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TOWARDS A PRACTICAL STRUCTURE-BORNE SOURCE CHARACTERISATION FOR MACHINES IN BUILDINGS

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Abstract
A practical structure-borne sound source characterisation is discussed for mechanical installations in buildings. The machines nearly always are installed in contact with plate structures such as heavyweight homogeneous structural floors and walls, or floating floor systems, or lightweight cavity constructions. Manufacturers require a laboratory-based measurement system which will yield single values of source strength in a form which is transferable to a prediction of the sound power generated in the installed condition, and thence the sound pressure in rooms removed from the source. A laboratory method is proposed which yields the source activity in the form of a free velocity, summed over the contact points. In addition, the source mobility is obtained separately, as the average of the effective mobility, also over the contact points. Both quantities are employed in estimating the installed power for a range of floors likely to be encountered in buildings. An approximate estimate is obtained by reference to a high source mobility condition, a low source mobility condition, or to a maximum value, the characteristic power.

INTRODUCTION

The structure-borne power, from an installed machine, requires three independent quantities: the activity of the source, the mobility (or impedance) of the source and the mobility (or impedance) of the receiving structure. The first two factors fully define the source in terms of its ability to deliver power but the third factor is required for the power when in the installed condition [1]. Source activity can be expressed by the free velocity, the velocity of the freely suspended source, or the blocked force, the force at the contact with an inert receiver. Mobility measurements require careful generation and registration of the applied forces, including moments, and rotational components of excitation in general are problematical. Manufacturers require simple laboratory-based measurement systems which will yield single values of source strength, typically with one third octave frequency resolution, and the conventional view is that these practical requirements conflict with the requirements for a physical and accurate source characterisation. An approach, which circumvents the complexities of the full mobility formulation, is based on three simplifying assumptions:

1. When the machine of interest is attached to a simple reception plate, the structure-borne sound transmission, through all contacts and components of excitation, can be rendered down to a single value, equal to the reception plate power, obtained from the mean square plate velocity, the loss factor and mass of the plate [2].
2. The mobility of plate-like receiver structures can be estimated as a characteristic (infinite plate) mobility, which requires knowledge of the plate material and dimensions, only [1]. The low frequency modal characteristic of the plate can be represented by an upper and lower limit, obtained from the mass and loss factor [3].
3. The mobility matrix representation of the power transmission through multiple contacts can be circumvented by invoking the effective mobility. This allows the single-contact-single-component formulation to be preserved whilst including the contribution of other contact forces to the contact under consideration [4].

LABORATORY MEASUREMENT OF STRUCTURE-BORNE SOURCES

Presently, laboratory measurements of structure-borne sound sources deliver either a sub-set of that required for prediction of installed power, or data on a power basis, which cannot be transformed into an installed power for all possible installation conditions. An example of the former is the magnitude of the free velocity at the contact points, expressed as a sum or an average value. Free velocity can be measured directly, according to [5] or indirectly by attachment to a thin reception plate of mobility significantly higher than that of the source under test. In figure 1, are the directly and indirectly measured free velocities of a fan unit and a whirlpool bath.

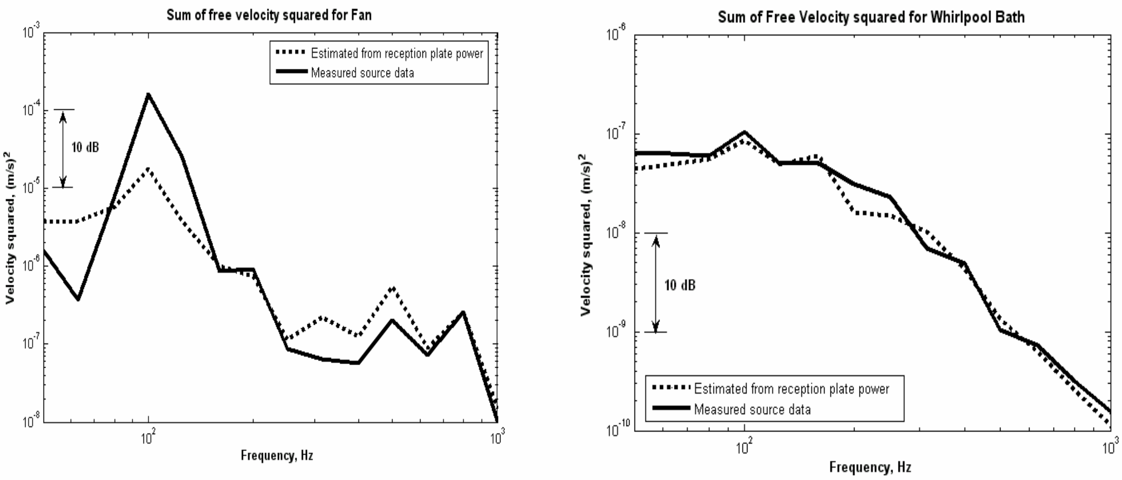

Figure 1 – Directly and indirectly free velocity: left, fan unit; right, whirlpool bath

An example of the latter is the reception plate power, obtained when the source is attached to a thick plate, of mobility significantly lower than that of the source [2]. In figure 2 is shown the level difference between the power into a laboratory reception plate and the installed power when on a 180 mm concrete floor. The installed power can be obtained from the laboratory (reception plate) measurement, corrected according to the ratio of reception plate to floor plate receiver mobilities. However, this simple conversion applies only to installations where a high source mobility condition applies i.e. heavyweight building constructions.

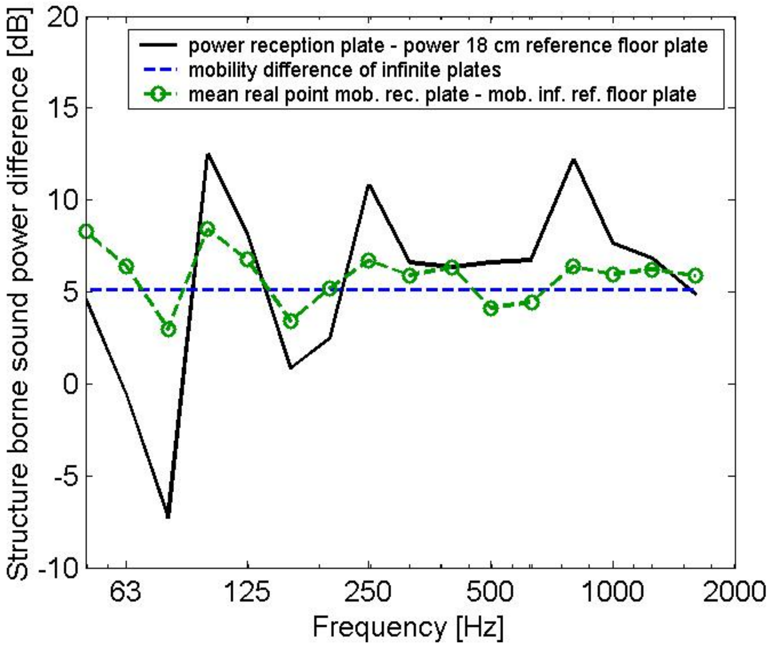

Figure 2 - Level difference between reception plate power and installed power

For other installation conditions, including a matched source-receiver mobility condition, then a laboratory measurement of source mobility is required in some form. Direct measurement of source mobility involves procedures and equipment beyond that of many test houses and R&D facilities. It is however, possible to indirectly measure source mobility in the form of an average effective mobility, from a two-stage procedure. The first stage yields the sum of the square free velocity, as in figure 1. The second stage involves estimation of the reception plate power when the source is connected to a thick plate. In figure 3 is shown the directly and indirectly measured values of the magnitude of the effective source mobility for the two sources in figure 1. Again, the source data is obtained as one-third octave values, rather than narrow band complex values conventionally required for estimating installed power.

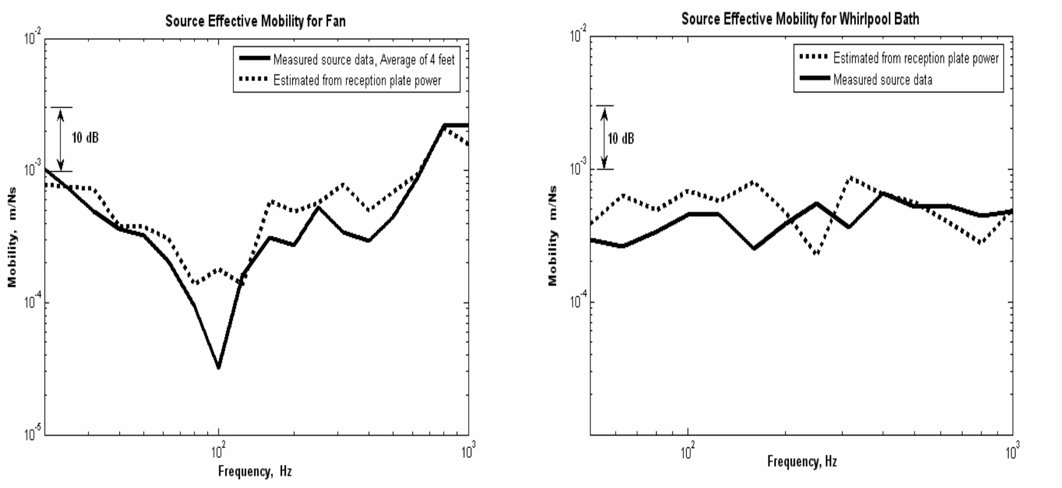

Figure 3 – Magnitude of average effective mobility: Left, fan unit; right, whirlpool bath.

INSTALLED POWER

This paper is primarily concerned with the applicability of source data, obtained in the laboratory, in predicting the structure-borne power when the source is installed in real structures. The particular challenge is to manipulate the laboratory data, which are real-valued, to describe installed power, conventionally calculated using complex values. In lightweight building constructions, such as timber-frame walls and timber joist floors, the mobility of the building elements can be greater than, less than or of the same order as that of the source. In figure 4 are shown typical point mobilities of building elements, along with two sources, a fan unit and a whirlpool bath.

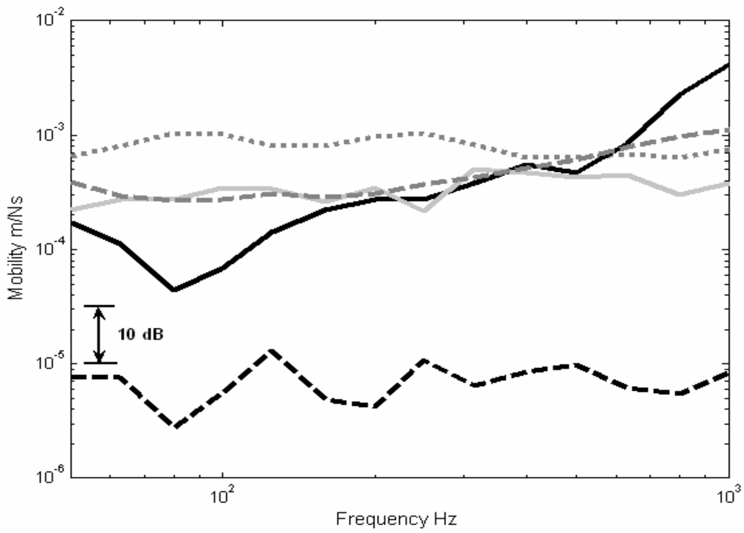

Figure 4 - Point mobilities of sources and building structural elements. Solid dark line, fan unit; solid light line, whirpool; dark dashed line, 100mm concrete floor; light dashed line, timber studding; light dotted line, plasterboard

If the source and receiver mobilities differ significantly, by more than 10 dB, simple idealisations can be invoked. If the machine is installed on a heavy structure such as a thick plate, a force source idealisation can be invoked. If the machine is installed on a high mobility structure, then a velocity source idealisation applies.

When mobility matching occurs, it can take two possible forms. The first is crossed-matching which, whilst influential, tends to occur in limited frequency bands, when one or both of the mobilities are resonance controlled. The second is tracking, where the source and receiver mobilities have the same value and signature. In this case, the mobilities are likely to indicate the same behaviour (e.g. rigid body or stiffness controlled). If and when a matched condition occurs, a maximum (characteristic) power can be invoked [6].

Consider the installed power of a single-point single component source of free velocity v_{sf} [7],

$$W = \frac{1}{2}\left|v_{sf}\right|^2 \frac{Y_R}{\left|Y_S + Y_R\right|^2} \tag{1}$$

Y_S is the complex mobility at the contact of the source and Y_R is the complex mobility at the contact of the receiver. The real parts of equations (1) – (4) denote the power flow into the receiving plate and then into the whole building structure.

Here, a single contact point and single component of excitation is assumed, in order to highlight the physical principles of structure-borne sound transmission. The case of multiple contacts is described in [6] and [7].

For the case of lightweight machines on/in heavyweight structures, the condition $|Y_S| >> |Y_R|$ applies and equation (1) reduces to,

$$W = \frac{1}{2}\frac{\left|v_{sf}\right|^2}{\left|Y_S\right|^2} Y_R = \frac{1}{2}\left|F_b\right|^2 Y_R \tag{2}$$

The associated force is independent of location and the blocked force only is required for the source characterisation. The installed power then is obtained from it in combination with receiver mobility Y_R.

Conversely, for the case of a machine attached to a flexible structure, $|Y_R| >> |Y_S|$ and equation (1) reduces to,

$$W = \frac{1}{2}\frac{\left|v_{sf}\right|^2}{Y_R^*} \tag{3}$$

The contact velocity is independent of location and a measure of the free velocity only is required to describe the source.

A third condition may occur where the ratio of receiver and source mobilities lies within the range $0.3 < |Y_R/Y_S| < 3$. Therefore, a matched mobility condition also is of relevance. A characteristic power also has been proposed [2], obtained from the product of the blocked force and free velocity,

$$W = \frac{1}{2}\frac{\left|v_{sf}\right|^2}{Y_S^*} \tag{4}$$

The characteristic power can be regarded as a sensible upper limit.

When considering an installed condition, it might be assumed that over significant parts of frequency range of interest the installed power can be estimated, from either one of the asymptotic conditions or by reference to the characteristic power, all of which can be obtained and expressed as one third octave data.

CASE STUDY

The case considered is of the fan unit supported, at four points, by a 50 mm homogeneous timber floor which is numerically modelled as a simply supported plate of dimensions 5 m x 4.5 m. The plate size and thickness was chosen in order to explore an installation where all three source-receiver mobility conditions occur. This allowed comparison of the three approximate values of total power and the exact value obtained through the mobility matrix method, obtained with complex narrow-band values, shown in figure 5.

At frequencies above 250 Hz, the force source estimate gives best agreement with the exact value. This is to be expected since the source mobility is significantly greater than that of the floor in this region.

It was predicted that there was a limited frequency region, 125 – 250 Hz, where mobility matching could occur. In this region, the characteristic power assumption appears to work.

Below 125 Hz, it was predicted that the floor mobility would be greater than that of the fan unit and velocity source assumption gives some agreement with the exact value. However, there are discrepancies below 125 Hz and this is because the receiver mobility is based in the characteristic (infinite plate) mobility of the floor. At low frequencies, the floor vibration response is modal and an infinite plate behaviour assumption is inappropriate.

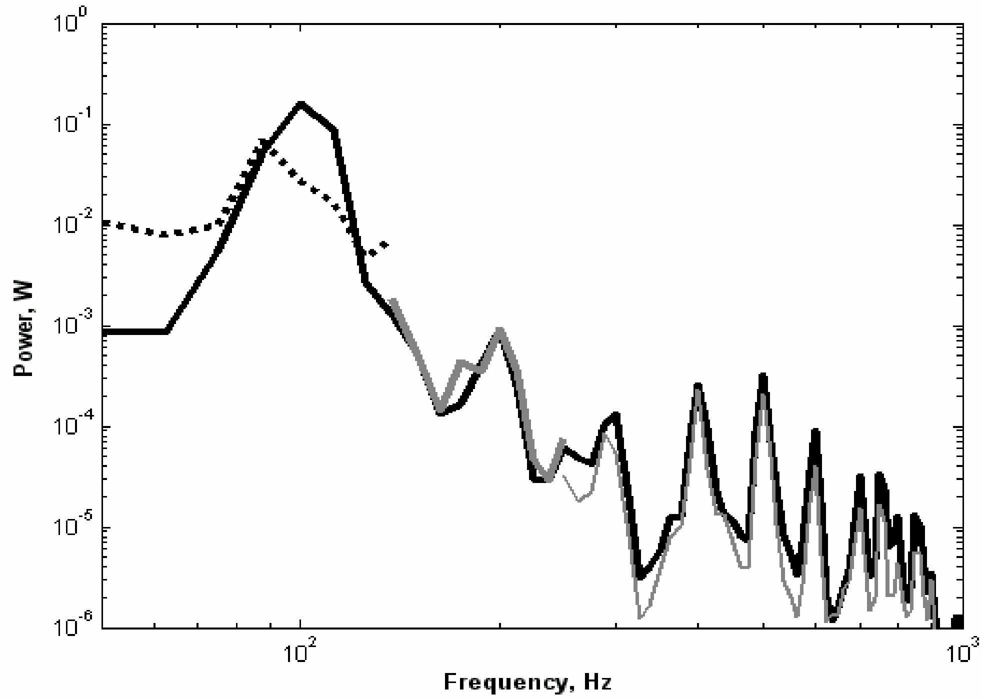

Figure 5 - Structure-borne sound transmission from a fan unit mounted on a 50mm solid timber floor: thick dark line, exact value; approximate values: dotted line, velocity source assumption; light thick line, characteristic power assumption; light thin line, force source assumption

DISCUSSION AND CONCLUDING REMARKS

A two-stage laboratory method of measuring structure-borne sound sources is proposed for mechanical installations in buildings. The laboratory data consists of the sum of the square velocities over the contacts, which can be obtained by direct measurement or by indirect measurement using an attached thin plate. The source mobility is obtained as a separate single value, the average of the mobilities at the contacts, by attaching the machine to a thick plate.

Both source quantities are required for prediction of installed power for the range of situations encountered in buildings, particularly lightweight constructions. The method applies to installations where the source and receiver mobilities differ significantly or for a matched mobility condition.

It is unlikely that floor and wall mobilities can be measured prior to predicting the structure-borne power from machines to be installed. However, for homogeneous floors, estimates of receiver mobility are possible, based on the characteristic mobility, with an upper and lower limit to represent modal behaviour at low frequencies.

It remains to explore the application of the method to non homogeneous constructions, such as timber joist floors where the floor mobility can be expected to vary significantly, for example, between joist positions and mid-joist positions.

The method proposed, as with most simplified methods, is a trade-off between practical application and accuracy. The practical benefits of a reception plate method are clear. The laboratory measurement data generated is in simple and transferable form. Manufacturers could check the efficacy of various vibration control stratagems, such as the introduction of anti-vibration mounts, by repeat measurements.

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