Uncertainties and validation procedures for the Compact Measurement Setup

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ABSTRACT

By using a small floor mock-up, the impact sound reduction of floor coverings can be determined by measuring the difference of the acceleration levels instead of measuring a sound pressure level in a receiving room (ISO 10140). The setup is validated for locally reacting floor coverings and standardized within the ISO 16251-1. To decide whether the covering under test can be considered as locally reacting, a validation procedure was developed on the basis of the standard uncertainties of the differences for every measurement position. A further issue for the method is that the measurement equipment must be capable of handling the signals. To check this, the bare floor acceleration levels of existing compact setups are proposed to be used as a criterion. Both validation methods are compared to actual measurements. Furthermore, the uncertainties of a measurement at a compact setup are considered due to the method of the GUM. This estimate of the uncertainty is compared to uncertainties according to ISO 12999-1. Finally, standard deviations of measurement results obtained at different compact setups and results obtained with different tapping machines at the same compact setup are presented which give an overview of the different uncertainty contributions.

Keywords: Compact Measurement Setup, validation procedure, uncertainties

1. INTRODUCTION

The impact sound reduction of a specific floor covering is determined by using a special test facility consisting of two vertically aligned rooms following the specifications of the standard ISO 10140 (1). During two AiF (Arbeitsgemeinschaft industrieller Forschungsvereinigungen) funded research projects a compact measurement setup was developed with the aim to reduce both the time needed and financial effort for a measurement of the impact sound reduction. The compact measurement setup for heavyweight ceilings is shown in figure 1.

Instead of the difference between the sound pressure level in a receiving room caused by the tapping machine on the bare floor and on the specimen under test, the acceleration level on the bottom side of the concrete slab is measured. The compact setup is standardized by ISO 16251-1 "Laboratory measurement of the reduction of transmitted impact noise by floor coverings on a small floor mock-up - Part 1: Heavyweight compact floor" (2). In figure 2a, the weighted impact sound reductions for 19 soft floor coverings (13 PVC and six carpets) determined at three different compact setups according to ISO 16251 (2) and three different test facilities according to ISO 10140 (1) are shown.

The grey area indicates the critical difference which describes a difference between two results which should not be exceeded with a statistical reliability of 95% (see ISO 12999-1 (3)). The mean values (black crosses) do not exceed the critical difference. Thus, measurement results obtained with the compact setup according to ISO 16251 (2) and the procedure according to ISO 10140 (1) show a very good agreement.

Investigations with hard floor coverings like laminates or screeds show larger differences between both methods (see figure figure 2b). Further investigations showed that the poor agreement between both methods with laminates is the result of a bad coupling between the covering and the floor. This causes additional air gaps between the covering and the floor which results in a higher impact sound reduction measured at the test facility according to ISO 10140 (1). Measurements of the mobility showed that the investigated laminate behaves more like a locally reacting spring-mass system (see (4)). Therefore, it can be stated that the impact sound reduction of locally reacting laminates can be measured at the compact setup according to ISO 16251 (2).

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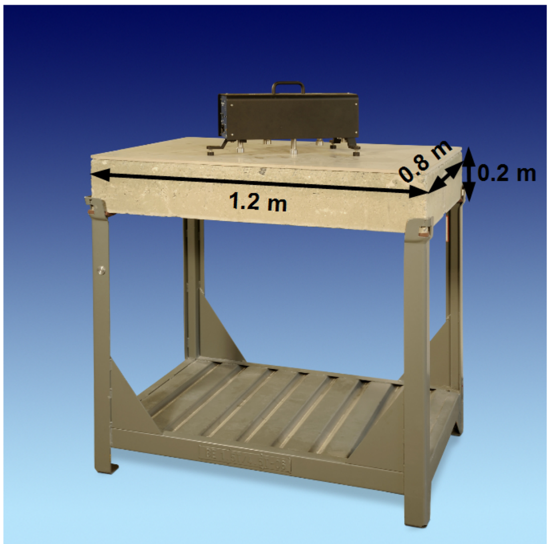
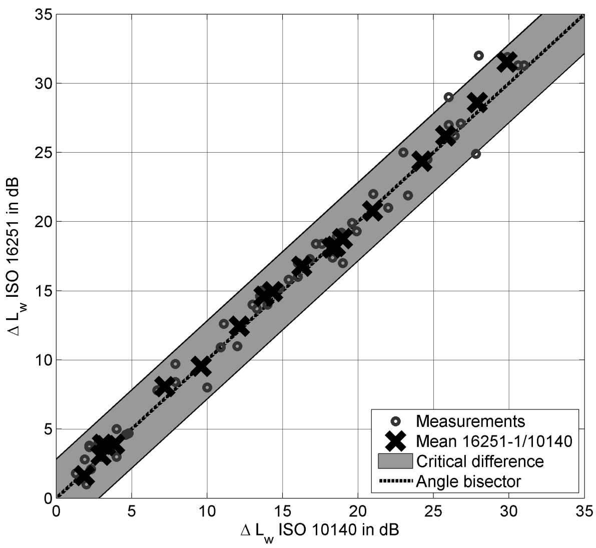
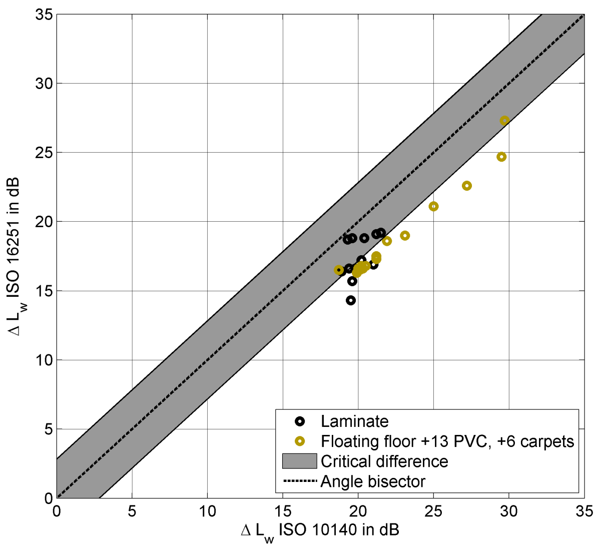


Figure 1 – Compact measurement setup for heavyweight floors.



(a) Comparison between the weighted impact sound reduction ΔL_w obtained at three different compact measurement setups according to ISO 16251 (2) and three different test facilities according to ISO 10140 (1).



(b) Comparison between the weighted impact sound reduction ΔL_w of twelve laminates and one floating floor combined with 13 PVC coverings and six carpets.

Figure 2 – Comparison between the method according to ISO 16251-1 (2) with a compact setup and the two room method according to ISO 10140.

The differences between both methods for the floating floor are caused by the fact that this floor covering changes the vibrational behaviour of the concrete slab. The compact setup works under the assumption that the floor covering under test only reduces the impact force at the point of excitation. Looking at the differences of $L_{1,t,a}$ (acceleration level with floor covering 1 at the position a and the position t of the tapping machine) and without $L_{0,t,a}$ floor covering (in this case six accelerometer with position a and two positions t for the tapping machine), a larger scatter can be seen comparing the measurement with a floating floor to a measurement with a PVC covering in figure 3.

$$\Delta L_{t,a} = L_{0,t,a} - L_{1,t,a} \tag{1}$$

This scatter leads to the assumption that the compact setup changes its vibrational behaviour and hence the

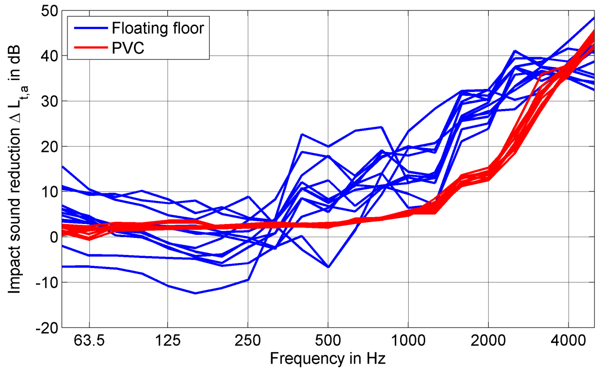


Figure 3 – Difference of the acceleration levels for every position of the accelerometers for measurements with a screed (blue) and with a PVC (red) covering.

compact setup is no longer applicable. To find the limits of the compact setup for heavyweight floor coverings, a validation procedure on the basis of the standard deviation of the differences in every measurement position $\Delta L_{t,a}$ is introduced in the following section.
Another possible error might be that the measurement technique is not able to handle the high acceleration levels during the excitation of the bare floor. This may lead to clipping effects in turn leading to incorrect acceleration levels. Therefore, an interval on the basis of the bare floor acceleration levels of three validated compact setups is introduced which can be compared with the bare floor acceleration level of a new compact setup.
Furthermore, the uncertainties are estimated according to the recommendations made by the GUM (Guide to the expression of uncertainty in measurement) (5). The estimation of the uncertainties is compared to the uncertainties according to ISO 12999-1 (3) and uncertainties obtained from actual measurements.

2. VALIDATION PROCEDURE FOR MEASUREMENTS AT A COMPACT MEASUREMENT SETUP

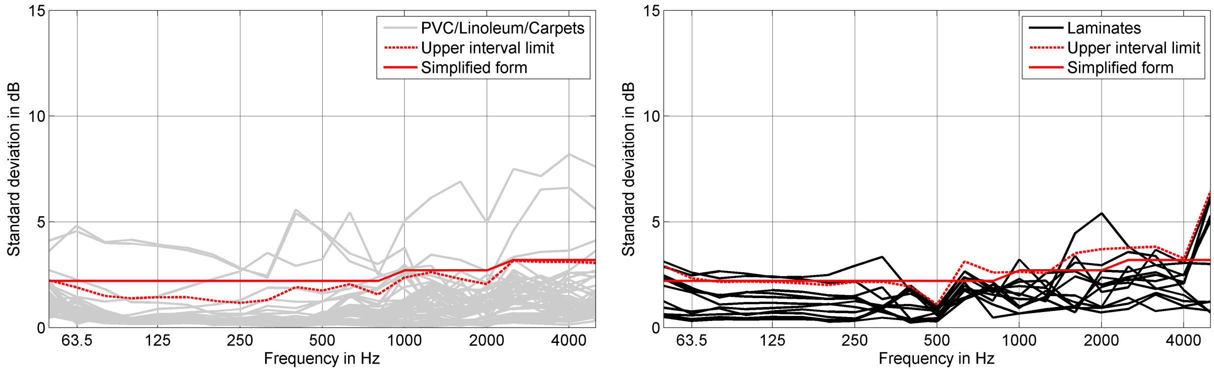
To find a validation procedure for the measurement at the compact setup, the data obtained from 52 soft floor coverings, twelve laminates and six screeds is evaluated. The standard deviation of the differences according to equation 1 of the six times two acceleration levels (six accelerometers and two positions for the tapping machine) are shown in figure 4a for the soft floor coverings. Under the assumption that the investigated floor covering does not change the vibrational behaviour, the standard deviation of the differences of the acceleration levels must be small.

2.1 Validation by means of the standard deviation of the acceleration level differences

The first idea of a validation procedure is to take a certain interval for the standard deviations obtained from the data from the 52 soft floor coverings. Assuming an χ^2 distribution of the standard deviations, the upper interval limit for a one-sided test for twelve degrees of freedom is calculated as follows.

$$\chi_{95\%} = \sqrt{\frac{n-1}{4.57} \cdot \overline{\sigma^2}} \tag{2}$$

This interval is depicted as a red dotted line in figure 4a and is the basis for the simplified shape, the straight red line. This line could be part of a validation procedure where the standard deviation of the differences should not exceed this line. Because of the instationary effects of carpets due to the excitation by a tapping machine, it may happen that the measurements with carpets have to be repeated. Due to the good conformity between the methods according to ISO 16251 (2) and ISO 10140 (1), the compact setup is validated for soft floor coverings. Thus, the simplified form of the interval could be used to validate measurements of other floor coverings. Figure 4b shows the standard deviation of the differences according to equation 1 for twelve



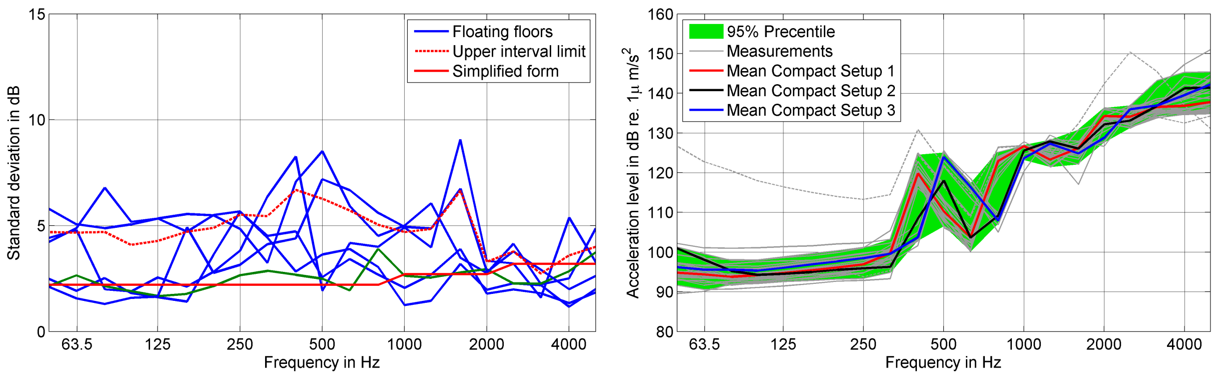
(a) Standard deviation of the differences of the acceleration levels for every position of the accelerometers for measurements with 52 soft floor coverings like linoleum, PVC and carpets.

(b) Standard deviation of the differences of the acceleration levels for every position of the accelerometers for measurements with twelve laminates.

Figure 4 – Standard deviations of the differences of the acceleration signals measured at the compact setup with and without soft floor coverings and laminates.

laminates. The dotted line shows the interval for the standard deviations of the measurements with laminates and the straight line the simplified interval for soft floor coverings. Both lines fit fairly well for the whole frequency range except for the 5000 Hz one-third octave band. It seems that the simplified confidence interval could also be used for the validation of measurements with laminates.

In figure 5a the standard deviations of the differences of six floating floors are shown. Some of these data were presented at other conferences (see (6) and (7)) in combination with the development of a compact setup at other institutions. The figure 5a contains data from three floating floor screeds, one dry screed, one doubled dry screed and one concrete slab. As already mentioned in the introduction the standard deviation of the differences in every position of measurement is higher due to the influence on the vibrational behaviour. Thus, the interval exceeds the simplified interval for soft floor coverings in nearly every one-third octave band. The standard deviation of the screed with the best accordance of both methods ($\Delta L_{w(16251)} = 16$ dB; $\Delta L_{w(10140)} = 16$ dB) is depicted as a green line. One can see that this standard deviation shows the best accordance with the simplified form of the interval for the data obtained with soft floor coverings. For the measurements on the doubled dry screed and the concrete slab, no data for measurements according to ISO 10140 (1) is available. For the other measurements the difference between both methods (ISO 10140 - ISO 16251) is between -1 dB and +3 dB.



(a) Standard deviation of the differences of the acceleration levels for every position of the accelerometers for measurements on six screeds.

(b) Acceleration levels of the bare floor during excitation by a tapping machine.

Figure 5 – Standard deviations of the differences of the acceleration signals measured at the compact setup according to ISO 16251 (2) with and without floating floors and the acceleration level for bare floor excitation with a tapping machine.

Applying the simplified interval to validate the measurements with the laminates, the floating floors and the soft floor coverings, some measurements are classified as invalid. A measurement is classified as invalid when more than two one-third octave band values exceed the interval. Figure 6 shows a comparison of the the weighted impact sound reductions of 52 soft floor coverings, of one floating floor combined with 13 soft floor coverings and twelve laminates between the compact setup according to ISO 16251 (2) and the method according to ISO 10140 (1). The weighted impact sound reductions marked as a triangle are classified as invalid. As expected all measurements at the floating floor are classified as invalid, due to the change of the

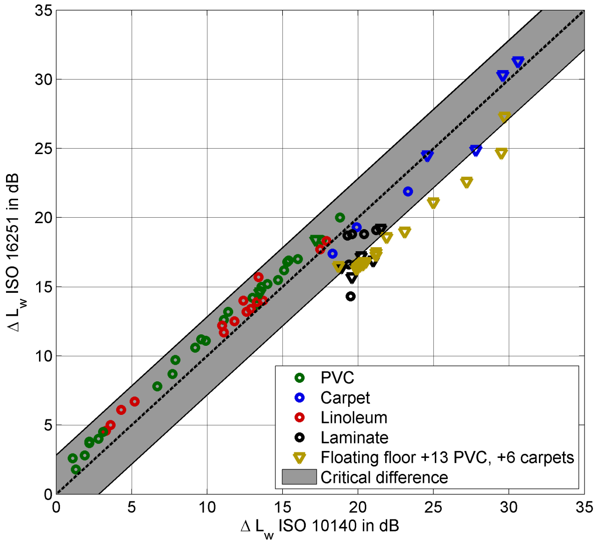


Figure 6 – Comparison between the weighted impact sound reduction ΔL_w obtained according to ISO 10140 (1) and ISO 16251 (2) with perspective to the introduced validation procedure based on the standard deviation of the acceleration level differences. Invalid classified measurements are marked as triangles.

vibrational behaviour of the compact setup. Two measurements at PVC coverings are also classified as invalid likewise four measurements at carpets. The two invalid classified measurements with PVC coverings are caused by random effects. Additional measurements with these coverings but with different tapping machines (see (8)) show valid results. The invalid measurements with carpets are related to the instationary effects of carpets. Four measurements with laminates are also classified as invalid. One can assume that this combination of laminate and impact sound reduction can not be considered as locally reacting. The assumption of locally reacting floor covering fits not for every combination of laminate and impact sound reduction. This can be checked with the introduced criteria.

2.2 Validation by means of the bare floor acceleration level

Another step to validate the compact setup could be to define a certain value for the bare floor acceleration level. Due to the fact that the ingredients of the concrete could vary, the interval should not be too small especially at the first resonance frequency of the slab. The acceleration levels with bare floor excitation by a tapping machine for three different compact setups obtained multiple times with different equipment are depicted in figure 5b. One can see that the resonance frequency is located somewhere between the one-third octave band 315 Hz and 500 Hz. The location of the resonance depends on the specific ingredients of the concrete slab. On the basis of the presented bare floor acceleration levels a confidence interval (95% percentile) is introduced as a part of a validation process (see figure 5b green area).

Some measurement systems might produce wrong values because of the high acceleration levels caused by the tapping machine on the bare floor. The dashed lines in figure 5b are the result of such measurements. With a validation procedure based on a comparison of the bare floor acceleration level with a reference curve such errors could be identified before the impact sound reduction is calculated.

3. ESTIMATION OF THE UNCERTAINTIES FOR MEASUREMENTS AT A COMPACT MEASUREMENT SETUP FOLLOWING THE METHOD OF THE GUM

The idea of the GUM (5) is to connect the results from measurements with a certain amount of uncertainties. The overall uncertainty is the result of the summation of different uncertainty components.

Regarding the uncertainties due to the use of a tapping machine and a one-third octave band analyzer the results published in (9) and (10) were used. Considering that the measurement at the compact setup is performed

with at least four accelerometers and no remounting is necessary, the uncertainties due to the accelerometers are neglected because of the fact that this is a relative measurement. Thus, a calibration of the setup is not necessary but recommended to check the measurement technique. By using only one accelerometer, higher uncertainties due to the different mounting conditions may occur. With respect to the guidelines for the correct mounting of accelerometers these uncertainties may also be neglected, due to the high acceleration levels. Also variations of the specification of the concrete slab can be neglected.
For the determination of the acceleration level $L_{a,t}$ at the position a and the position t for the tapping machine, the following corrections for the measured acceleration level $L'_{a,t}$ are considered.

$$L_{a,t} = L'_{a,t} - K_1 - K_{fil} - K_{av} - K_{cal} - K_{em} \tag{3}$$

The corrections due to the background noise level are considered as K_1, K_{fil} for the one-third octave band filters, K_{av} for the time averaging, K_{cal} for the calibration and K_{em} for the emission fluctuation of the tapping machine. The expected value for K_{fil}, K_{av}, K_{cal} and K_{em} is zero. However, the uncertainties of these values are not zero. For the acceleration level difference in every point of measurement it follows that

$$\Delta L_{a,t} = L'_{a,t,0} - K_{1,0} - K_{fil,0} - K_{av,0} - K_{cal,0} - K_{em,0} - L'_{a,t,1} + K_{1,1} + K_{fil,1} + K_{av,1} + K_{cal,1} + K_{em,1}. \tag{4}$$

The index 0 indicates the measurement without the specimen and the index 1, the measurement with the specimen. The correction due to the background noise level is only relevant for the measurement with the specimen. For the bare floor measurements, the signal-to-noise ratio is at least 20 dB (see figure 7).
Thus, equation 4 becomes

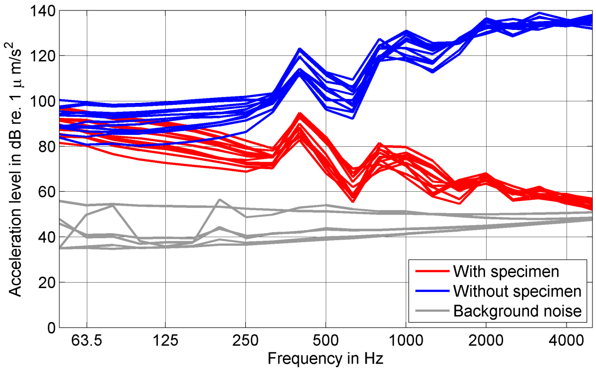


Figure 7 – Acceleration levels with and without a specimen and background noise level.

$$\Delta L_{a,t} = L'_{a,t,0} - K_{fil,0} - K_{av,0} - K_{em,0} - L'_{a,t,1} + K_{1,1} + K_{fil,1} + K_{av,1} + K_{em,1}. \tag{5}$$

The uncertainty for every difference $\Delta L_{a,t}$ is the result of the quadratic summation of the uncertainties of the single correction values.

$$u(\Delta L_{a,t}) = \sqrt{u^2(K_{fil,0}) + u^2(K_{av,0}) + u^2(K_{em,0}) + u^2(K_{1,1}) + u^2(K_{fil,1}) + u^2(K_{av,1}) + u^2(K_{em,1})} \tag{6}$$

The overall uncertainty is equal to the sum of the uncertainty for every difference $\Delta L_{a,t}$. In this example six accelerometers and two positions for the tapping machine were used.

$$u(\Delta L) = \frac{1}{at}\sqrt{\sum_{a=1}^{6}\sum_{t=1}^{2} u^2(u(\Delta L_{a,t}))} \tag{7}$$

The correction for the one-third octave band filter is applied for the measurements with and without the specimen, because of the different spectral shape of the acceleration levels. The correction for the tapping machine is calculated according to (9). These values were collected during validation measurements at many tapping machines, which were performed at PTB. During these validation measurements, the tapping machines were working on a cast stone slab. The uncertainty regarding the tapping machines results from the standard deviation of the introduced sound power in the cast stone slab.

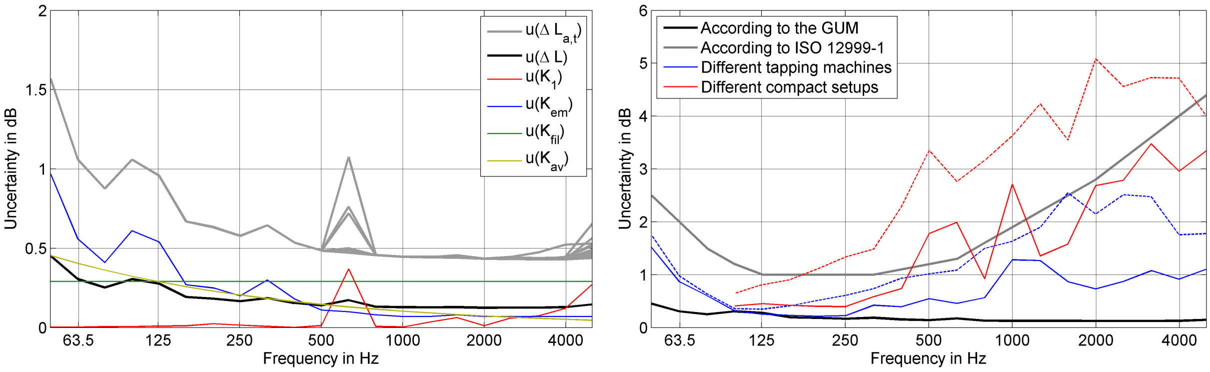
According to (10), the uncertainty for the correction due to the time averaging is calculated as follows.

$$u(K_{av}) = 20\,\log_{10}\left(1 + \frac{1}{\sqrt{B\Delta T}}\right)\,\mathrm{dB} \tag{8}$$

The absolute bandwidth is described as B and ΔT is the averaging time (in this case 30 s). The uncertainty due to the correction by the background noise level is also calculated according to (10) as follows

$$u(K_1) = \frac{10^{-0.1(L'_{a,t,1}-L_B)}}{1-10^{-0.1(L'_{a,t,1}-L_B)}}\sqrt{u^2(L'_{a,t,1})+u^2(L_B)}. \tag{9}$$

The uncertainty of K_1 is calculated by means of the acceleration levels shown in figure 7. Figure 8a shows the different uncertainty components.
Under the assumption of negligible correlation between the input quantities, the combined uncertainty for ΔL results in the black line in figure 8a.
In the following section the combined uncertainty is compared to the uncertainties obtained from actual measurements and uncertainties according to ISO 12999-1 (3).



(a) Single components of the uncertainty for measurements at the compact measurement setup.

(b) Comparison between the different uncertainty approaches. The blue and red dashed lines include 13 PVC coverings and six carpets. The carpets are excluded for the blue and red solid lines.

Figure 8 – Uncertainty components and comparison between different approaches to state the uncertainties.

4. COMPARISON OF THE UNCERTAINTIES ACCORDING TO THE GUM, ISO 12999-1 AND MEASUREMENTS

The approach of ISO 12999-1 (3) is to determine the uncertainty by means of the standard deviation of interlaboratory tests. The resulting standard deviation of reproducibility describes a normal measurement situation. Standard uncertainties for the reduction of impact sound pressure level see (ISO 12999-1 (3)) are depicted in figure 8b as a grey line. The combined uncertainty for the measurement of the impact sound reduction at a compact setup is depicted as a black line. The red line shows the mean standard deviation of the impact sound reduction measured with 13 PVC coverings (solid red) obtained at three different compact measurement setups (13 PVC and six carpets for the dashed red line).
The blue line shows the mean standard deviation for the impact sound reduction of 13 PVC coverings (solid blue) obtained with five different tapping machines at the same compact setup (13 PVC and six carpets for the dashed blue line). The standard deviation for the measurements including carpets (dashed lines) is larger than the standard deviations of the measurements only with PVC coverings. Due to the tapping machine the carpet changes its impact sound reduction over time. Thus, the averaging time has an influence on the impact sound reduction. During the measurements with the different tapping machines the operator was asked to keep the tapping machine working for two minutes before the measurement started, to obtain a stationary acceleration level. This procedure was not applied during the measurements at different compact setups. In this case the measurements were started right after the tapping machine was switched on. Because of these time variant effects of carpets, the standard deviation of the resulting impact sound reduction is larger.
The solid red line follows the uncertainty according to ISO 12999-1 (3) fairly well for the whole frequency range. For one of the three sets of measurements at different compact setups the results were obtained in one-third octave bands beginning at 100 Hz, so the uncertainty also starts at 100 Hz. The reason for the

increasing uncertainty at higher frequencies in the approach according to ISO 12999-1 (3) are the different thicknesses of the heavyweight floors. The standard ISO 10140 (1) suggests a thickness of 120^{+40}_{-20}mm. This leads to different thicknesses in test facilities and thus to a great variety of mobilities. Due to the differences in the bare floor acceleration levels of the three different compact setups (see figure 5b blue, red and black lines) the authors assume also a variety of mobilities of the compact setups even when the size of the concrete slab is well defined in ISO 16251 (2). Thus, the data obtained at different compact setups show a rising tendency of the uncertainties as well.
Four of five measurements with different tapping machines at the same compact setup were performed by the same operator and the same equipment (besides the tapping machines). This explains the lower uncertainty compared to the measurements at the different compact setups. The uncertainty for the measurements with carpets (dashed blue line) follows the uncertainty according to ISO 12999-1 (3) fairly well. The uncertainty excluding the carpets (solid blue line) is below 1.5 dB for the whole frequency range. Comparing this uncertainty to the approach according to the GUM (5), one can see much higher uncertainties for the frequencies below 80 Hz and above 315 Hz. The authors assume that the emission varieties are not fully covered by the model introduced in (9). The mentioned investigations at tapping machines include only measurements on a cast-stone plate. However, an influence of the floor covering on the emission is not considered yet.

5. SUMMARY

The results presented show that the impact sound reduction of soft floor coverings can be determined by measuring the acceleration level at a compact measurement setup instead of measuring the sound pressure level in a test facility according to DIN EN ISO 10140 (1) consisting of two vertically aligned rooms with a minimum volume of 50 m^3. For heavyweight plate-like coverings such as screeds the measurements at the compact setup may however lead to incorrect results. Because of the high mass of the screed the vibrational behaviour of the setup is changed. A validation method on the basis of the differences of the acceleration level at every point of measurement is proposed. If the standard deviation of the differences exceed a certain interval, the vibrational behaviour of the concrete slab is corrupted and the measurement is invalid. The proposed interval is based on the standard deviations of 52 soft floor coverings and can also be applied for laminates. Another validation method is to check the bare floor acceleration level and compare it to an interval which is calculated from already existing data for bare floor acceleration of compact setups.
Considering the uncertainties for a measurement at a compact setup the investigations show that measurements with carpets are quite uncertain due to the instationary effects of carpets. The uncertainty resulting from measurements with different tapping machines on the same compact setup with 13 PVC coverings is smaller than 1.5 dB for the whole frequency range. Compared to an estimate according to the GUM (5) the uncertainty is larger for low frequencies below 80 Hz and higher frequencies above 315 Hz. The low estimation of uncertainties by the method according to the GUM comes due to the lack of information of the emission variety when the tapping machine hits different floor coverings. Future models of the tapping machine will include more information regarding the emission variety in dependency of the investigated floor covering. The uncertainty for the impact sound reduction of 13 PVC coverings measured at three different compact setups follows the uncertainty according to ISO 12999-1 (3) very well.

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