Source quantities for vibro-acoustic transmission into lightweight building elements

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ABSTRACT

An approximate approach is described for obtaining the source quantities required for the calculation of structure-borne sound power from machines into supporting lightweight building elements. The approach is in two stages, which are based on existing international Standards for measurement. The first stage involves direct measurement of the source free velocity at each contact, to give the sum of the square velocity magnitudes. The second stage is based on the reception plate method and yields the single equivalent blocked force, which approximates the sum of the square blocked forces. This approach has been investigated in a case study of a fan unit on a timber joist floor. The approach contains several significant simplifying assumptions. For the case considered, the power transmitted into the floor is estimated by the approximate method to within 5 dB of the true value, on average.

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1. INTRODUCTION

For the structure-borne sound power from a vibrating machine to a lightweight building element, three quantities are required [1-3]. The first is the activity: either the measured free velocity of the freely suspended source, under otherwise normal operating conditions, or the measured blocked force, obtained when the source is attached to a rigid supporting structure, also under otherwise normal operating conditions. The second quantity is the source mobility. The third quantity is the receiver mobility. The source quantities can be measured directly or obtained indirectly by the reception plate method [4, 5].

This paper describes a two-stage procedure, which is a combination of direct and indirect measurements. The first stage is the direct measurement of the sum of the squared free velocities, over the machine contacts, and is based on the Standard method ISO 9611 [6]. Accelerometers are attached to the contact points of the freely suspended or resiliently supported machine and the velocities are recorded as 1/3 octave values, while the machine is in operation. The second stage employs the reception plate method (RPM), referred to in the Standard EN15657-1 [7]. The principle of the reception plate method is given in [1, 8]. The machine under test is attached to an isolated resiliently supported plate. With the machine in operation, the total structure-borne sound power transmitted equals the bending wave field power of the receiving plate. The plate power is obtained from the spatial average of the square plate velocity $\left\langle v^2 \right\rangle$:

$$P_{source} = P_{plate} = \omega \, \eta \, M \left\langle v^2 \right\rangle \tag{1}$$

M is the mass of the reception plate and η the total loss factor of the plate.

If the reception plate mobility is much lower than the source mobility, then the source can be characterized by a single quantity, related to the sum square blocked force over the machine supports [8]. The source power into a plate of known low mobility Y_{low} is:

$$P_{source} = F_{beq}^2 \ \mathrm{Re}\ (Y_{low}) \tag{2}$$

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The single equivalent value of blocked force F_{beq}^2 is extracted from equations (1) and (2) and used in combination with the measured sum square free velocity $\sum v_f^2$, to give the single equivalent source mobility [4, 5]:

$$Y_{Seq} = \sqrt{\sum v_f^2 / F_{beq}^2} \tag{3}$$

The single equivalent source mobility relates to the average point mobility magnitude over the contacts. The sum square free velocity and single equivalent source mobility are used in combination with measured or calculated single equivalent receiver mobility Y_{Req}, which also relates to the average point mobility magnitude over the receiver contact points (or the spatial average over the plate area), to predict the structure-borne power when the source is installed:

$$P_{installed} \approx \sum v_f^2 \frac{\mathrm{Re}\left(Y_{Req}\right)}{\left|Y_{Seq}\right|^2 + \left|Y_{Req}\right|^2} \tag{4}$$

The approximate expression in equation (4) involves spatial and spectral averaging, with a resultant loss of phase information (between source and receiver mobility, and between the contact forces for multi contact sources). These simplifications introduce uncertainties in the obtained source quantities and in the predicted installed power. These uncertainties are assessed in a study of a fan unit attached to a timber joist floor, described in detail in [9].

2. CASE STUDY OF FAN ON TIMBER JOIST FLOOR

A medium size centrifugal fan unit is assumed to be rigidly attached to a timber joist floor. Figure 1, left, shows the fan unit, which was located and measured in the Acoustics Research Unit of the University of Liverpool. Figure 1, right, shows the timber joist floor, which was constructed in the acoustics laboratory of Stuttgart University of Applied Sciences. The floor consisted of one layer of 21 mm chipboard sheathing supported by spruce joists, of section 0.096m x 0.192m, at spacing of 0.78m. The floor was without a ceiling plate.

Figure 1- Left, fan unit, with two of the four contact points indicated; right, timber joist floor.

In this example of sub-structuring, the fan and floor were measured in separate locations. Then, for the fan fictively attached to the floor, the power was calculated by the mobility method, where the general expression of complex power for multi-point excitation is given by [3]:

$$\overline{W} = \overline{v}_f^{*T} \left[\overline{Y}_S + \overline{Y}_R\right]^{*T-1} \left[\overline{Y}_R\right] \left[\overline{Y}_S + \overline{Y}_R\right]^{-1} \overline{v}_f \tag{5}$$

$\bar{v}_f$ is the source complex free velocity vector, $\overline{Y}_S$ and $\overline{Y}_R$ are the complex mobility matrices of the source and the receiver, respectively. * denotes complex conjugate and ^{T} denotes the transpose. Previous work has concluded that, in buildings, perpendicular forces are the dominant component of the total transmission and other components, including moments, can be neglected [10-12]. Therefore, only this component is considered. The total transmitted power is the real part of the sum of the complex products of the forces and associated contact velocities at four points. For the mobility method, the source free velocity was recorded at four contacts with the fan flexibly suspended and operating. The velocities were recorded as complex values with a frequency resolution of 2 Hz and a frequency range of 0 - 6400 Hz. In Figure 2 is shown the narrow-band magnitudes of velocity at four contacts, along with the sum square in 1/3 octaves. Within the frequency range 50 Hz – 2000 Hz, there are strong tonal components at 25 Hz, 50 Hz and 100 Hz, combined with a broad-band spectrum.

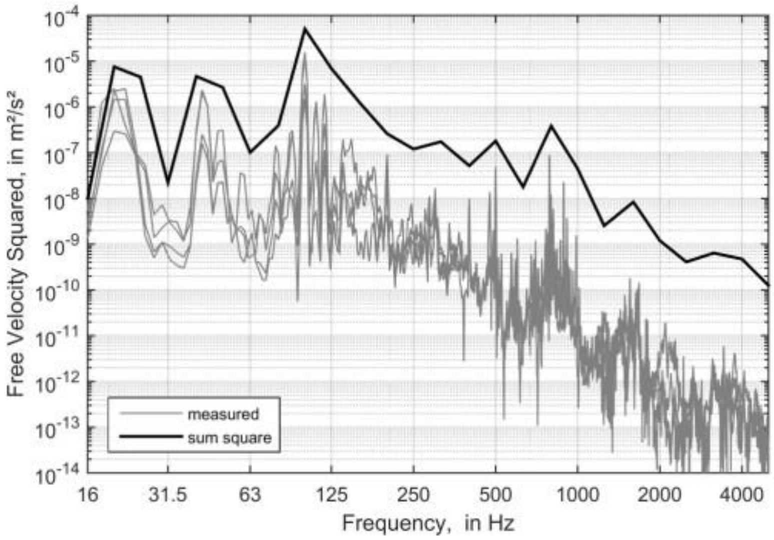

Figure 2 – Narrow-band free velocity squared at four fan mounts; sum square in 1/3 octaves

With the fan similarly suspended, the complex source mobility was recorded using a shaker with in-line force transducer and accelerometer. Complex values of point mobility and transfer mobility between contacts formed the source mobility matrix. In Figure 3 is shown the narrow-band point mobility magnitude at the four contacts, along with the average value in 1/3 octaves.

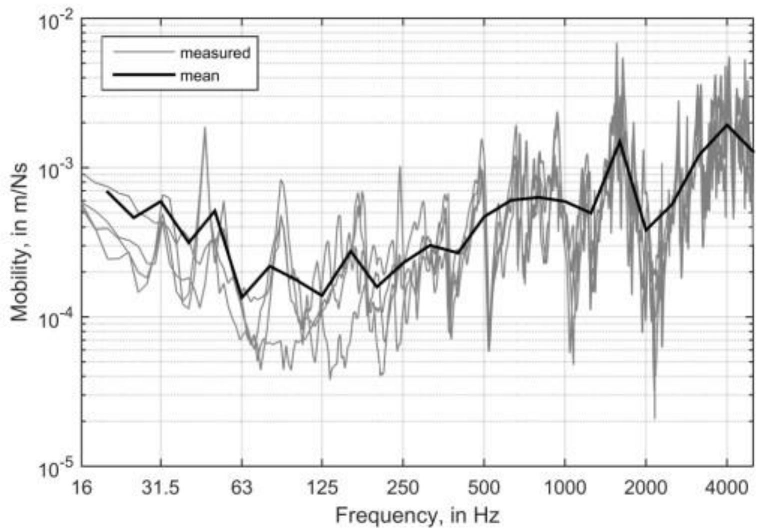

Figure 3 – Narrow-band point mobility magnitudes at four contacts; average in 1/3 octaves

The receiver mobility matrix was assembled from measured point and transfer mobility at each of ten locations over the timber floor. Each location consisted of four contact points at distances corresponding to the mount points of the fan base. An instrumented impact hammer registered the applied force and the response velocity was recorded as the average signal from a matched accelerometer pair, located either side of the impact point. In Figure 4 is shown a typical narrow-band point mobility in a bay, also in 1/3 octaves.

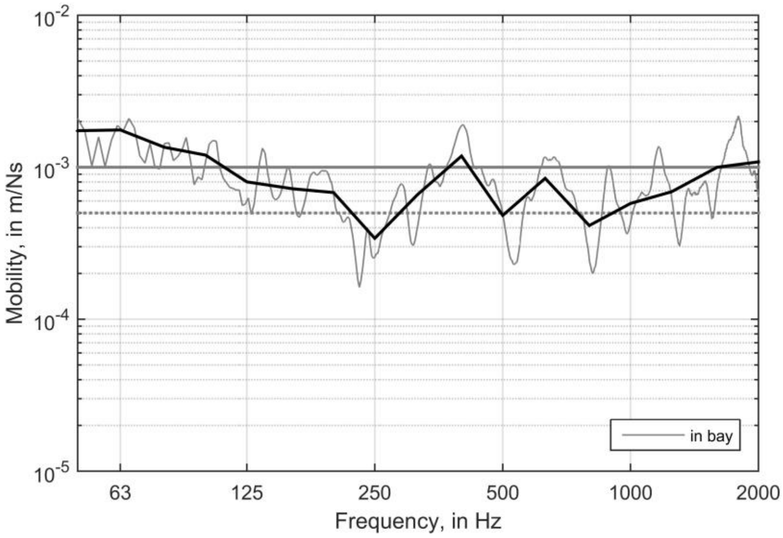

Figure 4 - Narrow-band point mobility in a bay, also in 1/3 octaves. Shown is assumed receiver mobility of 10^{-3} m/sN (grey solid line) and of 5.10^{-4} m/sN (grey dotted line).

In Figure 5 is shown the narrow-band point mobility over a joist, also in 1/3 octaves. The mobility is 10 dB below that in a bay at low frequencies and/or when near to a joist fixing. The mobility converges to that in a bay with increase of frequency.

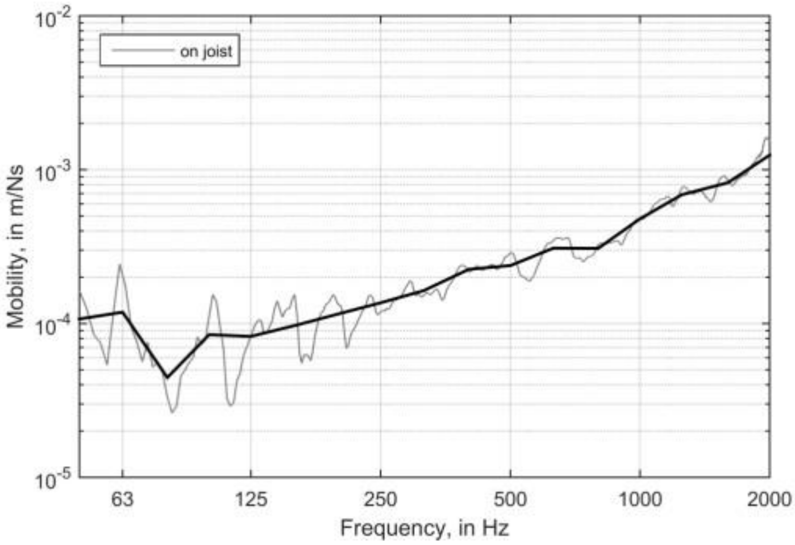

Figure 5 - Point mobility magnitude over a joist

The data was incorporated into equation (5) to provide the calculated powers, which formed the benchmark for comparison with the powers obtained by the approximate method in equation (4).

3. TWO STAGE LABORATORY METHOD

The first stage of the proposed laboratory method is the direct measurement of the fan free velocity, described earlier and according to the Standard ISO 9611 [6]. The velocities at four contact points were recorded in 1/3 octaves and stored as the sum square, shown in Figure 2.

For the second stage, the fan was glued to a low mobility plate of 20mm thick aluminium of dimensions 2.12m x 1.50m (Figure 6, left). The plate was supported at the corners by six visco-elastic pads (Figure 6, right). The supporting pads provided isolation and additional plate damping at low frequencies. With the fan operating, the plate response velocities were recorded at seven accelerometer positions, distributed over the plate surface, and the average square velocity of the plate incorporated into equation (1) to obtain the fan power and thence the sum square blocked force by re-arranging equation (2). Also for equation (2), the real part of the plate mobility was recorded.

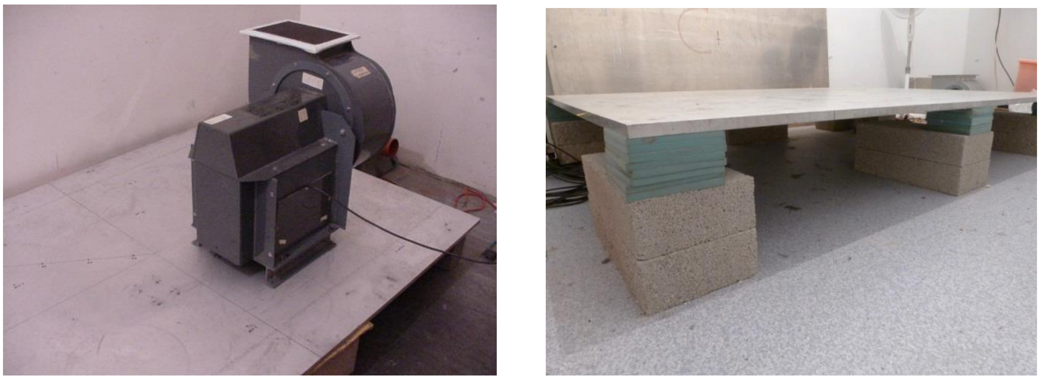

Figure 6 - Low mobility reception plate (left) with fan attached; plate on visco-elastic pads (right)

The average point mobility of the fan was approximated from equation (3). Figure 7 (left) shows the average mobility, from the two-stage method and the directly measured value, both in 1/3 octaves.

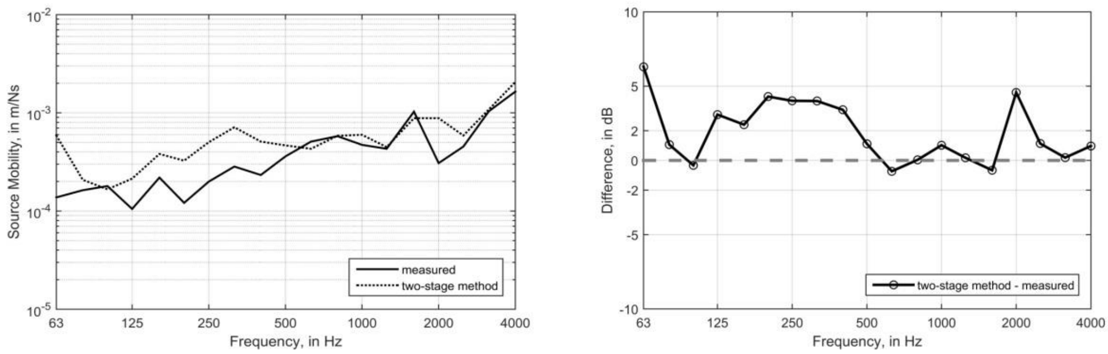

Figure 7 - Left: Measured average point mobility magnitude (solid line) and estimated by the two-stage method (dashed), right: level difference

The discrepancy below 500 Hz is caused by unwanted mobility matching (see Figure 21 in [9]), but overall, the level difference between the directly measured mobility and the two-stage estimate is within 5 dB.

4. PREDICTED INSTALLED POWER USING TWO STAGE METHOD

To assess how errors in the source data affect the estimated power in the installed condition, the fan data was obtained from the two-stage method and used, in combination with measured receiver data, according to equation (4). The powers are shown for two fan locations on the timber joist floor.

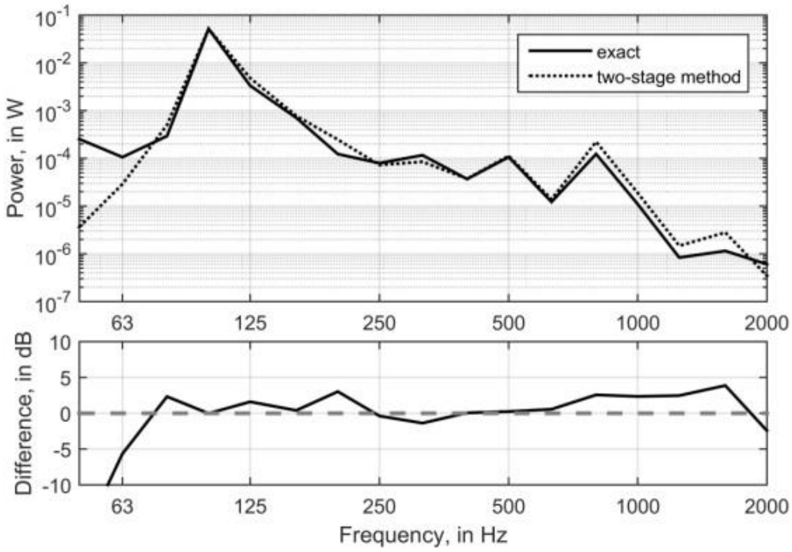

Figure 8 - Exact and approximate power for the fan located with four contacts in one bay

Figure 8 shows the powers for the fan with four contacts in one bay. Also shown is the level difference. The two-stage estimate is within 5 dB, often within 3 dB, of the exact value at frequencies above 63 Hz.

Results are shown in Figure 9 for the fan with two contacts on a joist and two contacts in a bay. Above 63 Hz, the two-stage estimate is within 5 dB of the exact value.

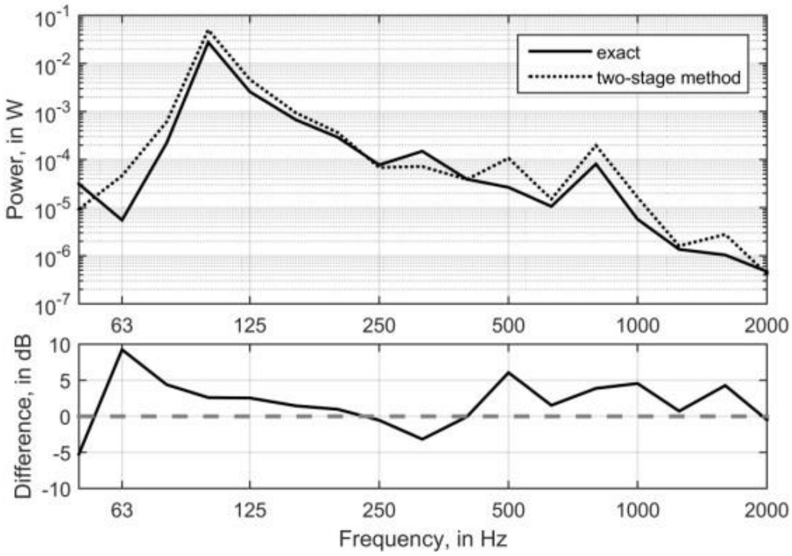

Figure 9 - Exact and approximate power for the fan with two contacts on a joist and two in a bay

Figure 10 shows the approximate power for ten fan positions on the timber joist floor, normalised with respect to the exact powers at the same positions. Also shown is the mean value. On average, the approximate power is within 2 dB of the exact power, between 80 Hz and 2000 Hz, with deviations of 4 dB at 1000 Hz and 1600 Hz.

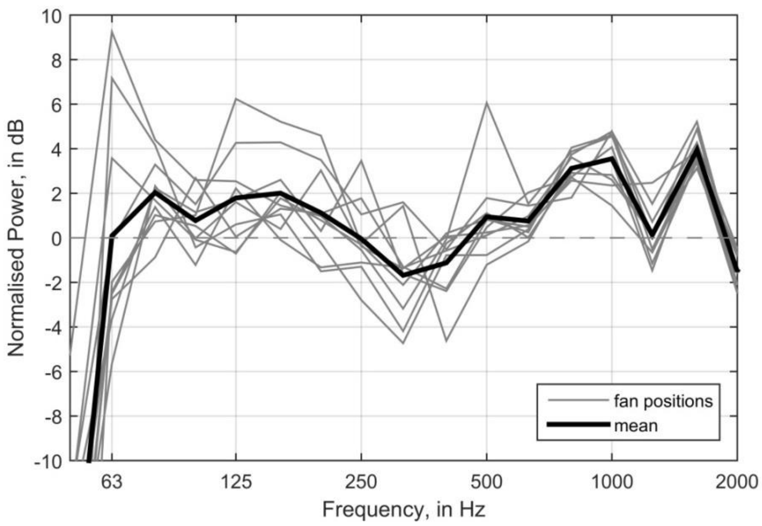

Figure 10 - Normalised power at ten fan positions with mean value, using measured floor mobility

The case described so far used measured receiver mobility data, which is usually not available. Therefore, the calculations were repeated using simple estimates based on the characteristic behaviour of plate-like structures [13]. From inspection of the mobility in a bay (Figure 4), frequency invariant values of 10^{-3} m/Ns and 5.10^{-4} m/Ns were assigned. Figure 11 shows the average normalised power for ten fan locations.

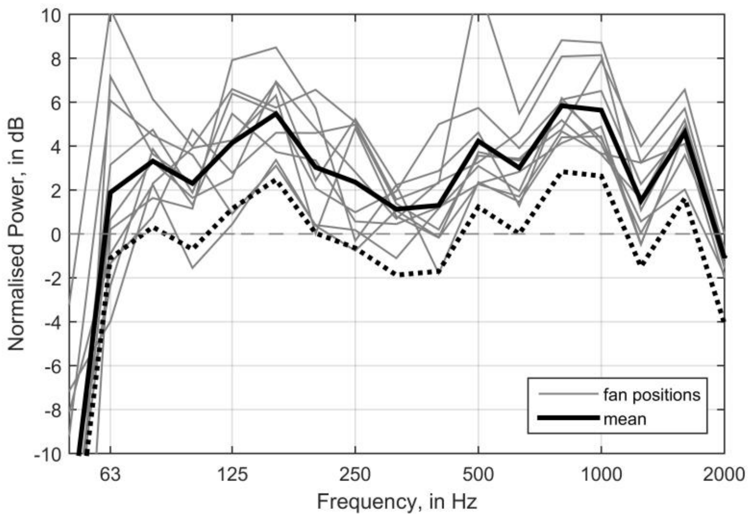

Figure 11 - Normalised power at ten fan positions with mean value, with assumed floor mobility of 10^{-3} m/Ns.

The discrepancies are greater than in Figure 10 at some individual locations, particularly for contacts over joists. On average, the power is over-estimated within 6 dB, between 63 Hz and 2000 Hz, if the assigned receiver mobility is 10^{-3} m/Ns. The over-estimate is within 2 dB, if the assigned receiver mobility is 5.10^{-4} m/Ns.

5. CONCLUDING REMARKS

An approximate method has been investigated for obtaining the source quantities required for calculating the structure-borne sound transmission from mechanical installations in lightweight buildings. The approximate method is a development of the two-stage reception plate method, where the first stage involves direct measurement of the velocity of the free source, expressed as the sum of the square velocities at the contacts. The second stage involves measurement of the reception plate power for the source on a low mobility plate and yields the blocked force as an approximation of the sum square value.

Using this method, in a case study of a medium size fan unit, the source mobility was estimated within 5 dB of the average measured point mobility.

The approximate estimates of installed power were compared with calculated powers obtained by the mobility method, for the source fictively connected to the supporting receiving structure. The case studied was that of the size fan attached to a timber-joist floor through four mounts.

The source data, obtained by the approximate method, gave estimates within 2-4 dB of the exact calculated powers on average, for the fan at 10 locations on the timber-joist floor.

When the floor mobility was assigned a frequency invariant value of 10^{-3} m/sN, irrespective of location, the power was overestimated by 2-6 dB on average.

When the floor mobility was assigned a frequency invariant value of 5.10^{-4} m/sN, irrespective of location, the power was within +/- 2 dB on average.

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