

DETERMINATION OF THE IMPACT SOUND PRESSURE LEVEL USING TRANSFER FUNCTIONS

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ABSTRACT

For predictions of the sound transmission from installations in buildings using EN ISO 12354 the normalised impact sound pressure level of floors and walls is required. An alternative to the ISO tapping machine, such as an electrodynamic tapping machine or a mechanical pendulum tapping machine, would be beneficial to directly measure on walls but is not available for purchase. Therefore, the indirect measurement of the wall impact sound pressure level via transfer functions was investigated. Transfer functions were measured according to EN ISO 10848-1 and the blocked force of the ISO tapping machine is used as an input. Two alternative tapping machines were characterised on a reception plate according to EN 15657, along with an ISO tapping machine, showing a good agreement of the blocked force. Hence, they are generally suitable for the direct measurement. Measurements in testing facilities conforming to EN ISO 10140 were performed to validate the indirect method. The results showed that the method with the transfer functions generally works well in the building acoustics frequency range when compared with the direct measurement. Accordingly, this method is proposed in prEN 17823 for the laboratory measurement of the impact sound insulation of stairs and stair isolating elements.

Keywords: *impact sound insulation, wall impact sound pressure level, transfer functions, building acoustics*

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1. INTRODUCTION

For calculations of the impact sound transmission of stairs in buildings according to EN ISO 12354-2 [1], the impact sound pressure level (SPL) of walls and the impact sound reduction of stair isolating elements or lightweight stairs are required.

Analogous to the procedure for floating floors, the isolated landing impact SPL reduction can be measured in the laboratory, which is illustrated in **Figure 1**. The normalised impact SPL of the reference wall $L_{n0,Wall}$ and of the isolated landing $L_{n,Landing}$ needs to be measured. From this, the landing impact SPL reduction $\Delta L_{Landing}$ is determined as [1]

$$\Delta L_{Landing} = L_{n0,Wall} - L_{n,Landing} \quad (1)$$

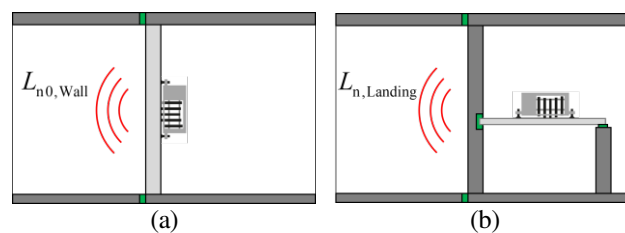


Figure 1. Measurement of the impact SPL reduction of an isolated landing; (a) impact SPL of the bare wall; (b) impact SPL of the isolated landing.

The measurement procedure for calculating the normalised impact SPL of a wall is specified in the German standard DIN 7396 [2] and requires a tapping machine that can be applied to walls. Two different types of tapping machines, the electrodynamic ‘midi’ tapping machine (MTM) and a mechanical ‘pendulum’ tapping machine (PTM) could be used instead of the ISO tapping machine (ISO TM). However, none of them is currently available for purchase.

While working on the new European standard prEN 17823 [3], which will replace the national standard DIN 7396, an alternative procedure was discussed, that uses transfer functions to determine the impact sound pressure level of walls. This method was first proposed by Schöpfer et al. [4] to estimate the sound transmission from equipment installed in lightweight buildings and was later embedded in EN ISO 10848-1 [5].

In this research, the method of using transfer functions with the theoretical blocked force of a tapping machine to determine the impact sound pressure level of walls is investigated and validated, so that it was possible to implement it in the new standard prEN 17823.

2. INDIRECT METHOD TO CALCULATE THE IMPACT SOUND PRESSURE LEVEL

2.1 Calculating the normalised impact SPL with transfer functions

In the indirect method to determine the normalised impact SPL of floors or walls, transfer functions need to be measured according to EN ISO 10848-1 and ‘combined’ with the installed power of the ISO tapping machine. The transfer function of the sound pressure in a room for a known input power into the structure is calculated as [5]

$$D_{TF} = 10 \log_{10} \left(\frac{\bar{p}^2 W_{ref}}{W p_{ref}^2} \right) \quad (2)$$

where \bar{p}^2 is the spatially averaged mean square sound pressure and W the injected structure-borne sound power, with $W_{ref} = 10 \text{ pW}$ and $p_{ref} = 20 \text{ }\mu\text{Pa}$. If several excitation positions are used, the transfer function is energetically averaged to $D_{TF,av}$.

For force sources, as usually encountered in heavy building structures, such as made from concrete and masonry, the installed power is given by (3):

$$W_{in} = \tilde{F}_b^2 \text{Re}\{\bar{Y}_R\} \quad (3)$$

where \tilde{F}_b^2 is the mean square blocked force and \bar{Y}_R the driving point mobility of the receiving structure averaged over the mounting points of the source.

Using the blocked force of a structure-borne source, like a tapping machine, the normalised impact SPL can be determined as

$$L_n = 10 \log_{10} \left(\frac{W_{in}}{W_{ref}} \right) + D_{TF,av} + 10 \log_{10} \left(\frac{A}{A_{ref}} \right) \quad (4)$$

where A is the equivalent absorption area of the receiving room, with $A_{ref} = 10 \text{ m}^2$.

2.2 Calculation of the blocked force

To obtain the installed power W_{in} required for applying the indirect method, the blocked force of a structure-borne sound source, like the ISO TM, is required. It can be obtained from measurements according to EN 15657 [6] using the reception plate method (RPM). For an active source, the power delivered to the reception plate in a stationary operating condition is given by

$$W_{RP} = \omega m \bar{v}^2 \eta \quad (5)$$

where ω is the circular frequency, m the mass, \bar{v}^2 the spatially averaged mean square velocity and η the loss factor of the reception plate.

Combining Eq. (3) with Eq. (5), the mean square blocked force of the source is given by (6):

$$\tilde{F}_b^2 = \frac{W_{RP}}{\text{Re}\{\bar{Y}_R\}} \quad (6)$$

As an alternative to the measurement procedure outlined above, the blocked force of a tapping machine can be calculated analytically assuming a point source [7]. The sequence of impacts with identical time difference T and the corresponding frequency spectrum with frequency lines at a regular spacing $1/T$ are shown in **Figure 2**, which can be expressed as a Fourier series [7].

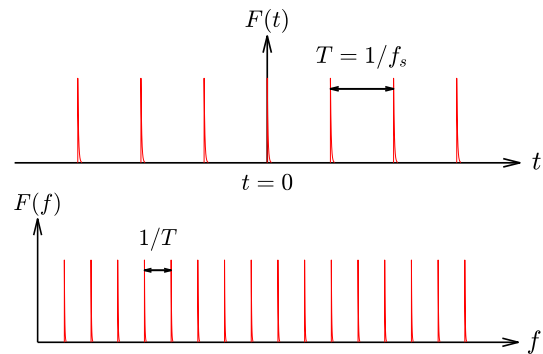


Figure 2. Force signal of a tapping machine in the time and frequency domain (reproduced from [7]).

Following the derivation in [7], the mean square blocked force of the tapping machine can then be calculated as

$$\tilde{F}_{b, TM}^2 = 2I^2 f_s^2 N \quad (7)$$

where I is the impulse, f_s the frequency of the impacts, and N the number of frequency lines within the frequency bandwidth Δf , with $N = \Delta f / f_s$.

The impulse generated by the falling hammer of a tapping machine with mass m_H is determined by its change of velocity ($v_0 - v_R$) during the impact, i.e. the impact velocity v_0 and the rebound velocity v_R . Thus, the impulse is delimited by $m_H v_0 \leq I \leq 2m_H v_0$, where the lower bound corresponds to a perfectly plastic impact ($v_R = 0$) and the upper bound to a perfectly elastic impact ($v_R = -v_0$). If the rebound velocity is unknown, the impulse may be approximated as [7]

$$I = \sqrt{2} m_H v_0 \quad (8)$$

which corresponds to a rebound velocity of $v_R \approx -0.41 \cdot v_0$. In the case of the ISO TM, where the impact velocity equals $v_0 = 0.866$ m/s, the rebound velocity is $v_R \approx -0.355$ m/s.

3. CHARACTERISATION OF THE TAPPING MACHINES

Three different types of tapping machines were available for this research. They are shown in **Figure 3**. In addition to the ISO TM, the prototype of a PTM from Centre Scientifique et Technique du Bâtiment (CSTB) in Grenoble and an MTM were characterised on the reception plate at the University of Applied Sciences (HFT) Stuttgart.

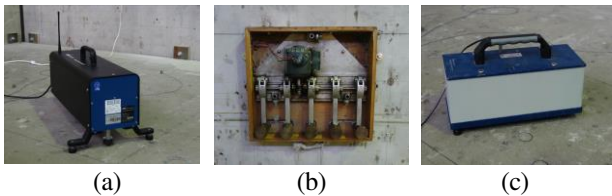


Figure 3. Tapping machines used in the studies; (a) ISO TM, (b) PTM and (c) MTM.

The ISO TM excites a structure with five identical hammers with mass $m_H = 500$ g. They fall sequentially from a height of 4 cm ($v_0 = 0.866$ m/s) and ideally generate an impact every 0.1 s. The operation of the PTM is similar, except that the hammers fall in a pendulum motion and the mass and height differ to the ISO TM. The MTM generates an impact frequency of 10 Hz with a single hammer, that is shaped like those of the ISO TM.

The blocked force of the three types of tapping machines was determined according to EN 15657 using the RPM. The plate velocity was spatially averaged using twelve

accelerometers. With an impact hammer and two accelerometers at an equal distance next to the hammer positions of the tapping machines, the driving point mobilities on the reception plates were measured. The mobilities of both accelerometers were averaged to obtain an estimate of the point mobility [8]. The ISO TM was characterized on the horizontal and the PTM and MTM on the larger vertical reception plate, which can be seen in **Figure 4**. The blocked force of the MTM was evaluated for the five hammer positions of the PTM and energetically averaged to obtain an equivalent point force. The measurements were performed with a narrow band frequency resolution of 1 Hz and the results were finally converted into one-third octave bands.



Figure 4. Reception plate test rig at HFT Stuttgart.

In **Figure 5** the measured blocked forces of the MTM and PTM are compared with the ISO TM and the theoretical values. The delimiting values corresponding to the fully elastic and plastic impacts are given for reference and differ by 6 dB. The approximation with the impulse from Eq. (8) is also shown. Due to the factor of $\sqrt{2}$, it lies between the two. In third-octave bands the blocked force increases with 3 dB/octave. Below 4 kHz, the measured values are within the limits. The measured blocked forces do not appear as straight lines, because they include a sampling uncertainty from the limited number of accelerometers, used to obtain the spatially averaged velocity of the reception plate.

Between 100 Hz and 1 kHz, the blocked force of the ISO TM is closer to the fully elastic impact than to the fully plastic impact. Other research [9, 10], where the impact and rebound velocities of an ISO TM were measured with a Laser Doppler Vibrometer, confirmed that the magnitude of the rebound velocity is larger than the assumed 0.355 m/s from Eq. (8) when the hammers are impacting a reinforced concrete plate.

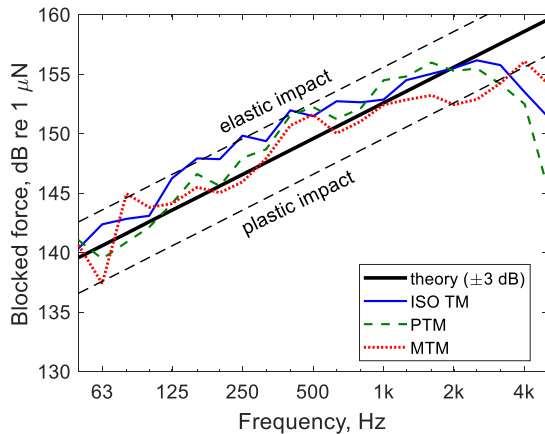


Figure 5. Blocked force of the three tapping machines measured on the reception plates at HFT Stuttgart compared with theoretical values.

Above 2 kHz, the measured blocked forces of the ISO TM and PTM are decreasing with frequency. This is due to the effect of the contact stiffness between the surfaces of the hammers and the reception plate which is not considered in the theory. Similar results were found by Wittstock, Scheck and Villot in [11], who evaluated results from a round-robin test, where an ISO TM was characterized on reception plates made of concrete in several European testing facilities. In the case of the MTM, some decrease occurs already above 1 kHz.

Overall, the blocked force spectra of PTM and MTM agree well with the ISO TM, so they could generally be used for direct measurements on walls. In the following calculations with the indirect method, the theoretical blocked force from Eq. (7) with the approximation of the impulse from Eq. (8) is applied, as it does not contain measurement uncertainties and is thus more accurate than the results from the RPM.

4. VALIDATION OF THE INDIRECT METHOD

The indirect method with transfer functions was validated in the floor toppings testing facility at HFT Stuttgart on the 14 cm reference floor made of reinforced concrete (350 kg/m²). The impact SPL of the reference floor was measured directly with the ISO TM for one location using six microphones in the receiving room below. The measurement setup is shown in **Figure 6**.



Figure 6. Direct measurement of the impact SPL of the reference floor at HFT Stuttgart; (a) source room with ISO TM; (b) receiving room with microphones.

The transfer functions were measured according to EN ISO 10848-1 at the five hammer impact positions of the ISO TM. Next to the hammer positions two accelerometers were attached to the floor. With this setup, the driving point mobilities, the injected power and the SPL in the receiving room were measured simultaneously for a transient impact hammer excitation. The injected power was averaged over the two accelerometers [4]. The measurement window was chosen to fulfil requirements in terms of the reverberation times in the receiving room, see [5]. To obtain optimal results in the frequency range of interest (50 Hz – 5 kHz), two impact hammers were used, a small one with a metal tip and a big one with a rubber tip, see **Figure 7**.

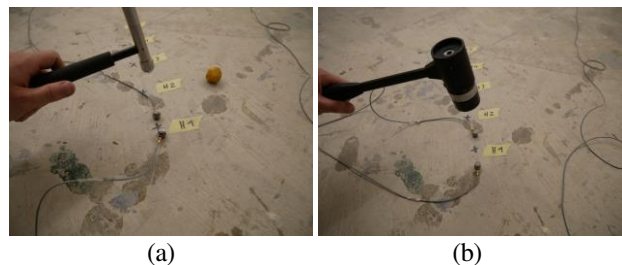


Figure 7. Measurement of transfer functions using transient excitation; (a) small impact hammer; (b) big impact hammer.

The transfer functions were calculated with Eq. (2) and energetically averaged over the five excitation positions. Below 100 Hz the results of the big hammer were used, above 1 kHz the results of the small hammer were used, while in between, the results for the small and the big hammer were averaged. The five transfer functions for each hammer position and their average are shown in **Figure 8** as one-third octave band values.

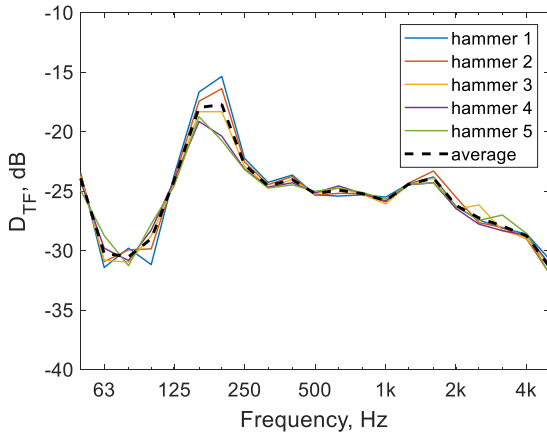


Figure 8. Transfer functions of the reference floor at HFT Stuttgart at the hammer positions 1-5 of the ISO TM and their average.

The installed power was calculated with Eq. (3) using the measured mobility of the receiving structure that was averaged over the five hammers and the theoretical blocked force of the tapping machine. The installed power of the individual hammer positions and the average is shown in **Figure 9**. The small deviations between the hammers show that the representation of the ISO TM as an equivalent point source is reasonable for a receiving structure made of reinforced concrete.

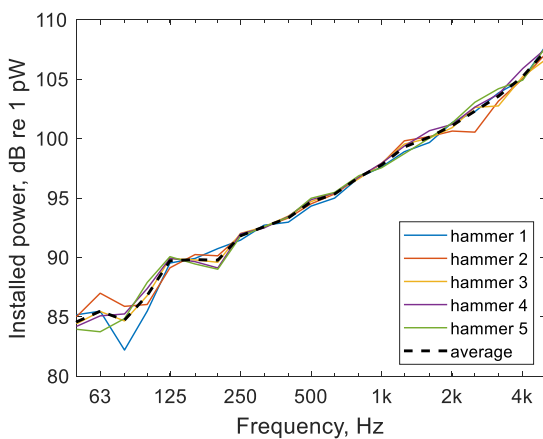


Figure 9. Installed power of the ISO TM on the reference floor at HFT Stuttgart calculated for hammer positions 1-5 and their average.

From the installed power, the averaged transfer function and the equivalent absorption area calculated from the measured reverberation times of the receiving room, the

normalised impact SPL was determined using Eq. (4). In **Figure 10** the direct measurement is compared with the indirect method. To quantify the differences between the two methods, the grey area denotes the extended uncertainty (95% confidence level, two-sided test, $k = 1.96$) in measurements of the impact sound insulation from EN ISO 12999-1 [12]. The result from the indirect method lies well within the uncertainty in most frequency bands. Up to 1 kHz, the indirect method underestimates the measurement almost constantly by 2 dB. This corresponds to the systematic underestimation of the rebound of the ISO TM hammers on a reinforced concrete plate if the blocked force is calculated for the impulse given in Eq. (8). If 5 dB are added to the blocked force of a plastic impact, instead of 3 dB, as suggested with Eq. (8), the deviations below 1 kHz almost vanish. Above 2 kHz the indirect method overestimates the impact SPL, as the theoretical force does not account for the decrease due to the contact stiffness. The weighted normalised impact SPL $L_{n,w} = 79.9$ dB from the indirect method agrees well with the 80.5 dB from the direct measurement. The results show that the indirect method with the transfer functions is generally suitable for calculating the normalised impact SPL.

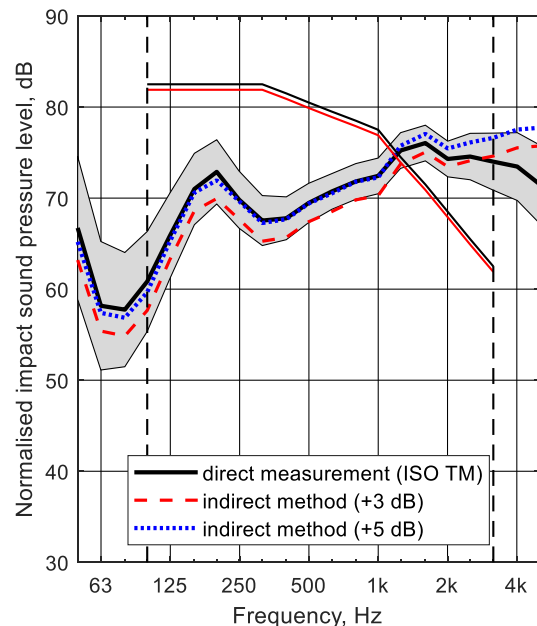


Figure 10. Normalised impact SPL of the reference floor at HFT Stuttgart from the direct measurement and the indirect method using blocked forces corresponding to a plastic impact +3 dB and +5 dB.

5. APPLYING THE INDIRECT METHOD TO WALLS

After the validation of the indirect method on a concrete reference floor in a floor topping testing facility, it was applied to masonry walls in the wall testing facility of Empa and in the staircase testing facility of STEP GmbH. Both walls were made from calcium silicate bricks. The Empa wall had a thickness of 25 cm (450 kg/m^2) with a plaster layer on the receiving room side. The STEP wall was 24 cm thick (432 kg/m^2) with layers of plaster on receiving and source room sides. The same measurement procedure as for the reference floor in Section 4 was applied, but now the PTM and MTM were used for the direct measurement, see **Figure 11**. When using the MTM, the walls were excited at ten positions as required according to DIN 7396. The PTM was only used at Empa and mounted to four different positions on the wall. The transfer functions were measured at the hammer excitation positions and averaged.

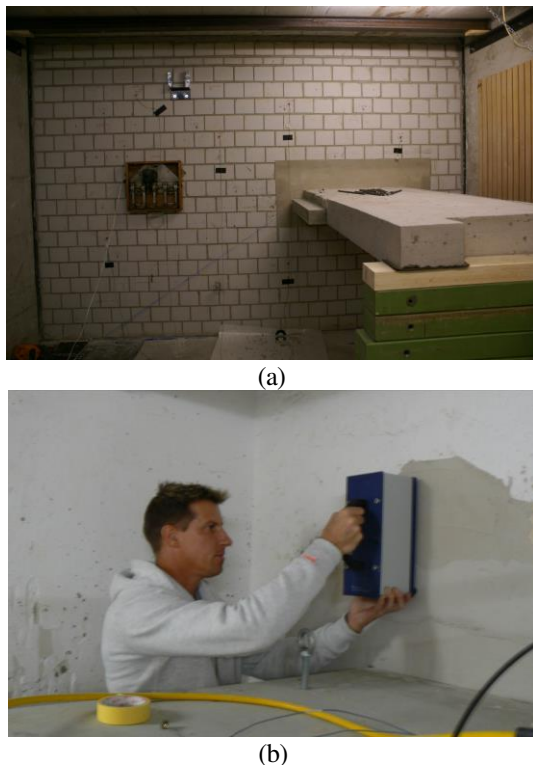


Figure 11. Direct measurement of the wall impact SPL; (a) Empa wall with PTM; (b) STEP wall with MTM.

Figure 12 compares the directly measured normalised impact SPL of the Empa wall using the PTM and MTM with the indirect method. Up to 2.5 kHz, the measurement results for both tapping machines are in good agreement. The indirect method works well up to 1 kHz. Compared to the results for the concrete floor in Section 4, the rebound of the hammers from the wall appears to be well approximated with the impulse from Eq. (8) (+3 dB). Above 1 kHz the indirect method overestimates the normalised impact SPL as the contact stiffness is not accounted for in the theoretical blocked force. For the single-number ratings, the weighted normalised impact SPL from the indirect method is $L_{n,w} = 77.1 \text{ dB}$ and overestimates the directly measured 70.6 dB (PTM) and 71.4 dB (MTM). The differences of up to 6.5 dB are due to the overestimation above 1 kHz when applying the weighting procedure of ISO 717-2.

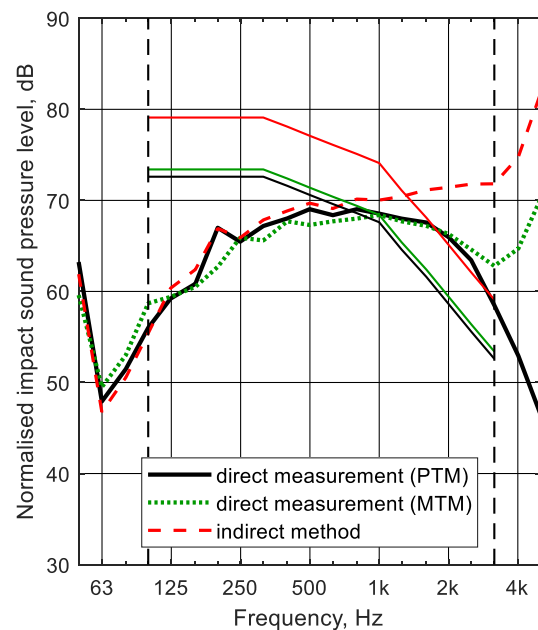


Figure 12. Normalised impact SPL of the wall at Empa from the direct measurement with the PTM and MTM compared with the indirect method.

In **Figure 13** the normalised impact SPL of the STEP wall is shown, comparing the direct measurement using the MTM with the indirect method. A reasonable agreement is given up to 1.6 kHz. Above an overestimation occurs due to the missing effect of the contact stiffness in the theoretical blocked force. The weighted normalised impact SPL for the direct measurement of $L_{n,w} = 69.8 \text{ dB}$ is almost 6 dB below the 75.7 dB from the indirect method.

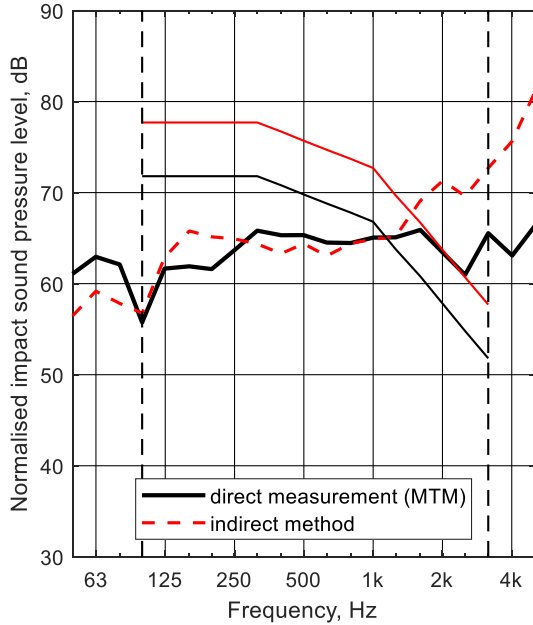


Figure 13. Normalised impact SPL of the wall at STEP GmbH from the direct measurement with the MTM compared with the result from the indirect method.

6. IMPLICATIONS ON PREDICTIONS OF THE SOUND TRANSMISSION IN BUILDINGS

In Section 5 it was shown that the normalised impact SPL of a wall is overestimated above around 1 kHz by the indirect method, due to the missing effect of contact stiffness in the theoretical blocked force. Consequently, the landing impact SPL reduction with the indirect method would be overestimated as

$$\Delta L_{\text{Landing}} = L_{n0, \text{Wall}} + \Delta L_{\text{contact}} - L_{n, \text{Landing}} \quad (9)$$

where $\Delta L_{\text{contact}}$ corresponds to the overestimate of the wall impact SPL due to the missing contact stiffness.

When calculating the impact sound transmission in buildings using the detailed (frequency-dependent) model from EN ISO 12354-2, the same theoretical blocked force is used to calculate the normalised impact SPL $L_{n, \text{situ}}$ of building elements (walls, floors). Hence, the effect of the contact stiffness is also neglected and the true $L_{n, \text{situ}}$ is given by

$$L_{n, \text{situ}} = L_{n, \text{theory}} + \Delta L_{\text{contact}} \quad (10)$$

where $L_{n, \text{theory}}$ is the normalised impact SPL of the wall (or floor) calculated using the theoretical blocked force of the ISO TM according to Annex B in [1]. Comparing $L_{n, \text{situ}}$ from Eq. (10) with $\Delta L_{\text{Landing}}$ from Eq. (9) obtained by the indirect method, one can see that both contain the overestimation $\Delta L_{\text{contact}}$.

According to EN ISO 12354-2, the impact SPL for the direct transmission through a building element is calculated as

$$L_{n, d} = L_{n, \text{situ}} - \Delta L_{\text{situ}} + \Delta L_{d, \text{situ}} \quad (11)$$

where ΔL_{situ} is the reduction of impact SPL (e.g. floating floor or isolated stair landing etc.) and $\Delta L_{d, \text{situ}}$ is the reduction from structural linings that may be added in the receiving room side. Adopting this to the case of impact sound transmission from the isolated landing through walls, as shown in **Figure 14**, $L_{n, \text{situ}}$ from Eq. (10) and $\Delta L_{\text{Landing}}$ (used as ΔL_{situ}) from Eq. (9) are substituted into Eq. (11). The impact SPL from the direct path 'd' thus becomes

$$L_{n, d} = L_{n, \text{theory}} - \Delta L_{\text{Landing}} + \Delta L_{d, \text{situ}} \quad (12)$$

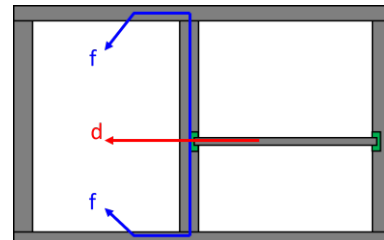


Figure 14. Impact sound transmission from a stair landing to an adjacent receiving room with the direct path 'd' (red) and two flanking paths 'f' (blue).

The overestimation $\Delta L_{\text{contact}}$ effectively cancels out. Likewise, cancellation occurs in the calculations of transmission paths over flanking elements 'f', for which the formulae are not given here. The transmission over the direct and all flanking paths is summed up to the total normalised impact SPL (L'_n) in a receiving room.

A correction of the theoretical blocked force to account for the contact stiffness would allow for more realistic data of $L_{n, \text{situ}}$, $L_{n0, \text{Wall}}$ and consequently $\Delta L_{\text{Landing}}$, but this would not change the results of L'_n in the predictions. Based on these results, it was decided to use the indirect method in prEN 17823.

7. CONCLUSIONS

The indirect method for determining the impact SPL using transfer functions was investigated and compared with direct measurements using different tapping machines. The ISO tapping machine and two tapping machines that allow the direct excitation of walls (mechanical pendulum and electrodynamic midi tapping machine) were characterised using the reception plate method according to EN 15657. The blocked forces of all three tapping machines are in good agreement in consideration of the measurement uncertainties. Thus, the two “alternative” tapping machines are suitable for the direct measurement of the normalised impact SPL of walls. The indirect method was validated on a concrete reference floor in a floor testing facility and applied to walls in two different testing facilities. Since the indirect method uses a theoretical blocked force as input, an overestimation of the wall impact SPL above 1 kHz occurs, as the effect of the contact stiffness is not taken into account. Therefore, the impact sound insulation of stairs or stair isolating elements will also be overpredicted. In predictions of the impact sound transmission in buildings according to EN ISO 12354-2, the same theoretical blocked force is used. Hence, the normalised impact SPL of the wall, where the stair landing is installed, is overpredicted by the same amount. When adding the landing impact SPL reduction, the error from the initial overestimation cancels out. Thus, the indirect method can be implemented in prEN 17823. For more realistic (unbiased) estimates of the normalised impact SPL, the theoretical blocked force needs a correction to account for the contact stiffness between the hammers and the receiving structure. In this study, such a correction was not considered. The current standardised models for impact sound transmission in buildings do not account for this effect as well.

8. ACKNOWLEDGMENTS

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