperienced ones.

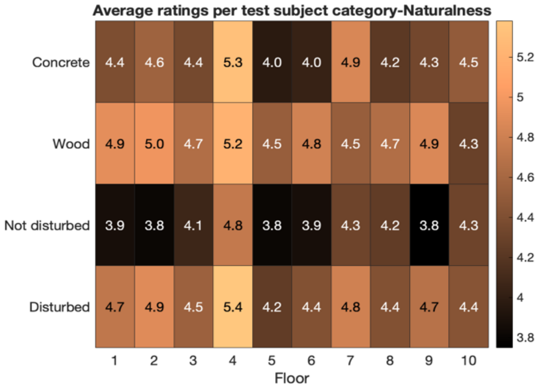


Figure 9. Naturalness judged by different groups with different experience of floor type and disturbance by walking sound

Evaluating the annoyance judged by different genders, as presented in Figure 10, does not show any systematic difference between the male and female participants. However, comparing different age categories indicate an increase of annoyance ratings with increasing the age. The responses from the youngest and the oldest subjects were significantly different. The rating of loudness also increased among the two higher age categories, as shown in Figure 11, but the differences between the groups are not statistically significant.

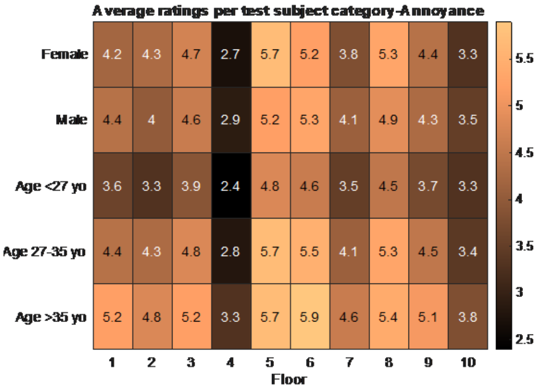


Figure 10. Annoyance judged by different groups for different floors

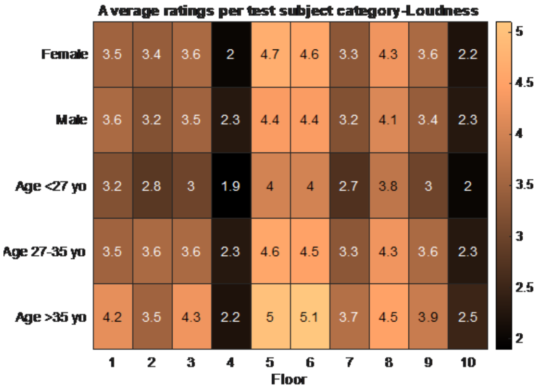


Figure 11. Loudness judged by different groups for different floors

5. CONCLUSIONS

A virtual design tool for impact sound, which has been developed by the authors, has been applied for subjective evaluation of walking sounds on various lightweight floors. This tool allows for controlled subjective evaluations, while creating a realistic living room experience in a listening laboratory. The tool enables investigation of the effect of floor design on perception and facilitates testing and optimizing floor structures in the design phase. This approach results in time and resource savings and promotes sustainable and cost-effective innovation.

The findings of the study confirm the importance of loudness for characterization of subjective response to impact sound, but also demonstrate a strong correlation between reverberation and thumpiness of walking sound and the perceived annoyance. The results also suggest that individual differences, such as age and previous experience of disturbance by impact sound, systematically influence the study outcomes. Therefore, it is necessary to identify such determining factors in subjective evaluations of impact sound and consider these factors when making decisions regarding changes in building standards and requirement levels.

6. AKNOWLEDGEMENTS

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