Acoutect Demonstrator for Lightweight constructions

Perceptual based design for reduction of annoyance caused by washing machine installed on a timber floor

January, 2021

Alessia Frescura
Carmen Rosas-Pérez
Xiaoxue Shen
Antonio Sorrentino

Table of contents

ACOUTECT

CHAPTER 1

Problem definition

Lightweight buildings are increasingly popular in Europe due to their modular design which has less waste and impact on site, lower carbon footprint, speed of construction and flexibility in the design of spaces. However, the inherent lightening of its structure affects sound and vibration insulation properties especially at low frequencies; it causes annoyance on both users and neighbours and even health problems, e.g. sleep disturbance at night and cardiovascular disease in the long run.

In contemporary modular lightweight construction, washing machines represent a difficult equipment to isolate, due to their complex dynamic behaviour and the variety of phases during their working cycle. In dealing with in-situ problems, structural information such as the joist spacing and position are “hidden” or not directly available. These factors make it difficult to rectify an acoustic problem that reduces the quality of life at home ultimately leading to negative impact on people’s health and wellbeing. This project targets the reduction of the annoyance caused by washing machines in lightweight structures, mixing subjective evaluation and technical characterization of the source.

Occurrence of the problem

Noisy washing machines is a popular issue all around Europe as can be seen from a survey shown in Fig. 1. In some European countries, such as the Scandinavian countries, washing ma-

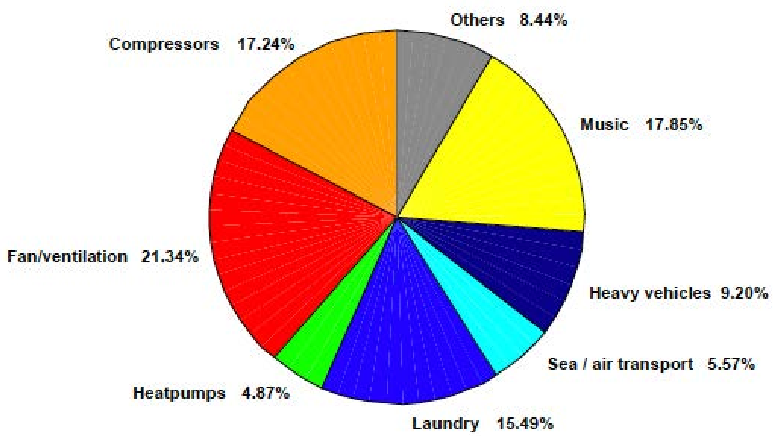

Figure 1: Percentage of sources causing complaints among municipalities in Sweden.

chines are shared among tenants of the same building and placed in the basement, trying to reduce the occurrence of the annoyance caused by their noise. But on a survey investigating low frequency noise nuisances in Sweden (Persson-Waye and Bengtsson, 2002), noise from laundry rooms was the fourth major source of complaints, being above heavy traffic vehicles (figure 1).

In other countries such as United Kingdom and the Netherlands the trend is different, the percentage of households with washing machines is increasing. For instance, a study to mark the first ever National Quiet Day has revealed the washing machine as the biggest noise-nuisance appliance in the UK home. In a national survey of two thousand adults conducted in 2016, it was found that over 47% of the people consider the washing machine to be the noisiest appliance. In the Netherlands noise from neighbouring dwellings can be heard in approximately 75% of dwellings. In approximately one third of all households at least some level of annoyance is experienced from washing machine noise; in approximately 13% to a severe extent. Results from a study by TNO, the Netherlands, show that noise from washing machines is heard at lease monthly by 28% of the population, of which 31% perceive some annoyance and 8% perceive severe annoyance. This noise is ranked 11th in terms of priority of hearing.

State-of-art

Solutions for machinery noise are more complex as the machinery source and the structural receiver cannot be assessed separately. A common approach is to place rubber pads or vibration isolators underneath the washing machine's feet in order to decouple the systems. These materials, if not chosen properly, can be ineffective in the range of frequencies which cause major annoyance. Referring to a low-frequency problem, the stiffening of the floor could be beneficial but this could drive to an increase of mass as well, not always appreciated in a lightweight environment. In case of inhomogeneous lightweight structures such as a wooden joists floor, the contact point properties can change widely between the joists' areas and the areas between these. Experimental investigations can be very helpful in order to better understand the structure and determine the washing machine activity and dynamics.

Approach

The core idea of the approach is to split the characterization of the problem in two binaries, dealing on a structural and a perceptual level. Measurements and recordings at the original situation are performed in order to assess the original configuration. The aim of the listening test is to identify which would be the most problematic condition for the users (e.g. critical frequency range to be treated, critical part of the washing cycle, etc.), will be based on filtered signals, and then a specific structural modification will be designed and applied.

A full description of the system physics is bounded to the evaluation of the source, the receiver and the contact condition properties. The idea is to estimate these quantities combining in-situ measurements and analytical solutions. (To validate the estimated source properties, lab-measurements with a washing machine of same type are going to be held as well.)

On this purpose, a double transfer function will be measured as representative of the whole vibro-acoustic problem:

- Structural Transfer Function, describing the interaction of the machine with the floor in a coupled condition, aiming to know the properties of the machine and floor
- Acoustic Transfer Function: relating floor vibrational levels with the pressure levels in the bedroom

A holistic approach is needed in order to offer a solution optimized for users and can be achieved merging technical solutions and user perception. To investigate perception can be quite ineffective when results are not applied in practice. Similar technical solutions can be inadequate when not keeping in consideration the final user requirements. In this project the subjective evaluation serves as basis for the design of the technical solution in order to make the best out of the two aspects. To combine the decisional loop of a solving process with a human evaluation can lead to unexpected and interesting results. A human evaluation in terms of annoyance ratings can help to optimise the structural intervention, tuning the process on a narrower range of frequencies or prioritizing some of these. Furthermore, a wooden floor and a washing machine can have infinite unique coupling conditions, i.e. slightly moving the machine on the floor, with a small rotation or translation, the structure properties can vary a lot and the structure can behave as a different one. For an in-situ vibro-acoustic problem this is a key point and it represents another reason why to apply a holistic approach.

Details of the specific problem

The space found is especially appropriate for this demonstrator project, it is a two-storey masonry house in Bladel, 30 km from Eindhoven. The first floor (source room) is used as laundry while the room underneath (receiving room) is used as bedroom (figure 2).

Figure 2: Case study: washing machine (top left), laundry (top right), view of the house (bottom left), bedroom (bottom right)

The washing machine is placed on the first floor on a lightweight wooden joist slab (figure 3).

Figure 3: Wooden joists floor supporting the washing machine.

A first round of measurements was carried out using omnidirectional microphones in order to make an initial assessment of the problem. A short (12 minutes) washing cycle was selected. During the entire cycle the noise levels in that room are relevant and this can be clearly perceived as a low-frequency problem (figure 4), where the highest values were measured during the spinning cycle phase.

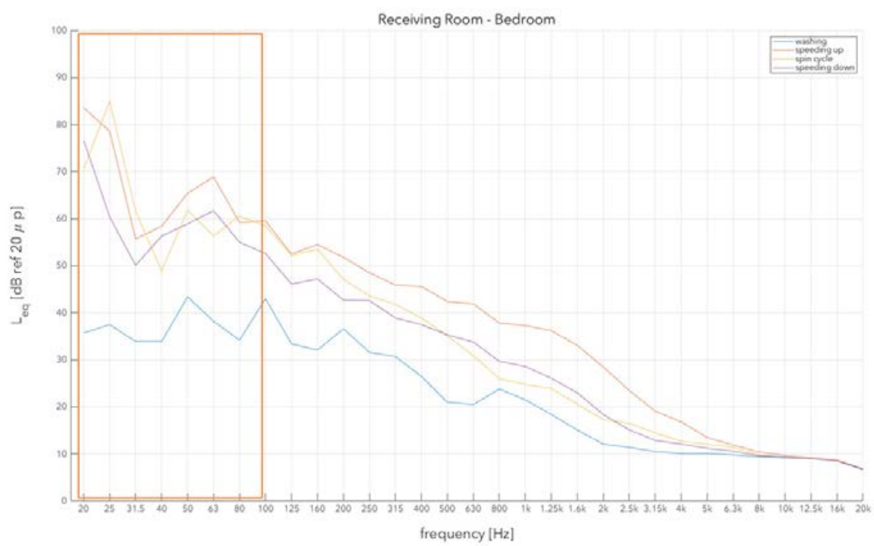

Figure 4: Equivalent sound pressure levels measured in the receiving room during different washing machine operating phases

In this case study, the floor is not representative of a situation where annoyance is due to a washing machine in a different dwelling/house. However, the low sound insulation performance suits the purpose of the demonstrators a complicated structure-borne problem involving “weak” lightweight structures is a conservative choice. In such a scenario, achievements and solutions should be helpful for the occupants and the approaches should be transferable to higher levels of sound insulation between separate dwellings.

Recordings of the washing machine in the actual setting will be performed and will serve as starting point for the subjective evaluation and the analysis of the structure. Sound pressure levels in the bedroom and the washing machine’s force on the floor will be related using the transfer function aforementioned (Section 4). The recordings in the receiving room will then be used for the generation of samples modified through the application of digital filters. A listening test will be performed with approximately 30 participants. The outcome will serve as basis for the design of the optimal solution targeting the specific frequency range or washing cycle part causing major annoyance on the users.

CHAPTER 2 ANALYSIS OF THE PROBLEM

Approach and methodology

Acoustics perception is a complex and multifaceted phenomenon involving, among others, psychological, physiological and cognitive aspects. When dealing with perceptual evaluation of auditory stimuli many factors need to be considered and some cannot be simply measured. Apart from the sound pressure level, other psychoacoustic parameters can be computed from recordings (e.g., loudness, sharpness, etc.) and models can be applied to link physical properties of sounds to the sensations likely to occur in listeners. However, the listening experience is affected by many more factors (e.g., mood, expectations, attitude, etc.) which cannot be fully captured just by looking at the physical properties of the sound itself.

Given the complexity of each subsystem involved and the strong heterogeneity of the whole assembly of machine and building, different types of quantities are measured. The goal is to describe and understand the physics of the system and also the relationship between the floor vibration and the sound pressure levels in the receiving room. The washing machine, a force hammer and a tapping machine are used as sources, with the response measured using accelerometers and microphones.

Operational velocities are recorded at the four contacts and on different structural elements in order to monitor the dominant vibrational paths. Sound pressure levels in the source and receiving room are recorded as well. The dynamics of the combined system of washing machine and timber floor is obtained experimentally with a force hammer.

A listening test using binaural recordings performed in both the source and the receiving room can be used to perform the perceptual evaluation of the sound.

Measurements and results

From the measurements the spinning cycle phase can be identified as the loudest part of the washing cycle in both rooms. For practical reasons it was decided to record a short washing cycle of 12 minutes with different loading conditions. In such washing program the spinning cycle length is approximately 120 seconds.

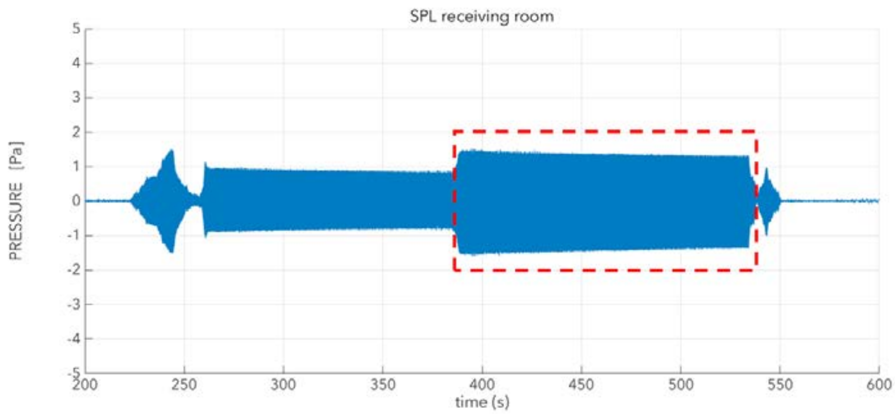

Figure 1: Sound pressure envelope of the washing machine in the receiving room. Spinning cycle in the red frame.

During the recordings, two loading conditions are considered: firstly, an eccentric 300 g load is placed inside the drum using six magnets of 50 g weight each, so it could be accurately repeated and also modifiable; secondly, additional recordings were conducted with 4 kg of towels in order to have a realistic situation, and following the recommendations of the standard IEC 60704 2-4 (2011).

A frequency spectrum analysis highlights two important aspects, the tonal character of the noise and the low frequency contents of the signals (Figure 2). The washing program used runs the spinning cycle to a rotational speed of 1600 rpm, corresponding to 26.6 Hz. This

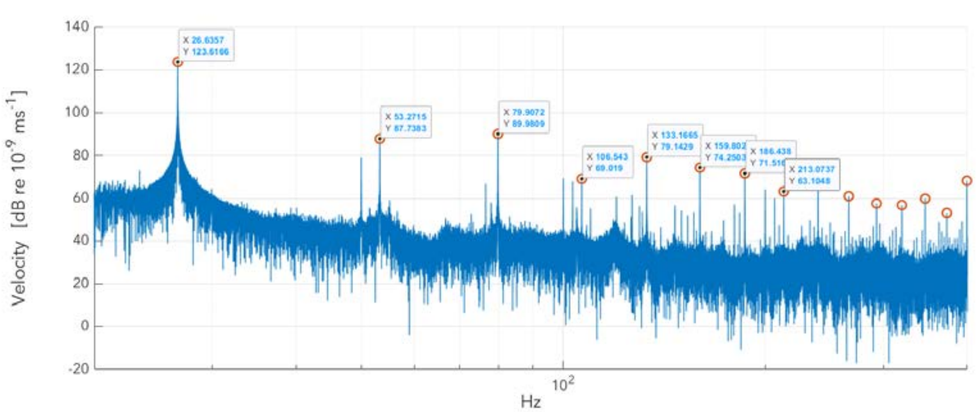

Figure 2: Vibrational levels on a washing machine contact. Harmonics labeled.

value matches exactly the fundamental tone (peak) of the measured spectrum. The amplitudes of the harmonics decrease with increasing frequency, whereby we perceive this as low frequency noise. Such tonal characteristic is verified also for vibration and sound pressure levels.

Figure 3 compares the velocities measured on the washing machine frame (source side) and on the floor for different types of loads. The load variation does not provide a significant difference in terms of magnitude. A similar trend is confirmed also for measured sound

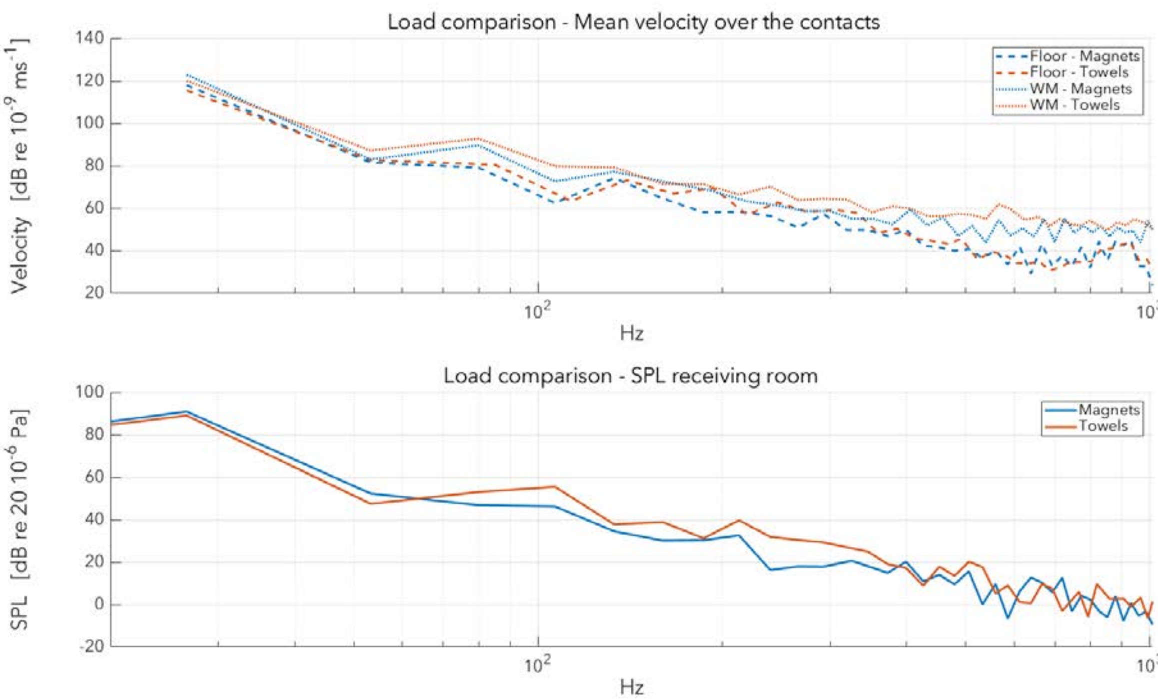

Figure 3: Comparison of the loading conditions for: vibrational mean levels over the washing machine contacts in the source room (top) and equivalent sound pressure levels in the receiving room (bottom).

Audio stimuli preparation for the listening test

For the setup of the listening test it was decided to extract some clips from the binaural recordings of the spinning cycle with the towel load, since it corresponds to the most realistic situation. After analyzing the spectra of the complete short washing cycle, for both source and receiving room, two clips of three seconds each were extracted at two instances: one at

6 minute and one at 7.4 minute (before and after the water discharge). These signals represent the original situation, and in the listening test they are compared with other plausible scenarios. As the implementation of any physical modification to the studied system was not possible, digital filtering was performed to the selected extracted audio signals in order to simulate alternative floor configurations (see Figure 4a). The following configurations were selected as solutions that were potentially applicable to the current timber beam structure, and correspond to the application of laboratory measurements of insulation when:

- adding an additional carpet finish;
- adding a floating floor;
- adding a floating floor and a suspended ceiling;

A noise level and loudness level characterization of the clips was conducted in terms of loudness level to validate the difference between configurations (see Figure 4b).

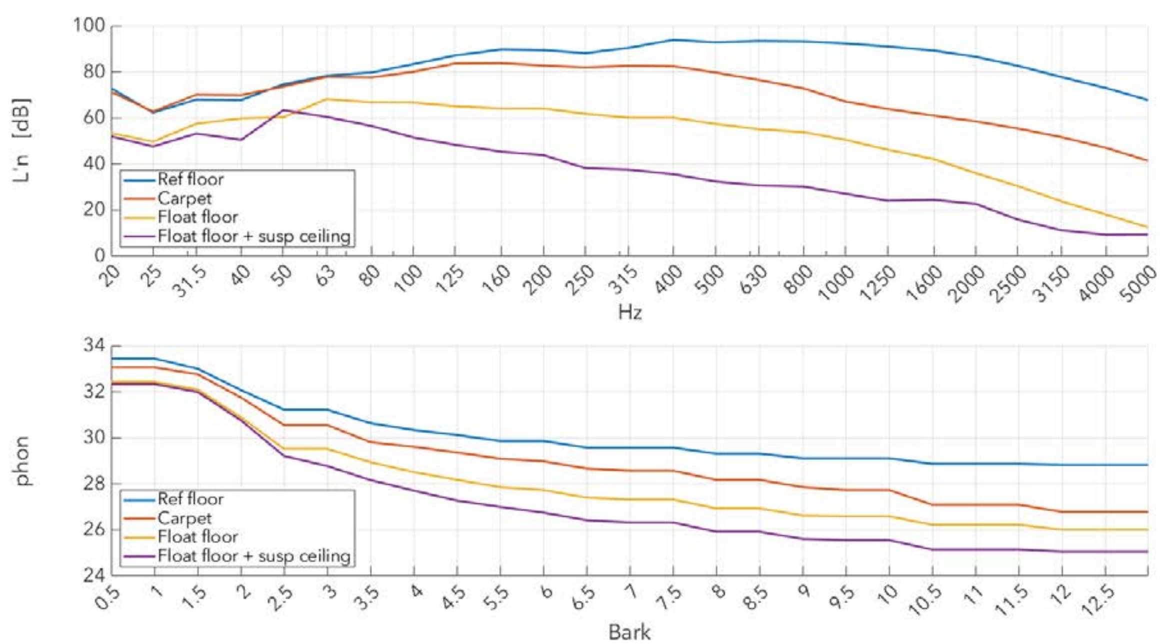

Figure 4: Impact sound pressure levels in-situ for the different floor configurations (top); Loudness level of the clip extracted at 6 min for the listening tests after applying different digital filtering (bottom)

As mentioned in the Chapter 1, the first recordings highlighted the critical level reached in the low frequency bands (20 to 200 Hz). To analyze the impact of these levels on the perception of the listeners, additional filtering was included reducing the levels by 9 dB in each frequency band below 200 Hz. Moreover, all the clips previously introduced were filtered considering different frequency ranges, from 50 to 5 kHz and from 20 to 5 kHz, in order to understand if including information in the low frequency range would change the preferences of the participants.

CONCLUSIONS

The measurement outcomes highlight how the sound pressure level is characterized by peaks at specific frequencies. The peaks are due to the rotational behavior of the drum inside the washing machine and its speed during the spinning cycle. The highest level identified is in the low-frequency range (120 dB at 26.6 Hz).

To increase acoustic comfort in the receiving room, the sound insulating solution needs to reduce the fundamental tone and its harmonics. The proposal of this demonstrator is to make such a decision through understanding the perceptual outcomes. For this reason sound stimuli have been generated from the binaural recordings, to be used in listening tests. Moreover, potential changes to the floor are auralised based on the original recording in order to make a preliminary evaluation of these potential solutions.

The setup for listening tests and proposals for an optimal solution to reduce annoyance for the dwellers will be presented in the next chapter.

CHAPTER 3 RESULTS AND SOLUTION PROPOSAL

Listening test results

The listening test took part at Siemens using Siemens Test Lab - Jury Test application. Twenty-six participants took part in the experiment during which sounds were presented through headphones. The selection of stimuli included sixteen samples of three seconds each recorded with the binaural head during two phases of the washing cycle including for each washing phase:

- A recording in the **source room**;
- A recording in the **receiving room**;
- One clip **attenuating by 9 dB** in each frequency band below 200 Hz;
- Three clips resembling the installation of 1) carpet, 2) floating floor, 3) floating floor and suspended ceiling filtering between **50 and 5000 Hz**;
- Two clips resembling the installation of 1) floating floor and 2) floating floor and suspended ceiling filtering between **20 and 5000 Hz**.

For each of the clips the participants were asked to rate how loud, thumping and annoying the sound was using seven-point scales. The results of the listening test in terms of annoyance are shown in Figure 1. Overall, the sounds recorded in the source room were more annoying than the ones recorded in the receiving room. It was found that the four clips filtered between 20 and 5000 Hz presented the lowest rates for annoyance. This highlights the importance of the frequency range below 50 Hz to reduce annoyance caused by washing machine sounds. When no treatment was installed or a carpet finish was simulated the ratings for annoyance were the highest. As much as it regards the clips at minute 6, almost no difference was found in terms of annoyance when the floating floor was simulated singularly or in combination with a suspended ceiling. When looking at the same comparison at minute 7.4, similar results are obtained when filtering between 20 and 5000 Hz; instead, when reducing the frequency range of the filtering between 50 and 5000 Hz the addition of a suspended ceiling is correlated with higher rates for annoyance if compared with the installation of the floating floor system only. In Figure 1 it is also possible to notice that applying a 9 dB cutoff in the frequency range below 200 Hz does not cause much difference from the unfiltered recording in the two different parts of the washing cycle.

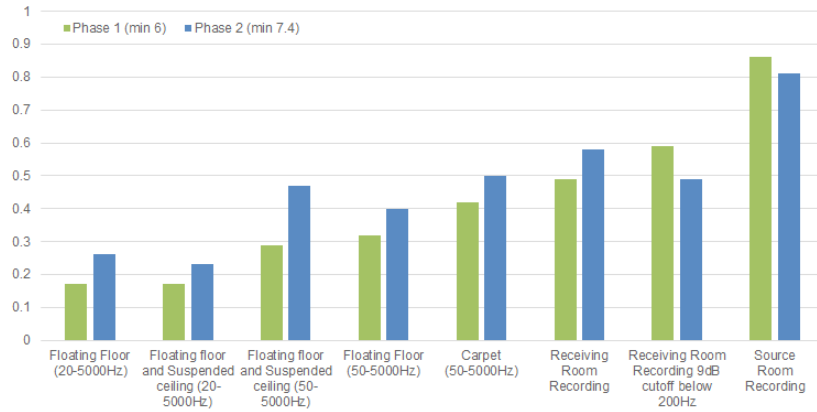

Figure 1: Annoyance ratings for the recordings and filtered clips of the two phases of the washing cycle analyzed.

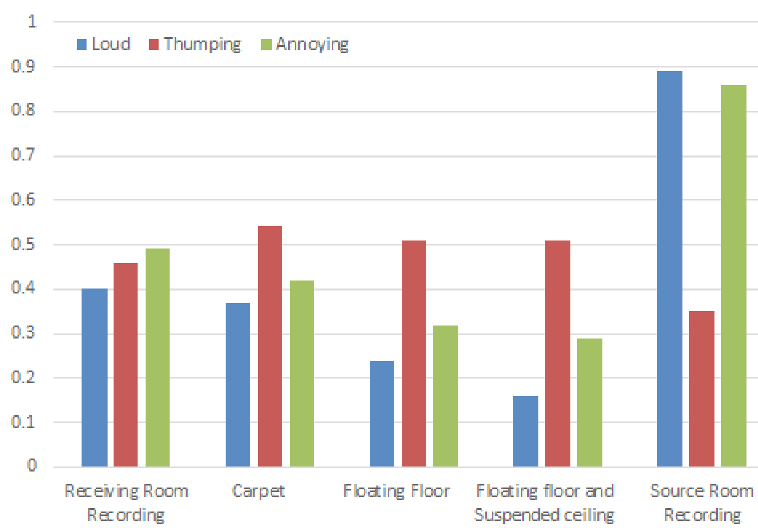

Figure 2: Subjective ratings for recordings and filtered clips between 50 and 5000 Hz of the minute 6 of the washing cycle.

In Figure 2, the results of the clip at minute 6 are shown including ratings for thumpiness and loudness. A decrease in annoyance was found when simulating the installation of any solution: a carpet, a floating floor or a floating floor with suspended ceiling. A similar trend is followed by the perceived loudness while when asking how thumping the sound was, the ratings made almost no difference between the three solutions. The ratings for thumpiness resulted much lower in the source room when compared to all the receiving room clips, probably due to the absence of floor vibrations and the reduction of high frequencies caused by the timber floor. In light of this listening test results and practical considerations, the floating floor seems to be the best solution to adopt in order to reduce the annoyance caused by washing machine sounds for the dwellers of the timber house. The additional installation of a suspended ceiling would cause a substantial volume reduction in the receiving room and would not be justified by the small reduction in annoyance ratings detected during the test.

Listening tests and measurements comparison

From measurements of the sound pressure levels in both the source room and the receiving room, it can be seen that the timber floor itself can reduce the washing machine noise by 20 dB above 50 Hz. By comparing the different high-pass filters with 20 Hz and 50 Hz cutoff frequency respectively in the listening test, it is concluded that the previous one has a significantly better sound insulation, which means that there is noise below 50 Hz which can cause much annoyance. On the current stage, the target frequency range is defined as from 20 Hz to 50 Hz.

To be more specific, as from the measurements of the vibration and sound pressure levels, it can be seen from narrow bands that the first resonance frequency is at 26.6 Hz, whilst the second one occurs at twice the frequency of the first resonance, 53.2 Hz, and the third one three times above, at 79.9 Hz. The first frequency corresponds to the rotational speed of 1600 rpm of the spinning cycle. In octave bands, the vibration level of the floor in terms of the L_{eq} is 85dB, nearly 25dB higher than that at the second resonance frequency. Besides, measurements of the vibration level on the ceiling and three walls show that the dominant sound transmission path is through the floor to which the washing machine is attached. Thus, only the noise transmission through the floor at the first resonance mode is considered to be reduced in this project.

Solution proposal

The floating floor has been indicated from the listening test users as the best sound insulating solution. The synthesis of the samples used for human based analysis are given on the basis of a previous measurement session, where firstly a bare wooden joist floor has been used as reference condition and then compared with different sound insulating solutions. From these measurements, audio filters have been derived in order to represent and foresee a structural modification of the original scenario. From a practical point of view this outcome looks quite realistic and potentially suitable for solving the problem in analysis. The floating floor might already be sufficient for our scope, whereas the addition of a suspended ceiling could also be considered after the assessment of this first modification.

As resumed in the previous paragraph, the vibration of the floor and the sound pressure levels in the receiving room have the first resonance peak at 26.6 Hz due to the spinning cycle. The aim is to tune the structural system so that the excitation cannot induce the resonance of the whole system and to have a lower natural frequency than the washing machine activity. The sound insulation design stage requires a simplification of the model. An assembly like this can be modelled as a mass-spring-mass system as shown in Figure 3 where only the vertical dynamics are accounted for and linearity is assumed.

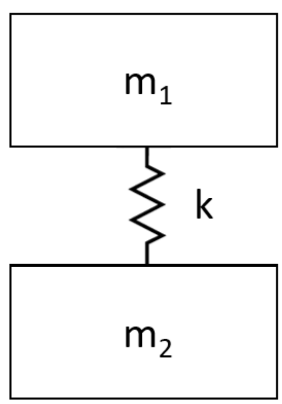

Figure 3: Floating floor modeling.

Here, m_1 identifies the floating floor top mass, k the vertical stiffness and m_2 the original floor mass. Floating floor structures can be of many different kinds and composed of several materials. In this case, in agreement with the listening tests, we decided to use a similar typology of floating floor as represented by the audio filtering. A scheme of the core structure is represented below in Figure 4.

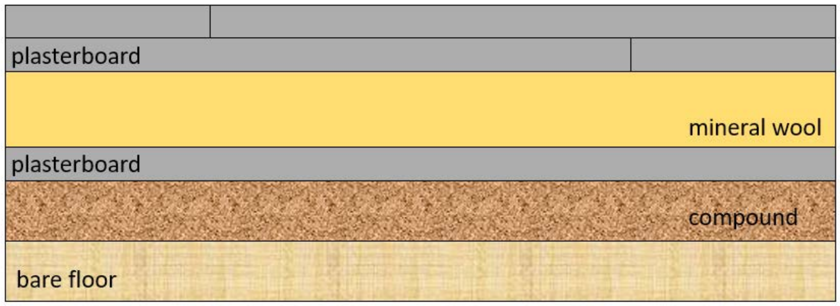

Figure 4: Drawing of floating floor construction.

The heterogeneity of the solution makes the prediction of the attenuation non-trivial, in particular the properties of the elastic part made of the mineral wool-plasterboard compound are not known apriori. Usually manufacturers indicate the sound insulation performance in terms of in dB of the overall floating floor but such a single number quantity is not enough for our design scope. The stiffness is a key parameter for the tuning goal, and given the specific frequency region of the washing machine activity, some characterization of a sample of the floor is needed in order to experimentally quantify the stiffness and to be precise in the choice of the floor layers. Further modeling is required also to include the washing machine in the vertical dynamics: the spreading of the weight of the source over the surface is a frequency dependent parameter that plays an important role. There are no clear standardized procedures yet and defining a wrong value of the mass can easily drive to a misleading prediction of the dynamics. The last part of this project requires a product development phase that will be carried out in the laboratory.

CONCLUSIONS

The in-situ measurement outcomes highlight the strong tonal behavior of the operating washing machine. The energy is localized in a very low frequency range, vanishing gradually with increasing frequency. At 26.6 Hz, 120 dB have been measured. This suggests the importance of reducing the sound pressure level in the low frequency range, from 20 Hz. To increase the acoustic comfort in the receiving room, an insulating solution should be tuned in order to cut out the fundamental tone and its harmonics. The listening test results suggest that the preferred solution, in terms of annoyance, would be to install a floating floor system. That human based solution is also in agreement with two fundamental requirements:

- source stability
- to preserve the lightweight structure

Given the complexity of the chosen solution, a product development phase is required in which a combination of experimental measurements and analytical methods will help to assess and customize the solution. The final scope will be the installation of such product in the demonstrator location.

Acoutect Demonstrator for Lightweight constructions

Perceptual based design for reduction of annoyance caused by washing machine installed on a timber floor

January, 2021

ACOUTECT

Eindhoven University of Technology
Maarten Hornikx (Project Coordinator)
Raúl Pagán Muñoz (Project Manager)

Alessia Frescura
Acoustics Research Unit, School of Architecture, University of Liverpool, Liverpool, UK

Carmen Rosas-Pérez
Division of Applied Acoustics, Chalmers University of Technology, Gothenburg, Sweden

Xiaoxue Shen
Acoustics Research Unit, School of Architecture, University of Liverpool, Liverpool, UK

Antonio Sorrentino
Level Acoustics & Vibration BV, Eindhoven, the Netherlands

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under the Marie Sklodowska-Curie grant Agreement, number 721536

acoutect.eu