Prediction of sound pressure levels in rooms using EN 12354 and the characteristic structure-borne sound power of structure-borne sound sources

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ABSTRACT

In residential and office buildings service equipment can be annoying if it produces noise. To avoid noise, especially structure-borne noise, a prediction and calculation of sound power injected into the structure is necessary. Standard EN 12354-5:2009 only provides little information regarding the characterisation of a structure-borne sound source. Especially for light-weight structures, when the mobilities of source and receiver could match, a practical method for the power prediction is missing. But they are necessary for an accurate sound pressure prediction.

This paper focuses on the prediction of sound pressure levels in rooms due to structure-borne sound sources. For the characterisation of the sources, the "Two-Stage Method" (TSM) was used. TSM yields the characteristic source parameters and the characteristic structure-borne sound power of the sources. With these source parameters, the sound pressure levels in a light-weight test facility were calculated and compared with measurements.

Furthermore it will be referred, if the prediction method in EN 12354-5:2009 using TSM for source characterisation is valid for the prediction of sound pressure levels due to structure-borne sound sources in light-weight constructions.

1. INTRODUCTION

Service equipment in residential and office buildings can be annoying, in case it produces noise. So called structure-borne sound sources in buildings can be for example pumps, compressors or ventilation vents which are more and more in use today. For the acoustic comfort in modern buildings, the investigation of the origin and the propagation of structure-borne sound is therefore necessary. Before a machine is installed on a wall or a floor, a structure-borne sound prediction is convenient. For that, sources have to be characterised by their specific parameters. With the knowledge about these values, the coupling elements and the receiving structure can be optimised to avoid annoying noise.

2. PREDICTION OF SOUND PRESSURE LEVELS WITH EN 12354-5

The prediction of sound pressure levels due to structure-borne sound sources can be done by EN 12354-5 [2]. There, a total normalised sound pressure level L_n represents the sum of all transmission paths in an energy based way. Therefore, the sound pressure level for each path between source (i) and receiver wall (j) is calculated separately, formula (1).

Additional to the knowledge of the specific parameters of the structure, the injected structure-borne sound has to be known. To describe the installed structure-borne sound, the parameter $L_\mathrm{Ws,inst}$ is used. Using this parameter, a good characterisation of the source has to be done. But structure-borne sound sources can be very different regarding their vibration behavior and their connection to the receiving structure. This makes a universally applicable characterization method necessary.

$$L_\mathrm{n,s,ij} = L_\mathrm{Ws,inst,i} - D_\mathrm{sa,i} - R_\mathrm{ij,ref} - 10\lg\frac{S_\mathrm{i}}{S_\mathrm{ref}} - 10\lg\frac{A_\mathrm{ref}}{4} \qquad \text{[dB]} \qquad (1)$$

$L_\mathrm{n,s,ij}$ Normalized sound pressure level for the propagation path between the "source" structure element i and the radiating element j in the receiving room – the sum of all involved paths

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	yields the total normalised sound pressure level [dB]
$L_{Ws,inst,i}$	Installed structure-borne sound power level on the mounted wall [dB]
$D_{as,i}$	Adjustment term for structure-borne to the air-borne excitation for the supporting building element i [dB]
$R_{ij,ref}$	Flanking sound reduction index for air-borne sound transmission from element i in the source room to element j in the receiving room, with reference to an element area of S_{ref} = 10 m²
S_i	Area of the structure element i with the mounted source [m²]
S_{ref}	Reference area, S_{ref} = 10 m²
A_{ref}	Reference equivalent absorption area, A_{ref} = 10 m²

But in [2], only little information about methods and their uncertainties is provided. Table 2 in [2] offers estimated values for the characterisation and the propagation of structure-borne sound. In [2], uncertainties of 5 dB are given for the determination of the source characterising parameters. In [8] it is shown, that source parameters can be determined with an uncertainty of about 4 dB. Even an uncertainty of 5 dB is provided for the determination of the transmission path parameters. This yields a total uncertainty of 7 dB, including the source characterisation and the propagation through the structure, if the determined source and transmission parameters are statistically independent. The provided values in table 2 in [2] have only an exemplary character. Actually, there are not enough measurement results for common structure-borne sound sources yet, which would yield more profound values of the uncertainties.

2.1 Characterisation of structure-borne sound sources

The characterisation of structure-borne sound sources can be done using the Two-Stage Method (TSM) [6]. In this paper, the source specific parameters blocked force F_b, free velocity v_{sf} and the resulting source mobility Y_S were used. Two-Stage means two different vibration stages of the source: the force acting and the velocity acting. If the source is installed on a very heavy weight receiver, force acting can be supposed and the blocked force can be determined. And in case the source is installed on a very light-weight receiver, velocity acting is supposed and the free velocity can be determined [3,4,5].

2.2 Characterisation of transmission paths

The sound transmission through the building structure with the sound radiation into the receiving room is described in the three last terms in formula (1) according to [1] for each single transmission path. Alternatively, the total transmission behavior of a building structure can be determined by the transfer function H resp. a transfer index γ, see formula (2).

With this parameter, the total sound transmission as a relationship between an excitation force acting at the building structure. The sound pressure level in a receiving room is characterised with only one parameter. In this parameter, separate and independent paths are not considered. Such transfer functions can be obtained directly from the prediction model in [2] or from measurements in buildings. Therefore, the transfer function can be determined by measuring the sound pressure p in the receiving room (system response) and the exciting force F (system stimulation), see formula (2). In-situ measurements in buildings are advantageous, because all paths of the sound propagation are determined exactly and simultaneous, without knowing the structure in detail.

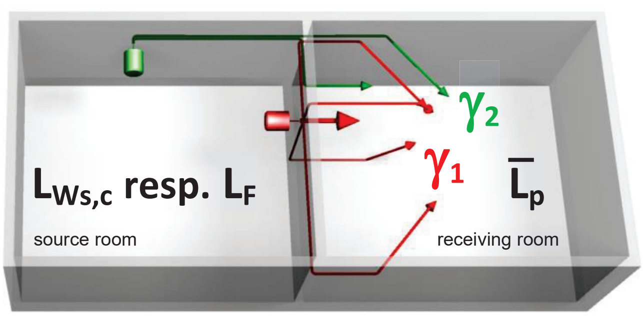


Figure 1 – Relevant sound transmission paths for the measurement of the transfer index γ. Type 1: Source connection on the separating wall (red). Type 2: Source connection on a flanking element (green)

The sound pressure level prediction according to [2] yields an averaged sound pressure level of the diffuse sound field in the receiving room. Therefore, the sound pressure has to be measured at different positions in the receiving room. Calculating the level and the mean of one-third octave bands, the participating transfer functions yields the transfer index γ, according to formula (2), [1]. Moreover, the transfer index can be expressed as an arithmetic mean value $\bar{\gamma}$ of different source connection points [1,2]. Subsequently, conclusions regarding the sound transmission behaviour independent of the connection point are possible considering the whole receiving structure. This can be important if light-weight constructions with strongly inhomogeneous constructions are used and considered.

$$H(f) = \frac{p(f)}{F(f)} \rightarrow \gamma = \bar{L}_{\mathrm{p}} - L_{\mathrm{F}} \qquad \text{[dB]} \qquad (2)$$

H(f)	Average (time-domain) transfer function between *p* and *F* [N/m² / N]
p(f)	Sound pressure in the receiving room [N/m²]
F(f)	Excitation force at the excitation point in the source room [N]
$\bar{L}_{\mathrm{p}}$	Average (different microphone positions) sound pressure level in the receiving room [dB]
L_{F}	Force level with reference force $F_0 = 2 \cdot 10^{-5}$ N [dB]

3. INVESTIGATIONS REGARDING THE STRUCTURE-BORNE SOUND TRANSMISSION

In this paper, the usability of experimentally determined transfer indices was investigated using calculated predictions and laboratory measurements. Especially the usability of source specific values determined with the Two-Stage-Method was investigated. For this propose, a method to predict the normalised sound pressure level due to structure-borne sound sources, according to [2], was used.

3.1 Characteristic structure-borne sound power

According to formula (3), the characteristic power $L_{\mathrm{Ws,c}}$ of a structure-borne sound source can be calculated. Therefore, the source parameters free velocity v_{sf} and source mobility Y_{S} were used, both determined by TSM.

$$L_{\mathrm{Ws,c}} = 10 \cdot \lg \frac{v_{\mathrm{sf}}^2}{W_{\mathrm{ref}}} \frac{1}{|Y_{\mathrm{S}}|} \qquad \text{[dB]} \qquad (3)$$

$L_{\mathrm{Ws,c}}$	Characteristic structure-borne sound power level [dB]
v_{sf}	Free velocity [m/s]
W_{ref}	Reference power 10^{-12} W
Y_{S}	Source mobility [m/Ns]

In [2], values of the characteristic structure-borne sound power level for different sources are provided. If the given values in figure 2 are compared to the results received by the TSM, all values are in a similar range. But a peculiarity has to be noticed regarding figure 2 in [2]. All source parameters were calculated for the assumption of force or velocity sources. This is valid if the receiver is much heavier or lighter than the source (black lines), shown in figure 2. The colored lines represent the source characterising parameters experimentally determined by TSM . Using the values obtained by TSM for a structure-borne sound power prediction, the acting system has not to be treated as pure force or velocity sources.

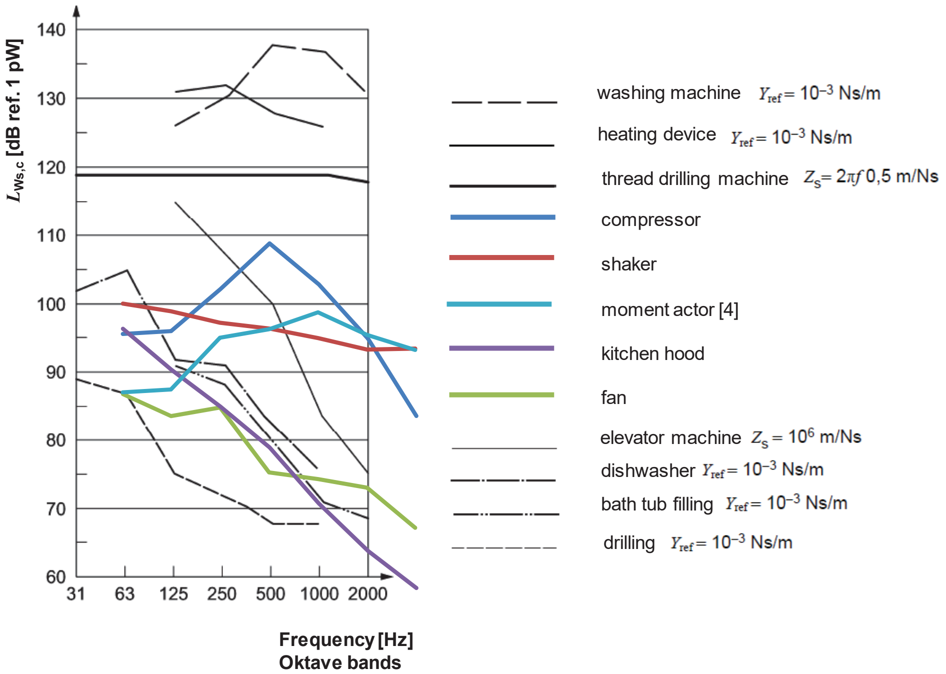


Figure 2 – Characteristic structure-borne sound power level $L_{\text{Ws,c}}$ according to [2] and for different sources characterised by TSM

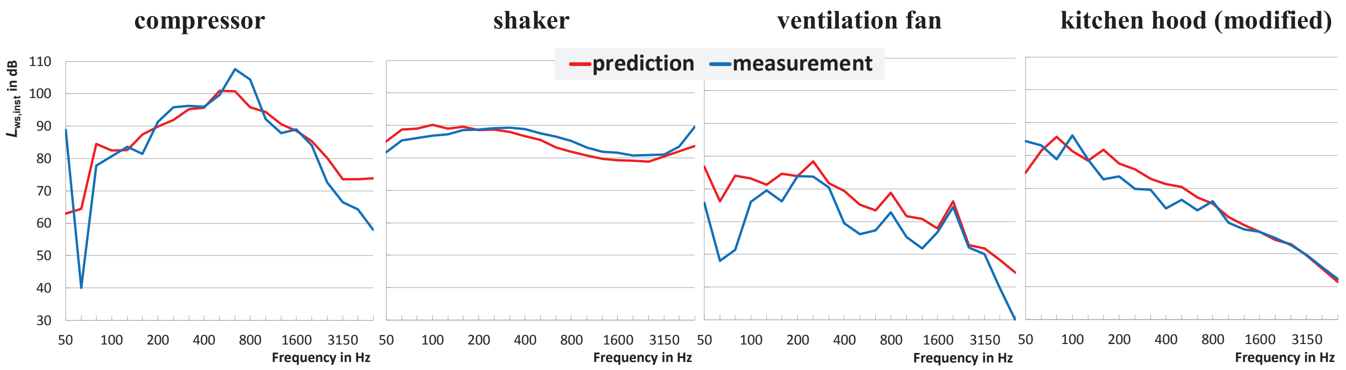


Figure 3 – Installed structure-borne sound power level $L_{\text{Ws,inst}}$ on a receiving structure for different sources; comparison of prediction according to [2] (red) and measurements with the reception plate method (blue)

3.2 Comparison of the injected structure-borne sound power level: prediction vs. measurment

The installed structure-borne sound power level $L_{\text{Ws,inst}}$ according to [2] describes the structure-borne sound power injected by a source into a receiving building element. It depends on the characteristic structure-borne sound power level $L_{\text{Ws,c}}$ of the source and on the relation of source mobility Y_{S} and receiver mobility Y_{i}, formula (5).

$$L_{\text{Ws,inst}} = L_{\text{Ws,c}} - D_{\text{C,i}} \qquad \text{[dB]} \qquad (4)$$

$$D_{\text{C,i}} = 10\lg\frac{|Y_{\text{S}}|^2 + |Y_{\text{i}}|^2}{|Y_{\text{S}}| \cdot \text{Re}\{Y_{\text{i}}\}} \qquad \text{[dB]} \qquad (5)$$

$L_{\text{Ws,inst}}$	Structure-borne sound power level injected into the receiving structure [dB]
$D_{\text{C,i}}$	Coupling term representing the relation between source mobility and mechanical structure mobility [dB]
Y_{S}	Source mobility [m/Ns]

Y_i Mechanical structure mobility of the receiving structure at force excitation point [m/Ns]

In figure 3, the comparison of the measured and predicted structure-borne sound power is shown. In the experiment, the power was measured by the reception plate method. At the most frequencies, the power level differences of all sources are comparatively low. Only the fan shows higher power differences. This can be due to its very low vibration activity.

3.3 Calculation of the transfer index

To examine the usability of the TSM, structure-borne sound sources were installed in a light-weight test facility located at PTB Braunschweig. The sources were mounted to a flanking wall between two neighbouring rooms, see also figure 1 (type 2) and figure 4. To characterise the sound transmission regarding the relevant transmission paths, a mean transfer index was determined [1]. Different excitation points on the receiving wall were measured, near to timber stands and in the middle of the gypsum plates.

According to the method described in [1], the transfer index was related to a reference impedance of the receiving structure (Z_0=400 kg/s), a reference reverberation time (T_0=0,5 s) and to the sound reduction index of the included structure elements. To describe the sound reduction index of the relevant transmission paths (type 2 in figure 1), the flanking sound reduction indices R_{ij} were determined with the intensity method according to DIN EN ISO 15186-2. This yields an in-situ intensity sound reduction index which is included in the sound pressure level prediction for the receiving room.

3.4 Comparison of the sound pressure level in the receiving room with different source assumptions

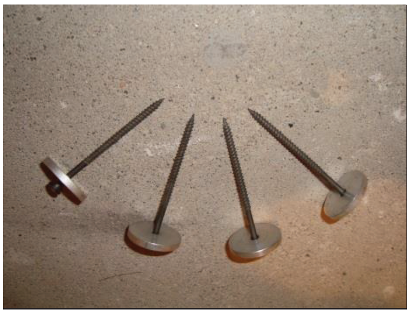
After the characterisation of the transmission path with a standardised transfer index and with the characterised sources, the sound pressure level in the receiving room can be calculated. The calculated value is compared with the measured sound pressure in the receiving room.

compressor

compressor connection to the receiver

shaker mounted to the receiving wall

modified kitchen hood



screws used for mounting the kitchen hood

fan on the receiving wall

Figure 4 – Common structure-borne sound sources in the source room of the light-weight test facility at PTB Braunschweig

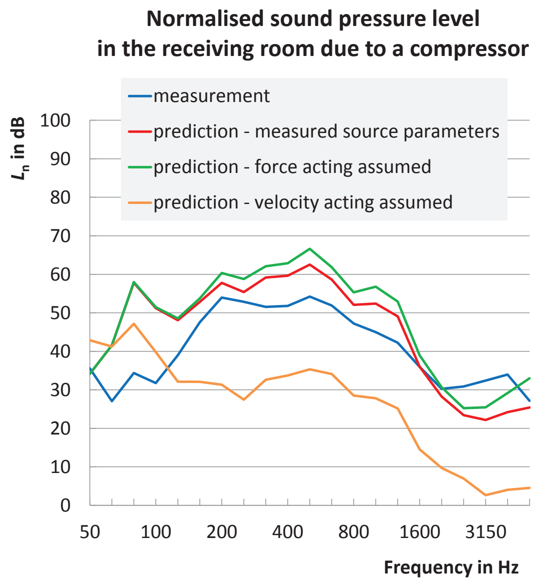


Figure 5 – Normalised sound pressure level in the receiving room; comparison of measurement and prediction with γ according to [1]

According to [1], different assumptions regarding the structure-borne sound source parameters can be used. Depending on the expected vibration behaviour of the source – force or velocity acting – different source impedances are given. Figure 5 shows the comparison of the predicted and the measured resulting sound power levels in the receiving room.

The lowest level differences between measurement (blue curve) and prediction can be observed for the source parameters determined with TSM. Here, the predicted sound pressure level is about 3 to 6 dB higher than the measured one. The green curve represents the sound pressure level due to a force source, which is also valid in this case, but the prediction using TSM parameters yields in the medium and high frequency range more exact values (2-5 dB).

The assumption of a velocity source is not valid in this case. The differences between measurement and prediction are 20 dB over the frequency range above the frequency band of 100 Hz. For the frequency bands less than 100 Hz no correlation between the results can be determined.

3.5 Comparison of the sound pressure level in the receiving room according to EN 12354-5: Calculation vs. measurement

In the following section, the measured normalised sound pressure levels L_n are compared to the approach of EN 12354-5. Therefore every transmission path was considered and the sum was calculated.

$$L_{n,s} = 10 \lg \sum_{j=1}^{n} 10^{L_{n,s,ij}/10} \quad [dB] \qquad (6)$$

$L_{n,s}$ Normalised sound pressure level in the receiving room due to a structure-borne sound source [dB]

$L_{n,s,ij}$ Normalised sound pressure level in the receiving room due to a structure-borne sound source mounted to supporting building element i in the source room as caused by sound transmission from element i to a radiating element j in the receiving room [dB]

n Number of elements in the receiving room contributing to the sound transmission [-]

In this case, the two main transmission paths were calculated with formula (1) using formula (4) and (5). The term $D_{sa,i}$ was calculated according to EN 12354-5. At this junction, in a first attempt the radiation factor σ was set to 1 over all frequencies, the transmission coefficient τ_i was calculated according to formula (7) and the structure-borne sound reverberation time T_s of element i was determined by measurements.

$$\tau_i = 10^{-\frac{R_i}{10}} \qquad [-] \qquad (7)$$

τ_i	Transmission coefficient of element *i* for airborne sound considering free vibrations only [-]
R_i	Sound reduction index of element *i* [dB]

The term $R_{\mathrm{ij,ref}}$ in formula (1) was calculated from a vibration reduction index K_{ij} by using a measured velocity level difference $D_{\mathrm{v,ij}}$ of the regarded transmission paths and an equivalent absorption length *a* of an element according to formula (8).

$$a = \frac{2{,}2\,\pi^2 S}{c_0 T_s}\sqrt{\frac{f_{\mathrm{ref}}}{f}} \, . \qquad [\mathrm{m}] \qquad (8)$$

S	Area of the supporting building element *i* in the source room [m²]
$T_{\mathrm{s,i}}$	Structure-borne sound reverberation time of element *i* [s]
f_{ref}	Reference frequency f_{ref} = 100 [Hz]
f	Frequency of the respective one-third octave band

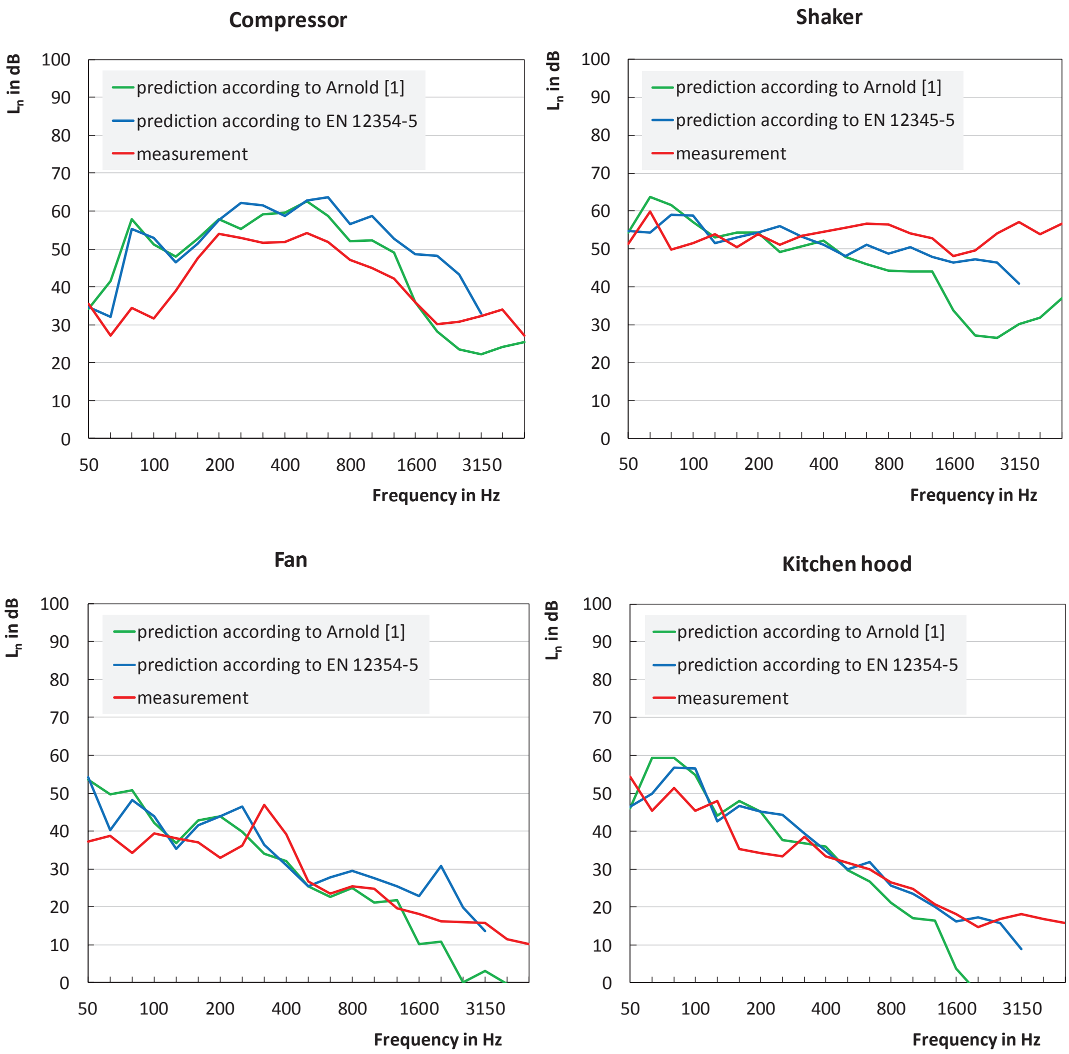


Figure 6 – Normalised sound pressure level in the receiving room; calculated sound pressure level according to [1] and EN 12354-5 [2].

If one compares the estimated values with the measured normalised sound pressure levels, a good agreement regarding structure-borne sound can be obtained. The qualitative characteristics of the curves in figure 5 are nearly the same for each source. Even the two approaches regarding [1] and [2] result in nearly the same behaviour, especially in the frequency range below 1000 Hz. Higher discrepancies occur for the source compressor and in the frequency range above 1000 Hz.

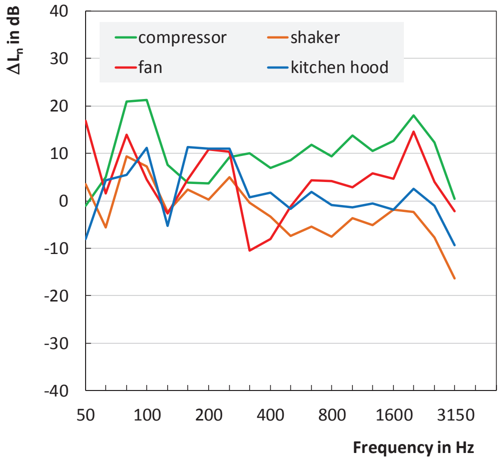


Figure 7 – Normalised sound pressure level differences between the approach according to EN 12354-5 and measurements in the light-weight test facility at PTB Braunschweig.

In figure 6, the differences between the calculated and the measured normalised sound pressure level in the receiving room are compared. At most frequencies, the sound pressure level is in a range of ±10 dB. It can be observed, that the proposed calculation method leads to larger values than the measured ones. At a first glance, the deviations seem to be quite large. Nevertheless, uncertainties of about 7 dB [2] are realistic which means that the deviation between measurement and prediction are in usual range.

4. CONCLUSIONS

In this paper, structure-borne sound sources were characterised with the Two-Stage Method. For this purpose, sources were installed in a light-weight test facility to measure the resulting structure-borne sound power levels on the receiving building element. The results have been compared to the prediction according to [1]. This comparison shows a good agreement. Subsequently, the sources were installed in a source room and the resulting sound pressure levels were measured in the receiving room. The comparison of the predicted sound pressure levels with the measured ones show discrepancies being similar to the uncertainties provided in [2].

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