Measurements of Impact Force Excitation on Wooden Floors

Jesse Lietzén
Tampere University of Technology, Laboratory of Civil Engineering, Finland

Juha Miettinen
Tampere University of Technology, Laboratory of Materials Sciences, Finland

Mikko Kylliäinen, Sami Pajunen
Tampere University of Technology, Laboratory of Civil Engineering, Finland

Summary

Impact sound insulation is measured using the ISO tapping machine as a sound source. However, the interaction between the tapping machine and the structure highly depends on the floor, and thus, the force excitation of the floor cannot be generalized for all floor systems. Several models describing the impact force generated by the tapping machine have been presented in the literature. However, only few measurement results of the impact force it generates have been reported in the literature. This paper presents a method for measuring the impact force excitation generated by the ISO tapping machine with an instrumented tapping machine as well as preliminary experimental results. The measurements were carried out on a wooden floor structure (CLT) with and without floor covering at five positions per structure. For each measurement, a spectrum of impact force excitation was determined. Moreover, the improvement of impact sound insulation ΔL of the floor covering was calculated on the basis of the force spectra and compared with the standard results.

PACS no. 43.40.At, 43.55.Ti

1. Introduction

1.1. Background

The ISO tapping machine, which produces impact force excitation to the structure, is commonly used as a sound source in impact sound insulation measurements. However, it is known that the interaction between the ISO tapping machine and the structure highly depends on the type of the floor [1]. For example, the spectrum of the impact force generated by the tapping machine on a wooden floor differs from the spectrum generated on a concrete structure. Thus, the impact force excitation cannot be generalized for all floor systems.

Information of the impact force exciting the structure is needed, in order to evaluate the impact sound insulation of the wooden floor computationally. In the first place, the information of the driving force is required in determining the structure-borne sound power input into the floor. Secondly, the data can be used for calculating the improvement of impact sound insulation ΔL of the surface structures, e.g. the floor covering.

Several models describing the impact force excitation generated by the tapping machine have been presented in the literature [1–6]. The models vary from the early simple models to the novel general models. The early models were developed for the impact force excitation on rigid floors [2, 3, 4]. Thus, these models are not always applicable for wooden floors, which are more flexible than concrete floors. The general models presented, however, are applicable for assessing the impact force on floor structures in general, for they take the elastic properties of the floor more accurately into account [1, 5, 6].

Even though many models have been presented, only few studies of the impact force measurements have been reported in the literature, see, e.g. [5]. The lack of experiments is mainly due to the fact that the impact force cannot easily be measured, for the measurement setup requires special equipment. One possibility is to modify the standard tapping machine for force measurement purposes.

1.2. Objectives

The object of this paper is to briefly describe a method for measuring the impact force excitation generated by the ISO tapping machine and, particularly, to present preliminary experimental results of the force on two wooden floor structures. Furthermore, the improvement of impact sound insulation ΔL of the floor covering on the wooden floor is determined on the basis of the force measurements.

2. Materials and methods

2.1. Experiments and structures

In this study, impact force excitation was measured on two wooden floors with an instrumented ISO tapping machine. The centre hammer of the tapping machine was modified and equipped with both force and acceleration sensors. The force sensor (Kistler type 9712B5000), covered with a custom-built impact cap, was placed at the bottom of the hammer in order to measure the impact force directly during the operation of the tapping machine. The acceleration sensor (Kistler type 8202A10) was placed at the top of the hammer in order to get further information on the motion of the hammer. The hammer itself was modified after the described changes in order to fulfil the requirements for the tapping machine presented in the standard ISO 16283-2.

The experiments were carried out on two wooden floors with a bearing structure of a 100 mm thick 3-layered cross-laminated timber (CLT) floor (Figure 1). The floors comprised the bare CLT-floor without any floor covering (F1) and the CLT-floor covered with a soft cushion vinyl (F2). The dynamic stiffness *s*' of the cushion vinyl product used was approx. 2900 MN/m^3. The size of the floor structures was 2,4 x 2,7 m^2 with a span of 2,7 m. The bearing structure was fixed with screw connections from its both ends to vibration isolated beam structures.

All the measurements were performed in time-domain, and therefore time history of the impact force was recorded. The length of each measurement was approx. 30 s. At the beginning of each measurement, the instrumented hammer was at rest in an arbitrary position.

The tapping machine was placed at five source positions S1…S5 per structure. The positions were at least at a range of 0,5 m from the edges of the structure. The position S3 was located at the centre of the structures. All the positions were kept same for both structures.

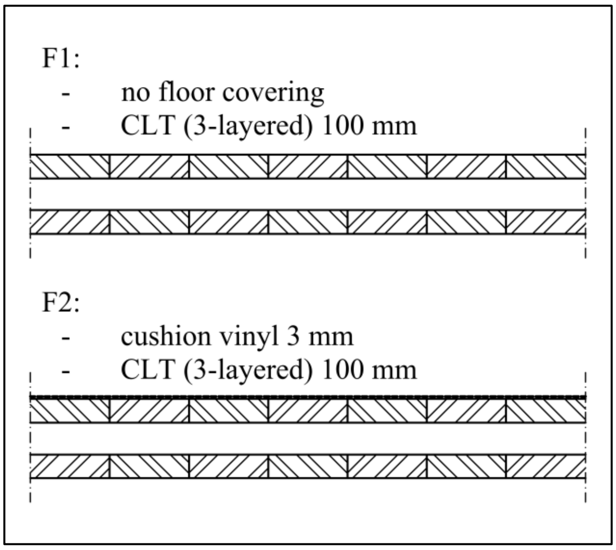

Figure 1. Floor constructions.

2.2. Post-processing of measurement results

As the impact force was measured with the sensor attached to the hammer, the acceleration of the hammer caused a slight force also between the impacts upon the floor. However, the counterforce of the force being measured drove the floor only when the hammer and the surface of the floor were in contact. Thus, in order to get information from the actual driving force of the floors, all the impact force peaks were sought and the force was set to zero between the impacts.

Since the position of the hammer in the beginning of each measurement was arbitrary, therefore not resulting in a full impact, the first impact was eliminated from the time history of the force. In addition, the time history from the beginning of the last impact to the end of the measurement was deleted, because of the lack of information of the beginning of the next impact after the measurement (the time between the impacts was not exactly 0,5 s).

The time history of the force, processed in accordance with the method described above, was filtered using 1/3-octave-band filters in the frequency range 20–5000 Hz. For each band the root-mean-square force F_{rms} was calculated.

Note that the values of the calculated force spectra are low compared to the peak values of the impact force pulses in time domain. This occurs, since between the short impacts upon the floor, the force driving the floor is zero, whereas the calculation of F_{rms} was carried out on the basis of the whole time history of the force.

2.3. Improvement of impact sound insulation ΔL

Improvement of impact sound insulation ΔL of the floor covering was determined according to Vér [2]. The calculation was made on the basis of the determined spectra of the driving forces, instead of the measured impact sound pressure levels or acceleration levels of the floor (cf. standards ISO 10140-3 and ISO 16251-1). The calculations were carried out individually for each tapping machine position S1…S5 in 1/3-octave-bands by

$$\Delta L = 20 \log \left(\frac{F_{\mathrm{rms,without}}}{F_{\mathrm{rms,with}}} \right), \qquad (1)$$

where $F_{\mathrm{rms,with}}$ and $F_{\mathrm{rms,without}}$ are the root-mean-square forces exciting the structure with and without the floor covering, i.e. the floors F2 and F1, respectively. The results were calculated in the frequency range 20–5000 Hz, as well. Since the tapping machine was equipped with one instrumented hammer, it was assumed that the impact force generated by all hammers are uniform.

3. Results

3.1. Impact force in time domain

An example of a measured time history of a force is presented in Figure 2. The Figure shows the whole post-processed measurement result of the impact force excitation on the floor F1 at the source position S3. The variation of the peak values of the impact force, as well as the impact rate of the hammer, are clearly seen from the Figure 2.

Examples of individual impact force pulses during the contact of the hammer and the floor are presented in Figures 3 and 4 on the floors F1 and F2 at the position S3, respectively. Thus, the impact force pulses shown in the Figure 3 are the same as shown in the post-processed time history of the force in the Figure 2. The collected pulses were centered such that the peak values of the forces occur at time 0,0 s. The amount of impacts of the hammer upon the floor varied from 60 to 61 (without the first and the last impacts).

When comparing the results presented in the Figures 3 and 4, the effect of the floor covering on the shape of the impact force pulse can be seen: the peak value of the force was significantly lower and the impact force pulse was wider when the floor was covered with the soft floor covering. From both Figures, it can also be seen that the driving force of the floor was set to zero between the impacts.

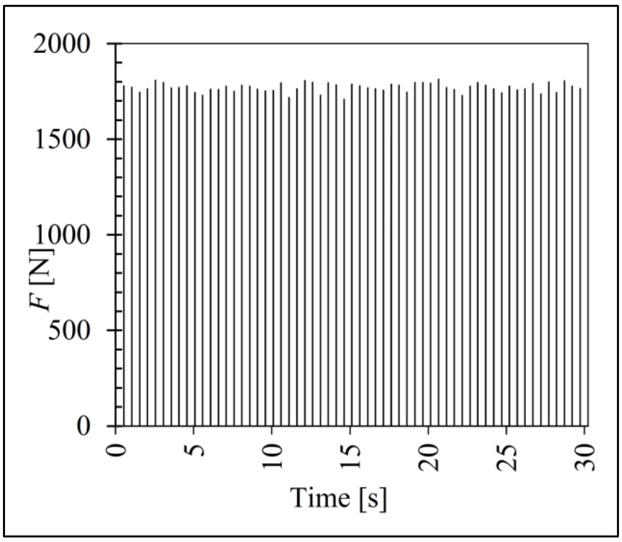

Figure 2. Post-processed time history of the impact force excitation (floor F1, position S3).

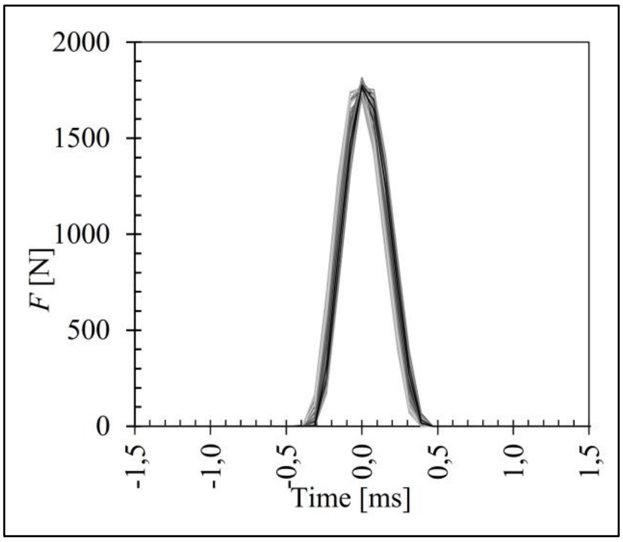

Figure 3. Impact force pulses (floor F1, position S3).

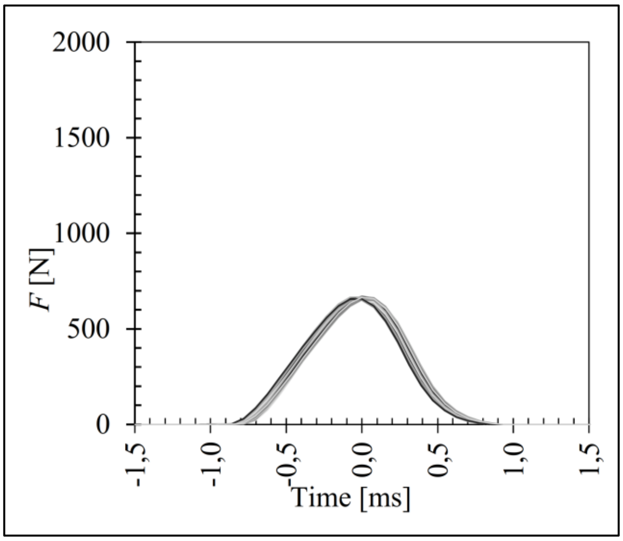

Figure 4. Impact force pulses (floor F2, position S3).

3.2. Impact force spectrum

The results of the spectra of the impact force excitation on the floors F1 and F2 are presented in Figures 5 and 6, respectively. The both results show that the force in frequency domain F_{rms} increases gradually from the low- to mid-frequencies and in the high frequencies rapidly diminishes to near zero value.

The maximum values of the impact force were averagely 13,7 and 7,4 N on the floors F1 and F2, respectively. The values were higher in the whole frequency range on the bare floor F1 than on the floor F2, since the soft floor covering reduces the force driving the floor. The differences of the forces between the floors were at largest in the 1000 Hz band.

The position of the peak value of the force spectrum depends on the floor. The maximum impact force lied in the 800 Hz and 315 Hz frequency bands on the floors F1 and F2, respectively. This is due to the difference in width of the impact force pulses: according to [4], a rapid impulse is capable of exciting higher frequencies.

The results show that there is little difference in the force between the source positions on the same floor, especially in the low-frequency range. In case of the bare CLT-floor F1, the differences between the force spectra were at largest in the frequency range 500–2000 Hz. Furthermore, the differences between the positions were minor on the floor F2 (see Fig. 6). Thus, the results imply that the impact force spectrum generated by the ISO tapping machine is quite uniform on the floors under study.

3.3. Improvement of impact sound insulation ΔL

Improvement of impact sound insulation ΔL of the floor covering was calculated according to the equation 1 on the basis of the determined rms force spectra. The results are shown in Figure 7.

The results in Figure 7 show that the improvement of impact sound insulation ΔL of the floor covering was positive and rather constant in the low-frequency range up to 250 Hz band. In this frequency range, the value of ΔL varied from 2 to 3 dB. In the range 250–1250 Hz ΔL increased exponentially up to over 20 dB. In the high-frequency range after the 1250 Hz band, the improvement of impact sound insulation ΔL decreased or at least remained at constant level compared to the latter.

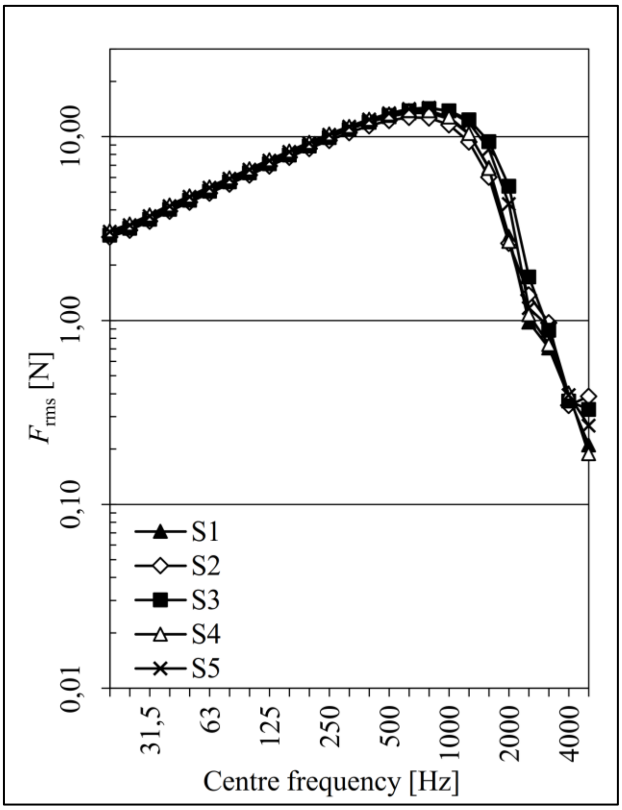

Figure 5. Spectra of impact force excitation (floor F1). Measured with one instrumented hammer of the ISO tapping machine.

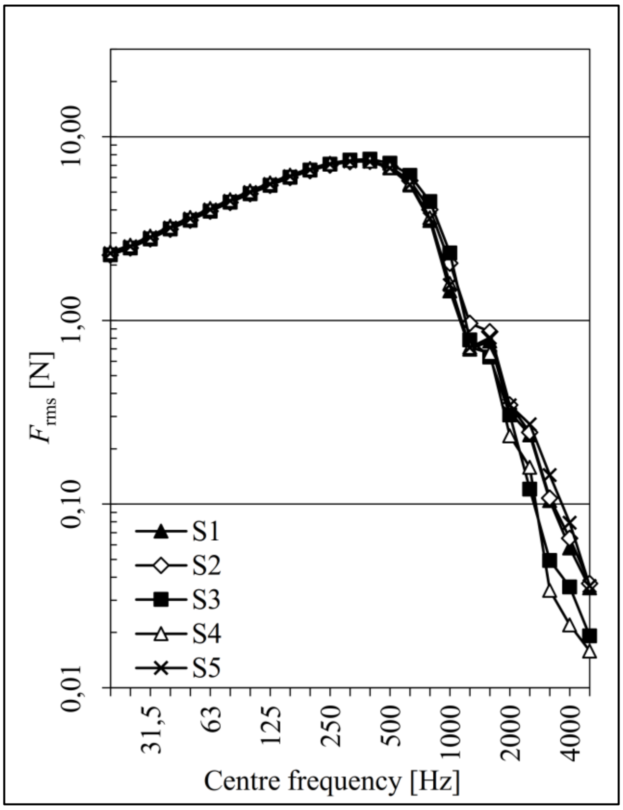

Figure 6. Spectra of impact force excitation (floor F2). Measured with one instrumented hammer of the ISO tapping machine.

According to the results, the differences of ΔL between the source positions were minor in the low- and mid-frequency range up to 1000 Hz. The maximum difference between the positions ranged from 0,4 dB in the low-frequency range to 3,8 dB in the 1000 Hz band. In the high-frequency range, the maximum differences of ΔL between the positions were larger and varied from 4,7 to 11,4 dB.

The spatial average of the measurement results presented in Figure 7 was compared with the results obtained from the standard tests presented in [7] (see Figure 8). The standard measurements were performed in accordance with the standards ISO 10140-3 and ISO 16251-1 on a hollow core slab (thickness h = 265 mm, surface density *m*' = 380 kg/m^2) and on a small concrete floor mock-up (h = 200 mm, *m*' = 401 kg/m^2), respectively. The results are shown in Figure 8.

The measured average in Figure 8 shows a good agreement with the results of the standard tests in the frequency range 50–1250 Hz. However, in the low- and mid-frequency range, the measurement result corresponds better with the results obtained using the standard ISO 16251-1 than with the result using the standard ISO 10140-3.

Compared to the results of the standard tests carried out on concrete floors, there seems to be a cut-off frequency in the 1250 Hz band in the measured average ΔL of the floor covering. In the frequency range higher than this cut-off frequency, the improvement of impact sound insulation ΔL does not increase as on concrete floors, but stays rather constant. This occurs probably due to the decreasing impact force on the bare CLT-floor F1 in the high-frequency range. A similar behaviour of ΔL can also be seen from the results for a massive wooden floor equipped with a soft vinyl covering presented in [8, 9]. On bare concrete floors, the impact force in the high-frequency range increases instead, thus producing higher difference in impact force with and without floor covering as well as better improvement of impact sound insulation ΔL. Thus, it could be beneficial to add, e.g. some sort of building board, on the wooden floor in order to obtain higher values of ΔL in the high-frequency range.

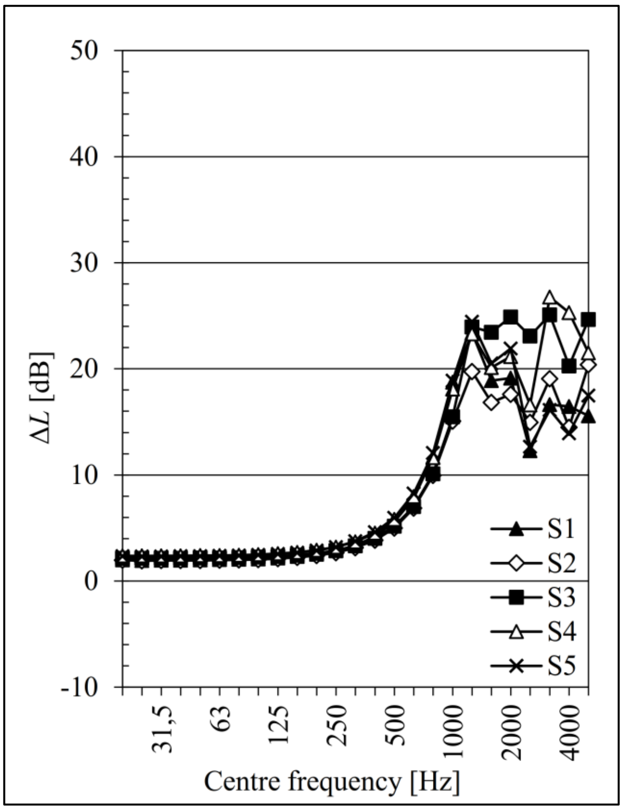

Figure 7. Measured improvement of impact sound insulation ΔL. Calculated according to equation 1.

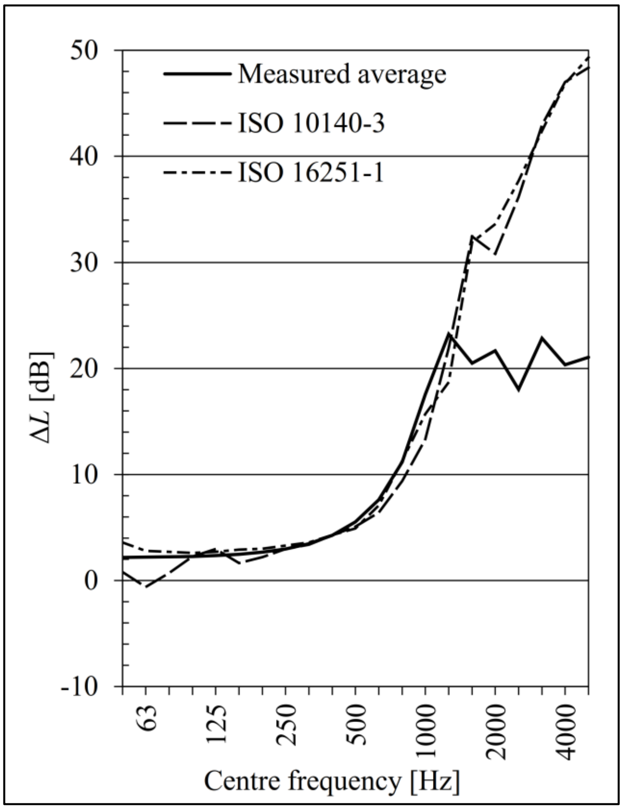

Figure 8. Comparison of the measured average improvement of impact sound insulation ΔL with the results of standard tests [7].

4. Conclusions

The impact force excitation generated by the ISO tapping machine was measured with an instrumented tapping machine on two CLT-floors. With a described post-processing method, the impact force excitation driving the floor was determined.

According to the results, the impact force spectrum depends on the floor structure. Particularly, the whole spectrum had lower values when the floor was equipped with the soft floor covering. Moreover, the maximum value of the spectrum lied in different frequency bands on the floors F1 and F2. This suggests that information of the force spectrum is indeed needed when evaluating the impact sound insulation of a wooden floor computationally. It seemed that there is little difference in the force spectrum between the source positions. This implies that in the case of massive wooden plates the impact force spectrum generated by the ISO tapping machine is quite independent on the machine position.

The results of the improvement of impact sound insulation ΔL of the soft floor covering showed good agreement in the low- and mid-frequency range with the results of the standard methods carried out on concrete floors. This suggests that the improvement of impact sound insulation of a soft floor covering could be calculated according to the known force spectra. Furthermore, this implies that measurement results of ΔL obtained using the standards ISO 10140-3 and ISO 16251-1 can be applied in evaluation of impact sound insulation of wooden floors in the important frequency range from 50 to 1000 Hz. In order to reach better improvement of impact sound insulation ΔL in the high-frequency range, installing an additional layer of a hard building board on a wooden floor could be beneficial.

Acknowledgements

The construction materials for this project has been donated by Christian Berner Oy, Saint-Gobain Finland Oy, Stora Enso Oy and Upofloor Oy. The research project has financially been supported by Yrjö ja Senja Koivusen Säätiö sr.

References

[1] J. Brunskog, P. Hammer: The interaction between the ISO tapping machine and lightweight floors. Acta Acustica united with Acustica 89 (2003) 296-308.

[2] I. L. Vér: Impact noise isolation of composite floors. Journal of the Acoustical Society of America 50 (1971) 1043-1050.

[3] W. Scholl, W. Maysenhölder: Impact sound insulation of timber floors: Interaction between source, floor coverings and load bearing floor. J. Building Acoustics 6 (1999) 43–61.

[4] L. Cremer, M. Heckl, B. A. T. Petersson: Structure-Borne Sound: Structural vibrations and sound radiation at audio frequencies. Springer, Berlin, Heidelberg, 2005.

[5] A. Rabold, M. Buchschmid, A. Düster, G. Müller, E. Rank: Modelling the excitation force of a standard tapping machine on lightweight floor structures. J. Building Acoustics 17 (2010) 175-197.

[6] V. Wittstock: On the spectral shape of the sound generated by standard tapping machines. Acta Acustica united with Acustica 98 (2012) 301-308.

[7] J. Keränen, J. Lietzén, M. Kylliäinen, V. Hongisto: Improvement of impact sound reduction by floor coverings – measurements using a small floor mock-up and an impact sound laboratory. Proc. Inter-noise 2013, paper no. 530.

[8] N. Balanant, C. Guigou, M. Villenave: Respect des exigences acoustiques dans les bâtiments à ossature bois, à vocation logements. Etape 2, Rapport final, Acoubois France, Qualitel, CSTB and FCBA, 2012.

[9] P. Latvanne: The acoustical properties and the calculation models of the wooden intermediate floor constructions (in Finnish). Master of Science Thesis. Civil Engineering, Tampere University of Technology, Tampere, Finland, 2015.