Structure-Borne Power from machines in buildings: Prediction of Installed Power from Laboratory Measurements

N Qi, B M Gibbs
Acoustics Research Unit, School of Architecture, The University of Liverpool, Liverpool, L69 3BX, UK, {n.qi, bmg}@liv.ac.uk

Much of the noise generated by vibrating components of mechanical services in buildings transmits as structure-borne sound before radiating into other rooms. Although predictive models are being developed for the sound pressure resulting from vibrating machines, there is not yet available a laboratory test method which provides input data for such models. A reception plate method is investigated, which reduces the large number of structure-borne transmission paths (through each contact and for each component of excitation) into a single value of the bending energy of the excited attached plate. The challenge is then to relate the laboratory reception plate power to that generated in the installed condition.

In the work reported, a reception plate has been modelled as a FFFF thin plate which yields the mobilities at any position for the three out-of-plane components of excitation (perpendicular force and two moments). Similarly, a building floor has been modelled as a SSSS plate which also allows estimates of the mobilities in the installed condition. The investigation draws on available free velocity and mobility data sets for a range of sources, including fans, electric motors and domestic appliances. When used in combination with the plate mobility data, this gives the structure-borne power from each source, either through single contacts or through multiple contacts. The work aims to establish a relationship between the reception plate estimates of total power and the predicted installed power. The sensitivity of the estimates, with respect to location of the source, also is considered.

1 Introduction

An international standard, EN 12354 part 5, is being developed for predicting the sound pressure level generated in buildings by active building components found in mechanical services and domestic appliances. Procedures are in place for treating the machines as airborne sound sources. However, there remains a need for procedures for structure-borne sound sources. It is proposed that the input data should be the structure-borne power into the supporting floor and the walls in contact with the source [1].

In order to measure the structure-borne power, a reception plate method is proposed. The machine under test is mounted onto a resiliently supported concrete plate and the total structure-borne power is measured indirectly. At present, the approach is confined to machines with mobilities significantly greater than that of the building elements (the force source assumption) and therefore applies to heavyweight homogeneous floors and walls rather than lightweight building structures. In the test laboratory, the total power, from the machine to the plate, is obtained from the averaged response velocity of the plate. However, the reception plate approach requires that the plate behaves as a thin plate with a high bending field modal density [2]. This is not likely to be the case for the reception plate required for machines and appliances in buildings, which will be of low mobility. A concrete plate will have its vibration modes well spaced in frequency and they will dominate the frequency response at low frequencies.

The aim of the present work therefore was to confirm or otherwise that a reception plate method can be employed where the plate is of low modal density. Further, that the modal characteristics of the plate and of a real floor, on which the machine is installed, can be included as a transformation from the laboratory condition to the installed condition.

The total structure-borne sound power $P$, from the machine under test to a reception plate, is obtained from the spatial- and time averaged velocity $v$ of the reception plate, of mass, $m$, and loss factor, $\eta$, according to [2]

$$P = \frac{\bar{v}}{v}^2 \eta \omega m$$  \hspace{1cm} (1)

Again, Equation (1) results from an assumed thin-plate behaviour where the bending field, generated by the attached source, is diffuse. This conflicts with the requirement that the reception plate needs to be sufficiently thick to ensure low receiver mobility. In addition, the edge conditions of the reception plate and do not correspond to the edge conditions of floors and walls in buildings. This difference will influence the effect of source location and the relative importance of translational and rotational components of excitation.

In a companion study by Späh et al [1, 4], the experimental practicalities of a reception plate method have been confirmed and a test procedure outlined. In
this parallel study, the laboratory test condition and the installed condition are numerically modelled and the differences in the dynamic contact conditions systematically considered. This has resulted in a simple transformation algorithm which agrees in all essential features with that in Späh’s proposal.

## 2 Numerical models

The plate and floor were modeled as homogeneous thin plates, with governing equations according to the compendium of Gardonio and Brennan [3]. This allowed consideration of excitation by forces perpendicular to the plane of the plate and through moments about axes in the plane of the plate (see Figure 1 for dimensions, coordinate system and source-receiver contact positions). The reception plate was assumed to have free edges, and $L_x = 2.80(m)$, $L_y = 2.00(m)$. The floor was assumed to have simply supported edges and $L_x = 3.50(m)$, $L_y = 2.22(m)$. The assigned damping loss factors were obtained from laboratory measurements of the reception plate and from empirical values from field surveys in Germany, for the floor [4].

![Figure 1: Dimensions, coordinate system and contact positions for reception plate and floor.](image)

In Figure 2(a) is shown the calculated point force mobility at a central location on the floor and also towards one edge. In Figure 2(b) are shown the moment mobilities, about the x-axis, at the same locations. It then is relatively straightforward to calculate point and transfer mobilities for the selected excitation points and plate response points, respectively. Figure 2(a) indicates that force components are more important away from floor edges than at the edges. Figure 2(b) indicates that moments become progressively more important with increase in frequency. However, in order to assess the relative importance of forces and moments, and thus the effect of source location, all components must be considered on a power basis.

![Figure 2: Point mobilities at a central and edge position on the floor: (a) force mobility; (b) moment mobility about the x-axis.](image)

### 2.1 Structure-borne source

In order to consider the powers received by the two considered plates, use was made of an existing data base of source free velocities and mobilities [5]. The power through one mount of a medium size fan base unit was calculated for the perpendicular force and two moment components of excitation. In Figure 3 are shown the force induced power into the reception plate and also for the moment about the axis parallel to the edge at a central position (a) and also near the edge (b). The power due to the perpendicular force predominates and the moment components could be neglected.
In Figure 4 is shown the force and moment induced powers at a central location and also at an edge of the floor. Again, for both source positions, the perpendicular force predominates and moments can be neglected.

2.2 Simulation of reception plate measurement

On installing the test source, on the reception plate, the average velocity is obtained while the source is operating in otherwise normal conditions. The total power, which is assumed to contribute to the bending field on the plate only, is obtained from Equation (1). Values, obtained from Equation (1) were compared with exact values obtained from the mobility expression,

\[ P = \frac{1}{2} \frac{|\nabla_{sf}|^2}{|\nabla_S + \nabla_R|} \nabla_S \]  

(2)

\( \nabla_S \) is the mobility of the source, \( \nabla_R \) is the mobility of the receiver and \( \nabla_{sf} \) is the free velocity of the source. In Figure 5 is shown the reception plate power for the single contact source at a central location, from Equation (1), from an average of 5 velocities and also from an average of 10 velocities. Also shown is the exact power obtained from Equation (2). Results indicate that a small sample of 5 accelerometer positions will give a satisfactory approximation to the power.
3 Powers into reception plate and floor

The power into the floor when the source was located at a central position was calculated according to Equation (2). In Figure 6 is shown the ratio of the power, obtained by the reception plate method, with the exact power, for the same source installed on the floor. Results are shown with a one third octave frequency resolution.

As expected, the power into the thinner (100mm) reception plate is greater than that into the 180mm concrete floor. Above 200 Hz, the ratio is independent of frequency and can be predicted from consideration of the ratio of the characteristic mobilities of the two plates according to [2].

The fluctuations below 200 Hz are the result of the modal behaviour of both reception plate and floor. This can be compensated for, in the case of the reception plate, by substituting the characteristic mobility with the spatial average mobility, which is a measurable quantity. It is not likely that detailed information will be available on the floor of the building in which the structure-borne source is to be installed. The method applies to homogeneous heavyweight floors and walls and the following information only is likely to be available: material (likely to be concrete for floors), thickness, floor/wall dimensions. This allows an estimate of the characteristic mobility. However, it also is possible to characterise the low-frequency fluctuation about the characteristic mobility by establishing limits to the mobility, according to [6]. The upper limit of mobility of a plate is given by:

$$Y_{\text{lim}} = \frac{4}{M \cos \eta}$$  \hspace{1cm} (3)

The loss factor $\eta$ can be obtained from empirical expressions formed from field surveys. It is further assumed that minima in mobility have a lower limit which is symmetric with the upper limit.
In Figure 7 is shown the ratio of the powers, and the ratio of spatial average point mobility of the reception plate to the characteristic mobility of the floor. The fluctuations in the power ratio are mirrored by variations in the mobility ratio but with a greater overall discrepancy than for the ratio of the characteristic mobilities.

4 Conclusions

A reception plate system can be designed which resolves the conflicting requirements that the test installation satisfies the mobility conditions for a force source idealisation, while allowing a thin-plate assumption. The total structure-borne power, through multiple contacts and through more than one component of excitation, is obtained as a single value function of frequency, the reception plate power. The reception plate power can be converted to the installed power from knowledge of the ratios of the real parts of the reception plate and floor/wall mobilities. The mobility ratio can be simply expressed in terms of the characteristic mobilities and gives promising agreement at mid and high frequencies. A correction for the low frequency modal characteristics of the reception plate and installation floor/wall can be included in the form of the measured spatial average mobility of the reception plate and as an upper and lower limit to predicted mobility for the installation floor/wall.

Acknowledgements

The financial support of the Engineering and Physical Sciences Research Council of the UK is gratefully acknowledged.

References


