Acoustics'08 Paris
June 29-July 4, 2008
www.acoustics08-paris.org

# Structure-borne sound transmission from machines into ribbed structures

Barry Gibbs[a] and Andreas Mayr[b]

[a]University of Liverpool, School of Architecture, Abercromby Square, L693BX Liverpool, UK
[b]Stuttgart University of Applied Sciences, Schellingstrasse 24, 70174 Stuttgart, Germany
bmg@liv.ac.uk

The total structure-borne sound power of an installed machine is a function of the source activity and mobility, and the receiver mobility, at each contact and for each component of excitation. The data and computational requirements for prediction therefore are large. Manufacturers view their products as single entities and desire corresponding single values of source strength. A laboratory reception plate measurement procedure has been proposed which yields single equivalent values of source strength and source mobility. The source data, in combination with an estimate of the single equivalent value of receiver mobility, yields the approximate total installed power. The accuracy of the estimate is strongly dependent on the spatial variation in contact conditions over the connections. In addition, phase information has been lost in the simplification. Case studies are described for multiple contact sources on a non-homogeneous plate (a timber-joist floor) where the approximate estimates of structure-borne power are compared with exact values obtained from full mobility matrix formulations.

# 1 Introduction

This paper considers machines or components which are installed in contact with rib-stiffened plates. Examples are mechanical installations in lightweight buildings composed of framed or joist supported structures. The aim of the work reported was to examine how laboratory data, in the form of single equivalent magnitudes, might be used for prediction of installed structure-borne sound power, which conventionally requires complex-valued data for each contact between machine and supporting structure [1].

The structure-borne sound power of a machine, transmitted to a receiving structure, is a function of source activity and mobility, and of receiver mobility. For a full description of the transmission, all three quantities are required for each contact and for up to six components of excitation at each contact [2-6]. For the case where the source mobility and receiver mobility are about the same magnitude, the phase difference between the source mobility and receiver mobility assumes importance and the complex values of mobility are required. A full prediction therefore is computational intensive and requires large data sets. Large spatial variations in contact power can be expected for asymmetric sources and inhomogeneous receivers and attempts to collapse source and receive data into single equivalent values may be inappropriate. However, manufacturers view their products as single entities and seek an associated single value of source strength. Consultants, test houses and small R&D facilities often are geared to measure spatial and spectral average values, typically as octave or third octave band magnitudes.

# 2 Single equivalent mobility

Consider a source connected through $N$ contacts to a receiver structure. In this study, forces perpendicular to the receiver structure only are considered. The total power, from a source S to a receiver R, can be expressed as

$$P_{SR}^{Total} = \frac{1}{2}\sum_{i}^{N}\left|\overline{v}_{sfi}\right|^2 \frac{Re(\overline{Y}^{\Sigma}{}_{Ri})}{\left|\overline{Y}^{\Sigma}{}_{Si}+\overline{Y}^{\Sigma}{}_{Ri}\right|^2} \quad (1)$$

For both the source and receiver, the effective point mobility [7] at the $i^{th}$ contact is

$$\overline{Y}_i^{\Sigma} = \overline{Y}_i + \sum \frac{\overline{F}_j}{\overline{F}_i}\overline{Y}_{i,j} \quad (2)$$

$\overline{Y}_i$ is the point mobility at the $i^{th}$ contact, $\overline{Y}_{i,j}$ is the transfer mobility between the $i^{th}$ and $j^{th}$ contacts and $\frac{\overline{F}_j}{\overline{F}_i}$ is the ratio of the forces at the $j^{th}$ and $i^{th}$ contact, respectively, where

$$\overline{F}_i = \frac{\overline{v}_{sfi}}{\overline{Y}_{Si}+\overline{Y}_{Ri}} \quad (3)$$

In the absence of detailed information on the contact forces, simplifying assumptions are necessary. The forces can be assumed to be of equal magnitude. If a zero phase difference is assumed, then the complex effective mobility can be given as

$$\overline{Y}_i^{\Sigma} \approx \overline{Y}_i + \sum \overline{Y}_{i,j} \quad (4)$$

If a random phase is assumed then the magnitude of the effective mobility is obtained

$$\left|\overline{Y}_i^{\Sigma}\right|^2 \approx \left|\overline{Y}_i\right|^2 + \sum\left|\overline{Y}_{i,j}\right|^2 ;\ \mathrm{Re}\left(\overline{Y}_i^{\Sigma}\right) \approx \mathrm{Re}\left(\overline{Y}_i\right) \quad (5)$$

Both phase assumptions were considered in this investigation.

This leads to two source quantities, required for prediction of the installed power, which can be expressed as single equivalent values. The first is the single equivalent source activity

$$\mathrm{SESA} = \sum_{i}^{N}\left|\overline{v}_{sfi}\right|^2 \quad (6)$$

The magnitude can be measured directly [8] or indirectly by a simple reception plate method [9].

The second quantity is the single equivalent source mobility SESM, which is the average complex effective source mobility

$$\overline{Y}_S^{\Sigma} = \frac{1}{N}\sum_{i}^{N}\overline{Y}_i^{\Sigma} \quad (7)$$

This can be measured directly but the data acquisition and computation requirements are large. It can be obtained indirectly, again by a simple reception plate method, but only as the magnitude $\left|\overline{Y}_S^{\Sigma}\right|$ [10].

These single equivalent values pre-suppose small spatial variations in effective source point mobility. In Fig. 1 is shown the magnitude of the effective point mobility of four mount points of a fan unit assuming random phase difference between contact forces.

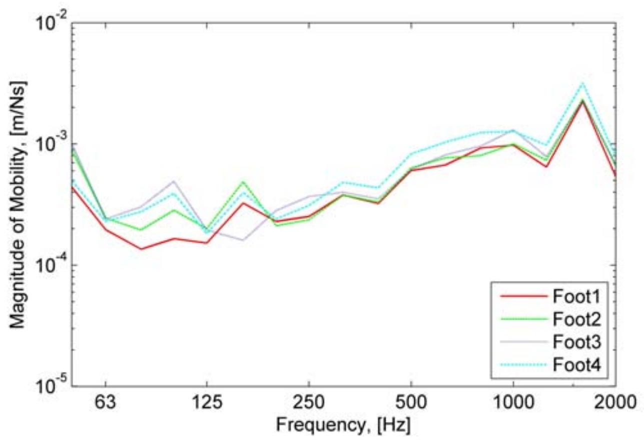


Fig. 1 Magnitude of effective source point mobility at four mounts of a fan unit, assuming random phase difference

In Fig. 2 are shown values at four mount points of a whirlpool bath. For the fan, the spatial variation is of the order of 5 dB; for the whirlpool bath, 10 dB. This might be regarded as sufficiently small to allow the calculation of the mean effective source mobility.

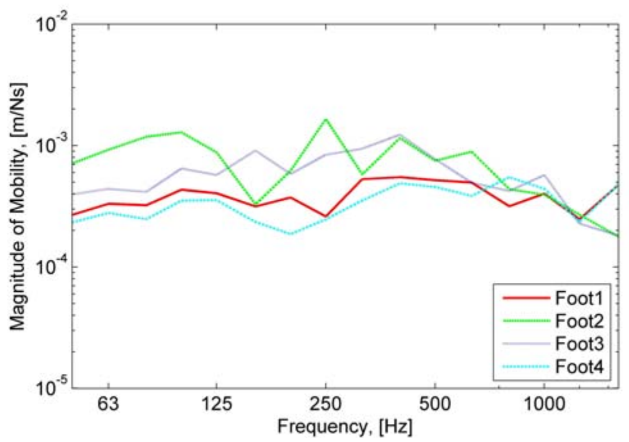


Fig. 2 Magnitude of effective source point mobility at four mounts of a whirlpool bath, assuming random phase difference

# 3 Predicted installed power from single equivalent values

For a prediction of the installed power, an estimate of the receiver mobility, such as of floors and walls, also is required. This can be obtained by direct measurement of point and transfer mobility [11] but again, this is time-consuming. In a companion conference paper, a method is proposed for estimating the point and transfer mobilities of joist floors from consideration of simple characteristic plate and beam mobilities [12]. The complex single equivalent receiver mobility SERM then is assembled and also $Re(\overline{Y}^{\Sigma}{}_{R})$ required for eq. (1).

A question remains about how the magnitude of the equivalent source mobility can be incorporated into eq. (1) for total power, which requires the phase difference between source and receiver mobility (see denominator $\left|\overline{Y}^{\Sigma}{}_{S} + \overline{Y}^{\Sigma}{}_{R}\right|^{2}$ in eq. (1)). The answer is that it cannot, except for the special but common case where there are large differences between source and receiver mobility i.e. when

$$\left|\overline{Y}^{\Sigma}{}_{S}\right| >> \left|\overline{Y}^{\Sigma}{}_{R}\right| \quad \text{or} \quad \left|\overline{Y}^{\Sigma}{}_{S}\right| << \left|\overline{Y}^{\Sigma}{}_{R}\right| \qquad (8)$$

If the source mobility and receiver mobility are of the same magnitude and same gradient, with respect to frequency, then a mirror condition can be assumed where real parts are equal and imaginary parts are equal and again phase is not required [1].

# 4 Case studies

The approximate prediction method, which employed single equivalent source and receiver mobilities, was examined by comparison with exact values of the installed power. Two cases were considered, a fan unit and a whirlpool bath, both mounted on a ribbed plate, a timber-joist floor. The floor was selected since large spatial variations in receiver mobility might be expected, depending on if the source contacts are over a joist, between joists or if there is a mix of contact conditions (see Figure 3). The floor was 21 mm chipboard screwed to seven joists 0.096 m x 0.192 m x 4.55 m, spaced 0.78 m on centre. The overall floor dimensions were 4.55 m x 4.95 m. It was assumed that sources might be fixed directly onto the joists or onto the bays between joists or in a combination of these two conditions. It was recognised that sources may be fixed with locating screws which do not penetrate to the joist below. Indeed, there are situations where sources rest on receiver structures without fixing. The point and transfer mobilities were measured using a calibrated force hammer. The data was used directly and also in the form of the SERM for each contact configuration (Fig. 3).

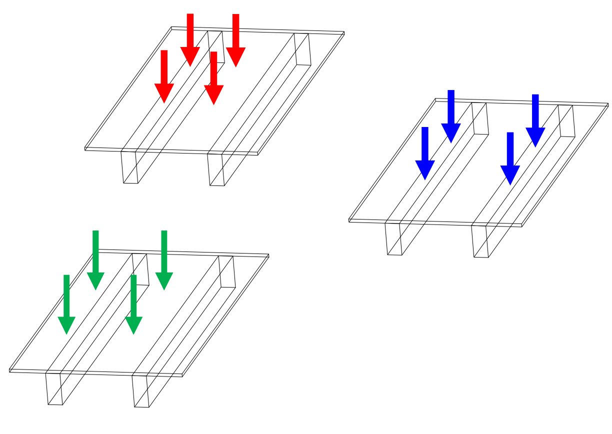

Fig. 3 Contact locations on a ribbed timber floor

## 4. 1 Fan unit

The free velocity of a fan unit was measured at four contact (mount) points while the fan was resiliently suspended and operating. The complex free velocity was input as the required quantity for the exact total power into the floor according to eq. (1). The same data was used to form the sum of the squares of the magnitudes of the free velocities $\sum_{i}^{N}\left|\bar{v}_{sfi}\right|^{2}$ as proposed for the simple approximate estimate.

The point and transfer mobility at the same contacts and for the same resiliently suspended condition, were recorded. The complex effective source mobility at each contact yielded the exact total power. The magnitude of the single equivalent source mobility also was obtained and used for the approximate estimate of the total power.

In Figure 4 is shown the magnitude of the single equivalent source mobility SESM and the magnitudes of the single equivalent receiver mobility SERM at several locations.

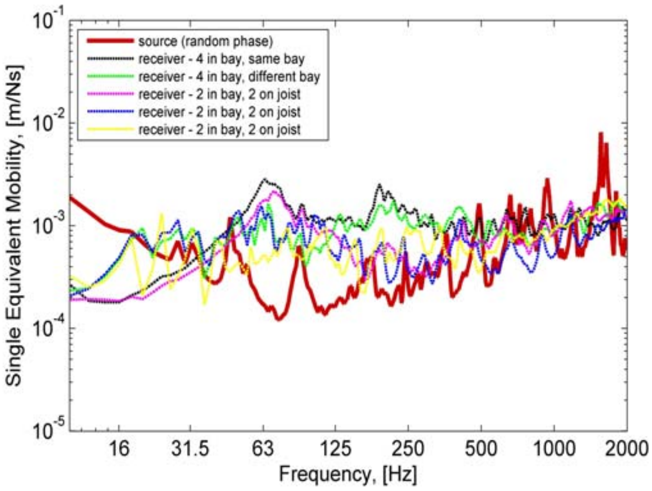


Fig. 4 SESM (red line) for fan unit and SERM for different mounting situations on the timber floor

In general the fan behaves as a low-mobility source from 50 Hz to 200 Hz. At frequencies above 200 Hz a matched source-receiver mobility condition is observed but with significant differences in several narrow frequency bands.

In Fig. 5 is shown the total power, obtained from the full expression, eq. (1), and from the approximate method, assuming random phase difference

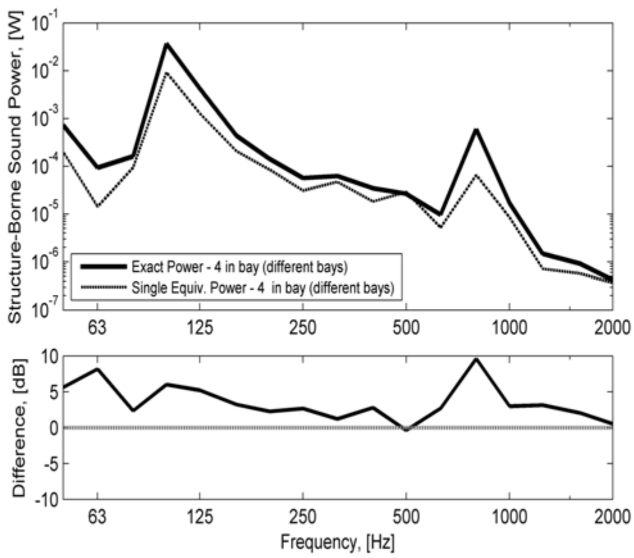


Fig. 5 Exact power and approximate value (random phase) for fan on timber floor: 4 contacts in 2 different bays

In this case, the approximate method gives an under-estimate of 5 dB with an underestimate of 3 dB in the mid frequency range. In Fig. 6 is shown the same case but where the approximate method assumes a zero phase difference. The agreement is within +/- 3 dB above 125 Hz.

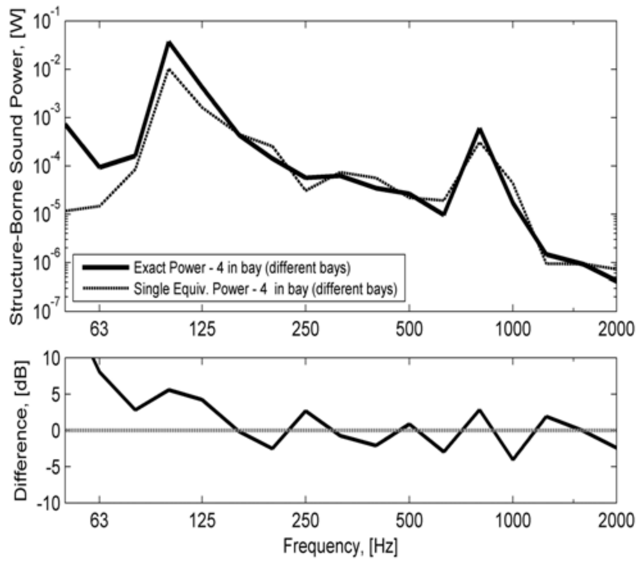


Fig. 6 Exact power and approximate value (zero phase) for fan on timber floor: 4 contacts in 2 different bays

The discrepancy is of the same order for the other mount locations (Fig. 7 and Fig. 8). The agreement still is within 5 dB over most of the frequency range of interest. The agreement is surprisingly good when the fan has two contacts on one joist and two contacts in one bay. This is despite the fact that there is a large spatial variation in receiver point mobility.

In general, the random phase approximation leads to an underestimate and the zero phase approximation leads to a larger fluctuation about 0 dB.

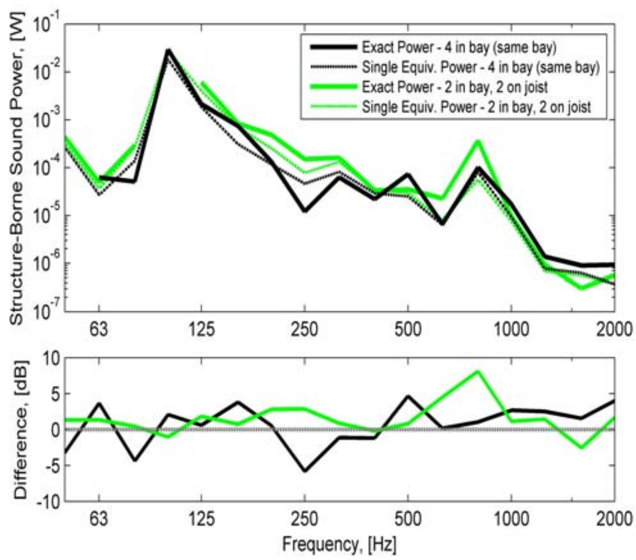


Fig. 7 Exact power and approximate value (random phase): 4 contacts in one bay; 2 in one bay, 2 on rib

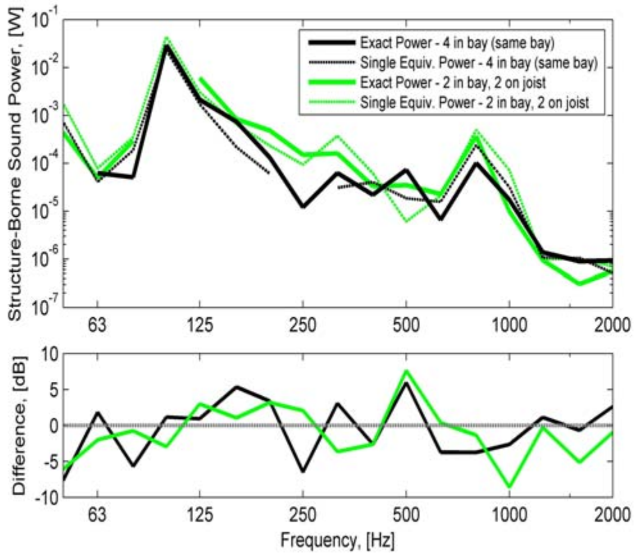


Fig. 8 Exact power and approximate value (zero phase): 4 contacts in one bay; 2 in one bay, 2 on rib

## 4. 2 Whirlpool bath

The measurement procedure for the whirlpool bath was similar to that for the fan unit. In this case, the free velocity was measured at eight mount points while the bath was resiliently suspended and fully operational. Four inner mounts supported most of the weight of the bath, with four outer mounts providing stability. In Fig. 9 is shown the magnitude of the single equivalent source mobility and the magnitudes of the single equivalent receiver mobility at several locations on the timber floor. In general the whirlpool bath behaves as a matched-mobility source from 50 Hz to 400 Hz. At frequencies above 400 Hz, it behaves as a low-mobility source, relative to that of the receiver.

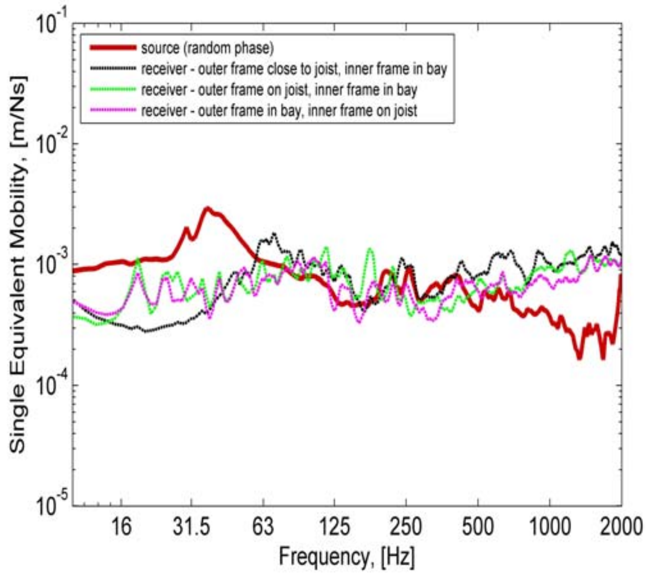


Fig. 9 Single equivalent source mobility of whirlpool bath (red line); also shown is the single equivalent receiver mobility at different locations on the timber floor

In Fig. 10 is shown the total power through the 8 mount points of the whirlpool bath into the floor, obtained from eq. (1), and from single equivalent values (random phase assumption). When the source is mounted with the inner (load-bearing) contacts over the joists and the outer contacts in bays, the agreement between the exact installed power and the approximate value is within +/- 3 dB in the frequency range 100Hz - 2 kHz. This is because most of the installed power is through the load-bearing inner contacts. The spatial variation in point mobility over the inner contacts is small, for both source and receiver, and the single equivalent receiver mobility is appropriate. This also is seen for the zero phase assumption (Fig. 11) where the agreement is within +/- 3 dB over the whole frequency range of interest.

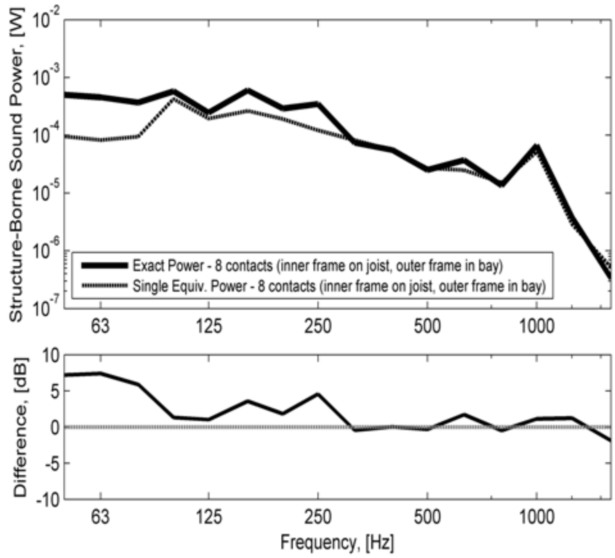


Fig. 10 Exact power and approximate value (random phase) for whirlpool bath on timber floor; 4 inner contacts on rib, 4 outer in bay

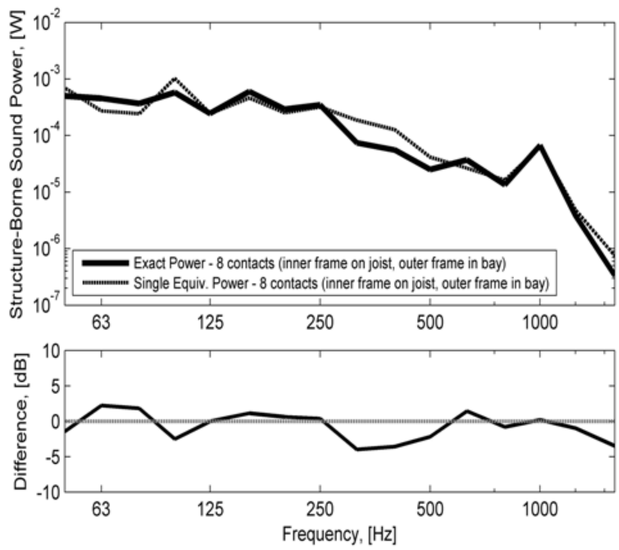


Fig. 11 Exact power and approximate value (zero phase) for whirlpool bath on timber floor; 4 inner contacts on rib, 4 outer in bay

Results are presented for other contact locations in Fig. 12 and Fig. 13. For both phase assumptions, the approximate method over-estimates the installed power by 5-10 dB at low frequencies. Above 125 Hz, the agreement is within +/- 5 dB.

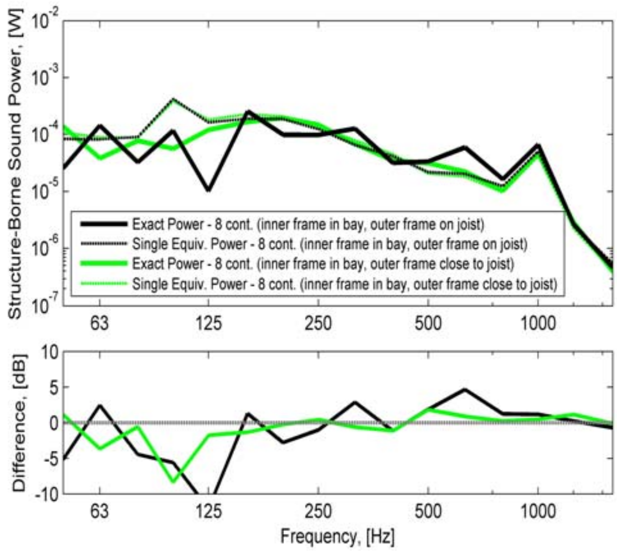


Fig. 12 Exact power and approximate value (random phase) for whirlpool bath on timber floor; 4 inner contacts in bay, 4 outer on rib; 4 inner in bay, 4 outer close to ribs

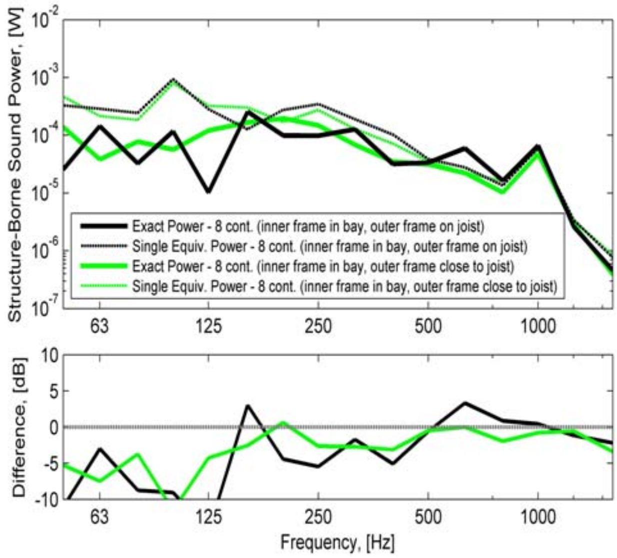


Fig. 13Exact power and approximate value (zero phase) for whirlpool bath on timber floor: Upper; 4 inner contacts in bay, 4 outer on rib; 4 inner in bay, 4 outer close to ribs

## 5 Conclusions

A simple method is proposed for predicting the total structure-borne sound transmission from machines installed on plate-like structures. The special case of a ribbed plate is considered, in the form of a timber-joist floor. The method employs single equivalent values of source strength and source mobility, combined with the single equivalent receiver mobility. Case studies are given for multiple contact sources on a timber-joist floor where the simple method gives agreement with exact values of installed power within +/- 5 dB, often within +/- 3 dB at mid and high frequencies. The accuracy of the simple approximate prediction method depends on the spatial variation in contact conditions. The floor selected offered the largest likely variation on receiver point mobility.

## Acknowledgements

The authors gratefully acknowledge the financial support of EPSRC, UK and the collaborative work on this study with Professor Heinz-Martin Fischer of Stuttgart University of Applied Sciences, and Dr. Andrew Moorhouse of Salford University Acoustics Research Centre.

## References

[1] B. M. Gibbs, N. Qi, A. T. Moorhouse, "A practical characterization for vibro-acoustic sources in buildings" Acta Acustica united with Acustica, 93, 84-93 (2007)

[2] L. Cremer., M. Heckl, B. A. T. Petersson, "Structure-borne Sound", Springer (2005)

[3] B. A. T. Petersson, B. M Gibbs, "Towards a structure-borne sound source characterization", Applied Acoustics 61, 325-343 (2000)

[4] A. T. Moorhouse, "On the characteristic power of structure-borne sound sources", J. Sound and Vib. 248(3), 441-459 (2001)

[5] T. ten Wolde, T. G. R. Gadefelt, "Development of standard methods for structure-borne sound emission", Noise Control Engineering Journal 28, 5-14 (1987

[6] J. M. Mondot, B. A. T. Petersson, "Characterisation of structure-borne sound sources: The source descriptor and coupling function", J. Sound Vib. 114 (3), 507-518 (1987)

[7] A. T. Petersson, J. Plunt, "On effective mobilities in the prediction of structure-borne sound transmission between a source and a receiving structure, Part 1: Theoretical background and Basic Experimental Studies", J. Sound Vib. 82 (4), 517-529 (1982)

[8] ISO 9611: 1996 "Characterization of sources of structure-borne sound with respect to sound radiation from connected structures - Measurement of velocity at the contact points of machinery when resiliently mounted"

[9] R. Cookson, N. Qi, "A reception plate method of measurement of the free velocity of machines in buildings", 13th International Congress on Sound and Vibration, Vienna (2006)

[10] N. Qi, R. Cookson, "A reception plate method of measurement of the source mobility of machines in buildings", 13th International Congress on Sound and Vibration, Vienna (2006)

[11] A. R. Mayr, B. M. Gibbs, "On the use of an equivalent receiver mobility in lightweight buildings", Proc. International Congress on Acoustics, Madrid (2007)

[12] A. R. Mayr, B. M. Gibbs, "Approximation of single equivalent mobilities of timber joist floors", Proc. Acoustics 08, Paris (2008)