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SOURCE CHARACTERIZATION FOR HEAVY AND LIGHT WEIGHT BUILDINGS – USE CASE HEATPUMP

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Abstract

EN 12354-5 describes methods for predicting noise from technical equipment based on both airborne and structure-borne sound emissions. With respect to structure-borne sound, laboratory methods for source characterisation are specified in EN 15657, providing the necessary input data for prediction models. In particular, for timber constructions, a complete characterisation of the source, including its mobility and the single-equivalent free velocity, is essential for reliable predictions of building-services noise. This paper presents a use case for the structure-borne sound characterization of heat pumps using indirect measurement methods on both high- and low-mobility reception plates. Furthermore, comparisons of source mobility obtained using the two-stage method and the direct measurement method according to EN 15657 are provided. Measurements on high-mobility reception plates require particular attention to mounting conditions, as the static load of the source may influence the results if not properly controlled. A key advantage of indirect measurement methods is the determination of blocked force levels and free velocity levels under realistic installation conditions. This is especially relevant for distributed contact interfaces between the source and the receiving structure, where direct methods are only of limited applicability.

Keywords: *structure-borne sound, source characterization, building acoustics, reception plate method*

1. Introduction

Recent developments, such as those presented by EN 12354-5:2023 [1], have introduced methods for predicting noise from building services systems [2]. The required input data for prediction of noise originating from structure-borne sound excitation (these are: source single equivalent blocked force $L_{F\mathrm{b,eq}}$, source single equivalent free velocity $L_{v\mathrm{f,eq}}$, and source single equivalent mobility $Y_{\mathrm{S,eq}}$) cannot yet be provided by most manufacturers. Information about building services systems can be provided in various ways. For sanitary or wastewater installations, methods in accordance with EN 14366:2023[3] are available. In building acoustics, methods for characterising several structure-borne sound sources can be applied in accordance with EN 15657:2017[4].

Additionally, source characterisation may be conducted in six degrees of freedom, encompassing three translational directions and their corresponding moment components, using the methods described by ISO 20270:2019[5]. These methods, however, require significantly more measurements.

In this study, both direct and indirect methods, as outlined by EN 15657:2017, are employed. The initial section presents the full source characterisations for rigid couplings between the source and the structure. In this context, directly measured source mobilities are compared with those obtained through indirect methods. Subsequently, elastic coupling elements are employed to connect the source and receiver. For full characterisation, the decoupling elements are considered as part of the source, and the characterisation is performed for the source together with the respective decoupling element. The indirect measurements are performed with the sources mounted on high- and low-mobility plates, and the source properties are calculated from measurements of the plates. This procedure is usually called the two-stage method.

2. Measurement Setup

2.1. Test rig for the use-case

A reception plate test rig was built according to EN 15657:2017 and is described in [6]. Indirect measurements of equivalent blocked forces were conducted on the heavy reception plate, made of a 10 cm concrete slab. Single equivalent free velocity levels were indirectly measured on the light reception plate, which was made of 1 mm steel with 55% perforation. Air-

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Figure 1: Heat pump A with rubber granulate mounting socket on the light reception plate, bearing of air-filled rubber balls.

Figure 2: Heat pump A with rubber granulate mounting socket on the light reception plate.

filled rubber balls supported the plate. Supporting the light reception plate on the rubber balls increases the plate's loss factor. This does not lead to any distortion of the measurement results [7]. Initial measurements of this configuration with an artificial structure-borne source are reported in [7].
The heat pumps under investigation had a weight of 140 kg and 200 kg and had exhibited an eccentric weight distribution. To minimize pre-stressing and maintain horizontal alignment of the light reception plate, level support must be provided. For this, the positioning and air pressure of the rubber ball bearings should be adjusted accordingly (see Figure 1).
The loss factor of the reception plates was determined using a modal shaker at two excitation positions. A separate loss factor was measured for each installation condition. On the light reception plate, the shaker is coupled during the operational measurements (see Figure 2).

2.2. Heat Pump as Sources

Two heat pumps from a single manufacturer are investigated in this use case. These comprise an indoor monoblock heat pump A and an outdoor monoblock heat pump B. For the investigations, several operating conditions were defined together with the manufacturer. For each operating point, the compressor speed, fan control, and heat-transfer medium flow rate were specified. The temperature conditioning of the supply air and return flow could not be controlled precisely. In general, the investigations were conducted with a supply temperature of approximately 23 °C and a supply air temperature ranging from approximately 7 °C to 23 °C. Previous experimental investigations indicate that compressor speed, rather than compression ratio, primarily influences sound excitation [8].
The heat pumps were investigated with rigid mounting and with different elastic decoupling elements.
Source mobilities were also determined using a reproducible substitute excitation, in which an inertial shaker was applied to the heat pump housing at two positions. This approach minimizes the influence of operating conditions that cannot be perfectly reproduced.

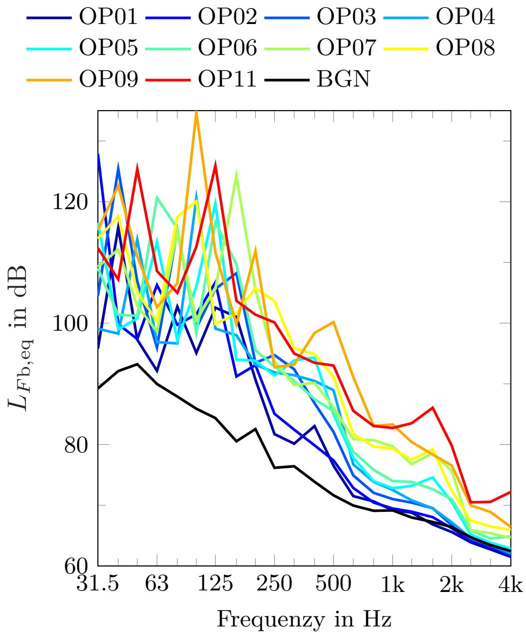
3. Results

3.1. Blocked Force and free velocity

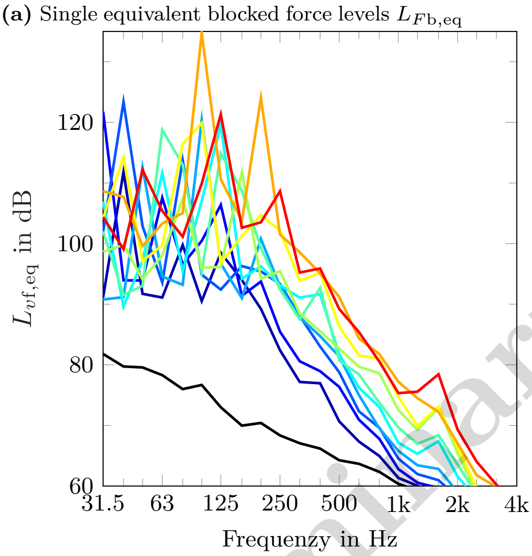
In Figure 3, the results for the single equivalent free velocity level $L_{v\mathrm{f,eq}}$ and the single equivalent blocked force level $L_{F\mathrm{b,eq}}$ of ten operating conditions are presented. The black lines indicate the minimum measurable values due to the background noise levels. In the frequency range $< 200\,\mathrm{Hz}$, distinct peaks are evident, which can be attributed to the compressor rotational speed between $20\,1/\mathrm{s}$ and $120\,1/\mathrm{s}$. The $L_{F\mathrm{b,eq}}$ are already sufficient for predictions in the so-called force-source situation (in the case $Y_\mathrm{S} >> Y_\mathrm{R}$). In the case of the lightweight reception plate, the high-frequency range is limited due to the mass load of the accelerometers. The weight of the accelerometers is about 5 g, and above 2000 Hz the measured surface velocity of the plate increases by more than 1 dB.
It is also shown that the source's most powerful excitation is not at the highest operating point. For heat pump A, the operational point nine (OP09) has the highest peak in $L_{F\mathrm{b,eq}}$ and also in $L_{v\mathrm{f,eq}}$ (see in figure 3a and 3b).

3.2. Source mobility: rigid coupled

The source mobility is determined using direct and indirect methods, as described in EN 15657:2017. It cannot be ruled out that suspending the source from the crane introduces forces or moments into the source that do not occur under normal installation conditions. However, as a first approximation, it is assumed that within the considered frequency range, the source mobility can be determined using direct measurement methods without big error. The measurement was carried out on the underside of the mounting feet using two accelerometers and a central excitation with a modal hammer (see Figure 4). Due to the ribbed, cavity-filled design of the device feet, direct measurement of the source mobilities of the four mounting feet is associated with increased uncertainty. This is caused, on the one hand, by the limited possibilities for



(a) Single equivalent blocked force levels $L_{F\mathrm{b,eq}}$



(b) Single equivalent free velocity Levels $L_{v\mathrm{f,eq}}$

Figure 3: The structure-borne sound characterisation of heat pump A in several operational points (OP) and levels due to the background noise (BGN).

Figure 4: Setup for direct measurement of source mobility of the heat pump A.

attaching the accelerometers and, on the other hand, by the small available areas for hammer excitation. Both limitations lead to a larger spread of the measured values, as shown by the wide range between the minimum and maximum values of $Y_{\mathrm{S,eq,rig}}$ in Figure 5a. The arithmetic mean of the one-third-octave-band values of the source mobility across the housing feet is shown by the solid blue line.

From the previously determined $L_{v\mathrm{f,eq}}$ and $L_{F\mathrm{b,eq}}$, the source mobility can also be calculated according to EN 15657:2017 using equation 1. This is referred to as the two-stage Method.

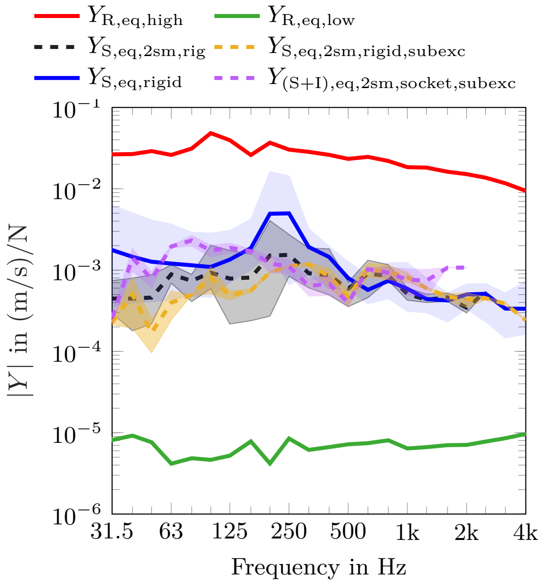
$$\frac{|Y_{\mathrm{S,eq}}|^2}{Y_0^2} \approx 10^{(L_{v\mathrm{f,eq}}-L_{F\mathrm{b,eq}})/10} \cdot 10^{-6} \qquad (1)$$

For the calculations, only one-third-octave-band values with an SNR >6 dB above the background-noise levels were used. However, certain limitations must be considered when applying the two-stage method. For indirect measurement of Y_{S}, the mobility of the light reception plate must be much higher than that of the source, and the mobility of the heavy reception plate must be much lower than that of the source: $Y_{\mathrm{R,eq,high}} \gg Y_{\mathrm{S,eq}} \gg Y_{\mathrm{R,eq,low}}$. Figure 5a compares the mobilities of the high- and low-mobility reception plate to the source mobility; the differences are sufficient for the application of the two-stage method. The source mobilities were determined for each operating condition investigated. Their arithmetic mean is shown in Figure 5a as the dashed black line, and the grey shading indicates the minimum and maximum values. Deviations may arise from operating conditions that cannot be reproduced precisely. For subsequent prediction calculations, the arithmetic mean of the calculated mobility for the several operation points or the substitution excitation points should be used as the source quantity. It can be assumed that the heat pump's source mobility is independent of the operating point, and observed deviations may arise from measurement uncertainties and uncertainties in operating conditions.

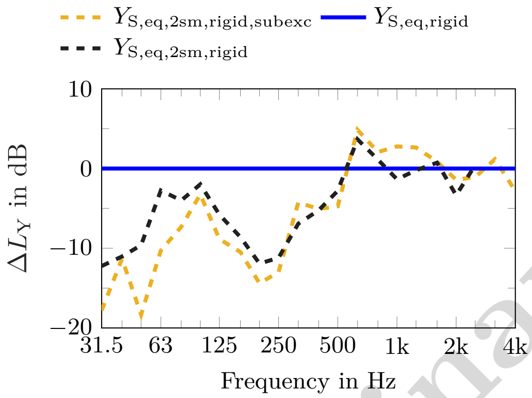
Due to variations in the determination of source mobility under operational conditions, substitute excitation was performed at two positions on the housing using an inertial shaker. For these substitute excitations, the source mobility was also determined using the two-stage method. These results are shown in Figure 5a as the orange dashed line, and the minimum and maximum values are shown in the orange shaded area. The variations are considerably smaller than those obtained from the operational-condition measurements.

The differences between the methods used to determine the source mobility of rigidly mounted sources are shown in Figure 5b. The results from the indirect methods are similar and can be considered as satisfactory. The differences compared with the directly measured source mobilities range from −18 dB to 4 dB.

For heat pump B, mobility was also determined using



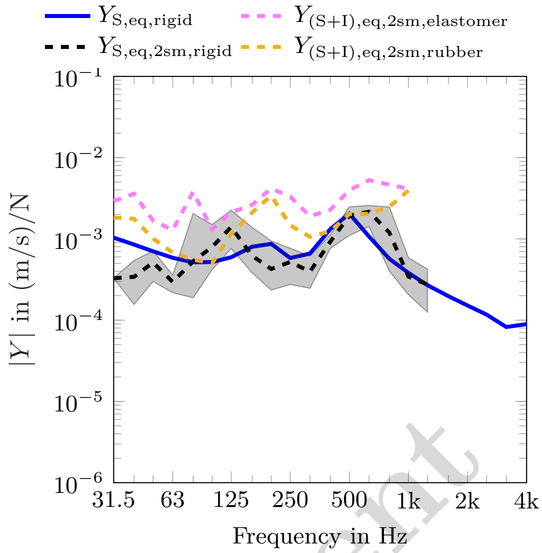
(a) Magnitude of the point mobility from the high- and low-reception plates and the heat pump A. Shaded areas represent the envelopes of all measurement points (min/max). Dashed lines: calculated mobilities per two-stage method (2sm); solid lines: directly measured mobilities.



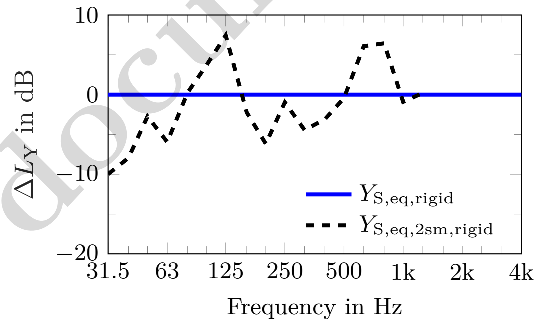
(b) Level differences of the calculated source mobilities for the rigid coupling.

Figure 5: Comparison of measured and calculated mobilities of source (heat pump A) and reception plates. Measured in operational conditions or with substitution excitation with a shaker (subexc).

both direct and indirect methods. For rigid coupling, the source mobility showed, on average, smaller deviations in the determination of the source mobility (see Figure 6b) than for heat pump A. One reason for the deviations could be that the source is relatively large compared to the light reception plate. For point-like structure-borne sound excitation, the reverberation distance on the light reception plate is approximately 4 cm at 4 kHz. It can therefore be assumed that there is a pronounced reverberation field on the light reception plate. However,it is unclear which method reflects the true source mobility best.



(a) Magnitude of the point mobility from heat pump B. Shaded areas represent the envelopes of all measurement points (min/max). Dashed lines: calculated mobilities per two-stage method (2sm); solid lines: directly measured mobilities.

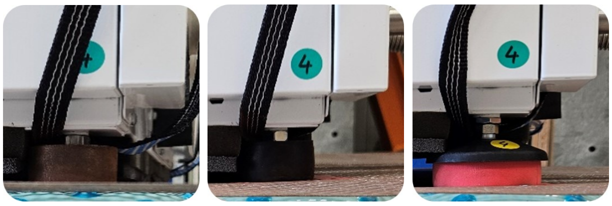


(b) Level differences of the calculated source mobilities for the rigid coupling.

Figure 6: Comparison of measured and calculated mobilities of heat pump B.

3.3. Source mobility: elastic bearing

The two-stage Method offers the benefit of capturing the source mobility of sources, along with their specific installation conditions. For example, consider installing a heat pump on a rubber granulate mounting socket (see Figure 2). In this case, the source mobility was measured at various operating conditions using the substitute excitation. The equivalent source mobility of the heat pump with the mounting socket, as determined by the two-stage method, is shown in Figure 5a as the purple dashed line, with its minimum and maximum values indicated by the shaded area. Directly measuring mobility is challenging when surface contact exists between the source and the structure. Furthermore, the mobility of elastic materials cannot be determined directly. Heat Pump B was also mounted on a rubber foot and an elastomer foot (see Figure 7), and the source mobility with resilient bearing ($Y_{(S+I),eq}$) was determined using the indirect methods with substitute excitation by an



(a) rigid **(b)** rubber **(c)** elastomer

Figure 7: Rigid coupled heat pump B and two different elastic bearings.

inertial shaker at two positions on the heat pump housing. The results are shown in Figure 6a. It can be seen that the source mobility $Y_{(\mathrm{S+I}),\mathrm{eq}}$ increases when elastic bearings are used compared to the rigid coupled source $Y_{\mathrm{S,eq,rigid}}$. With the rubber foot, the mobility lies between 63 Hz and 160 Hz, and again at around 500 Hz, within the same range as the rigid source mobilities. The investigations demonstrate that the two-stage method can yield results for mobility of decoupled sources $Y_{(\mathrm{S+I}),\mathrm{eq}}$ using the indirect measurement approach. If the mobility of the elastic elements approaches or exceeds the mobility of the light reception plate, the two-stage method cannot be applied.
According to [1], the difference between the installed power of the source under rigid coupling and the installed structure-borne sound power with a resilent mounted source can be estimated using Equation 2.

$$L_{\mathrm{Ws,isol}} - L_{\mathrm{Ws}} \approx 10\lg\left(\frac{|Y_{\mathrm{S,eq}}|^2 + |Y_{\mathrm{R,eq}}|^2}{|Y_{\mathrm{S,eq}}|^2 + |Y_{\mathrm{I}}|^2 + |Y_{\mathrm{R,eq}}|^2}\right) \tag{2}$$

This approximation already represents a simplification compared with the fundamental machine-acoustics equation. Consequently, interactions between the systems are not taken into account, and the calculations are limited to one-third-octave bands. Nevertheless, for the calculation it is necessary that the mobility of the decoupling element, Y_{I}, is known. In practice, this is usually unavailable and can only rarely be provided by the manufacturer. It is therefore unclear whether the mobility determined for resilient-mounted sources using the two-stage method $Y_{(\mathrm{S+I}),\mathrm{eq}}$ can already be used as an input quantity in the denominator of Equation 2:

$$|Y_{(\mathrm{S+I}),\mathrm{eq}}|^2 \stackrel{?}{=} |Y_{\mathrm{S,eq}}|^2 + |Y_{\mathrm{I}}|^2 \tag{3}$$

If that were the case, however, the mobility of the rigid-mounted source Y_{S} would still be needed for the calculation according to Equation 2.
For prediction calculations and for assessing the effectiveness of different resilient elements, it would therefore be necessary to have the mobility of the resilient element available separately. To this end, further measurements are planned using different methods for the indirect determination of dynamic stiffness in accordance with [9], as well as insitu methods according to [10], to evaluate their applicability for prediction purposes.

4. Summary and conclusion

Using the two heat pumps as examples, it was shown that the full source characterisation in accordance with EN 15657:2017 can be applied for rigid coupling. An important parameter of the structure-borne sound excitation of heat pumps is the selected operating condition. This parameter, however, is not yet clearly regulated for determining structure-borne sound power, unlike as it is the case for airborne sound power.
Measurements on the light reception plate are nevertheless difficult due to the high mass of the units, which deflect the plate under the applied load. The concept of bearing a light reception plate on air-filled rubber balls is feasible, though it requires some effort to set up the testrig.
For rigidly mounted sources, the directly measured source mobility and the source mobility determined by the two-stage method still show larger deviations. With respect to the simplified methods used in building acoustics, these differences are considered acceptable, though not fully satisfactory. In addition, decoupled sources can also be characterised using the two-stage method. However, since the effectiveness of decoupling elements depends on the specific sources and components involved, the suitability of the two-stage method for source-specific decoupling elements requires further discussion. For decoupled sources, the additional option of substitute excitation has proven useful for the indirect determination of mobility. The signal-to-noise ratio could decrease due to substitute excitation if the source's operational excitation is insufficient.

5. Acknowledgment

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