Characterisation of structure-borne sound sources

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ABSTRACT

Noise is one of the most disturbing factors in buildings. This paper focuses on noise and vibrations generated by structure-borne sound sources, e.g. equipment for HVAC. For the prediction of the sound pressure level in a receiving room the characterisation on structure-borne sound sources as well as knowledge on the transmission of vibrations in the building structure are needed. The vibration transmission is already well investigated. However the characterisation of structure-borne sound sources has not been done thoroughly. Especially for light-weight constructions, detailed information on structure-borne sound sources are needed, because a high sound pressure level may occur when the mobility of the source matches with the receiver mobility. This paper describes investigations on the characterisation of structure-borne sound sources by using the two-stage reception plate method. This method based on a laboratory-based measurement by using both a high- and low-mobility reception plate to get knowledge on both the source activity and source mobility. Results on measurements on different sources are presented. The most relevant characteristics of the sources were measured. Furthermore by using these characteristic parameters of the sources, the normalised sound pressure level in a receiving room was measured after mounting and activating a structure-borne sound source. The results were compared with the predicted values according to EN 12354-5 by using the characteristics of the sources.

1. STRUCTURE-BORNE SOUND SOURCE CHARACTERISATION

Many methods can be used for the characterisation of structure-borne sound sources. The differences of the methods consist in the parameters which have to be measured and in the accuracy (Mondot, 1987). If higher effort is done, more accuracy of the prediction is achieved and vice versa. For a high precision, it is recommended that every source contact point with its three degrees of freedom for velocity, force and moment is measured. Additionally, the phase shifts concerning forces, velocities and moments between several contact points have to be measured. If less parameters are measured respectively with less accuracy, the precision of the characterisation decreases (Vogel, 2012).

The two-stage reception plate method is a rather simple and practicable method for source characterisation (Gibbs, 2007). It is an indirect method, based on the impact a source has on reception plate. The power transmitted to a receiving structure due to a single component of excitation at a contact point can be expressed in terms of the free velocity v_f of the source and the complex source mobility Y_s and receiver mobility Y_r (Cremer, 1996), (Gibbs, 2007), (Gerretson, 2008), (Vogel, 2013), (Vogel, 2014).

$$P = |v_f|^2 \cdot \frac{\mathrm{Re}\{Y_r\}}{|Y_s|^2 + |Y_r|^2} \cdot \tag{1}$$

The source mobility Y_s is given by

$$|Y_s| = \frac{|v_f|}{|F_b|}, \tag{2}$$

where F_b is the blocked force of the source. Therefore the transmitted power is a function of both the free velocity and the blocked force of the source on one side and the receiver mobility on the other side. The source itself is characterised by the free velocity v_f and the blocked force F_b.

For the case of a heavy-weight building structure with $|Y_s| >> |Y_r|$, Eq. (1) reduces to

$$P \approx |v_f|^2 \cdot \frac{\mathrm{Re}\{Y_r\}}{|Y_s|^2} = |F_b|^2 \cdot \mathrm{Re}\{Y_r\} \cdot \tag{3}$$

The source acts as a so called *force source* when the power transmitted to a receiving structure is only a function of the blocked force and independent from the free velocity of the source. Conversely, for a light-weight structure with $|Y_r| >> |Y_s|$, Eq. (1) results in

$$P \approx |v_f|^2 \cdot \frac{\mathrm{Re}\{Y_r\}}{|Y_r|^2} = |v_f|^2 \cdot \mathrm{Re}\{\frac{1}{Y_r *}\} \cdot \tag{4}$$

Y_r* is the conjugate-complex receiver mobility.

The source acts as a *velocity source* and in this case the power is a function of the free velocity.

In the two-stage reception plate method this effect is used to determine both the free velocity and the blocked force of a source by mounting the source on a heavy respectively a light-weight reception plate. Assuming the mobility of the reception plates is known, the characteristic parameters of the source - free velocity and blocked force - can be calculated by Eq. (3) and (4) by measuring the power transmitted to the receiving plates (Gibbs, 2007).

1.1 Reception Plates

Using the two-stage reception plate method to characterise structure-borne sound sources, two kinds of reception plates - a heavy-weight and also a light-weight plate - have to be used. The properties of the plates used for the investigation described in this paper are shown in Table 1. The highest value of the impedance level is the steel plate, while the smallest is the perforated aluminium plate. The size of the perforations are smaller than the bending wavelengths of the plate up to 5 kHz. Then, they have no effect on measurement of the plate vibrations.

Table 1: Properties of reception plates to characterise sources

reception plate	thickness in (mm)	area in (m²)	mass in (kg)	impedance level in (dB) ref. 400 (Ns/m)
light-weight reception plates				
perforated aluminum	1.5	4.5	12	-8.2
perforated steel	1.0	4.5	23	-7.1
plywood	8.0	4.5	16	-4.2
heavy-weight reception plates				
gypsum fibre	22.0	6.0	158	7.3
steel	10.0	2.0	190	13.9

Using a shaker mounted on the reception plates to stimulate the plates, Figure 2, the point impedance Re{Z} was determined by measuring the force F, the velocity v and the phase shift φ_{Fv} at the same time, Eq. (5). The mobility of the reception plates is given by the reciprocal value of the point impedance according to Eq. (6) (Cremer, 1996).

$$\mathrm{Re}\{Z\} = \frac{|F|}{|v|}\cos\varphi_{Fv} \tag{5}$$

$$|Y_r| = \frac{1}{|Z|} \tag{6}$$

Additionally to these five plates, which were used for the source characterisation, other reception plates were utilized in this investigation as shown in Table 2. The impedance level of all investigated reception plates is shown in Figure 1. In the investigated frequency range from 50 to 000 Hz the measured impedance values of the plates fit fairly well to the theoretical values for infinitely large homogeneous thin plates (Cremer, 1996).

The light-weight structure consists of wooden studs, gypsum cardboard and chip board on both sides with mineral wool in between.

Table 2: Properties of reception plates

reception plate	thickness in (mm)	area in (m²)	mass in (kg)	impedance level in (dB) ref. 400 (Ns/m)
wood-MDF	8	5.6	31	-2.8
light-weight structure	20	6.0	130	1.6
plywood	12	4.5	25	2.9
chipboard	22	5.6	74	5.1

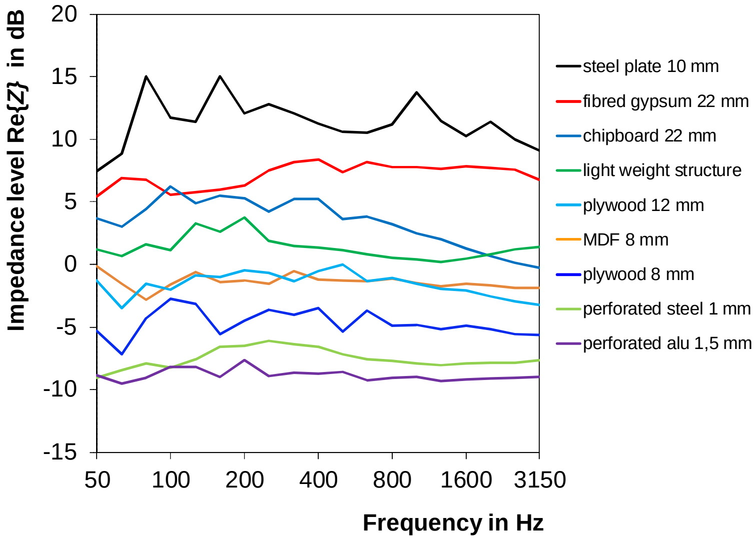

Figure 1: Measured point impedance of the reception plates used

1.2 Structure-borne Sound Sources

Structure-borne sound sources can be very different in their vibration behaviour and their type of connection to the receiving structure. Typical structure-borne sound sources can be pumps, heating machines, gas compressors, fans, kitchen exhaust hoods or other air condition units.

Very important for an accurate characterisation of a structure-borne sound source is a solid connection between source and reception plates. In this work, all sources were mounted by screws on the reception plates. Even the connection of the electrodynamic shaker with the reception plates for measuring their point impedances was screwed, except the connection to the heavy steel plate, where a magnetic connection was used. This kind of connection differs from the screwed connection in this case only in the high frequency range when high forces were used. Then, the connection can breakaway.

The kitchen hood is a special one because the fan inside is modified with a mass to generate more vibrations. Of course, this is not realistic but it is useful for the investigation of the method in this paper. The kitchen hood has three levels of ventilation velocity but only the first level, the lowest one, is used.

The investigated structure-borne sound sources are shown in Figure 2. To get an idea of the vibration spectrum generated by the sources the frequency spectrum of the acceleration at one point on the reception plate made of MDF (medium-density fibreboard) with a thickness of 8 mm is added in Figure 2.

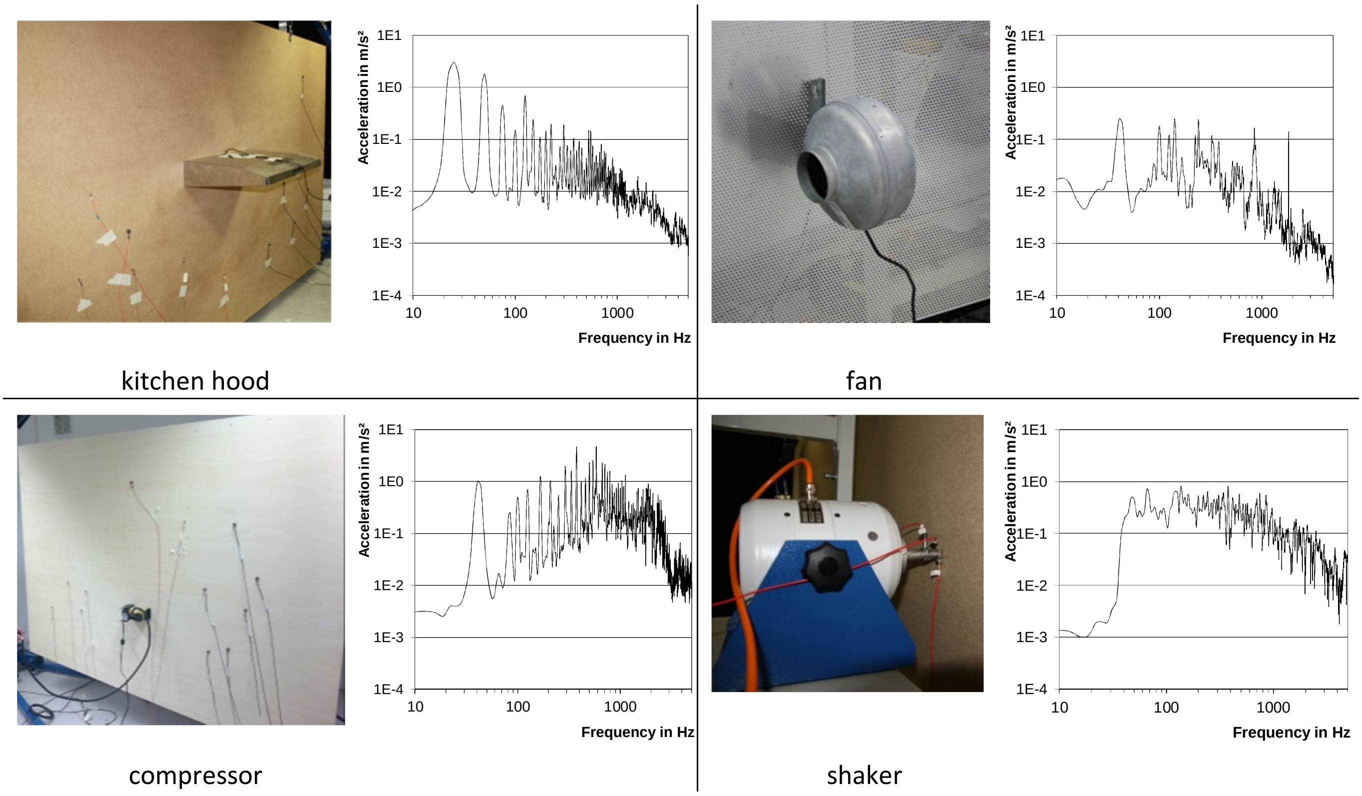

Figure 2: Used structure-borne sound sources and acceleration spectra – 8 mm MDF

1.3 Results

The structure-borne sound sources kitchen hood, fan and compressor according to Figure 2 were characterised by using the two-stage reception plate method (the shaker is absent because it represents an ideal source with an ideal perpendicular force). The reception plates, which were used for this, are shown in Table 1. The power transmitted to a receiving structure was directly measured by 12 acceleration sensors on the reception plates. By using Eq. (3) and (4), the characteristic parameters - free velocity and blocked force - of the three sources were determined.

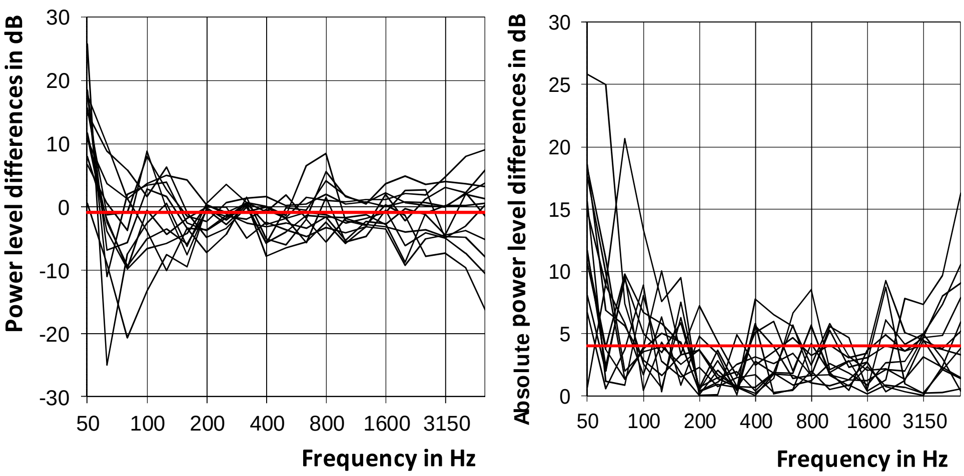

Figure 3: Differences between measured and predicted power – red line represents the mean (Vogel, 2015)

While knowing the characterisation parameters of the three sources, the predicted power transmitted to the four reception plates described in Table 2 was calculated by using Eq. (1) and (2). Additionally to this, the power was measured directly by mounting the sources on the reception plates and averaging the values gained by 12 acceleration sensors.

The difference between the predicted and the measured value of the power transmitted to a receiving structure is shown in Figure 3. The results of the 3 sources connected to the 4 reception plates are plotted in Figure 3. The average on the differences is very close to zero, red line in the left diagram, while the average of the absolute values is 4.7 dB, right diagram. This value denotes the accuracy of the two-stage reception plate method.

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

2.1 Measurement of the sound pressure level under realistic conditions

In the next step of the testing structure-borne sound sources were mounted to walls under a realistic light-weight building condition, Figure 4. The investigation was done in the test facilities at the Physikalisch-Technische Bundesanstalt (PTB - the National Metrology Institute of Germany) in Braunschweig, Germany. After mounting and activating the structure-borne sound sources the resulting normalised sound pressure level in a receiving room (V = 13 m³) was measured.

shaker modified kitchen hood compressor

Figure 4: Structure-borne sound sources in the source room (V = 35 m³) (Vogel, 2016)

2.2 Calculation of the sound pressure index

Having characterised a structure-borne sound source, EN 12354-5 “Estimation of acoustic performance of building from the performance of elements – Part 5: Sounds levels due to the service equipment” facilitates the prediction of the sound pressure level in a receiving room in a real building (EN 12354, 2009). The method is based on the consideration of all relevant transmission paths from the source to the receiving room. The resulting normalised sound pressure level in a receiving room, $L_{\mathrm{n,s}}$, for one sound source is given by

$$L_{\mathrm{n,s}} = 10 \lg \sum_{j=1}^{n} 10^{L_{\mathrm{n,s,ij}}/10}, \qquad \text{[dB]} \qquad (7)$$

where

$L_{\mathrm{n,s,ij}}$ is the 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 is the number of elements j in the receiving room participating in the sound transmission.

$L_{\mathrm{n,s,ij}}$ depends on the characteristics of the structure-borne sound source, the type of mounting and the supporting building element as well as the flanking sound reduction index, R_{ij}, in accordance with EN 12354-1 (EN 12354, 2000). Using the characteristics of the four sources - shaker, kitchen hood, compressor and fan - the normalised sound pressure level in a receiving room, $L_{\mathrm{n,s}}$, was calculated by solving Eq. (7).

2.3 Comparison between Measurement and Calculation

In Figure 5 the differences between the calculated and measured normalised sound pressure level in a receiving room, $L_{n,s}$, for the four investigated structure-borne sound sources are shown. At most frequencies, the differences are in a range of ±10 dB. It can be observed, that the proposed calculation method leads to larger values than the measured ones. That means the prediction of the mean sound pressure level in the receiving room according to EN 12354 is significantly over-predicted for the used structure-borne sound sources.

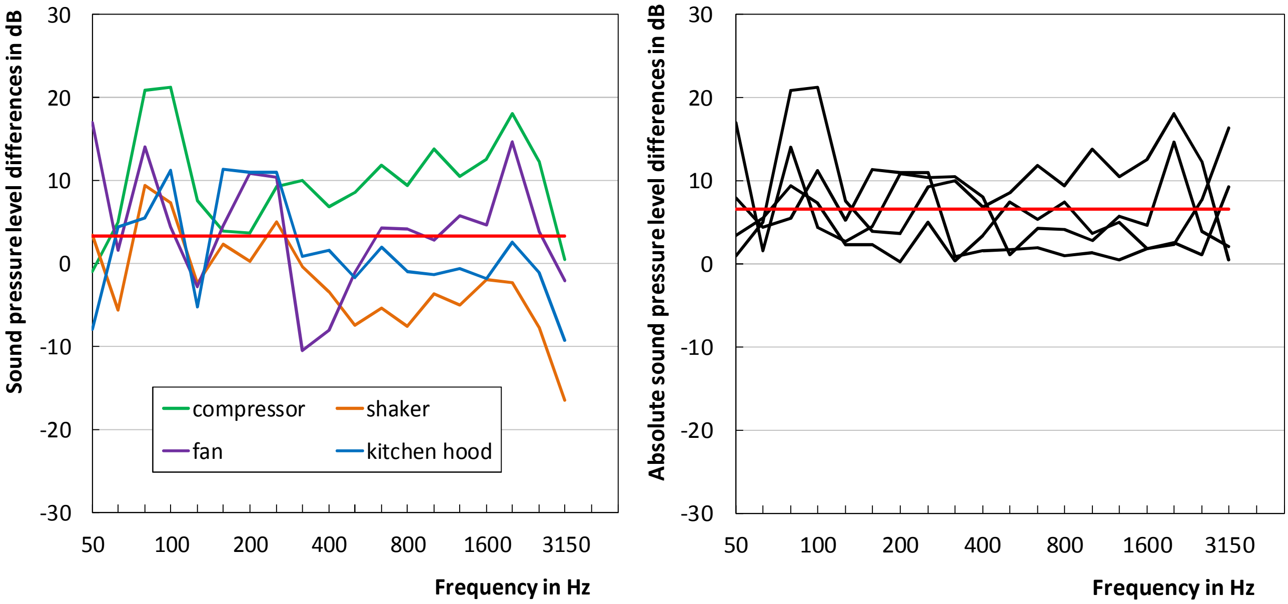

Figure 5: Difference of the normalised sound pressure level – calculated minus measured values, red line represents the mean (Vogel, 2016)

2.4 Uncertainties

According to EN 12354-5 the total uncertainties are calculated by Eq. (14). The values for single uncertainties u_{source} for the source and $u_{transmission}$ for the transmission paths from the source to the sound pressure level in a receiving room are given in Table 3 (EN 12354, 2009).

$$u = \sqrt{u_{\text{source}}^2 + u_{\text{transmission}}^2} \quad \text{[dB]} \qquad (14)$$

For the conditions investigated in this paper, the total uncertainty of the source and the transmission paths represents 7 dB according to EN 12354-5, which is in good agreement to the measured value of 6.6 dB by considering all investigated sources. Looking more specifically at the different equipment larger deviations can be found. In general the uncertainties are rather high, showing that there are still more investigations needed to come to a more precise prediction of the sound pressure level in a receiving room due to structure-borne sound sources (Vogel, 2016).

Table 3: Uncertainties according to EN 12354-5 and measured data

source		**source** u_{source} (dB)		**transm.** $u_{transmission}$ (dB)	**source and transm. path** u (dB)	
EN 12354-5	sources used	EN 12354-5	measured	EN 12354-5	EN 12354-5	measured
all	all	5	4.7	5	7	6.6
air supply	fan	2	5.4	2	3	6.7
heating	compressor	3	4.4	4	5	9.8
(lifts)	-	4	-	3	5	-
water supply	-	3	-	5	6	-
household equipment	kitchen hood	3	4.0	3	5	4.8
-	shaker, white noise	-	1.2	-	-	5.1

3. CONCLUSION

The characterisation of structure-borne sound sources is needed for the prediction of the normalised sound pressure level in a receiving room. However, finding a reliable and accepted characterisation method is still a topic of research. The challenge is to develop a method with both sufficient accuracy and manageable complexity. In the first part of the investigation it was shown that a characterisation of structure-borne sound sources using the two-stage reception plate method is practical. The measurement procedure was straightforward and the accuracy by averaging over all investigated sources was detected to be 4.7 dB corresponding to the value of 5 dB given in EN 12354-5. In the second part of the investigation the sources were installed in a light-weight test facility to measure the normalised sound pressure level in a receiving room. The measured values were compared to the predicted values. The prediction was done according to EN 12354-5 by the characterisation of the structure-borne sound sources done by the two-stage reception plate method. The average difference between predicted and measured values is 6.6 dB. This value agrees well with the uncertainty calculated according to EN 12354. However the uncertainty is still very high, more investigations are needed to enhance the accuracy.

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