Single rig two-stage method for characterizing structure-borne sound sources in buildings

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ABSTRACT

Two source quantities are required to predict the structure-borne power into lightweight buildings and other structures: source mobility and free velocity or blocked force. The average source quantities can be measured using the reception plate method (RPM). A thin reception plate gives an estimate of the sum-square free velocity. A thick reception plate gives an estimate of the sum-square blocked force. The ratio of these quantities approximates the square of the average source point mobilities. In this proposal, only one reception plate is required. The transfer mobilities from several remote points to a single measurement centre are recorded. The source is attached about the measurement centre and the transfer mobilities re-recorded. The ratio of the transfer mobilities gives an estimate of the source mobility. The source then is operated and the velocities at the remote points recorded. For each remote point, the recorded velocity and previously estimated source mobility give an estimate of the source free velocity. In this method the installation conditions are unchanged; knowledge of source-receiver mobility ratio is not required; the reception plate can be relatively thin/light; the method automatically collapses the source quantities to single equivalent values.

Keywords: Building noise control; structure-borne sound sources: 51; 43

1. INTRODUCTION

Structure-borne sound in buildings is generated by vibrating or impacting sources, which inject vibrations into supporting and connecting building elements. To predict the structure-borne sound power into the supporting structure(s), two source quantities (vibration activity and structural dynamics at the contacts) are required for all likely installation conditions, including in lightweight buildings (1,2). For activity, the source quantity is either free velocity or blocked force; for structural dynamics, the source quantity is the mobility, or its inverse impedance, at the contacts. The source quantities are obtained by laboratory measurement to provide input data for building propagation models (3,4).

The source quantities can be measured directly or indirectly using reception plate methods (5). Direct measurements can be time-consuming and costly. Reception plate methods are generally simpler but less accurate. To obtain the two source quantities, a two-stage measurement method is required. One method is by measuring the source free velocity directly and then attaching the operating source to a low-mobility reception plate to obtain the blocked force as a sum-square value (6). Alternatively, the free velocity is obtained as a sum-square value by attaching the operating source to a thin high-mobility plate (1,2). There are practical problems in such two-stage methods, which require the source to be set up on two test rigs. It is not always possible to ensure repeatable operating conditions.

In this proposal, only one reception plate is required. The transfer mobilities from several remote points on the plate to a single 'measurement centre' are recorded. The source then is attached about the measurement centre and the transfer mobilities re-recorded. The ratio of the transfer mobilities corresponds to the ratio of the velocities at the centre, which gives an estimate of the source mobility. The source then is switched on and the velocities at the same remote points recorded. For each remote point, the recorded velocity and previously estimated source mobility gives an estimate of the source free velocity. Repeating the process for several remote points allows averaging and estimates of standard deviation. This method offers the following advantages: the installation and operating conditions are unchanged; knowledge of source-receiver mobility ratio is not required; the reception plate can be relatively thin/light and easily installed in laboratories; the method automatically collapses the source quantities to single equivalent values.

2. THEORY OF METHOD

2.1 Set-up

The source mobility is measured indirectly by recording the transfer mobility of a single reception plate before and after attaching the source under test. Figure 1 is of a rectangular reception plate of arbitrary dimensions and thickness, with a designated measurement centre c.

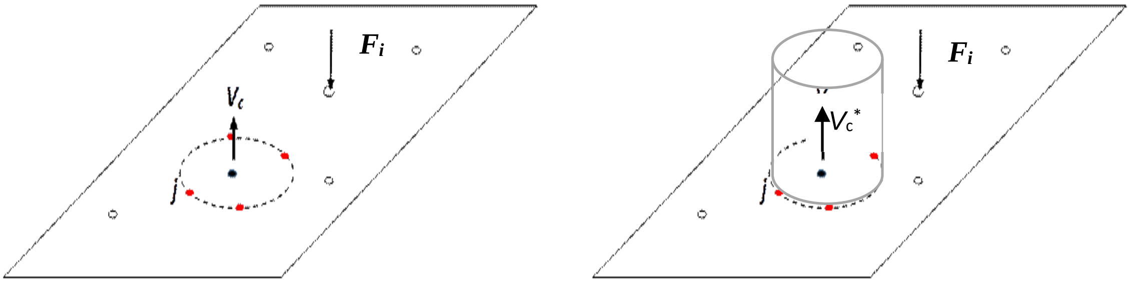

Figure 1 - Transfer mobility from a remote point on reception plate to measurement centre without (left) and with (right) the source attached.

The transfer mobilities to the measurement centre $Y_i^c = \frac{v_c}{F_i}$, without the source attached, are recorded from several (ten in this study) remote points i. The measurement centre is not at the plate centre but located such that the remote locations surround it.

2.2 First Stage

The source under test is placed at the measurement centre and attached at contact points j and the transfer mobility from the remote points to the measurement centre $Y_i^{c*} = \frac{v_c^*}{F_i}$ are re-recorded. The new velocity at the centre is due to the forces F_j at the contacts

$$v_{ci}^* = F_i\ Y_i^c - F_j\ Y_j^c \tag{1}$$

The forces F_j result from the plate velocities at the contact points and the source and plate mobilities combined at the same points

$$F_j = \frac{F_i\ Y_i^j}{\left(Y_S^j + Y_j^j\right)} \tag{2}$$

Y_s^j is the source mobility at contact j and Y_j^j is the plate mobility at contact j. For multiple contacts, these are matrices. From equations (1) and (2) the coupled transfer mobility is

$$Y_i^{c*} = Y_i^c - \frac{Y_j^c Y_j^j}{\left(Y_S^j + Y_j^j\right)} \tag{3}$$

The ratio R of the coupled and uncoupled transfer mobilities corresponds to the ratio of coupled and uncoupled velocities at the centre, which is the measured quantity of interest

$$R = \frac{v_c^*}{v_c} = 1 - \frac{Y_j^c Y_j^j}{Y_j^c\left(Y_S^j + Y_j^j\right)} \tag{4}$$

If it is assumed that the velocity at the measurement centre is due to a single equivalent source with mobility Y_{seq} at the centre, the ratio now is

$$R^* = 1 - \frac{Y_C^C}{\left(Y_{Seq} + Y_C^C\right)} \tag{5}$$

Assuming $R^* = R$, then the equivalent single source mobility is

$$Y_{Seq} = Y_C^C \frac{R}{(1-R)} \tag{6}$$

2.3 Second Stage

The source under test is switched on and the velocities at the remote points i are recorded

$$v_i = F_j \ Y_i^j$$

F_j are the forces at the contact positions j where

$$F_j = \frac{v_{fi}}{\left(Y_S^j + Y_j^j\right)} \tag{7}$$

v_{fj} is the source free velocity at contact j.

Assume that the remote velocity is due to a single equivalent source with single equivalent free velocity v_{feq}, again at the measurement centre. The remote velocity at the i^{th} point

$$v_i^* = \frac{v_{feq} Y_i^C}{\left(Y_{Seq} + Y_C^C\right)} \tag{8}$$

From (8)

$$v_{feq} = \frac{v_i^* \left(Y_{Seq} + Y_C^C\right)}{Y_i^C} \tag{9}$$

The process is repeated for each remote point and average values calculated from all points.

3. NUMERICAL MODEL

3.1 Plate Model

Prior to the experimental investigation, the transfer mobilities were modelled by modal summation of a free (FFFF) plate, which corresponds to a resiliently supported reception plate in a laboratory. The plate eigenmodes are expressed as products of orthogonal beam eigenmodes (7). The plates modelled were of aluminium and the thicknesses were varied between 5-20mm. Dimensions were varied between 2.8m x 2.0 m and 4m x 3m. The total plate loss factor was assigned a frequency independent value 0.03. The process, represented by equations (1) to (9), was completed for to give an estimate of source mobility and free velocity squared for each remote point. Figures 2-4 show some of the calculated plate point and transfer mobilities.

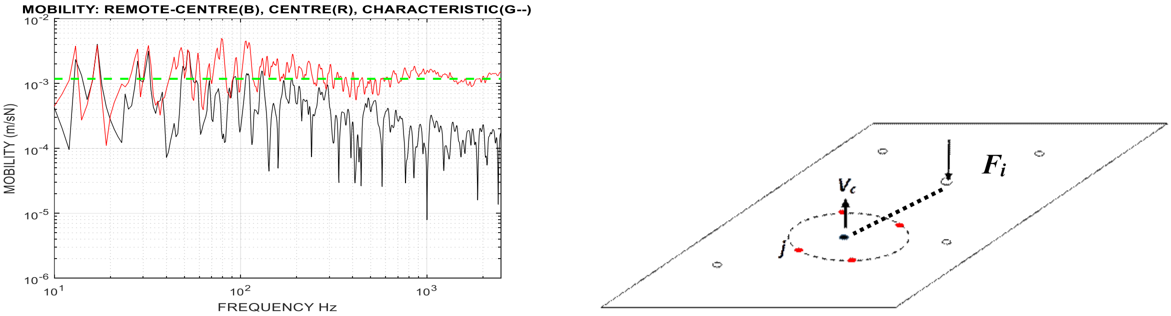

Figure 2 - Point mobility at measurement centre (red) and transfer mobility from a remote location to centre (black).

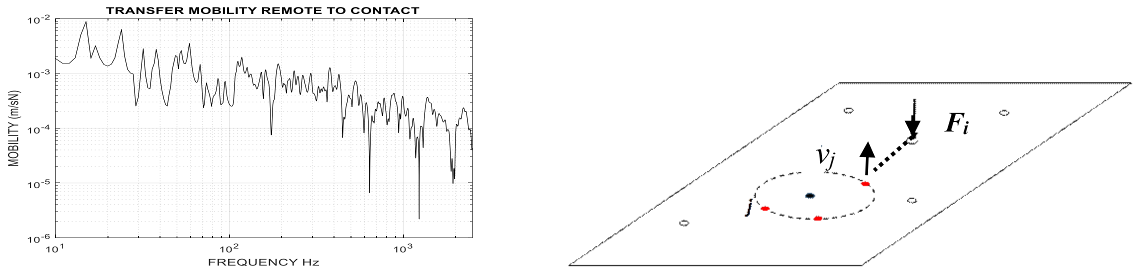

Figure 3 -Transfer mobility from remote location to a contact point.

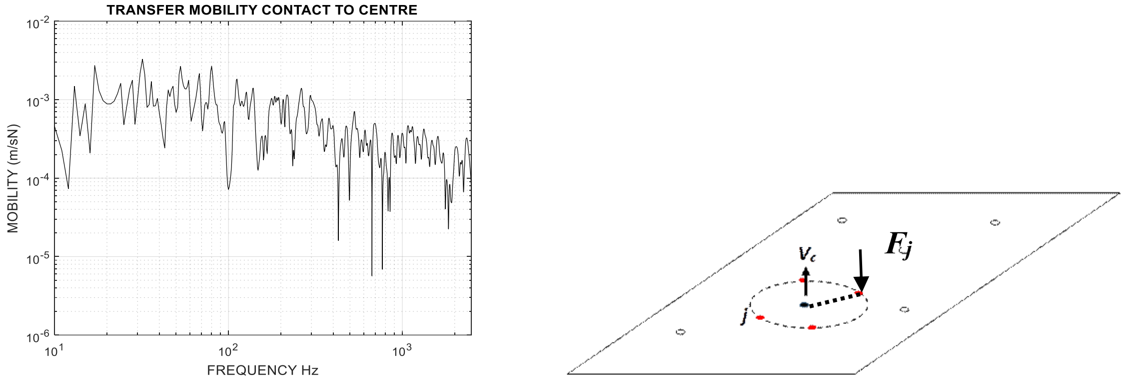

Figure 4 - Transfer mobility from a contact point to measurement centre.

3.2 Tested sources

The average point mobility and sum square free velocity were measured for a compact air pump (Figure 5) and for a small fan unit (Figure 6). Also shown are the transfer mobilities between mount points, which are lower than the point mobilities. The average point mobilities were taken as the target quantities to be evaluated by the proposed method.

The free velocities of both sources were tonal with significant low-frequency components, and the frequency range of interest was 20-2000 Hz.

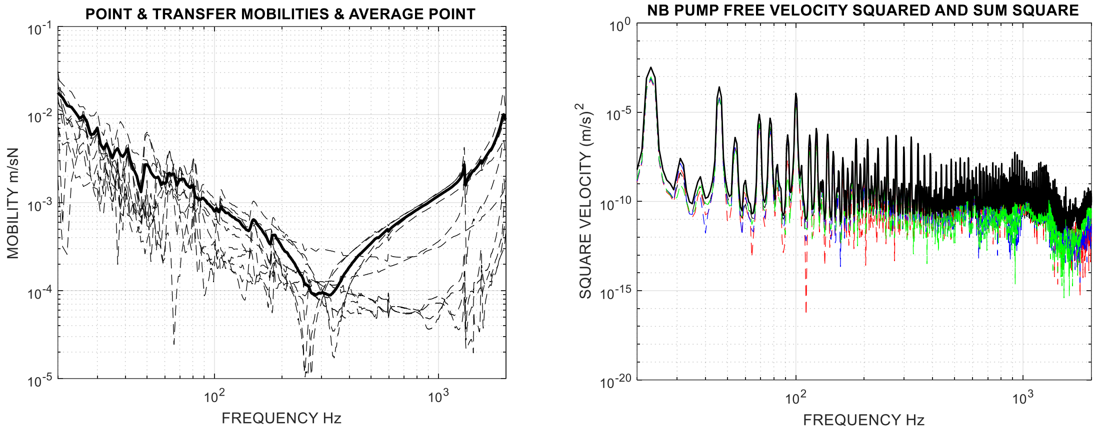

Figure 5 – Left, pump point and transfer mobilities and average point mobility over four mounts (black line); right, free velocities squared over four mount points and sum-square (black line).

The pump measured source data was for four mount points. The point mobility varies little with mount location and displays a mass-law behaviour below 400 Hz and a stiffness-controlled behaviour above 400 Hz. The free velocity spectrum is tonal with a fundamental frequency of 25 Hz and first harmonic at 50 Hz.

The fan measured source data was for four mount points. Figure 6, left, shows the point and transfer mobilities between mount points. Figure 6, right, shows the free velocity squared at each contact and the sum-square value. The fan point mobility varies significantly with mount location and displays resonance behaviour. The free velocity spectrum also is tonal with a fundamental frequency of 50 Hz and first harmonic at 100 Hz.

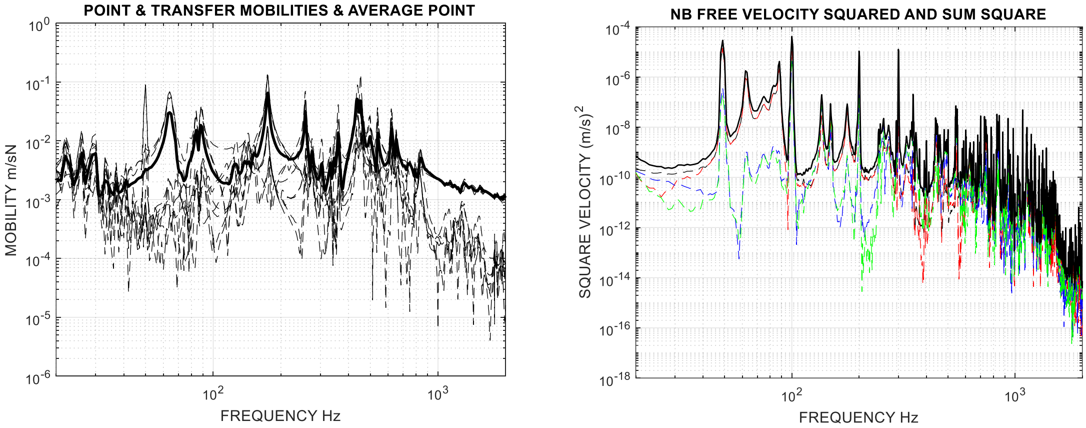

Figure 6 - Point and transfer mobilities of fan and average point mobility over four mounts (black line, left) and free velocities squared over four mount points with sum-square (black line, right).

3.3 Results

Figure 7 shows estimates of pump mobility and sum square free velocity from a simulation of the steps described by equation (1) to equation (6), as modelled for a 10mm aluminium plate. The average estimates and standard deviations are in one-third octaves and assume a log-normal distribution. The estimate of mobility tracks the measured value within 5 dB, but with greater discrepancies above 1600 Hz. The estimate of free velocity squared, from equation (9), is within 10 dB of the measured value at the peaks at 25 Hz and 50 Hz, and at 125 Hz and above. The estimate at the 100 Hz peak is 15 dB less than the measured value.

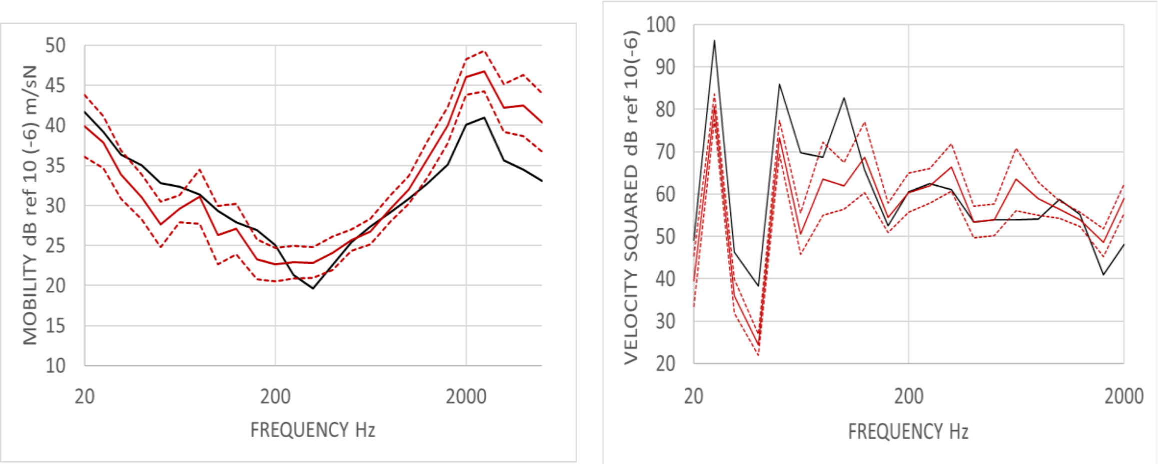

Figure 7 - Pump mobility (left) and free velocity squared (right) from modelled 10mm plate: average from ten remote points (red); standard deviation (dashed); measured (black).

In Figure 8, the estimate of fan mobility is within 5 dB of the measured value, irrespective of the thickness of reception plate. In Figure 9, the estimate of free velocity squared is within 10 dB of the true value for the 5mm reception plate, with greater discrepancies for the 20mm reception plate.

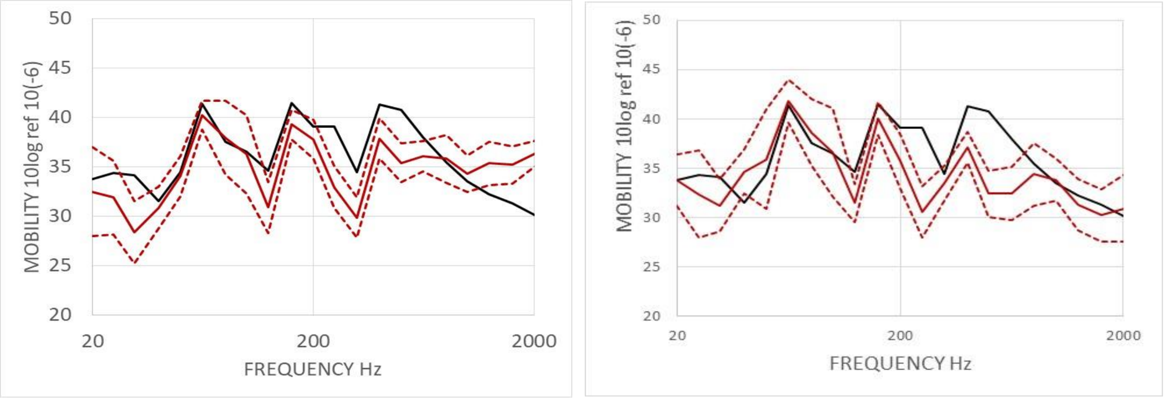

Figure 8 - Fan mobility from modelled 20mm plate (left) and from 5mm plate (right): average of ten remote points (red); standard deviation (dashed); measured average point mobility (black).

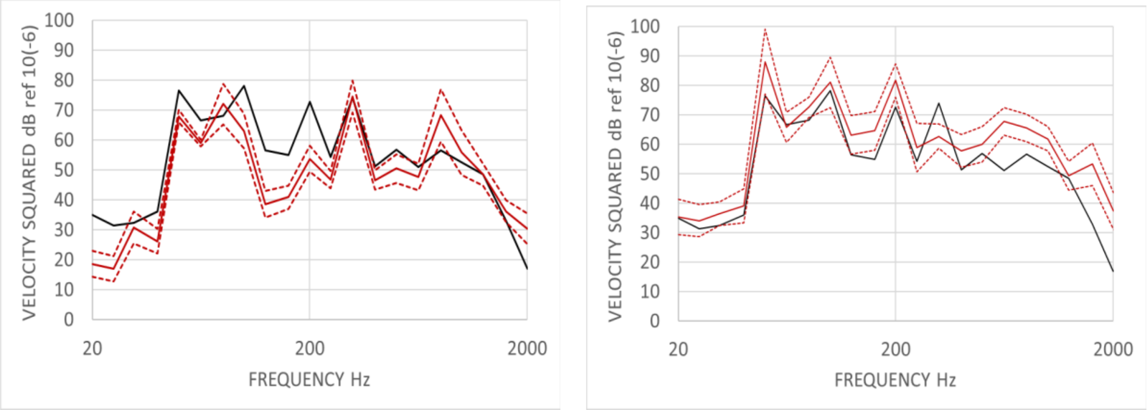

Figure 9 - Fan free velocity squared from modelled 20mm plate, left, and 5mm plate, right: average (red); standard deviation (dashed); from measured at four mounts (black).

4. EXPERIMENT

4.1 Set-up

Figure 10, left, is a photo of the 5mm aluminium plate (1.96m x 1.22m) supported on resilient pads, with the pump attached. Ten accelerometers are distributed around the measurement centre. An instrumented impact hammer registered the applied forces for mobility measurements. Figure 10, right, shows typical ratios of transfer mobilities, for the fan in place and without the fan.

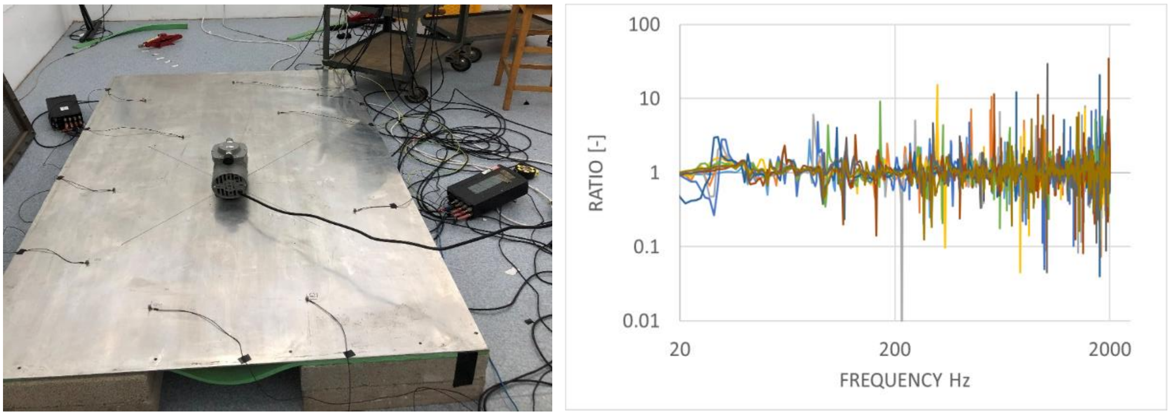

Figure 10 - Left: test arrangement with pump attached; right: ratio of transfer mobilities between plate with source and plate without source.

4.2 Results

Figures 11 and 12 show mobility and free velocity squared for the pump and fan, respectively.

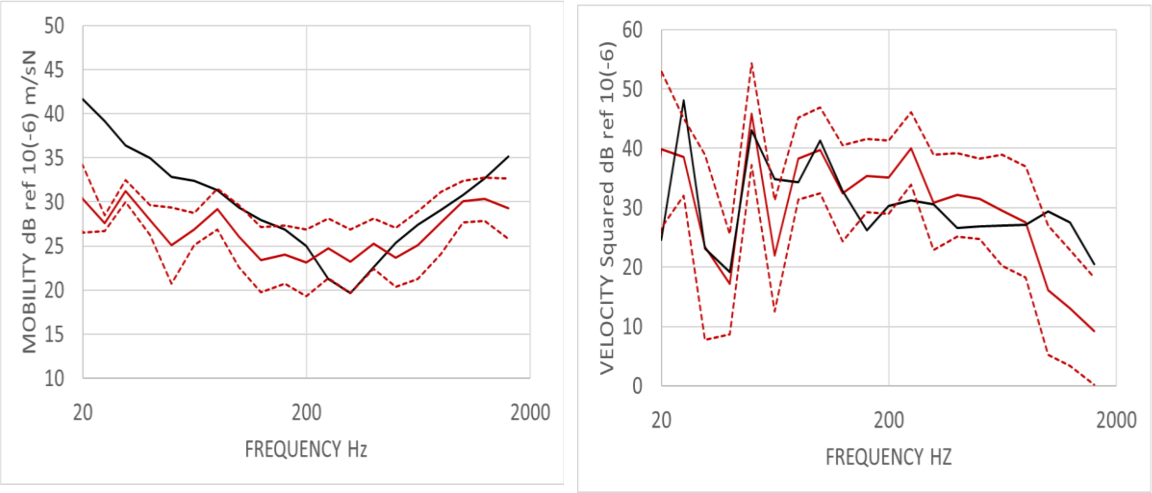

Figure 11 - Pump mobility (left) and sum square free velocity (right) from measured 5mm plate: average (red), standard deviation (dashed), measured (black).

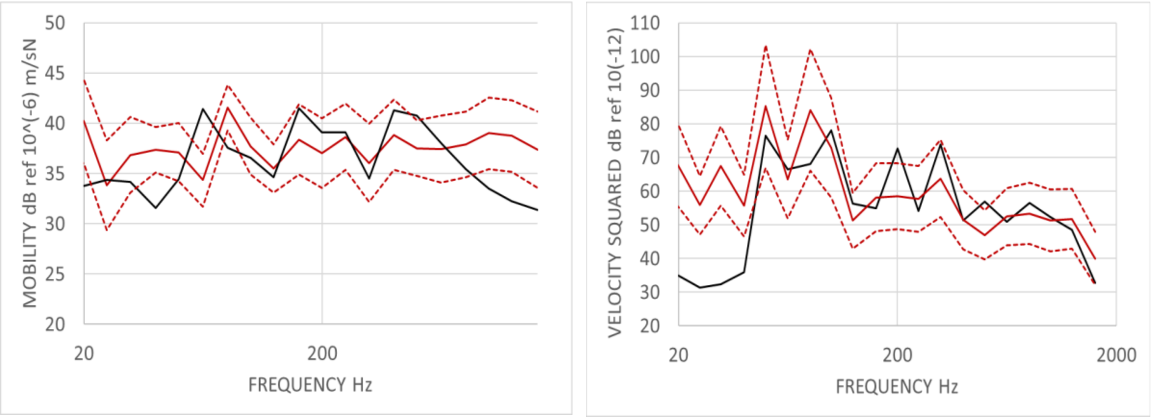

Figure 12 – Fan mobility (left) and sum square free velocity (right) from measured 5 mm plate: average (red), standard deviation (dashed), measured (black).

The estimated pump mobility is within one standard deviation (approximately 5dB) of the measured value at frequencies above 63 Hz. The estimated sum square free velocity is within one standard deviation (10 dB) of the measured value except at frequencies above 1000 Hz.

The estimated fan mobility is within one standard deviation (5 dB) of the measured value at frequencies between 50 Hz and 630 Hz. The estimated sum square free velocity is within one standard deviation (10 dB) of the measured value except at frequencies below 50 Hz.

5. CONCLUDING REMARKS

The numerical models and the experimental measurements ‘capture’ the frequency trends of source mobility and free velocity squared of both sources.

The numerical model results show that the estimates of source mobility and sum square free velocity are not dependent on the reception plate dimensions and thickness, i.e. between that of a 5mm free plate and a 20mm free plate. This has practical implications since it gives the designers of laboratory test rigs a certain freedom of choice in the selection of plate dimensions and material.

The modelled and measured estimates of pump mobility are more promising than that of the fan. This is because the variation between mount points is smaller for the former than the latter.

For both the fan and pump, the target measured mobility generally lies within one standard deviation of the average estimate.

Likewise, the target measured sum-squared free velocity of the fan is within one standard deviation, but with greater discrepancies away from tonal maxima.

Since the free velocity squared estimates depend on previous estimates of source mobility, then the standard deviations of the former are greater than those of the latter.

It is interesting to note that although the estimates are magnitudes, the source quantities initially were obtained as complex quantities. The corresponding measurement of transfer mobility to, or velocity ratio at, the centre location is complex, and it remains to explore what happens if real-value measurements only are performed.

The experimental investigation did not encounter signal-noise problems, either for the mobility measurements in stage 1 or for the remote velocity measurements in stage 2.

6. AKNOWLEDGEMENTS

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