ESTIMATES OF MOBILITY FOR PREDICTION OF STRUCTURE-BORNE SOUND TRANSMISSION IN BUILDINGS

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This paper aims to provide a practical approach to the prediction of structure-borne sound power of mechanical installations in buildings. For structure-borne power, two source quantities, activity and mobility, are required, in combination with one receiver quantity, the receiver mobility. The source activity, in the form of free velocity or blocked force, is usually measured. For source mobility and receiver mobility, estimates, based on simple expressions, can provide a useful starting point. Also, machine bases may be categorised as: compact, plate-like, flanged or framed. Receiver structures, floors and walls, may be categorised as: plate-like, ribbed plate or framed plate. The estimates of source mobility are based on the rigid body value, the characteristic plate mobility and the fundamental plate frequency. For ribbed and framed plate structures, the mobility will vary with location, but again simple estimates of mobility, based on characteristic values and distance from the ribs, are possible.

1. Introduction

Building services machinery can cause noise problems through vibration transmission at contacts with building elements, vibration propagation across building elements and then radiation into rooms at distance from the sources. International Standards are now in place for such machines as structure-borne sources [1], which provide input data for prediction of the resultant sound pressure [2]. However, the Standards apply only to heavyweight buildings, with receiver mobilities much lower than the source mobilities and where the source is characterised in terms of one quantity only, the blocked force. For machines in lightweight buildings, e.g. of timber-frame or timber composite construction, the source and receiver mobilities can be of the same order of magnitude and both are required for prediction. Again, Standards are available for the measurement of free velocity [3] and of mobility [4], but measurements and calculations for the latter lie beyond the time and cost constraints of practicing consultants. In addition, machines are connected to buildings through multiple contacts, with multiple transmissions and these must be considered, in reduced form, when estimating the total transmission.

In this paper, single values of source free velocity, source mobility and receiver mobility are proposed for prediction of structure-borne sound power from machines in lightweight buildings. Whilst it is recognised that free velocity generally is a measurable quantity only, source mobility and receiver mobility are estimated from basic dynamic properties at the mount points. A form of reduction is to neglect the interaction (i.e. transfer) terms between contacts and this will be explored in detail. These estimates and reduced data sets are incorporated into approximate predictions of the total power from a multi-point source (a fan unit) on a ribbed plate (timber-joist floor).

2. Single equivalent excitation

In general, machines impart structure-borne power into connected and supporting structures through all contacts. The general expression of complex power for multi-point and multi component excitation, such as in [5], is given by:

$$\overline{W} = \overline{\mathrm{v}}_{S\,f}^{\,H} \left[\overline{\mathrm{Y}}_S + \overline{\mathrm{Y}}_R\right]^{-H} \left[\overline{\mathrm{Y}}_R\right]\left[\overline{\mathrm{Y}}_S + \overline{\mathrm{Y}}_R\right]^{-1} \overline{\mathrm{v}}_{S\,f} \qquad (1)$$

where $\overline{\mathrm{v}}_{S\,f}$ is the r.m.s. source free velocity vector, $\overline{\mathrm{Y}}_S$ and $\overline{\mathrm{Y}}_R$ is the complex mobility matrices of the source and the receiver, respectively. H is the Hermitian transpose, where $[\ ]^H = [\ ]^{T*}$ and $[\ ]^{-H} = [[\ ]^{T*}]^{-1}$. The total power is the sum of the complex products of the forces and moments and their associated translational and rotational responses at the contacts of interest. Consideration of all transmission paths is rarely possible.

2.1. Single equivalent free velocity

Source activity can be expressed as a free velocity vector, see equation (1), or as a blocked force vector. In seeking a single value of source activity, reference is made to indirect measurement methods, using reception plates [6]. If a source is attached to a thin high-mobility plate, it can be demonstrated that the source free velocity is obtained indirectly as the sum of the squares of the free velocity over the contacts $\sum_{i=1}^{N} \left|v_i\right|^2$. The free velocity also can be obtained by direct measurement [3]. This form of single value is used throughout the following discussion.

2.2 Single equivalent source and receiver mobility

In general, mechanical and water installations in buildings transmit vibrations by forces perpendicular to the surface of the receiving structure and other components of excitation can be neglected [7, 8]. A further simplification results by neglecting transfer terms, in the estimate of the real part and magnitude of the receiver mobility and the magnitude of the source mobility. Figure 1 shows the approximate power, where the transfer terms have been neglected, normalised with respect to the exact power, for ten locations of a fan unit on a timber floor. Neglect of the transfer terms gives an average overestimate of 3 dB at low frequencies. The overestimate reduces with increase in frequency because of the reduced contribution of transfer terms in the full expression. Individual approximate estimates can be 10 dB different from the exact values, depending on frequency and location. However, this simplification warrants further consideration, when assembling single equivalent values.

Manufacturers view their products as single entities and seek an associated single value of source strength, along with single values of source and receiver mobility, required for prediction of the installed power. Consider the source quantities, free velocity and source mobility as two single equivalent values, also the receiver mobility as a single equivalent value.

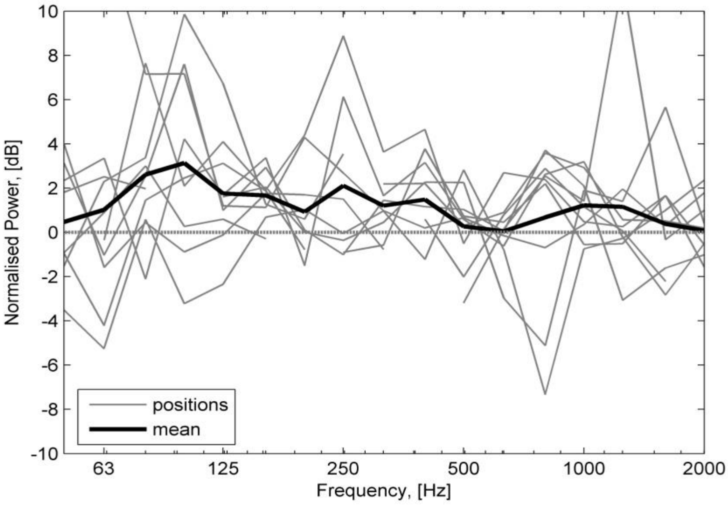

Figure 1. Normalised power assuming independent contacts, for a fan unit at ten positions on a timber joist floor, after [8].

The total structure-borne sound power now is given as:

$$P_{SR} \approx \frac{\mathrm{Re}\{Y_{R\,eq}\}}{\left|Y_{S\,eq}\right|^2 + \left|Y_{R\,eq}\right|^2} \sum_{i=1}^{N} \left|v_i\right|^2 \tag{2}$$

The single equivalent free velocity is as defined earlier. The single equivalent mobility is expressed as the average of the point mobilities over the contacts. The source mobility is a magnitude. The receiver mobility is a magnitude and also a real part of the value. This allows source quantities to be assembled as band average values, favoured by consultants and test houses. However, the complex relationship between the source and receiver mobility terms has been lost, and through the transfer terms between contacts, and errors can be expected, particularly at low frequencies. The effect of using magnitudes and neglecting cross and transfer coupling was examined by comparing approximate and exact powers.

The final simplification is through calculating, rather than measuring the source and receiver mobilities and it remains to estimate the point mobility of a range of machine bases and a ribbed-plate lightweight building structure.

3. Point mobility of machines

The mobility at the contact points of machines is largely dictated by the material and geometry around the contacts. On this basis, it is possible to categorise machines bases into four types: compact sources; flanged bases; plate bases; frames. For compact sources, there is a rigid body (RB) motion. Above this region, the machine base plates are stiffness controlled (SC). At higher frequencies, the base plates display resonant controlled (RC) behaviour. Individual machines can display all these dynamic characteristics, depending on the frequency. In Figure 2 is shown the point mobility at the four mount points of a fan unit. The four point mobilities are similar and can be represented by a single estimate, based on simple dynamic characteristics. F denotes the first resonance at the contact location and CM denotes the characteristic (infinite plate) mobility, given by $Y_{char} = \frac{1}{8\sqrt{B'\ddot{m}}}$, where $\ddot{m}$ is the mass per unit area and B' is the bending stiffness [9].

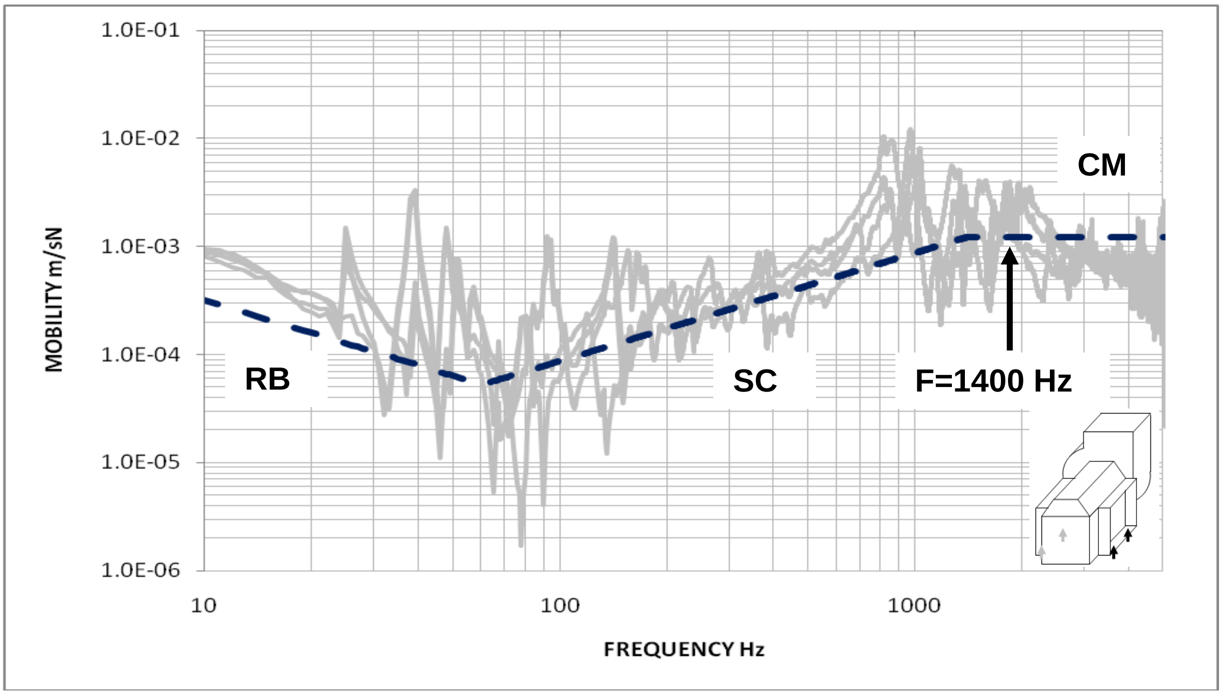

Figure 2. Point mobility of a flange base of a fan unit.

It is assumed that the first resonant frequency forms the transition between stiffness controlled and plate-like behaviour. The value depends on the plate thickness and material and the edge conditions [10]. In Figure 3 the same procedure is used for a fan unit on a base plate, likewise in Figure 4 for another unit. For these two machine bases, plate like behaviour is evident over much of the frequency range of interest, although there are large fluctuations in the measured values.

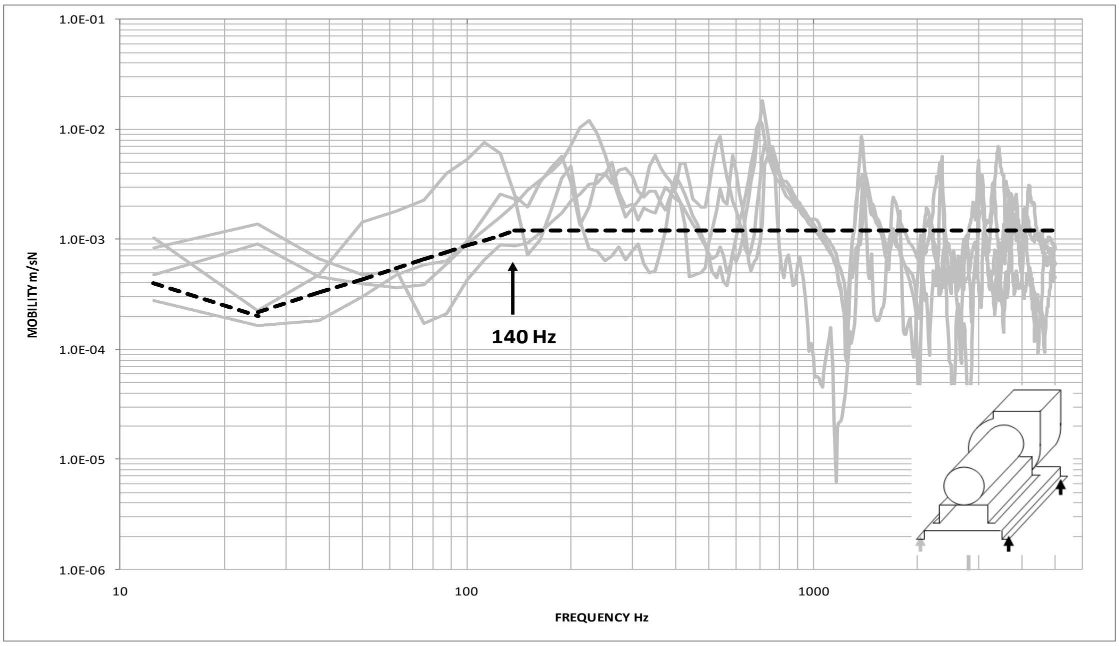

Figure 3. Point mobility of plate base of a fan unit.

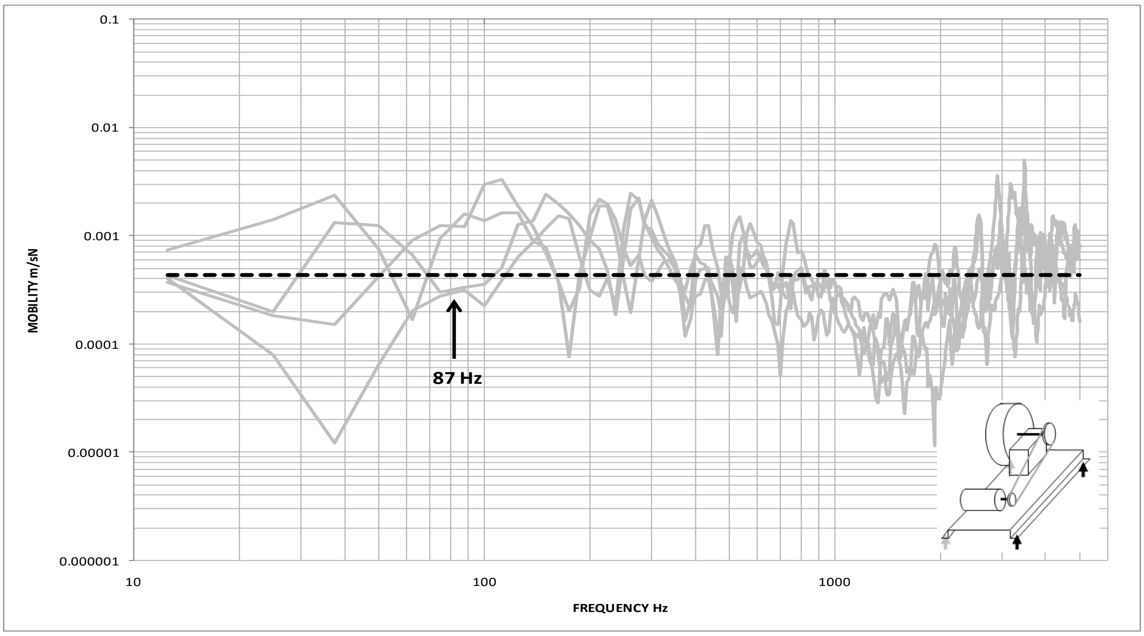

Figure 4. Point mobility of plate base of a fan unit.

Frame structures are more variable in behaviour and difficult to characterise. In Figure 5 are shown the point mobility at eight mount positions of a frame base of a whirlpool bath [8]. Below 100 Hz, the mobilities are highly variable and sensitive to distance from structural discontinuities. Above 100 Hz, the measured values converge towards the characteristic (infinite) beam mobility [9], where $Y_{char} = \dfrac{1}{2\dot{m}c_B(1+j)}$.

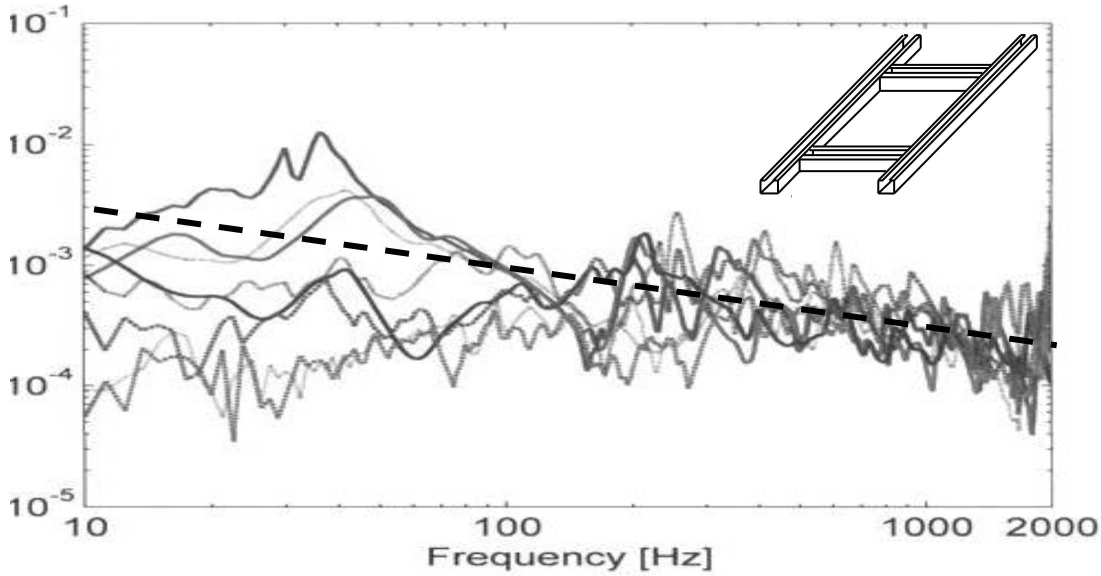

Figure 5. Point mobility of frame base, from [7]; also shown (dashed line) is the characteristic beam mobility for the rectangular cross section of the framing.

4. Point mobility of lightweight building structures

Prediction of the installed power requires an estimate of both the real part and magnitude of the receiver mobility. In lightweight buildings, the receiver is usually a ribbed or framed plate structure. In a measurement survey, the point mobility, at various locations on fifteen lightweight constructions was recorded [11]. The measurements were at locations on, near and distant from ribs and frames (i.e. in bays). The point mobility ranged over two decades, with a mean value of 10^{-3} m/Ns in bays and 10^{-4} m/Ns at the ribs/frames. In Figure 6 the point mobility of a timber floor is shown for various distances from the nearest supporting timber joist. The mobility is normalised with respect to the characteristic mobility of the floor boarding and the distance is normalised with respect to the bending wavelength on the boarding. At distances ≤ 0.1 wavelength, the mobility corresponds to the characteristic (infinite) beam mobility. At distances ≥ 0.25 wavelength, the mobility corresponds to the characteristic (infinite) plate mobility Y_{char}. A monotonic transition occurs between the two regions and all three regions are shown as a dashed line.

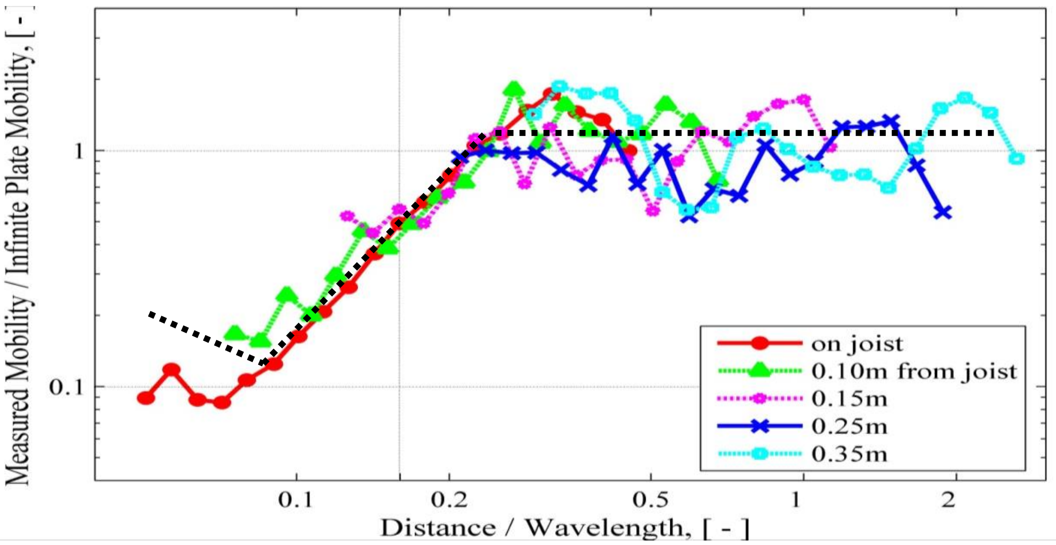

Figure 6. Point mobility as a function of distance from a joist, after [12].

Using this idealisation, the point mobility at any location on the ribbed or framed lightweight structure can be estimated. In Figure 7 are shown the calculated real parts of point mobility of the top plate (21 mm chipboard) at incremental distances from the nearest joist.

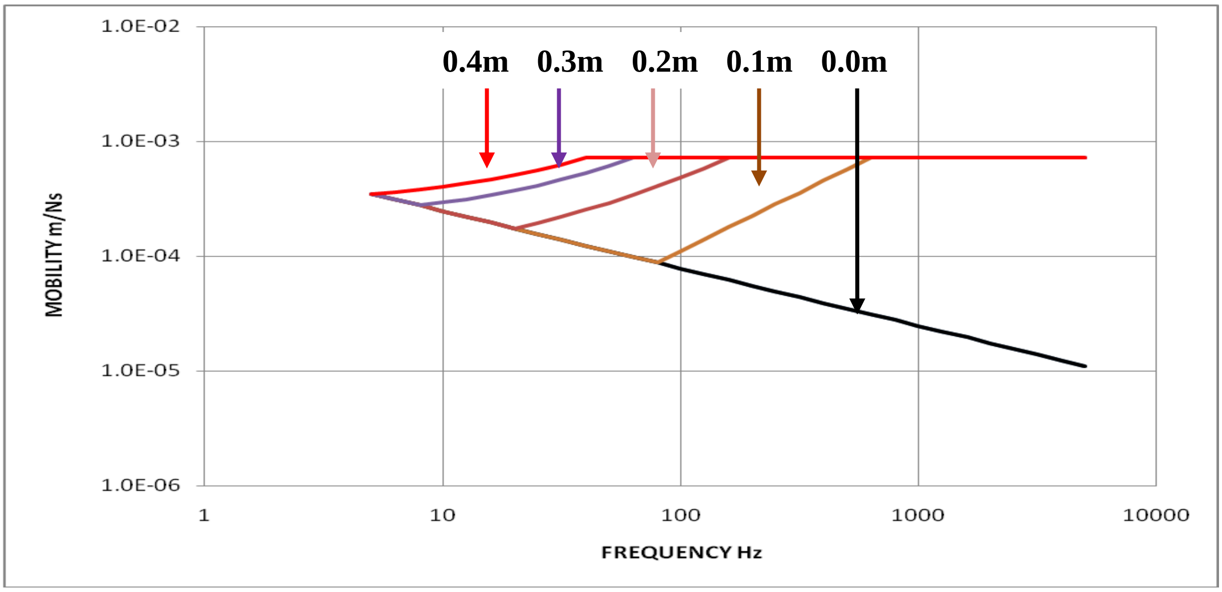

Figure 7. Real part of point mobility at incremental distances from a joist.

5. Predicted structure-borne power for a fan on a timber floor

The case study is of a fan unit (see point mobility in Figure 2) at ten locations on a timber joist floor. For each location, the *exact* power is calculated from equation (2) and from measured values of free velocity, complex source mobility, complex receiver mobility, for each of the four contacts, including complex transfer mobilities between contacts.

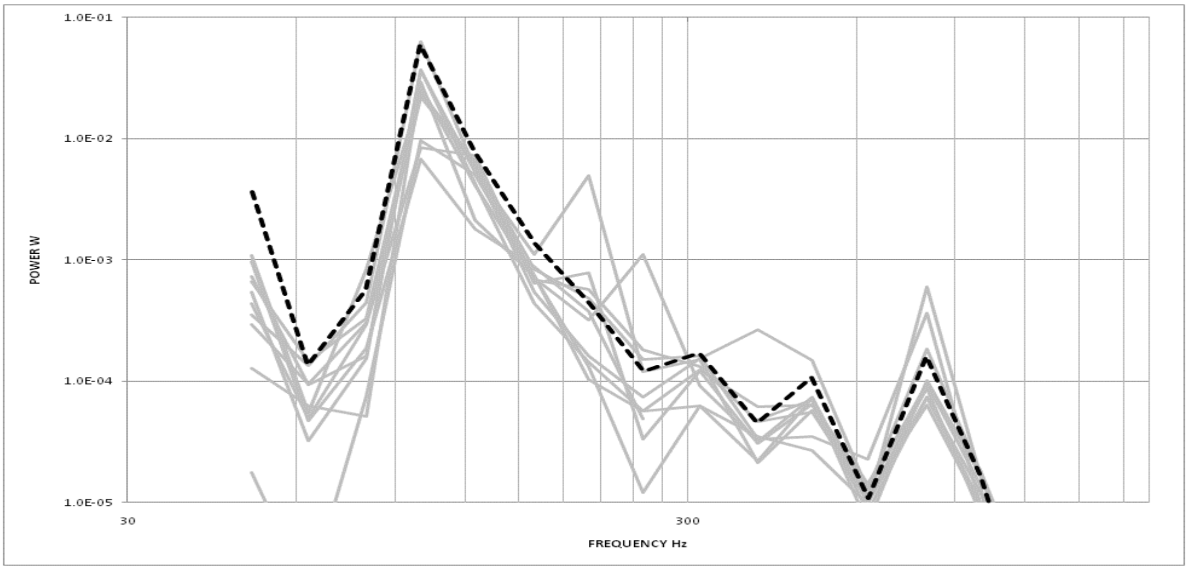

Figure 8. Power of a fan unit at ten locations on a timber floor; dashed line, approximate value.

For the approximate value, the receiver mobility is given by the characteristic plate mobility, which is a real value and $\left|Y_{\mathrm{Re}\,q}\right| = \mathrm{Re}(Y_{\mathrm{Re}\,q}) = Y_{char}$. Therefore, the approximate value gives an overestimate at low frequencies and/or when near to the joists, but generally is within 5 dB of the exact values.

Can the approximate method, with calculated values of mobility, be used to predict the effect of distance from ribs/frames on the structure-borne power? This is possible if all contacts are at the same distance. In Figure 9 is shown predicted power, as the fan unit is moved incrementally from the nearest joist to a central bay location.

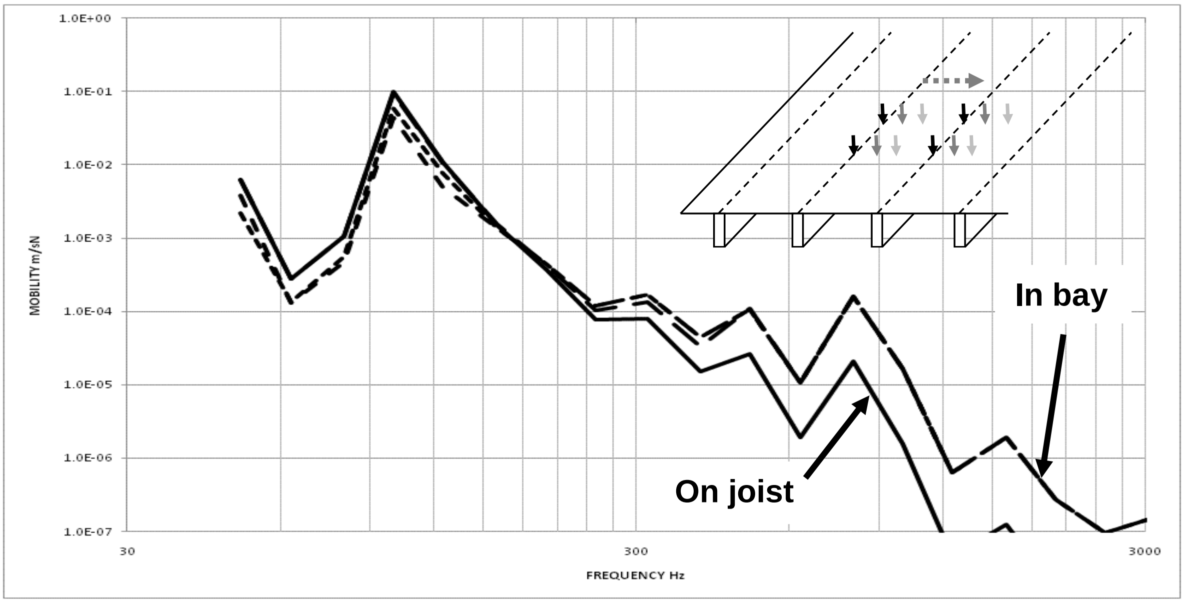

Figure 9. Predicted power as a function of distance from joists.

The power in a bay is predicted to be 10 dB more than when on joists but this difference is where the power level is 20 dB below the maximum level and can be assumed to be outside the frequency range of interest. This, in part, explains the relatively small spatial variation in total power shown in Figure 8.

6. Concluding remarks

A practical approach to the prediction of structure-borne sound power of mechanical installations in lightweight buildings is described. The required source activity, the free velocity, must be measured but the source mobility and receiver mobility can be calculated, based on characteristic dynamic properties. The described case study of a fan unit on a timber joist floor has applications to wall-mount installations, which are usually attached to the frame or ribs. This could provide separately the power into the structural frame and into the cladding, as a first step in the prediction of structure-borne sound propagation in lightweight buildings.

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