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New Acoustic Test Procedure for Hard Floor Covering Systems with Soft Underlay

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Summary
Walking with hard heeled shoes generates especially on laminate floorings a well noticeable “clack-clack” sound. Heard in the same room where the walker is, this sound is called “walking sound” and sometimes also “drum sound”. In order to qualify acoustically the different flooring products, a test method is needed. The goal was to define a reliable measurement method which provides comparable results to real walking of an experienced walker using a reference shoe. Numerous studies have shown that the ISO tapping machine used in building acoustics is not adequate for this purpose. After a review of the properties of the impact and the floor response, attention is given to the interaction of the impedance of shoe and floor. In contrast to a heavy concrete floor, the hard floor covering system with a soft underlay has impedance values in the same order of magnitude than the impacting heel. Thus, there is no easy way around: If an impacting hammer is expected to evoke the same floor excitation than the shoe’s heel, the hammer has to have about the same source impedance than the shoe. An impact hammer with a weight of 200 grams an a rather hard, resilient tip of 1.3 MN/m fulfills this requirement.

PACS no. 43.58-e, 43.40-r

1. Introduction

1.1. The characterization of flooring products

People walking on floors generate a sound called “reflected walking sound” or “drum sound”. This is not the impact sound transmitted to the neighbor, measured according to ISO 140 [1], but the sound heard in the same room where the walker is. Walking sound depends on four factors: (i) the force impact of the hard heeled shoe to the floor covering, (ii) the sound emission of the floor covering in response to the force impact, but also (iii) the sound emission of the shoe excited by the force impact and (iv) additional sounds from the shoe like snaring or clapping of the sole on the floor. The new test method shall provide values to characterize different floorings. Therefore, the work is focussed on the force excitation of the flooring and provision had to be made that the other three sound emission factors are minimized.

The loudness and the timbre of the reflected walking sound depend on the floor construction. The goal was to specify a test method for comparing the acoustic impression of different laminate floor constructions. Investigations by Johansson [2], [3] have shown that loudness according to ISO 532B [4], [5] correlates well with the subjective rating of sounds from various floors. The problem to solve was to specify the appropriate impacting device and the corresponding measurement procedure.

The Association of European Producers of Laminate Floorings (EPLF) has published preliminary standards [6] using the ISO tapping machine [7]. Measurements with the tapping machine showed that the self noise was too high [8, 9] and - most important - the measurements on various floor constructions did not agree with the subjective ranking of those floors: the impact of the tapping machine is too strong, driving some floor systems into nonlinearity. And the impedance of the heavy hammers does not correspond to the impedance of a shoe.

The central question to answer was to define the reference excitation to compare with. It was agreed by the EPLF working group, that the new test method shall provide comparable results to the sound from the real walking of an experienced walker, as used in the test method of IHD [10], where the sound generation of a single step was measured and converted into loudness. As the test method aims at characterizing flooring constructions, the focus is not on reproducing the complete walking sound with its four components listed above, but to provide a test for the acoustic reaction of the floorings to the force impact of the heel. Experience showed that the heel must be rather hard to generate distinguishable sounds on different floorings. A professional female dancing shoe was evaluated as the reference. The test method reported here is based on an “artificial shoe” with the same properties than the reference shoe. It consists of a small impulse hammer with similar weight and stiffness than the shoe. The correspond-

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ing fully formulated draft standard was submitted in summer 2009 for discussion to the working group CEN/TC 126/WG 1/AHG 7 [11].

1.2. Review of impacting devices and footfalls

1.2.1. The ISO tapping machine

For heavy floor constructions, the impact sound is measured with the ISO tapping machine [7]. The machine uses hammers of 500 grams and the impacting tip has a diameter of 30 mm. Watters [12] has shown that the impulse duration differs for impacts on soft wooden floors depending on the impact velocity: the contact impedance varies with the intensity of the stroke because the contact area of the hammer depends on the degree of deformation in the wood. This gives rise to nonlinear results.

Investigations to use the tapping machine also for walking sound measurements on floating hard floors are numerous, e.g. the withdrawn internal Norm of EPLF [6], Schröder [8], the investigation for Nortest [9], Sarradj [13], Lievens [14], Johansson [15] and the French Standard NF S 31-074 [16]. The very noisy operation of the tapping machine often masks the floor sounds to be measured. Self noise is produced by the driving mechanics but also by the ringing sound of the impacting cylinders excited by the counteracting force of the stroke. A shielding case could reduce the self noise. This is impractical, because the case also shields the sound emission of the floor in the vicinity of the impacting point.

It has been noted since a long time that the steel hammers of the ISO machine are too hard for lightweight floor constructions. Many investigations have been made adding a resilient layer at the tips of the hammers. The modifications of the ISO machine to be used with walking sound are reported by Scholl [17], [18]. The use of the modified tapping machine for impacts on lightweight floors with an intermediate resilient layer is described in the informative Annex C of EN ISO 140-11 (2005) [19]. That the ISO machine is unsuited for walking sound measurements was summarized by Bütikofer [20].

1.2.2. Other impacting devices

Other impacting devices are the Japanese "bang" machine (a rubber tire falling down) [21] or the Japanese heavy rubber ball [22], [23]. These two excitations concentrate on low frequencies (the "bumping" noise of barefoot children running around), an irrelevant topic in our context. An experimental machine had been designed at NRC, Canada: the NRC Foot Simulator [24], which models the dynamics of both, shoe and leg. It consists (bottom up) of a hard resilient layer (0.7 µm/N), a small mass (170 grams), a softer resilient layer (4 µm/N) and finally a larger mass (4.7 kg). Schultz [25] proposed a device similar to a shoe consisting of a hammer of 200 grams and a resilient layer at the tip. The next section gives an overview over some models.

1.2.3. Dynamic models of leg / foot and shoe

The dynamics of a footfall on rigid ground can be modeled by a series of springs and masses (for simplicity, the damping elements are left out). The dynamic mass of the leg and foot is reported to be about 4 kilograms. However, the mass of the leg and foot only becomes an important factor for low frequencies. Other factors are the mass of the shoe and the overall rigidity of that part of the heel contacting the floor first.

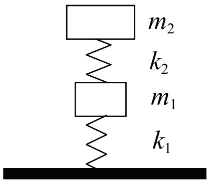

Figure 1. Dynamic model of the leg / foot and shoe.

Table I. Values for dynamic active masses and springs.

	k_1 [kN/m]	m_1 [grams]	k_2 [kN/m]
ISO 140-11 [19]	24	500	–
NRC [24]	1’400	170	250
Scholl [17, 18]	–	50 .. 120	12
Lievens [26]	4’600	220	740
EPLF (this paper)	1’300	200	–
	m_2 [grams]	$f_r(k_1/m_1)$ [Hz]	$f_r(k_2/m_2)$ [Hz]
ISO 140-11 [19]	–	35	–
NRC [24]	4’700	450	37
Scholl [17, 18]	500	–	24
Lievens [26]	2’500	727	87
EPLF (this paper)	–	405	–

Figure 1 shows the model of springs and masses and Table I indicates some values from literature.

The spring k_1 (if existent) represents a resilient sole, the mass m_1 the shoe's heel, the spring k_2 is the soft coupling to the foot by sock and flesh and m_2 the dynamic mass of the lower part of the leg and foot. For a rough estimation of system properties, Table I also indicates resonant frequencies for a system that would only consist of m_1 and k_1 or m_2 and k_2,

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k}{m}}. \quad (1)$$

With a cut-off frequency of 35 Hz, the modified tapping machine (ISO 140-11) will generate only low frequency sound. The other models with a soft spring k_2 and the heavy weight m_2 will also generate a (very) low frequency impact. In our context, these "bumps" e.g. of bare foot walking are of no interest. The model of Lievens [26] also models the upper part of the leg with two additional springs and masses. But for frequencies above say 200 Hz the interactions with the floor are governed only by k_1 and m_1. Therefore, for the acoustic floor response to walking, it is sufficient to model the dynamics of the shoe's heel (k_1 and m_1).

The "EPLF" solution proposed in this paper (sole of 1'300 kN/m and a weight of 200 grams) compares well with the lower components k_1/m_1 of the NRC impactor.

2. Methods

As this paper reports on the investigation of several effects towards the proposed new impacting device, different methods apply. Some specific details are therefore indicated only later with the specific investigation.

2.1. The concept of the floor as a linear system

The rigid board of the laminate floor is typically 7mm thick. When excited at one point, it radiates sound from a limited area around that point (Lievens [27], Volz [28], Jakob [29]). For our investigations there is no need to understand in detail the very complex processes of damped plate vibration with the boundary conditions of the plate's limited size and a soft layer underneath, nor to model the mechanisms of sound radiation. Under the assumption that the floor system is linear (or at least, that it can be linearized around the excitation with the low energy impact of the shoe's heel) the floor can be described globally by a transfer function H, relating the resulting sound to the exciting force.

With $p(f)$ denoting the measured sound spectrum (e.g. at 1 m from excitation) and $F(f)$ denoting the exciting force spectrum, the transfer function is $H(f) = p(f)/F(f)$. It is normally expressed as amplitude and phase in function of the frequency. In the present case only the level of the sound pressure is of interest, i.e. the logarithm of the RMS-amplitude. Thus, the description of the floating hard floor covering system can be even more simplified by looking only at the levels, e.g. of one-third octave band measurements,

$$L_p = 20\lg\left(\frac{p}{p_0}\right), \tag{2}$$

$$L_F = 20\lg\left(\frac{F}{F_0}\right), \tag{3}$$

with $p_0 = 20\,\mu\text{Pa}$ and $F_0 = 1\,\text{N}$,

$$L_H = 20\lg\left(\frac{p}{p_0}\frac{F_0}{F}\right) = L_p - L_F. \tag{4}$$

The function L_H is usually a 1/3 octave band spectrum. It characterizes the flooring material that makes up the flooring system. L_H predicts the resulting sound spectrum for a given force spectrum as excitation (This will be discussed in section 3.3).

It is assumed that the floor is a linear system. A system modifier influencing the properties of the floor system might be the weight of the walking person altering the contact quality between board and elastic layer and hence the dynamic stiffness of the floor. However, this effect has only been observed when preloading the floor by a person standing as close as 10 cm from the point of excitation. Standing in a distance of 50 cm or more has virtually no influence. During walking, the loading of the floor takes place only after the impulse sound has been emitted. Linearity may also be violated by a high energy impact driving the system into a nonlinear state.

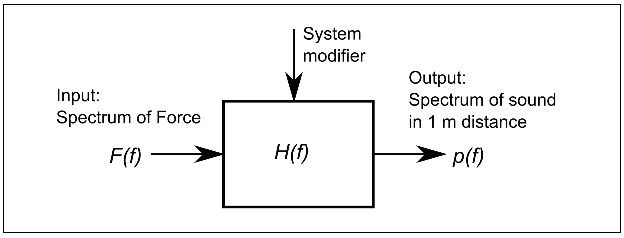

Figure 2. The floor modeled as a linear system.

The sound is measured at 1 m distance from the point of excitation in basically a free field. Requirements for the semi-anechoic measurement room are according to the standard ISO 3744 for sound power [30].

2.2. Equipment used

The test equipment used was: impulse hammer: PCB 086B03; free field microphones with ICP supply: B & K 4189 plus B & K 2671; accelerometers: PCB 352C22, eventually with integration to velocity using B & K 2692 "Nexus"; sound recorders Sound Devices T744. Spectra were measured with the one-third octave band analyzer N840 and with the FFT analyzer Photon II (400 or 800 lines). The impacting force of the step was measured with a force measuring platform using four Kistler force cells 9031. The angle dependent sound emission was measured at Empa on a 7 mm laminate floor using a small shaker for continuous broadband excitation. Provision was taken to avoid background noise where feasible or to correct for it and overloads of devices was thoroughly controlled.

2.3. The reference shoe

After tests with various male and female shoes, the need arouse for a well defined shoe, manufactured for many years and with replaceable parts if worn out. The following reference shoe from the German manufactory Diamant was selected for the comparative walking sound measurements with an experienced walker: professional dancer's shoe, for women, model "practice" with cuban heel [31]. For the walking tests, the reference shoe had been equipped with a 4 mm thick hard sole of the material SBR1 [32]. This is a synthetic rubber vulcanizate of 96° Shore A.

2.4. Investigations and round robins

Data reported come from various investigation over three years. The investigations for developing the method have been made at Empa, Dübendorf in the semi-anechoic room SH2-323 (Dimensions 12.8 m × 6.0 m × 2.8 m). The IHD

Figure 3. The reference shoe “Diamant”.

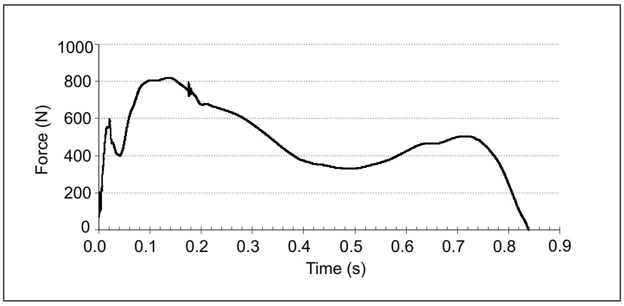

Figure 4. Example of the force of a step.

(Institut für Holztechnologie) in Dresden has a long tradition of measuring walking sound using a female walker. At IHD the measurement of 11 floor constructions have been made. The floor constructions were representative for the full range of laminate floorings, including boards from 7 to 14 mm, a cork laminate and variations in the sublayers. The floors were excited (i) by the experienced female walker, (ii) by a ISO tapping machine and (iii) by the impulse hammer. Also, a recording was made with an artificial head for subjective evaluation. After having defined the characteristics of the new impacting device, a round robin test was made using 10 of the 11 flooring constructions in the test stand at SEKISUI-Alveo in Littau, Switzerland, as well as at IHD and Empa. For the subjective evaluation of ten different floorings recorded with the artificial head at IHD, the recordings were reproduced with head sets in a jury panel comparison and the answers of 300 test person were used in the final comparison between subjective rating and various measurement results.

3. Steps towards the solution

3.1. The temporal evolution of a single step

Based on our video recordings of steps and on measurements on a force measuring platform at Empa, the evolution of a step of a hard heeled shoe can be described as follows: first, the edge of the heel hits the floor. The contact area is the small area at the back of the heel that is worn out first. This impact lasts about 2 milliseconds. As this impact is very short, it is governed only by the dynamic properties of the shoe’s heel. After quite a while, i.e. some milliseconds later, the heel has revolved to get in full contact with the floor. Now the person’s weight is applied to the floor. Later, the front part of the shoe gets also in contact with the floor, taking over the weight and after 600 to 900 milliseconds, the step is finished and the shoe removed from the floor. Figure 4 shows the force of a male’s step walking over a force measuring platform.

The onset of the step of Figure 4 is enlarged in Figure 5. The simultaneous recording of the sound reveal that walking sound is generated by the very first impact, irrelevant of the continuation of the step.

Beside the impact of the heel, a step generates two other kinds of sound: The impacting force excites not only the floor, but also the shoe, giving rise to a sound emission from the shoe. This depends heavily on the shoe’s properties. For the investigations with a walking person, a rather “quiet” type of shoe was selected. Further, the clapping of the front sole typically 60 milliseconds after initial impact generates another sound. A soft type of sole was selected to minimize this effect.

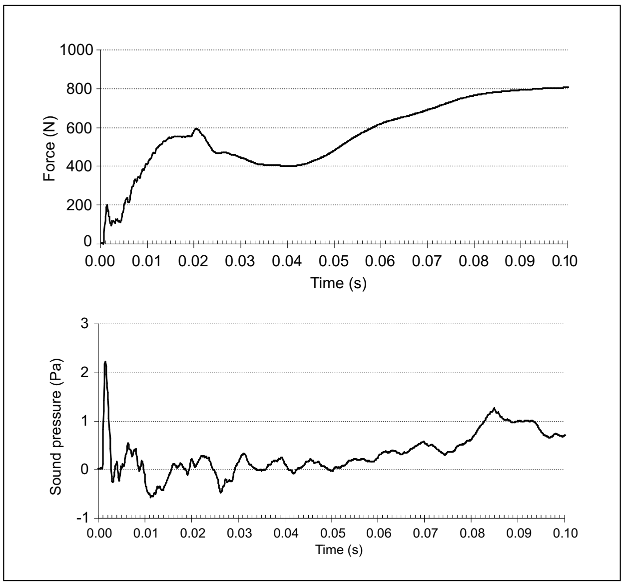

Figure 5. Force (upper graph) and emitted sound pressure (lower graph) at the onset of a step.

Sarradj [33] also claims a clapping effect when a hammer with a large diameter hits the floor, the clapping being produced by the air expelled below the impacting hammer. As the heel of the shoe hits the floor at the beginning only with the edge, this effect was not observed.

To summarize, the walking sound generation of a step may be reduced for the purpose of floor testings to the impact generated by the dynamically active mass of the shoe’s heel of about 120 to 200 grams and by a small contact area of the resilient sole of a few millimeters square.

3.2. Directivity of the floor’s sound emission

The sound emission of laminate floors depends for frequencies above 1 kHz on the emission angle. This was measured as follows: a laminate floor (7 mm on 3 mm PE underlay, coincidence frequency of the free board at 3.5 kHz) was excited at the central point with continuous

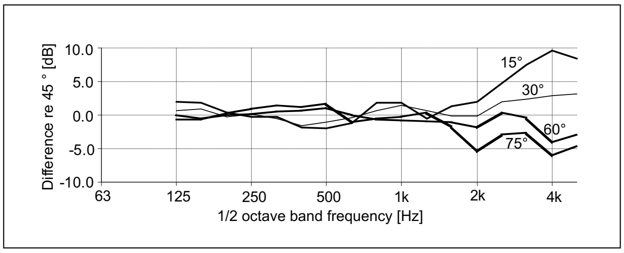

Figure 6. Variation of measured sound level in function of the emission angle. Shown is the level at the indicated elevation angle minus the level at 45 degree.

broadband noise by a shaker. The sound spectra in 1 m distance at the elevation angles 15° (close to the board), 30°, 45°, 60° and 75° (close to perpendicular) were measured in 4 directions around the shaker and the 4 spectra for the same elevation angle were averaged. Figure 6 shows the level differences compared to the spectrum at 45°. High frequencies are heard louder when the ear is close to the board (15°) and they are markedly reduced for a listening point above the exciter (75°).

Thus, the self-heard sound of a walking person (emission perpendicular to the floor, i.e. 90°) is slightly different from the sound experienced by a sitting person, listening to the steps of another person walking by (emission angle around 45°). Under the aspect of health protection for the sitting person the latter case was judged to be more important, and it was decided to limit investigations to the emission angle of 45°. Anyway, as the walking sound spectrum has its maximum usually below 1 kHz, this angle dependent emission has a minimal effect on the resulting sound level.

3.3. Variations in the emitted sound with various floors

Figure 7 shows the spectra of L_H for 10 typical laminate floor constructions, including laminates from 7 to 14 mm thickness and soft layers of fibreboard, Polyethelene (PE) and Polyolefine (PO).

The function L_H reflects the material properties similar to the sound reduction R used to characterize the sound insulation properties of walls, doors and windows [34]. However, in the case of walking sound, the question to answer is not to characterize the material property, but the behavior of the test material under a specific excitation. The question is (analogous to the impact measurements with the tapping machine): how loud is a specific floor construction for a well specified force excitation? This is calculated by

$$L_p(f) = L_H(f) + L_F(f). \tag{5}$$

The problem to solve is to characterize the force excitation $F(f)$ respectively its spectrum $L_F(f)$.

3.4. General properties of the force spectrum

The system of the hammer hitting the floor may be modeled by the mass of the hammer, the stiffness of the hammer tip and the input impedance of the floor. Brunskog [35] analyzed such systems in detail for the ISO tapping machine. In order to discuss some basic system properties and limitations the system is reduced to a simple mass-spring system on rigid ground. Comparisons with own measurements support the findings of this simple model.

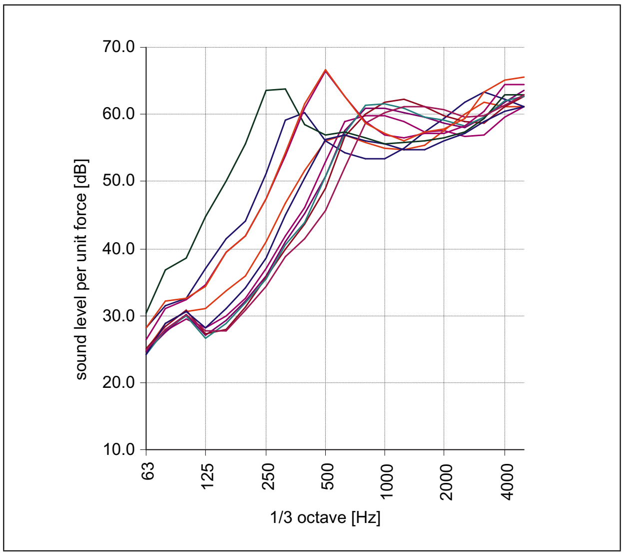

Figure 7. Examples for L_H of 10 floor constructions.

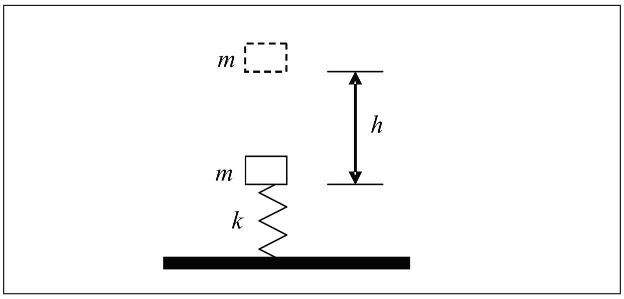

Figure 8. Mass-spring model.

The impact is modeled by a mass m, falling down from the height h, hitting the spring k with the velocity v_1. The spring stands on the rigid ground. Figure 8 shows the system.

If the mass would remain attached to the spring, a harmonic oscillation would result. In our case only compression forces are possible. The oscillation ends after the first half sine wave when the mass is repelled from the spring. The duration of the half sine is T, according to equation (6) (T denotes here the duration of the impact, not the period of the full sine-wave),

$$T = \pi\sqrt{\frac{m}{k}}. \tag{6}$$

Note that the duration of the impact does not depend on the initial velocity, i.e. if there is a soft or hard impact has no influence on the duration T. The amplitude of the Fourier Transform of the half-sine wave is given in equation (7) and in Figure 9.

$$F(f) = 2F_{peak}\frac{T}{\pi}\left|\frac{\cos(\pi f T)}{1-(2fT)^2}\right|, \tag{7}$$

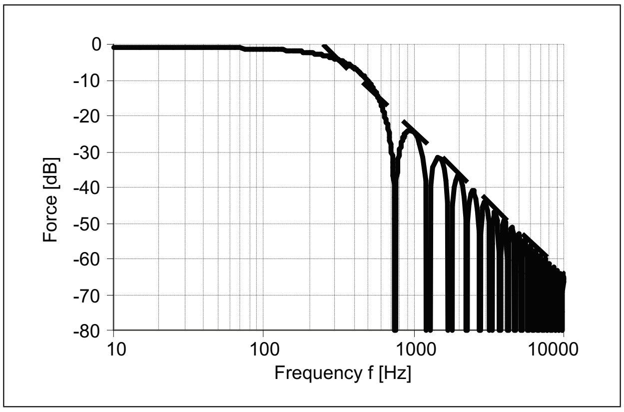

Figure 9. Spectrum $F(f)$ for $T = 2$ms shown for equal bandwidth.

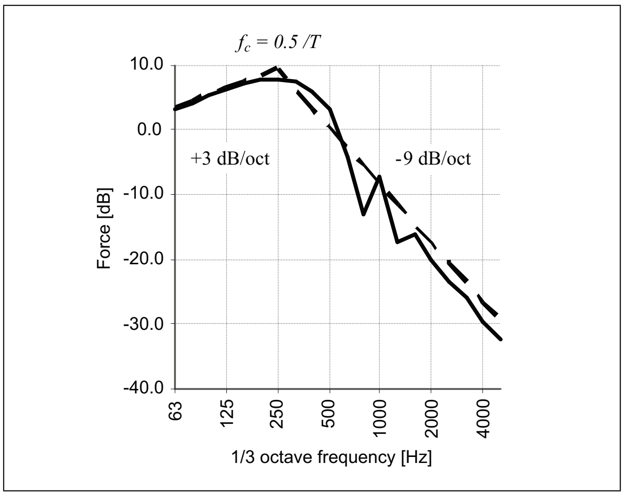

Figure 10. Spectrum $F(f)$ for $T = 2$ms for relative bandwidth of 1/3 octave.

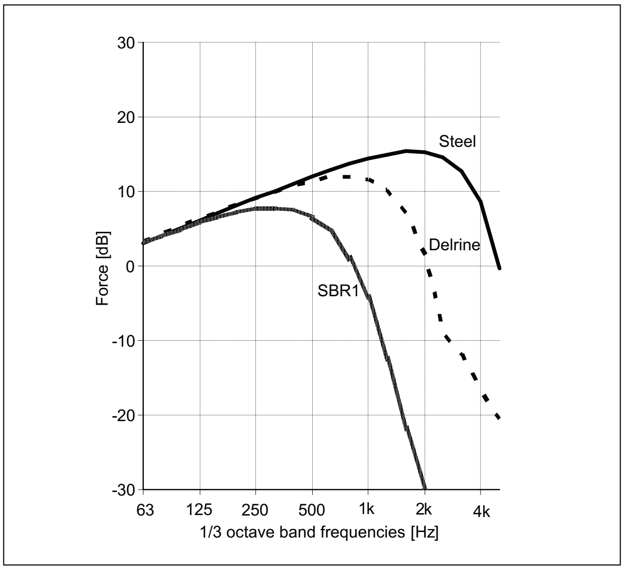

Figure 11. Spectra of impulse hammer with three different tips hitting a rigid steel mass.

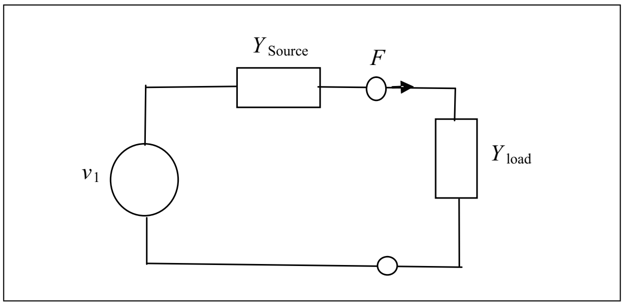

Figure 12. Ideal source v_1 and mobility of the source Y_{source} and of the load Y_{load}.

where || denotes the absolute value.

If the frequency bands of Figure 9 are summed up in bandwidth of 1/3 octave bands, the spectrum of Figure 9 looks like in Figure 10. The asymptotic behavior of a force impact is characterized in the 1/3 octave band representation as follows: The levels of the 1/3 octave bands increase by +1 dB per 1/3 octave until to the cut-off frequency f_c,

$$f_c = \frac{0.5}{T} = \frac{1}{2\pi}\sqrt{\frac{k}{m}}, \qquad (8)$$

and then decrease by 3 dB per 1/3 octave. This is shown in Figure 10 by the dotted lines.

As an example, Figure 11 shows the 1/3 octave band force spectra of an impulse hammer of 200 grams with 3 kinds of tips, hitting on a rigid steel mass. The tips are made of steel, delrin and a hard elastomer (SBR1).

4. Interaction of impacting device and floor: impedances

The dynamic properties of the impacting device and of the floor may be characterized by their impedance Z respectively their mobility $Y = 1/Z$. This may be illustrated by the equivalent circuit of Figure 12. (Similar circuits are numerous, e.g. Thaden [36] or Watters [12]). The resulting force F depends on both mobilities Y, that of the source and that of the floor.

The mobilities are complex functions of frequency. If the impacting device hits on a rigid mass (e.g. a concrete floor), we may set $Y_{load} \approx 0$ and we get the maximum possible (short circuit) force spectrum, as shown in Figure 11. However, given the unknown mobility Y_{load} of the laminate floor under test, the resulting force is also unknown. In the case of a lightweight board (the laminate) excited by the heel of a shoe, the two impedances interact in a sensible way. None of them can be neglected. This dilemma can only be solved by standardizing the source in both aspects, its mobility Y_{source} (for the shape of the force spectrum) and its velocity amplitude v_1 (for the overall amplitude). This means, that the properties of the reference shoe used to walk during the tests on the laminate floor have to be defined precisely and that the step intensity has to be normalized. Consequently, the impact hammer used as a replacement of the shoe has to behave dynamically exactly as the reference shoe: An artificial shoe has to be defined to end up with an easy to use solution. (For research purpose it is also possible to measure directly the input impedance. Then the resulting force spectrum can be calculated e.g. with electro-mechanical analogies and the software for electrical analog circuit simulation PSpice [37]. In this case any kind of source impedance with known properties can be used, provided the impact is not so intense to drive the system into nonlinearity.)

4.1. Measurement of the mechanical impedance

Although in the equivalent circuit of Figure 12 the mechanical mobility Y was used, it is more common to speak about the mechanical impedance Z, which is $Z = 1/Y$. An overview article on impedance and mobility is published by Hynnä [38]. The mechanical impedance Z of a structure is the applied force F divided by the resulting velocity v,

$$Z = \frac{F}{v}, \tag{9}$$

and the logarithmic magnitude is

$$20\lg(Z) = 20\lg\left(\frac{F}{F_0}\frac{v_0}{v}\right), \tag{10}$$

with $v_0 = 1\,\mathrm{m/s}$ and $F_0 = 1\,\mathrm{N}$. Specifically we talk about the point (or input) impedance, where the velocity-component in direction of the force is measured at the point where the force is applied.

To evaluate the impedance of the shoe and of the laminate floor, the frequency response function (FRF) was measured with a two-channel FFT analyzer, using the acceleration sensor PCB 352C22 to measure the response when the mechanical system was excited by an impact with the impulse hammer PCB 086B03.

The measured amplitude of the FRF is presented in a logarithmic scale,

$$20\lg(FRF) = 20\lg\left(\frac{a}{a_0}\frac{F_0}{F}\right), \tag{11}$$

with $a_0 = 1\,\mathrm{m/s^2}$.

Using the measured lg(FRF), the logarithmic magnitude of the impedance Z in dB is calculated in Excel by integration (i.e. subtracting $20\lg(2\pi f)$) and by changing the sign to convert from $20\lg(1/Z)$ to $20\lg(Z)$.

The impedance is composed of mass, stiffness and damping (resistive component). In the logarithmic impedance plots these elements produce the following curves: a mass relates to an increase with 20 dB per frequency decade; a stiffness to a decrease with 20 dB per frequency decade; and a resistive element relates to a constant level.

4.2. Impedance of the reference shoe

The accelerometer PCB 352C22 was attached with wax on a small support screwed on the inner side of the heel (Figure 13). While holding the shoe at the tip, an impulse was applied with the impulse hammer PCB 086B03 vertically to the sole. The FRF converted to impedance is shown in Figure 14.

Figure 13. Reference shoe with mounted accelerometer.

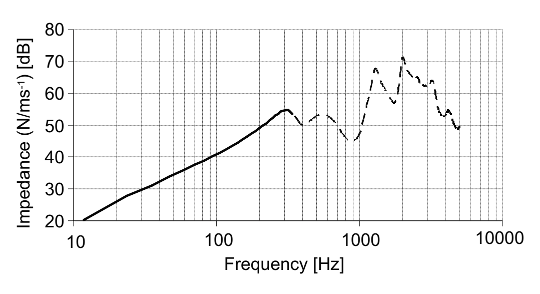

Figure 14. Impedance (active mass) of the reference shoe.

Using Figure 14, the active mass of the reference shoe's heel is evaluated in the frequency range of 30 to 100 Hz: it is 158 grams. Note that the active mass is lower than the total mass of the shoe of 210 grams. The stiffness of the sole would show up at frequencies above 400 Hz, but there the measurement is distorted due to the eccentric position of the acceleration sensor. The main result to retain is that the active weight of the reference shoe is around 160 gram.

4.3. Impedance of the hard covering floor with elastic underlay

Cremer [39] showed mathematically that the amplitude of the point impedance of an infinite, thin plate depends only on the mass per area. However, the plate behaves not like a mass, but like a resistive element i.e. the impedance is real and independent of the frequency. In this chapter the point impedance of such a plate installed on an elastic underlay is investigated.

Method:

The measurements reported here are made with the reference board defined by EPLF. This is a monolithic laminate floor board of 2.0 m by 2.4 m, produced in accordance to EN 13329-23/31 [40] by the DPL method and consists of a HDF carrier plate, density 850 ± 50 kg/m^3 with melamine backing. The thickness is 7.0 mm and the weight is 6 kg/m^2. The point input impedance was measured in the middle of the board, using the hammer PCB 086B03 with steel tip and accelerometer PCB 352C22, and converting the FRF to impedance in Excel. The stiffness of the layers were estimated using the methods of ISO 9052 [41]. The board was measured with three elastic underlays, installed on a very flat area on a concrete ceiling of 20 cm thickness:

- PE: The EPLF reference PE foam (extruded, closed-cell non-crosslinked polyethelene (LD-PE) foam, thickness 3 ± 0.5 mm, density 25 ± 5 kg/m^3),
- PO: A closed-cell physically crosslinked polyolefine foam of 2 mm thickness (Alveolit TU 4001-2mm from Sekisui-Alveo)
- Fibre: A soft fibreboard of 6 mm thickness (Underfloor Uni-softboard for laminate floors).

Result:
For low frequencies Figure 15 shows that the input impedance is about equal to the stiffness of the underlay material (falling curves; PO is hardest, PE softer and the fibreboard is softest). As the board is the same in the three measurements, the resonant frequency depends only on the stiffness of the underlay material. The resonant frequency is about 260 Hz for fibre, 600 Hz for PE and 1000 Hz for PO. For higher frequencies the floor behaves like a resistive element as predicted by Cremer (horizontal line).

The stiffness of the air may contribute considerably to the resulting stiffness of a layer between two plates. It may be estimated by the formula: $s_L = 111 \cdot 10^6/d$ [N/m^3] where d denotes the distance of the plates in mm. For a 3 mm layer, the stiffness of the air would be $37 \cdot 10^6$ N/m^3. The stiffness of the PE-layer is about $200 \cdot 10^6$ N/m^3 and that of the PO-layer about $700 \cdot 10^6$ N/m^3. Hence, the contribution of the air is not dominant.

Figure 16 shows the resulting sound level L_p for three floor constructions, using the same hard floor cover (7 mm laminate) and the same 3 kinds of elastic underlay as in the previous section. According to equation (5), the graph shows the addition of the floor property (L_H) plus the spectrum of the exciting force (L_F). Maximum sound levels are in the frequency region between 250 and 1000 Hz. This is also the frequency span in Figure 15 where the impedances differ.

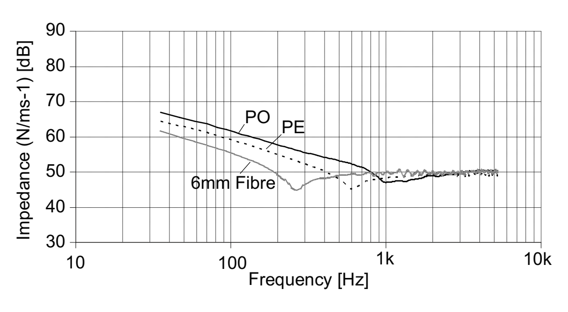

Figure 15. Input impedance of a 7 mm laminate floor on 3 types of elastic underlay.

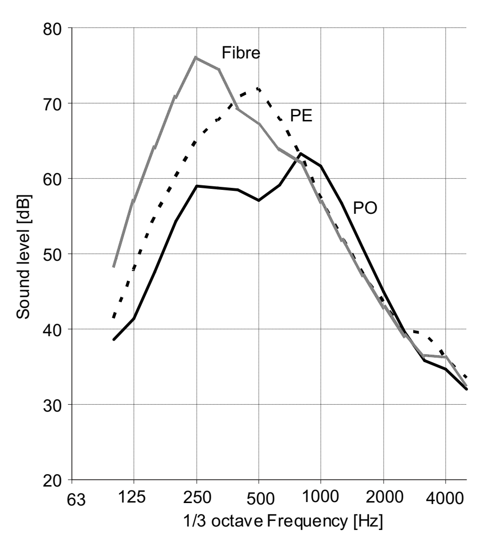

Figure 16. 1/3 octave band spectrum of the sound level L_p from walking with the reference shoe on a laminate of 7 mm thickness and 3 kinds of elastic underlay.

5. Design and application of the hammer

5.1. Requirements

It has been shown that the sound generation of walking can be reduced to the impact of the heel, which can be replaced by a hammer. The requirements are:

- The hammer has to have the same dynamic properties than the reference shoe's heel in terms of mass and stiffness ("artificial shoe" with approximately the same impedance).
- The size of the hammer tip's contact area shall not vary during the impact. (Otherwise the hammer's stiffness varies, introducing a nonlinear element). If a hammer with a handle is used, which is operated by a person, the contact area shall be insensitive to small variations in the contact angle between hammer tip and floor.
- If any driving mechanism with a case were used, sound radiation from the tip in the direction towards the microphone shall not be shielded by the case.
- The sound emission of the hammer, caused by the reacting force of the impact, shall be at least 15 dB below the sound emission from the floor.
- The final velocity of the hammer before contacting the floor has to be controlled, such that it can be related to a reference velocity derived from walking measurements.

5.2. Realization

Impulse hammers used for modal testing fulfil the requirements of low self sound and no acoustic shielding. The integrated force cell allows for scaling, and a small, resilient tip allows for a well defined contact area.

First tests were made with a tip of SBR1, the same material as used for the sole of the reference shoe. Test measurements showed, that a cylinder with a diameter as tiny as 5 mm was adequate. Even this 5 mm diameter tip was still somewhat too hard. Thus, according to equations (6) and (7), the effective mass of the hammer was increased to 200 grams to adjust the force spectrum of the hammer to the force spectrum of the shoe. The SBR1 wore out too quickly. Thus it was replaced by a 10 mm long cylinder with 5 mm diameter of PE-HWU-B (a standard material used for soldering of PE tubes) having the same stiffness. Figure 17 shows the impact hammer used with the detachable cylindrical tip of PE.

5.3. Scaling

The appropriate mass and stiffness of the impulse hammer produces the required spectral shape of the walking sound similar to the reference shoe. But the overall sound level depends on the intensity of the impact applied. The sound produced shall be scaled to a reference velocity v_{ref} at the onset of the impact. If there were a kind of tapping machine used, no scaling is needed provided the impacting velocity is well defined. With an impact hammer, the following scaling may be used.

Measurements are made simultaneously as 1/3 octave band Leq-spectra for the force (measured by the force cell of the impact hammer) and the sound. The number of strokes and measurement time are irrelevant, but all strokes should have about the same impact intensity. The sound spectrum of a single step is calculated by adding an overall level adjustment ΔL, which accounts for measurement time, number of strokes and impact intensity. This level adjustment is calculated using the force spectrum $L_{F,i}$.

For the elastic impact, the mechanical impulse of the hammer is

$$I = m\Delta v = \int F(t)\,\mathrm{d}t, \qquad (12)$$

where m is the dynamic mass of the hammer and $F(t)$ is the measured force. The change in velocity Δv is the difference of the velocity v_1 just at the onset of the stroke and the velocity v_2 of the repelling hammer at the end of the stroke (with v_2 being oriented in the opposite direction),

$$\Delta v = v_1 + v_2 = v_1(1+\alpha) \quad \text{with} \quad \alpha = \frac{v_2}{v_1}. \qquad (13)$$

The factor α may be estimated from measuring the force over time of the rebounding hammer: α equals the quotient of the time intervals between successive impacts. The integral for the force in equation (12) may be evaluated in the frequency domain. Integration is made in the frequency domain by decrementing successive 1/3 octave band levels by 2 dB. Then the band levels are summed up energetically. Thus, equation (12) combined with equation (13) may be solved for v_1,

$$v_1 = \frac{\sum_i 10^{(L_{F,i}-I_i)/20}}{m(1+\alpha)}, \qquad (14)$$

with $L_{F,i}$ the 1/3 octave force level from 50 Hz to 5 kHz and $I_i = 20\lg(2\pi f_i)$ with f_i the center frequency of the corresponding 1/3 octave band. Finally, the level adjustment ΔL for scaling the walking sound results from the comparison with the reference velocity v_{ref},

$$\Delta L = 20\lg(v_{ref}/v_1). \qquad (15)$$

Figure 17. Example of a hammer with cylindrical tip of PE, adapter for the tip, force cell, intrinsic mass and additional mass.

5.4. Application

The complete measurement procedure is described in the draft Standard [11] submitted to the CEN working group TC126/WG1/AHG7 on "walking noise on floors". The main features are as follows: Measurements are made in a room with low reverberation ("free field conditions"). The remaining room correction is calculated according to ISO 3744 [30] for a hemisphere with a radius of 1 m. The laminate flooring has dimensions of 2 m × 2.4 m and is installed on a concrete slab of at least 120 mm. The impulse hammer is operated by a person, hitting locations on the floor having a distance of 1 meter to the microphone and being located on a circle of 71 cm with the center perpendicular below the microphone. To average the floor properties at several places, the hammer is operated along an arc of the circle. The operator is outside of this arc, i.e. as far away from the microphone as feasible. Measurements are made simultaneously for the force and the sound level as one-third octave band Leq for an arbitrarily long time interval and number of strokes. The factor α can be determined by the quotient of two consecutive time intervals between impacts of the hammer rebounding on the floor. The measured sound spectrum is first corrected for background noise and for the room influence and then scaled by the factor ΔL evaluated from the force measurement and α. (The time duration of the measurement and the number of strokes is included in the Leq of the force and hence is corrected for in the scaling procedure for the sound spectrum). Finally, the sound spectrum is converted into loudness (sone) using an Excel routine implementing ISO 532B [4]. To cover a larger area of the floor, the procedure is repeated with different centers for the arcs of a circle.

6. Validation

A round robin was made with ten floors in three laboratories as described in section 2.4. The loudness is compared according to the method proposed by Bland/Altman [42]: The difference between "method 1" and "method2" is plotted versus the average value of both methods. Results for various floors measured with the impulse hammer in the three laboratories are compared to the loudness of the reference walker with the shoe (Figure 18). For sone values between 11 and 25 sone, the bias and standard deviations are listed in Table II.

The bias of 1 sone or less indicates that for very different kinds of laminate floorings, the results measured with the impact hammer agree well with the reference situation of the experienced walking lady. The standard deviation of 1.3 sone or less is mainly due to local variations of the laminate's sound, depending on how well it contacts the underlying layer. Note that these figures also include the variations of the room acoustics of the three measurement sites, three operators, three different measurement equipments (B+K, Norsonic and 01dB) and three mountings of the floors.

Table II. Values for the differences between loudness of a real walker and measurements with the impact hammer in three different laboratories.

	n	bias [sone]	std.dev [sone]
Laboratory 1	10	1.0	0.6
Laboratory 2	6	1.0	1.3
Laboratory 3	10	-0.1	1.3

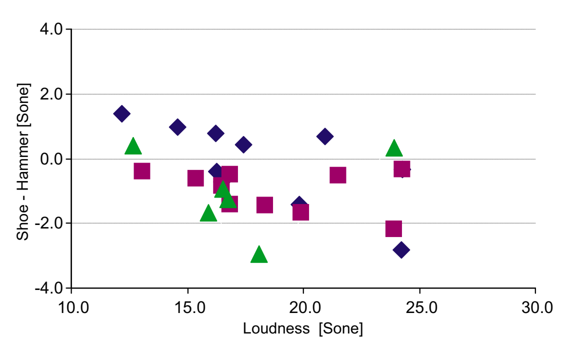

Figure 18. Deviations between the loudness of a walker and the loudness of the impulse hammer measurement for several floor constructions with sone values between 10 and 25. The shape of the points represent measurements in three laboratories.

7. Discussion

The goal was to find a technical mean to imitate the heel impact of real walking. The spectrum of the acoustic response of different flooring constructions depends on the force spectrum of the excitation, which depends on source and floor impedance. For laminate floorings, the impedance of the shoe and of the floor are of the same order of magnitude, which means that the source impedance becomes an important parameter. The excitation must be made with an "artificial shoe" having a similar impedance than a real shoe. This is in contrast to massive floorings like concrete ceilings, where the source and floor impedance differ by factors, allowing for any source impedance, including the ISO tapping machine.

The amplitude of the impact is normalized to a reference impacting velocity corresponding to real walking. The tests could also be made with some kind of a tapping machine which operates silently, with a constant impacting velocity and which has a hammer of about 200 grams and a resilient tip of 1.3 MN/m. As this device is not readily available, an alternative method is used with a commercially available impulse hammer and an appropriate scaling. The effects of the presence of the hammer operator has been investigated. Of course, noise generated by the operator has to be controlled. The disturbance of the sound field by the presence of the operator was found to be not detrimental. The sound from the impacting location being reflected at the operator propagates over roughly twice the length of the direct sound path, i.e. the reflection is at least 6 dB lower. Further, reflection at the operator is incomplete, and as the operator is always needed, its presence is part of the test environment. As Lievens [27] has shown, radiation of the floor is limited to a small area around the impact point. Investigations on the sound emission depending on the operator standing on the floor showed, that a noticeable influence only occurs if the operator's weight is applied closer than 0.5 m away from the impact point. Still other mechanical impact devices could be conceived, as long as the source impedance matches the requirements.

For laminate floorings the underlying concrete slab is practically decoupled; the ceiling's sound emission is about 20 dB lower. But for other floor coverings like carpets, parquets or tiles, the ceiling's sound emission becomes an important factor. For this case the measurement procedure has to be expanded with an auxiliary measurement, using a reverberation room underneath the ceiling to convert the ceilings contribution to the sound spectrum of the reference floor conditions according to ISO 717-2 [43]. This expansion of the test procedure is under investigation.

The validation showed that the measurements can be made independently of the walker in various laboratories within reasonable deviations. For manufacturers of floorings, the most important question to answer was the ranking of different floors: Does a floor being ranked subjectively as "quiet" also have a low loudness value? This was investigated by presenting sound from 10 floors to 300 test subjects, asking them to rank the floors from quiet to loud using headsets and a jury-panel method. The regression coefficient of that ranking with several measurements was as follows: with the loudness evaluated from the walking lady: $R^2 = 0.94$; with the loudness from impulse hammer tests (the method presented here): $R^2 = 0.90$ and using A-weighting instead of loudness $R^2 = 0.85$; finally, with the loudness from tests using the ISO tapping machine according to the EPLF-Standard, Version 4 [6]: $R^2 = 0.62$. The conclusions are (i) that the real walking evaluated using loudness correlates well with the subjective rating; (ii) the impulse hammer measurements agree nearly as well as the real walking with the subjective rating, (iii) loudness fits the ranking slightly better than A-weighting and (vi) the ISO tapping machine is not adequate.

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