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# Structure-borne sound sources in buildings – Estimating the uncertainty of source properties and installed power from interlaboratory test results

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**Abstract** – A low immission due to structure-borne sound sources is a major component of the acoustic quality inside buildings. After many years of research, methods have been standardised to characterise such sources (EN 15657) and to predict their impact in buildings (EN 12354-5). This contribution is dedicated to the question what the uncertainty of the source descriptors and the predicted installed sound power is. To answer this question, an interlaboratory test with an artificial source was performed. Altogether seven laboratories participated, and estimates for the uncertainties of the source quantities could be deduced from the measurement results. Additionally, measurements were performed with a standardised structure-borne sound source, the ISO tapping machine, by all participating laboratories. The measured source quantity for this source turned out to be in good agreement with the theoretically predicted values thereby validating this theoretical prediction.

**Keywords:** Structure-borne sound sources, 2-stage method, Installed power, EN 15657, Uncertainty of single equivalent source quantities

## 1 Introduction

Structure-borne sound in buildings is generated by vibrating sources, which inject vibrations through the contacts with building elements. The vibrations propagate throughout the building and radiate sound into rooms. Handling structure-borne sound has been the subject of research work in building acoustics for more than 40 years and the subject of International and European standards for more than 10 years [1], where source characterization as well as measurement and prediction of structure-borne sound generated in buildings are handled using a power-based approach, similar to the one used for handling airborne sound and consisting in a reduced form of statistical energy analysis [1].

The structure-borne sound generated in buildings depends on the source and the building structures involved in the transmission and the quantity to express the amount of sound emitted by the source is the installed power (structural power transmitted to the receiving building element). The installed power is not a characteristic of the source only but also depends on the receiver. Its expression is not simple, except if the receiver mobility is much lower than the source mobility (the source is then referred to as "force source"), which is often the case for common service equipment mounted in heavy concrete buildings. This simplicity led to the writing of the first two European standards on this subject in 2009, their scope being restricted to low mobility receiving structures:

- One standard aimed at the laboratory characterisation of service equipment (EN 15657-1:2009, [2]), where the source quantity was expressed in terms of characteristic power. The characteristic power is derived from measurements of the vibrational energy with the source connected to a 10 cm thick concrete plate, the plate loss factor and the plate mobility.
- Another standard aimed at predicting airborne and structure-borne sound in buildings due to the service equipment (EN 12354-5:2009, [3]), where the source input quantity for predicting structure-borne sound was the in-situ installed power, obtained from the characteristic power corrected for the ratio between the laboratory reception plate and the in-situ receiving plate.

There was no information on the uncertainty related to the determination of the installed power in EN 15657-1:2009. Therefore, a first round robin based on this standard was performed in 2011 [4, 5] to determine the uncertainty. The reference source tested consisted of a

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shaker mounted (via a force sensor to control the source activity) on a metal plate resting on three feet; the standard deviation of reproducibility of the characteristic reception plate power obtained was 4 dB in 1/3 octave bands.

Later on, the need for considering the general case of any structure-borne sound source mounted on any type of building structure (heavy or lightweight, of low or high mobility) led to the revision of EN 15657-1:2009 and the definition of other quantities for source characterisation and corresponding measurement methods. The new standard (EN 15657:2017, [6]) includes both cases: general case and case of low mobility receivers. The new source quantities used in the revised document and corresponding characterisation methods are recalled in Section 2.1 below.

Work on extending also the applicability domain of the prediction method to lightweight buildings followed, leading to the revision of EN 12354-5:2009 and the definition of new prediction calculation methods, written in a draft standard (Pr EN 12354-5:2021(E), [7]), which has just been submitted for enquiry to the CEN Technical Committee 126 (Building Acoustics) and is therefore not published yet. The input quantity for prediction of the sound propagation in the building is still the installed power in the general case. However, the prediction method and corresponding source input quantity to obtain the installed power can be simplified in the case of a "force source". These input quantities for prediction are recalled in Section 2.2 below.

Once again, the need for knowing the uncertainty related to the determination of the source characteristics and of the input quantities for a prediction of the sound propagation in the building (installed power in the general case) led first to research work (briefly recalled in Sect. 2.3), and once the revised standard EN 15657:2017 was published, to performing another round robin based on it. This second round robin is the main subject of this paper: the interlaboratory tests performed are described in Section 3 and their results given in terms of source characteristics in Section 4.

The estimation and results of the uncertainty related to the calculation of the input quantities for prediction (installed power in the general case) from the uncertainty of the source characteristics obtained in the round robin, are presented in the last section (Sect. 5).

## 2 Structure-borne sound sources in building acoustics

### 2.1 Source properties

The power-based approach used in building acoustics leads to describe structure-borne sound sources by three quantities for a prediction of the power transmitted to the receiver [8]: source activity (either the free velocity or the blocked force of the operating machine), source mobility and the receiver mobility of the supporting structural element, to which the source is connected. Service equipment is usually connected through multiple contacts to building elements. The total power transmitted is often close to the sum of the sound powers transmitted via the individual connection points since interaction between different connection points has proven to be negligible in case studies e.g. for fans, whirlpool baths, air-conditioning units [9, 10]. Furthermore, the force-induced powers are usually dominant, moment-induced powers are smaller e.g. for machines, lightweight stairs and waste water pipes [11–13]. As a result, equivalent single quantities reduced to forces and velocities perpendicular to the receiving surfaces can be used [9] and have been defined and used in EN 15657:2017, leading to the following source characteristics: (i) source activity, which can be directly measured as the sum of the squared free velocity over the contacts and expressed in terms of single equivalent free velocity level $L_{\mathrm{vf,eq}}$ in dB ref $10^{-9}$ m/s, or as the sum of the squared blocked forces, expressed in terms of single equivalent blocked force level $L_{\mathrm{Fb,eq}}$ in dB ref $10^{-6}$ N, and (ii) source mobility, expressed as single equivalent mobility (notation $Y_{S,\mathrm{eq}}$) and obtained as the average point mobility over the contacts. It should be noted that these three characteristics, expressed as complex values, are related to each other, the source mobility being equal to the ratio between the source free velocity and blocked force [1]. Using velocity and force levels, this relationship becomes [6]:

$$|Y_{S,\mathrm{eq}}|^2 \approx 10^{\frac{(L_{\mathrm{vf,eq}}-L_{\mathrm{Fb,eq}})}{10\,\mathrm{dB}}} \cdot 10^{-6} \cdot Y_0^2, \tag{1}$$

with $Y_0 = 1$ m/Ns.

Different laboratory characterisation methods are proposed in EN 15657:2017 to determine these three source characteristics:

- for the blocked force, an indirect measurement using the low mobility reception plate method defined in EN 15657-1:2009 is proposed; the source single equivalent blocked force is deduced from the measured installed power and the reception plate mobility, also measured and averaged over the contacts (see Sect. 2.2, Eq. (3b)); alternatively the blocked force can be calculated from the measured free velocity and the measured source mobility (see next two bullet points).
- for the free velocity, two possibilities are offered: direct measurement at the contacts with the source being either mounted on isolators or freely suspended, or indirect measurement using a high mobility reception plate; the installed power is then measured using the same method as for the low mobility reception plate, from which the source single equivalent free velocity is deduced, knowing the reception plate mobility, also measured (see Sect. 2.2, using Eq. (3a)).
- the source single equivalent mobility can be either directly measured using a standardised measuring method [14], or deduced from the measured source free velocity and blocked force as explained before.

The indirect method to determine both the free velocity and the blocked force using reception plates is referred to as the "two-stage method".

### 2.2 Source input quantities for prediction

As before, the input quantity for prediction using EN 12354-5 is in the general case the installed power [7], which can be determined from the source and receiver properties using the following approximation [1]:

$$L_{\mathrm{Ws},i} \approx 10\lg\left(\frac{\mathrm{Re}(Y_{R,\mathrm{eq},i})\,Y_0}{|Y_{S,\mathrm{eq}}|^2 + |Y_{R,\mathrm{eq},i}|^2}\right)\mathrm{dB} + L_{\mathrm{vf,eq}} - 60\,\mathrm{dB}, \quad (2a)$$

where,

$|Y_{S,\mathrm{eq}}|$ is the equipment single equivalent mobility magnitude as defined in EN 15657,

$\mathrm{Re}(Y_{R,\mathrm{eq},i})$ and $|Y_{R,\mathrm{eq},i}|$ are respectively the single equivalent mobility real part and magnitude of receiving element $i$, as defined in EN 15657,

$L_{\mathrm{vf,eq}}$ is the equipment single equivalent free velocity level in dB ref. $10^{-9}$ m/s as defined in EN 15657.

A similar expression of the installed power in the general case can be written as a function of the blocked force [7]:

$$L_{\mathrm{Ws},i} \approx 10\lg\left(\frac{\mathrm{Re}(Y_{R,\mathrm{eq},i})}{\left(1+\frac{|Y_{R,\mathrm{eq},i}|^2}{|Y_{S,\mathrm{eq}}|^2}\right)Y_0}\right)\mathrm{dB} + L_{\mathrm{Fb,eq}}, \quad (2b)$$

where,

$L_{\mathrm{Fb,eq}}$ is the equipment single equivalent blocked force in dB ref. $10^{-6}$ N as defined in EN 15657.

Expression (2a) becomes simpler if the receiver mobility is significantly higher than the source mobility, which is the case for the high mobility reception plate used in EN 15657 (see Sect. 2.1):

$$L_{\mathrm{Ws},i} \approx 10\lg\left(\frac{\mathrm{Re}(Y_{R,\mathrm{eq},i})\,Y_0}{|Y_{R,\mathrm{eq},i}|^2}\right)\mathrm{dB} + L_{\mathrm{vf,eq}} - 60\,\mathrm{dB}. \quad (3a)$$

And Expression (2b) becomes simpler if the receiver mobility is significantly lower than the source mobility, which is the case of the low mobility reception plate used in EN 15657 (see Sect. 2.1):

$$L_{\mathrm{Ws},i} \approx 10\lg\left(\frac{\mathrm{Re}(Y_{R,\mathrm{eq},i})}{Y_0}\right)\mathrm{dB} + L_{\mathrm{Fb,eq}}. \quad (3b)$$

Note, that for these two extreme cases, only one source quantity is required (either the free velocity or the blocked force). As a result, and in the case of a receiving building element with a significantly lower mobility than the source, the method for predicting structure-borne sound in buildings also becomes simpler: the structure-borne sound generated by the equipment connected to element $i$ can be simply deduced from the impact sound generated by a tapping machine connected to the same element, corrected for the difference in blocked force level between the equipment and the tapping machine,

$$L'_{\mathrm{ne},s,i} = L'_{\mathrm{n},i} + L_{\mathrm{Fb,eq}} - L_{\mathrm{Fb,eq,stm}}, \quad (4)$$

where,

$L'_{\mathrm{n},i}$ is the apparent impact sound pressure level of element $i$ calculated according to EN 12354-2, or measured on site if the building already exists,

$L_{\mathrm{Fb,eq}}$ is the single equivalent blocked force level in dB ref. $10^{-6}$ N of the source, measured according to EN 15657 and given by the manufacturer of the source;

$L_{\mathrm{Fb,eq,stm}}$ is the single equivalent blocked force level in dB ref. $10^{-6}$ N of the ISO tapping machine given in a Table in prEN 12354-5:2020(E).

The prediction of impact sound is according to EN 2354-2 [15], and the result is corrected to obtain the sound level generated by the source considered. However, the blocked force level of the tapping machine must be known and this is why tapping machines were also tested during the round robin (see Sect. 3.1).

### 2.3 Estimating the uncertainty of the installed power

Once the "two-stage" laboratory characterisation method had been developed, research work on the uncertainty associated to this method and the calculation of the installed power was undertaken, as reported in several papers (see [1]) and particularly the following two papers:

- [16], where a partial derivative equation obtained from the linear expression of the installed power allows an estimate of the effect of uncertainties in determining the required input data. The result shows that if the uncertainty of input values is 1 dB, then the uncertainty of the predicted installed power is 4.5 dB.
- [17], where the characteristics of three different sources were determined using the two-stage method. Then, the sources were connected to receiving structures and the installed power was measured and also predicted. The average difference between the predicted and the measured installed power was about 4 dB in one-third octave bands between 50 Hz and 5 kHz.

In the case of the round robin reported in the paper, free velocity and blocked force are expressed as levels in dB and the corresponding standard deviations of reproducibility obtained are also expressed in dB; consequently, a partial derivative equation obtained from the expression of the installed power in dB (Expression (2b)) has been derived, allowing the estimation of the installed power uncertainty using the round robin results as input data. This derivation is shown in Section 5.

## 3 Interlaboratory test

### 3.1 Sources

The same source as in [5] was used again for this new interlaboratory test with slight modifications. It consists of an aluminium plate mounted on three feet which is excited by an inertial shaker connected to the aluminium plate in line with a force transducer (Fig. 1). The results reported in [5] were suspected to be biased by a variation in the level of the electrical excitation signal. It was therefore decided to provide a noise generator with fixed output

**Figure 1.** RRRS (round robin reference source) on a low mobility reception plate.

and a power amplifier with well-defined settings. Instructions for the operation and mounting of the round robin reference source (RRRS) were given to the participants.

It was also decided to provide an electromagnetic standard tapping machine, a SINUS TM 50 (Fig. 2) which is designated as Reference tapping machine – RTM. Additionally the labs were asked to perform measurements with their own tapping machines (Laboratory tapping machine – LTM). For their own tapping machines, all labs used only two different types, NOR 211 (Fig. 3) and NOR 277 (Fig. 4).

**Figure 2.** Reference tapping machine (RTM).

**Figure 3.** Laboratory tapping machine (LTM), type 1.

**Figure 4.** Laboratory tapping machine (LTM), type 2.

### 3.2 Participating laboratories and performed measurements

Within the interlaboratory test, measurements were performed by Empa (Switzerland), CSTB (France), IBP (Germany), Geberit (Switzerland), PTB (Germany), HFT Stuttgart (Germany) and TH Rosenheim (Germany). The task was to determine the single equivalent blocked force, the single equivalent free velocity and the single equivalent mobility of the RRRS according to [6]. For both tapping machines, only the single equivalent blocked force was to be measured using a low mobility reception plate. One laboratory reported results with an isolated and a non-isolated low mobility reception plate. These two results are considered to be independent. A high mobility reception plate was applied only by one laboratory.

### 3.3 Properties of the reception plates

All low mobility reception plates are concrete plates. Four isolated plates are used with surface masses of 190 kg/m$^2$, 240 kg/m$^2$, 250 kg/m$^2$ and 250 kg/m$^2$ and surface areas of 5.6 m$^2$, 5.6 m$^2$, 5.7 m$^2$ and 10.4 m$^2$. Such data is not required for non-isolated plates as they were calibrated using a known input power. Nevertheless, for two of the non-isolated plates it is known that the surface mass is 350 kg/m$^2$ and the surface area is about 20 m$^2$. This corresponds to reference floors for the measurement of impact noise reduction according to ISO 10140-5 [18].

Equivalent mobility levels are mainly in the range between −50 dB and −60 dB for the low mobility reception plates (Fig. 5) if calculated by,

$$L_{\mathrm{Re}(YR)} = 10\lg\left(\frac{\mathrm{Re}(Y_{R,\mathrm{eq}})}{Y_0}\right)\,\mathrm{dB}. \tag{5}$$

The isolated low mobility plates have larger mobilities than the non-isolated plates due to the smaller thicknesses. Also shown is the mobility magnitude of a mass of 500 g. This represents the mobility of a hammer of a tapping machine. In the considered frequency range, the mobility of all reception plates is more than 10 dB lower than that of the hammers. Hence the precondition for the measurement of the blocked force of the tapping machines is fulfilled.

For the high mobility plate, [6] requires a receiver mobility of at least −20 dB. This is fulfilled between 125 Hz and

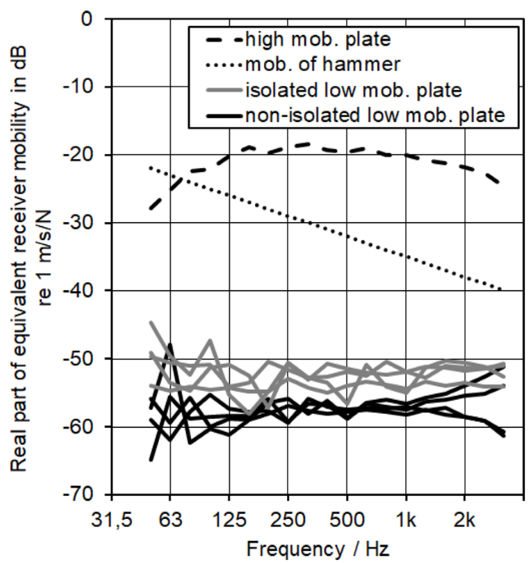


**Figure 5.** Measured real parts of equivalent mobility of reception plates and mobility magnitude of a mass of 500 g.

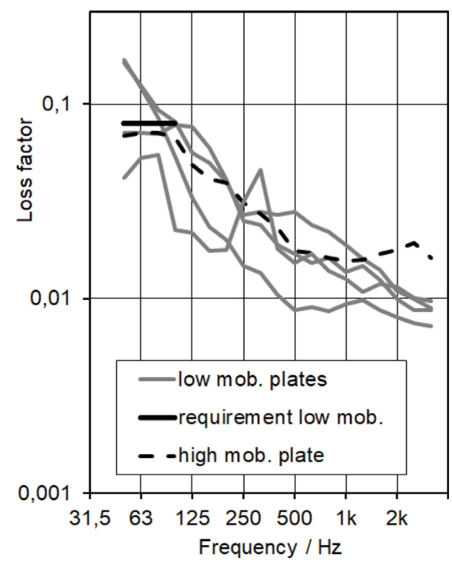


**Figure 6.** Loss factors of the isolated low mobility and the high mobility reception plates and minimum loss factor required by [6].

1 kHz. Above and below this frequency range, the mobilities are up to 8 dB lower.

The total loss factor, required for the isolated reception plates only, shows a typical decrease with increasing frequencies (Fig. 6). The minimum loss factor required by [6] for low mobility reception plates is 0.08 in the one-third-octave-bands from 50 Hz to 100 Hz. This is not fully met by all isolated low mobility reception plates.

For the non-isolated reception plates, a calibration by the power injection method is required. The difference between the injected structure-borne sound power and the spatial average velocity level on the reception plate is then considered to be the plate-individual calibration factor e.g. level difference. It is remarkable that this value is similar for the low mobility reception plates used (Fig. 7).

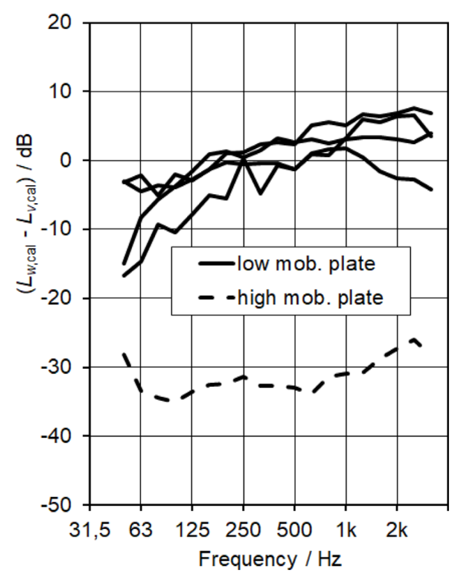


**Figure 7.** Difference between injected sound power level and mean velocity level on the non-isolated low mobility and the high mobility reception plates.

## 4 Measurement results

### 4.1 Results with tapping machines

#### *4.1.1 Theoretical value for the single equivalent blocked force*

Based on the findings from [19], the blocked force level of a tapping machine can be expressed in one-third octave bands by:

$$L_{F,\mathrm{bl},1/3-\mathrm{oct}} = 20\lg\left[\frac{\sqrt{2}\mathrm{m}\ v_{\max}}{T\ F_0}\left(1+\frac{v'_{\max}}{v_{\max}}\right)\sqrt{N}\sqrt{M}\right]\mathrm{dB}, \tag{6}$$

with hammer mass $m$, velocity of the hammer immediately before impact $v_{\max}$, velocity of the hammer imediately after the impact $v'_{\max}$, time between impacts $T$, number of hammers $M$ and number of lines in the respective one-third octave band $N$, and the reference force $F_0 = 10^{-6}$ N. The level of the blocked force depends on the type of impact. For an elastic impact ($v'_{\max} = v_{\max}$), it is 6 dB higher than for a plastic impact ($v'_{\max} = 0$). In reality, the impact is somewhere between these two cases. The number of lines in each frequency band can be determined from the bandwidth of a one-third octave band by,

$$N = \left(2^{1/6} - 2^{-1/6}\right) f\, T, \tag{7}$$

with the centre frequency of the one-third octave band $f$. Equations (6) and (7) can be applied with the assumption

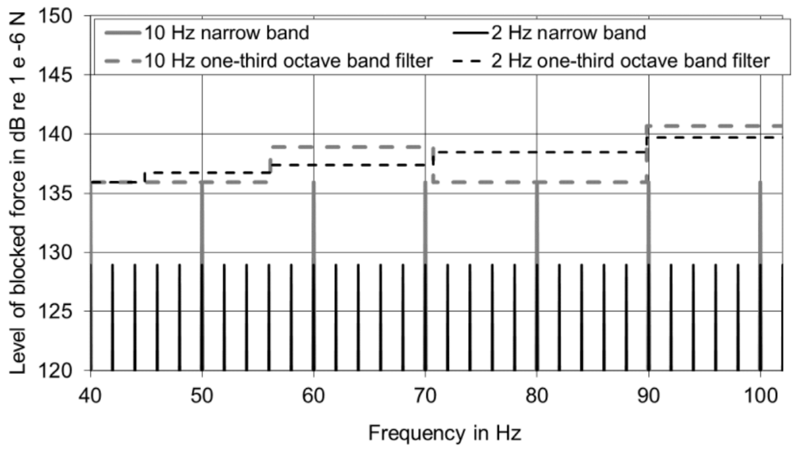


**Figure 8.** Visualisation of Equation (6) in combination with Table 1 showing the summation of spectral lines to one-third octave bands for the theoretical assumptions of a 10 Hz line spectrum and a 2 Hz line spectrum, plastic impact ($v'_{max} = 0$).

**Table 1.** Number of lines in each frequency band.

| $f$/Hz | 50 | 63 | 80 | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630…5 k |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T = 0.1$ s, $M = 1$ | 1 | 2 | 1 | 3 | 3 | 3 | 5 | 6 | 7 | 9 | 11 | Equation (7) |
| $T = 0.5$ s, $M = 5$ | 6 | 7 | 9 | 12 | | | | Equation (7) | | | | |

of one hammer with a 10 Hz line spectrum or with the assumption of five hammers with a 2 Hz line spectrum. As for the impact, the reality is somewhere in between these two cases [19]. The number of frequency lines in the one-third octave bands must be an integer whereas Equation (7) gives a real number. This is illustrated in Figure 8, where the summation within the one-third octave bands is shown for the 2 Hz line spectrum and for the 10 Hz line spectrum. The number of lines used for the calculation is given in Table 1.

Differences between the 2 Hz and the 10 Hz assumption are only observed at low frequencies (Fig. 9). The typical frequency pattern follows from the fact that the assumption of a 10 Hz line spectrum leads to only one spectral line in the one-third octave bands at 50 Hz and at 80 Hz (see Tab. 1 and Fig. 8) whereas the other bands include larger numbers of lines. Under the assumption of a 2 Hz line spectrum, the resulting single equivalent blocked force levels are a much smoother function of frequency.

#### *4.1.2 Measured single equivalent blocked forces*

The single equivalent blocked forces are measured by the participating laboratories by placing the tapping machines at one position on the low mobility reception plates. The averaged plate velocity is measured by accelerometers distributed on the plate. For the non-isolated plates, the calibration factor of Figure 7 is applied to calculate the structural power level injected to the reception plate whereas for the isolated plates the sound power is calculated from the loss factors (Fig. 6) and the plate masses under the assumption of a diffuse field. With the assumption that the receiver mobility is much smaller than the source mobility (Fig. 5), the single equivalent blocked force is calculated

Measured single equivalent blocked force levels are mainly within the theoretically expected limits (Fig. 10). The majority of the results is closer to the upper limit, indicating an elastic impact. For some isolated plates the results are closer to the lower limit. A possible explanation would be a higher damping of these reception plates. The spectral shape as predicted for a 10 Hz line spectrum with a local maximum at 63 Hz and lower values at 50 Hz and 80 Hz is clearly seen in some of the spectra.

All participants reported results with both tapping machines on the same reception plate at identical measurement positions. The differences between measured single equivalent force levels and the theoretically expected force level for a medium collision (Eq. (6) with $T = 0.5$ s and $v'_{max} = \left(\sqrt{2} - 1\right) v_{max}$) shows a systematic behaviour in some laboratories (e.g. Fig. 11). The level of the RTM is about 1 dB higher than the level of the LTM. This is the case in three laboratories. The levels from both machines are nearly identical in four laboratories (e.g. Fig. 12).

In one laboratory, an overload of the accelerometers was detected after the sources were sent to the next laboratory. It occurred only with the measurement of the RTM. When these overload cases are omitted, the standard deviation of reproducibility of the single equivalent blocked force level is almost identical for RTM and LTM (Fig. 13). It is about 4 dB in the lowest bands and about

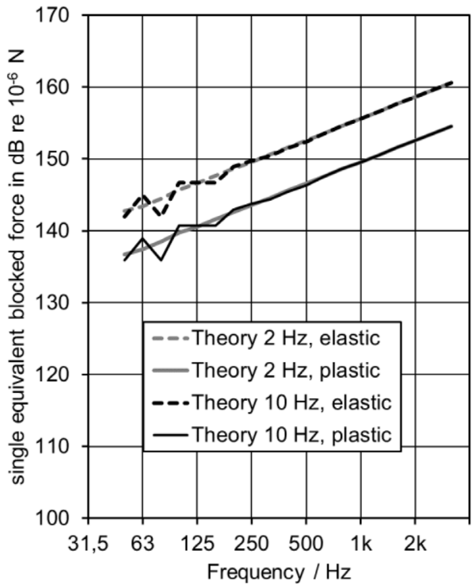


**Figure 9.** Range of theoretically expected equivalent blocked force levels in one-third octave bands calculated for a 2 Hz and a 10 Hz line spectrum and for elastic impacts ($v'_{\mathrm{max}} = v_{\mathrm{max}}$) and plastic impacts ($v'_{\mathrm{max}} = 0$).

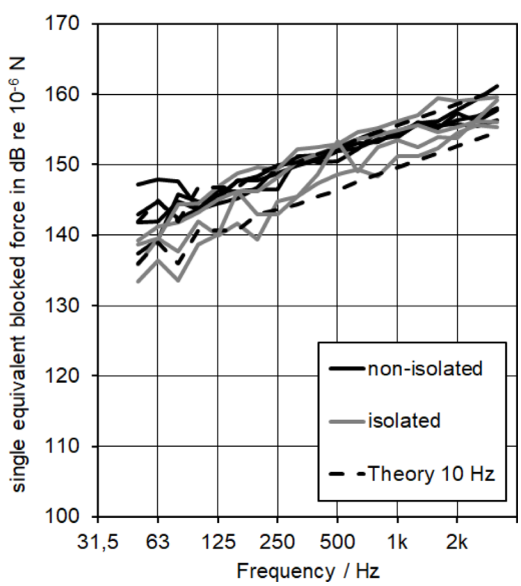


**Figure 10.** Single equivalent blocked force levels for the laboratory tapping machines LTM measured on isolated and non-isolated reception plates in comparison to the theoretical results for elastic and plastic impacts (Eq. (6) with $T = 0.1$ s).

2 dB between 400 Hz and 3.15 kHz. It is interesting to note that these values are slightly larger than the values from ISO 12999-1 situation B [20]. This situation covers cases where different teams measure an impact noise level with their own equipment in the same transmission situation, i.e. the receiving structure is identical. In this round robin,

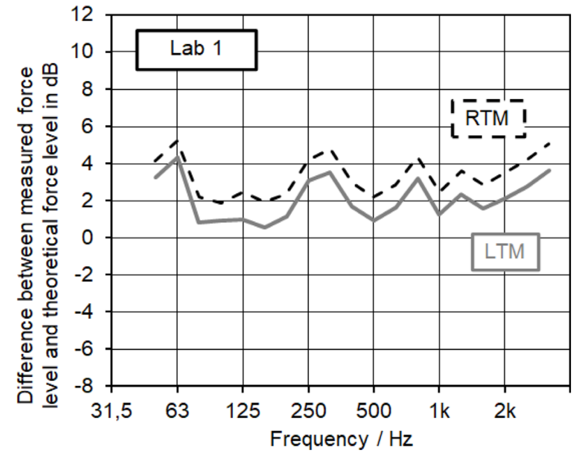


**Figure 11.** Difference between measured level of equivalent blocked force and theoretical value with $T = 0.5$ s and $v'_{\mathrm{max}} = \left(\sqrt{2} - 1\right) v_{\mathrm{max}}$ for RTM and LTM in lab 1.

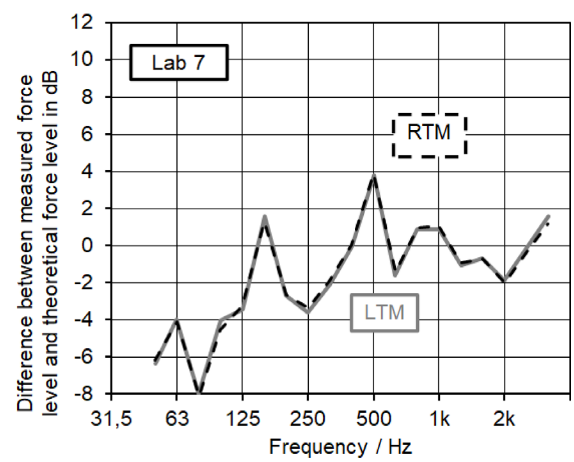


**Figure 12.** Difference between measured level of equivalent blocked force and theoretical value with $T = 0.5$ s and $v'_{\mathrm{max}} = \left(\sqrt{2} - 1\right) v_{\mathrm{max}}$ for RTM and LTM in lab 7.

different receivers were used which may cause a different behaviour of the tapping machines and therefore the standard deviation may be slightly higher than for situation B in ISO 12999-1.

## 4.2 Results with the round robin reference source

### *4.2.1 Single equivalent blocked force*

The single equivalent blocked force levels for the round robin reference source are measured on the low mobility reception plates at one position in the centre of the plate as for the tapping machines. The results show a spectral pattern with peaks and troughs (Fig. 14). One result from an isolated reception plate clearly stands out. The reason for the discrepancy could not be identified. Therefore, this result was omitted from further processing. At low frequencies and especially at the peak at 200 Hz, the results from

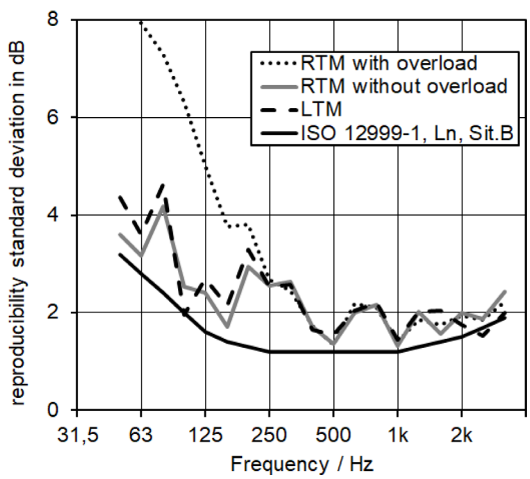


**Figure 13.** Standard deviation of reproducibility for the single equivalent blocked force for the round robin tapping machine RTM and the laboratory tapping machine LTM.

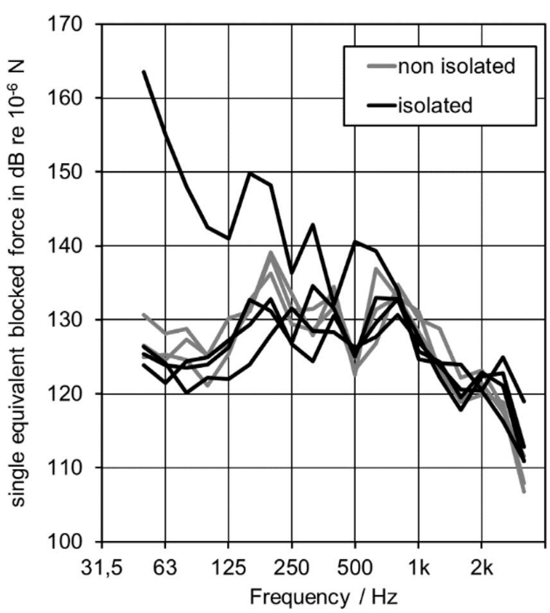


**Figure 14.** Measured single equivalent blocked force levels for the round robin reference source.

the three isolated plates tend to be systematically smaller than the results from the three non-isolated plates.

The source was equipped with an internal force sensor (Fig. 1). Applying a correction for a constant internal force changes only the outlying result drastically whereas the other results are hardly affected. This is seen from the standard deviation of reproducibility (Fig. 15) which was calculated for the case with and without correction. Furthermore, the standard deviation of reproducibility reflects the spectral shape of the measured single equivalent blocked force levels. Smoothing out the peaks and troughs in this curve, a very rough estimate is about 3 dB for all frequencies.

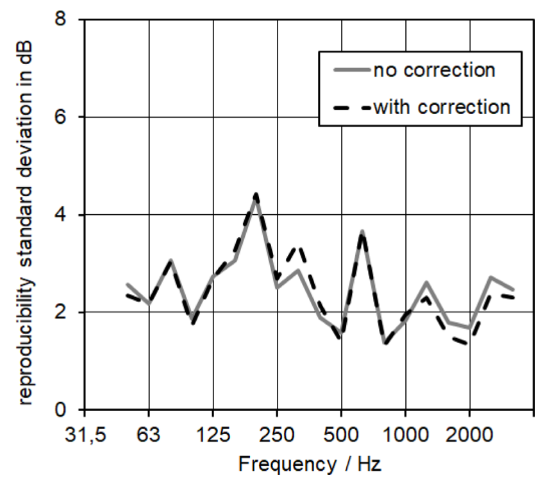


**Figure 15.** Reproducibility standard deviation of the single equivalent blocked force level.

#### 4.2.2 Single equivalent free velocity

The single equivalent free velocity levels are measured by participating laboratories by freely suspending the source and measuring the free velocity at the three feet of the source by accelerometers, while the shaker is operating according to the instructions (see Fig. 18). The single equivalent free velocity level is obtained by energetically summing the contributions from the three feet.

The spectral shape of the single equivalent free velocity levels exhibits some similarities to the shape of the single equivalent blocked force level (Figs. 14 and 16). Peaks and troughs are clearly visible. One laboratory also applied an isolated high mobility reception plate. When the calibration procedure is applied (see Clause 3.3), this result tends to get closer to the results of the freely suspended source (Fig. 16). A noticeable difference occurs around 200 Hz. Whereas all the results with the freely suspended source are peaking at 200 Hz, the result from the high mobility reception plate has a much smaller peak at 250 Hz. The connection of the source to the high mobility reception plate seems to change the source properties.

Applying the correction for changes of the internal force reduces the standard deviation of reproducibility for the single equivalent free velocity level slightly (Fig. 17). Furthermore, the standard deviation exhibits variations with frequency which reflect the spectral shape of the free velocity. As a frequency average, a value of 4 dB seems to be a realistic estimate.

#### 4.2.3 Single equivalent source mobility

To measure the single equivalent source mobility, the source is freely suspended. Accelerometers are attached to the feet of the source. The feet are then excited by an instrumented hammer with an integrated force sensor (Fig. 18). The single equivalent source mobility magnitude is finally calculated by averaging the mobilities at the three feet. Measurement results obtained by the participants are in excellent agreement (Fig. 19). The standard deviation of

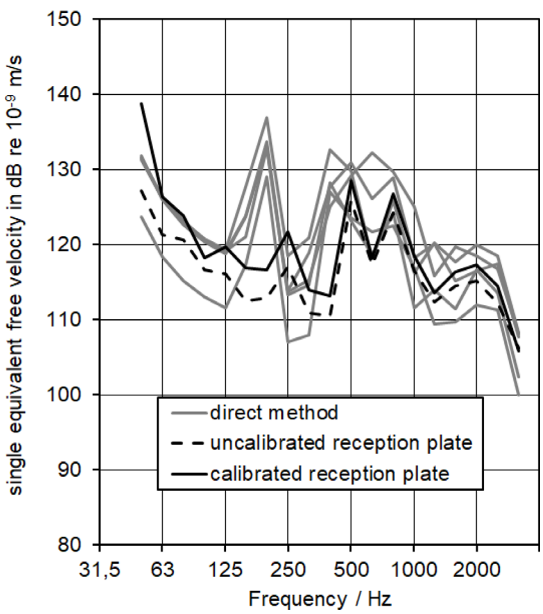


**Figure 16.** Measured single equivalent free velocity levels for the round robin reference source.

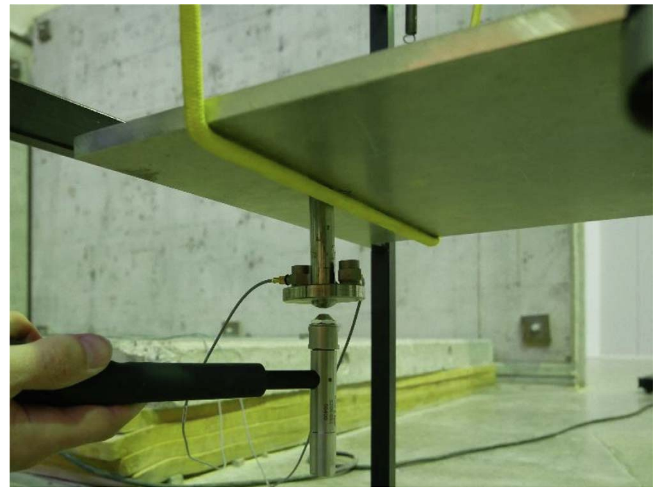

**Figure 18.** Suspended source, with two mounted accelerometers at one source foot and an impact hammer for excitation for the measurement of the source mobility (the impact hammer is not used for the measurement of the free velocity).

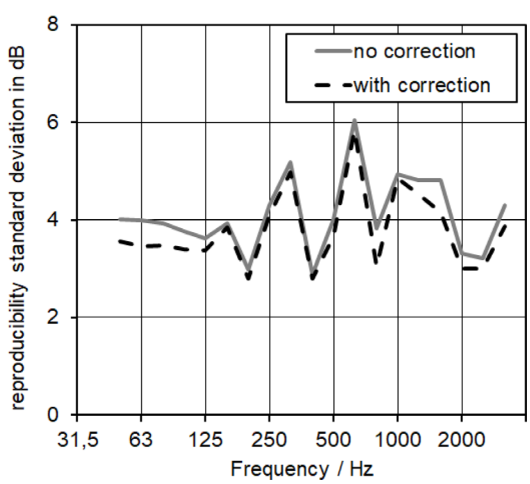


**Figure 17.** Reproducibility standard deviation of the single equivalent free velocity level.

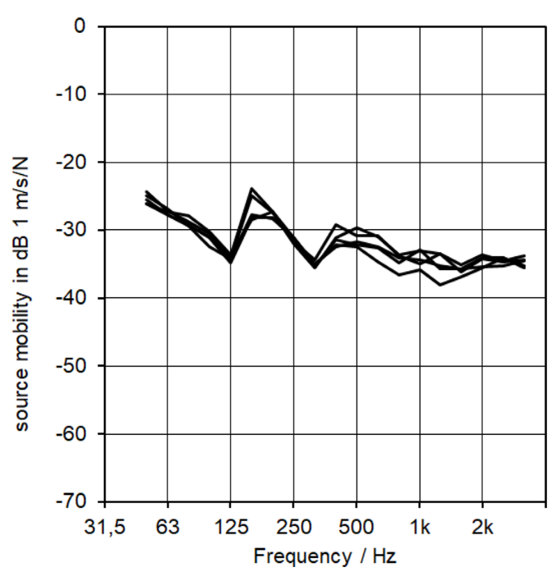


**Figure 19.** Measured single equivalent source mobility magnitude levels for the round robin reference source.

reproducibility exhibits some variation with frequency which is attributed to the source properties (Fig. 20). Therefore, an estimate of 1 dB is considered to be an appropriate estimate for all frequencies.

It is furthermore observed that the single equivalent source mobility of the round robin reference source is sufficiently large compared to the mobility of the low mobility reception plates (see Figs. 2 and 19) to enable a correct measurement of the single equivalent blocked force. In contrast to this, the mobility of the high mobility reception plate is not high enough below 250 Hz. The measurement of the single equivalent source velocity on this reception plate is therefore slightly influenced by the coupling of the source to the plate, see also Clause 4.2.2.

### *4.2.4 Consistency test*

The round robin reference source is characterised by independent measurements of the three quantities: free velocity, blocked force and source mobility. Due to the existence of three contact points, the single equivalent values are used. For each of these quantities, an estimate for the uncertainty is available. Furthermore, the three source describing quantities are not independent since any two of these quantities allows calculation of the third. It is therefore possible to check whether the uncertainty estimates are realistic by calculating the level of the single equivalent free velocity from the level of the measured single equivalent

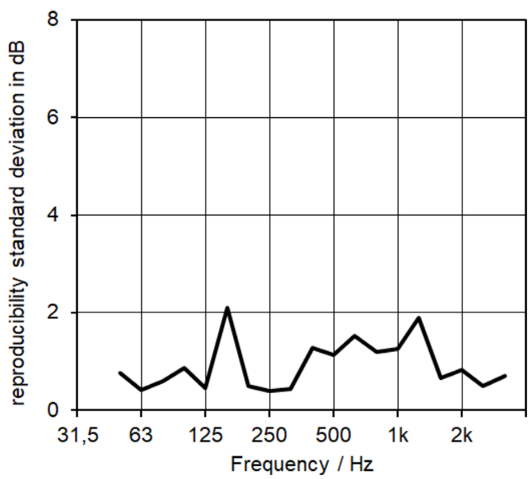


**Figure 20.** Reproducibility standard deviation of the single equivalent source mobility level.

blocked force $L_{\mathrm{Fb,eq,meas}}$ and the level of the measured single equivalent mobility magnitude $L_{|YS|,\mathrm{meas}}$ (see Eq. (1)),

$$L_{\mathrm{vf,eq,\,calc}} \approx L_{\mathrm{Fb,eq,meas}} + 2\,L_{|YS|,\mathrm{meas}} + 60\,\mathrm{dB}. \tag{8}$$

This calculated single equivalent free velocity level is now compared to the measured single equivalent free velocity level by a test quantity $\zeta$,

$$\zeta = \frac{L_{\mathrm{vf,eq,calc}} - L_{\mathrm{vf,eq,meas}}}{\sqrt{u^2(L_{\mathrm{vf,eq,calc}}) + u^2(L_{\mathrm{vf,eq,meas}})}}, \tag{9}$$

which involves also the uncertainty $u$ of the measured and calculated single equivalent free velocity levels. The former is estimated to be 4.0 dB (see Clause 4.2.2) whereas the latter follows from Equation (8) to be,

$$u(L_{\mathrm{vf,eq,\,calc}}) = \sqrt{u^2(L_{\mathrm{Fb,eq,meas}}) + 4\,u^2\left(L_{|YS|,\mathrm{meas}}\right)} = 3.6\,\mathrm{dB}, \tag{10}$$

with the uncertainty estimates from Clauses 4.2.1 to 4.2.3. This calculation is performed for the results from each laboratory individually. The test quantity $\zeta$ should be in a range between $-2.0$ and 2.0 for a statistical confidence level of 95%. At most frequencies, this is the case (Fig. 21). Especially in the 160 Hz and 250 Hz bands, larger values are observed. This means that deviations between calculated and measured free velocity levels are statistically significant, or in other words, uncertainties are larger than the simple frequency-averaged estimates. At the frequencies in question, observed uncertainties are higher due to the spectral characteristics of the source. Additionally, the observed deviation may be interpreted to indicate limitations in the whole approach where the source is considered to have constant properties regardless of a free suspension or a connection to a reception plate.

Assuming independent one-third octave band results, the percentage of the $\zeta$ – values within $\pm$ 2.0 is an indicator for the quality of the uncertainty estimates. For the presented analysis, six laboratories reported 19 band results each. From these altogether 114 results, 100 are within $\pm$ 2.0 which corresponds to 88% of the results. This is considered to be a sufficiently large percentage to prove that the uncertainty estimates are realistic.

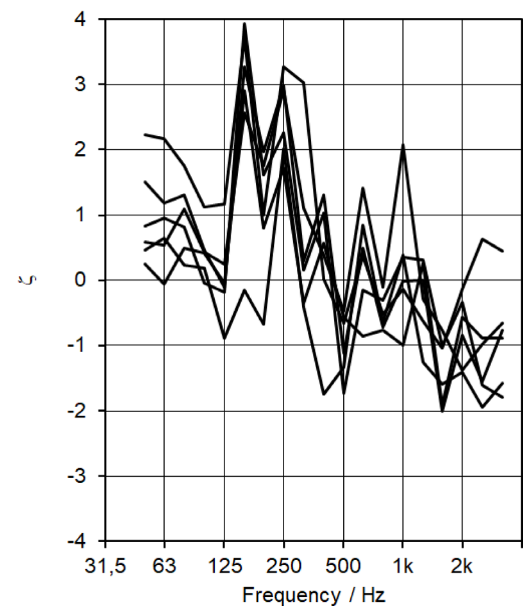


**Figure 21.** Test quantity for the consistency test.

## 5 Uncertainty of installed power

In principle, the installed power can be calculated from Equation (2a) or from Equation (2b). Here, Equation (2b) is used. For a single receiving element, this equation can be rearranged to,

$$L_{W,\mathrm{inst}} \approx L_{\mathrm{Fb,eq}} + L_{\mathrm{Re}(YR)} - 10\ \lg\left(1 + 10^{0.2\,L_{(YR/YS)}/\mathrm{dB}}\right)\mathrm{dB}, \tag{11}$$

with Equation (5) and,

$$L_{(YR/YS)} = 10\ \lg\left(\frac{|Y_{R,\mathrm{eq}}|}{|Y_{S,\mathrm{eq}}|}\right)\mathrm{dB}. \tag{12}$$

The underlying assumption is that the three quantities single equivalent blocked force level $L_{\mathrm{Fb,eq}}$, the level of the real part of the receiver mobility $L_{\mathrm{Re}(YR)}$ and the level of the mobility ratio $L_{(YR/YS)}$ are independent quantities. This is not fully the case since the receiver mobility is involved in both mobility terms once as the real part and once as the modulus. Nevertheless, since the latter is used only relative to the modulus of the source mobility, it is considered to be appropriate to use the real part of the receiver mobility as one independent quantity and the mobility ratio as another independent quantity. The uncertainty of the installed power becomes,

$$u(L_{W,\mathrm{inst}}) \approx \sqrt{u^2(L_{\mathrm{Fb,eq}}) + u^2\left(L_{\mathrm{Re}(YR)}\right) + \frac{4\,u^2\left(L_{(YR/YS)}\right)}{\left(1 + 10^{-0.2\,L_{(YR/YS)}/\mathrm{dB}}\right)^2}}. \tag{13}$$

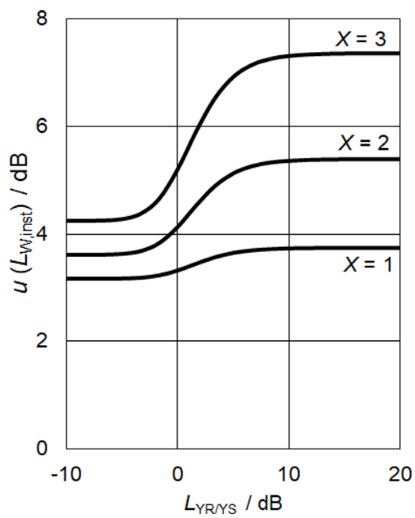


**Figure 22.** Uncertainty of the installed sound power level with assumed uncertainties $u(L_{\mathrm{Re}(YR)}) = u(L_{(YR/YS)}) = X$ dB.

A quantitative estimate of the installed power requires reasonable assumptions on the uncertainty of the input quantities. For the single equivalent blocked force level, the uncertainty estimate from the round robin of 3.0 dB is used. For the real part of the receiver mobility and the mobility ratio, uncertainties of 1.0 dB, 2.0 dB and 3.0 dB are assumed. The resulting uncertainty of the installed sound power level is then between 3.2 dB and 4.2 dB when the receiver mobility is much smaller than the source mobility (Fig. 22). In this case, the mobility ratio and its uncertainty do not influence the predicted installed sound power level. In the opposite case, i.e. when the receiver mobility is much larger than the source mobility, the uncertainty of the predicted installed power is between 3.7 dB and 7.4 dB and thus significantly larger. This is caused by the additional influence of the mobility ratio and its uncertainty, see Equation (13). Between these two extreme cases of mobility ratios, a smooth transition region is observed (Fig. 22).

It is interesting to note that the uncertainty of the installed sound power level becomes larger when Equation (2a) is used for the prediction. One reason is that the uncertainty of the single equivalent free velocity level is larger than the uncertainty of the single equivalent blocked force level if the estimates from the round robin are used. Furthermore, the mobility terms are of larger influence in Equation (2a) compared to Equation (2b).

As a conclusive example, the installed sound power level of the round robin reference source and its uncertainty is calculated for the two cases that it is connected to a low mobility infinite plate with $Y = 10^{-5}$ m/(s N) and a high mobility infinite plate with $Y = 10^{-2}$ m/(s N) (Fig. 23). The resulting 68% confidence intervals for the installed sound power level differ by about 30 dB which is caused by the second term of Equation (11). The difference between both cases is smaller when the source mobility (see Fig. 19) gets closer to the mobility of the high mobility receiver which is the case e.g. at 50 Hz and at 160 Hz.

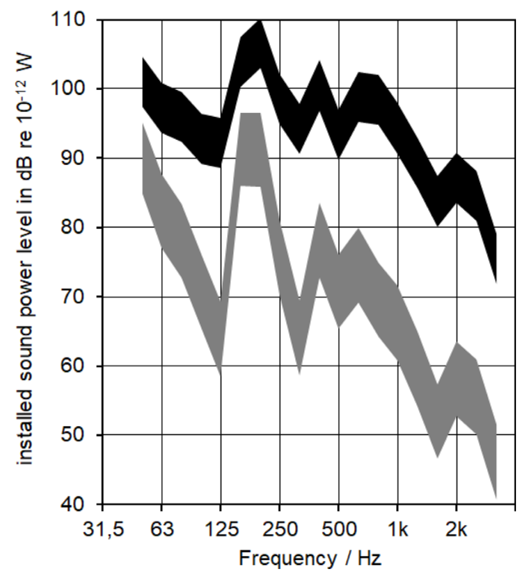


**Figure 23.** Sixty eight percent confidence intervals of the predicted installed sound power level of the round robin reference source when it is connected to a low mobility receiver ($Y = 10^{-5}$ m/(s N), black) and a high mobility receiver ($Y = 10^{-2}$ m/(s N), grey) under the assumption $u(L_{\mathrm{Re}(YR)}) = u(L_{(YR/YS)}) = 2.0$ dB.

## 6 Conclusion

An interlaboratory test has been performed with a structure-borne sound source. Source quantities were measured according to EN 15657:2017 [6]. From these measurement results, the uncertainties are estimated to be 3 dB for the single equivalent blocked force level, 4 dB for the single equivalent free velocity level and 1 dB for the level of the single equivalent source mobility,

$$u\left(L_{\mathrm{Fb,eq}}\right) \approx 3\,\mathrm{dB};\; u\left(L_{\mathrm{vf,eq}}\right) \approx 4\,\mathrm{dB};\; u\left(L_{|YS|}\right) \approx 1\,\mathrm{dB}. \quad (14)$$

These values are valid for one-third octave bands from 50 Hz to 3.1 kHz. From these uncertainties, the uncertainty of the installed sound power level was estimated. When the receiver mobility is much smaller than the source mobility (force source situation), the uncertainty of the installed sound power level is about 3 dB to 4 dB. In the opposite case, when the receiver mobility is much larger than the source mobility (velocity source situation) much larger uncertainties of up to 7 dB are yielded,

$$u\left(L_{W,\mathrm{inst}}\right) \approx \begin{cases} 3\ldots4\,\mathrm{dB} & \text{for } Y_R/Y_S \ll 1 \\ 4\ldots7\,\mathrm{dB} & \text{for } Y_R/Y_S \gg 1. \end{cases} \quad (15)$$

Furthermore, the single equivalent blocked force level of two tapping machines has been determined by the participating laboratories, also according to EN 15657:2017 [6]. One tapping machine was provided within the interlaboratory test whereas the other one was selected by each laboratory from their own equipment. Measured single equivalent blocked force levels are well within the theoretically predicted range. There is no significant difference for using different tapping machines observed.

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## Conflict of interest

The authors declare that they have no conflicts of interest in relation to this article.

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