Reception plate method for tonal vibro-acoustic sources in buildings

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Summary
This paper considers the application of the reception plate method to low-frequency tonal vibro-acoustic sources in buildings. The source quantities, required for prediction of the transmitted structure-borne power into a supporting/connected structure, are: source activity (either the free velocity or the blocked force) and source mobility. The reception plate method was developed to yield the source data as frequency band averaged values. However, building services equipment (fans, motors, pumps, etc.) have strong low-frequency tonal components, which can strongly influence the human perception of the resultant noise. To obtain the required narrow-band data, the reception plate method is applied to two tonal sources: an air pump and a small centrifugal fan. The uncertainties in the method are considered by measurement of the free velocities and mobilities of the sources, and of the mobilities of several receiver plates, and then by numerical simulations of the transmitted power when the sources and receivers are combined.

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1. Introduction

To obtain the structure-borne transmitted power from vibrating machines into supporting/connected building elements, three quantities are required in some form: source activity (either the free velocity or the blocked force); source mobility; receiver mobility [1]. The quantities can be measured directly, which is often time consuming, or indirectly using the reception plate method (RPM). The RPM quantities are expressed as equivalent single values and as frequency band averages [2]. However, structure-borne sound sources usually are low frequency in character, with strong tonal components, which may adversely affect the perception of the resultant noise by occupants of the building. This paper considers the application of the reception plate method, to obtain the required source quantities in narrow frequency band form. The two sources measured were a compact air pump and a small centrifugal fan on a plate base. Three receiving plates were measured independently and then the sources were fictively connected to the receivers, using the mobility method, to provide the transmitted power. RPM estimates of the same source quantities and transmitted powers then were compared with results using the mobility method.

2. Measurement of source quantities

2.1. Free velocity

The source free velocities were measured while resiliently suspended during otherwise normal operation. Accelerometers at the mounts recorded the complex accelerations in the frequency range 0-6400 Hz with 1 Hz resolution, to assemble the free velocity vector v_f. Figure 1 shows the free velocity squared at the pump mounts and the sum-square.

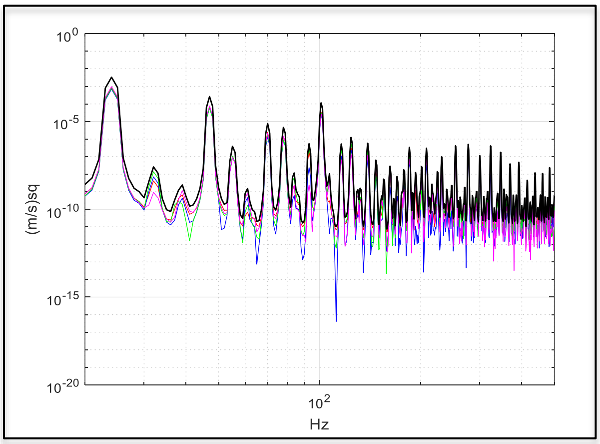

Figure 1. Pump mount free velocity squared and sum-square (black line).

The frequency range 20-500Hz shows tonal maxima at 25Hz, 50Hz and 100Hz, etc. The geometries of the four mounts are similar and there is little difference in the velocities. Figure 2 shows the square of the free velocity of the fan base at four mounts and the sum-square.

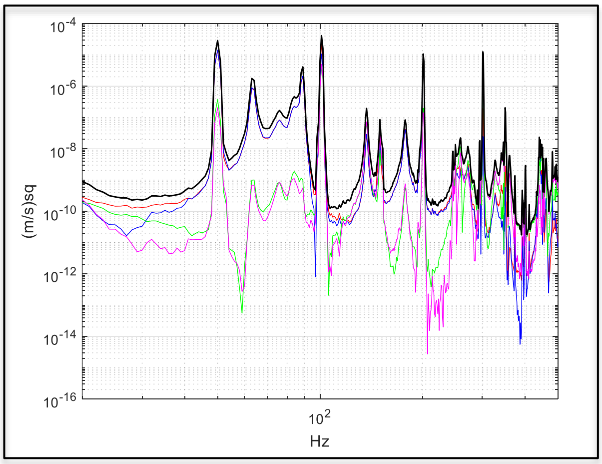

Figure 2. Fan mounts free velocity squared and sum-square (black line)

The fan base has two mounts at a flexible end and two at a more rigid end. The velocities at the flexible end (red and blue lines) are higher than at the rigid end (green and magenta). Tonal maxima are at 50Hz, 100Hz, 200Hz, 300Hz.

2.2. Source mobility

Whilst resiliently suspended, the complex source mobility was recorded with a calibrated impact hammer and matched accelerometer pairs located about the mount contacts. The complex mobility matrix $\mathbf{Y_S}$ was assembled. Figure 3 shows the point mobility magnitude at each mount and the average, which can be assumed to be representative.

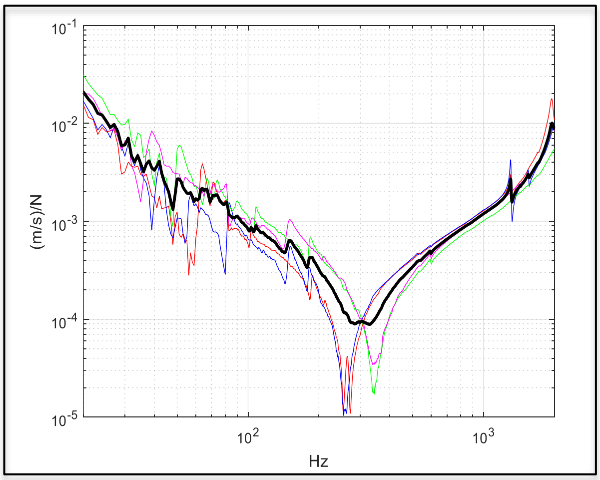

Figure 3. Pump mounts point mobility and average (black line).

Figure 4 shows the mobilities of the fan base. Again, there are large differences between the two higher values at the flexible end (red and blue lines) and the two at the rigid end (green and magenta), and the former dominate the average mobility.

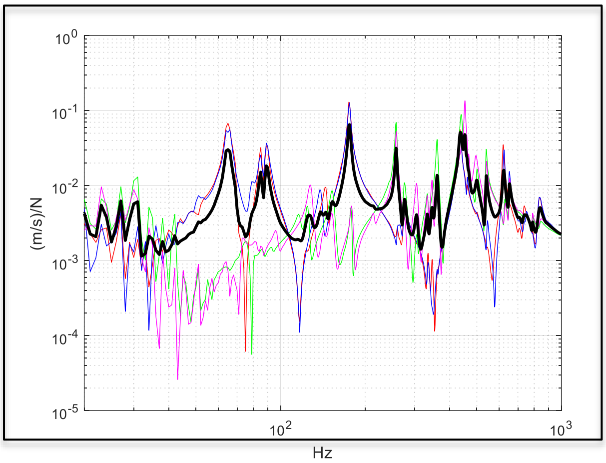

Figure 4. Fan point mobility at mounts and average (black line).

2.2. Blocked force

The blocked force vector $\mathbf{F_B}$ was calculated from the free velocity vector and source mobility matrix

$$\mathbf{F_B} = \mathbf{v_f}^{\mathbf{T}}\ \mathbf{Y_S}^{-1} \qquad (1)$$

Figure 5 shows the pump blocked force squared at each mount point and the sum-square.

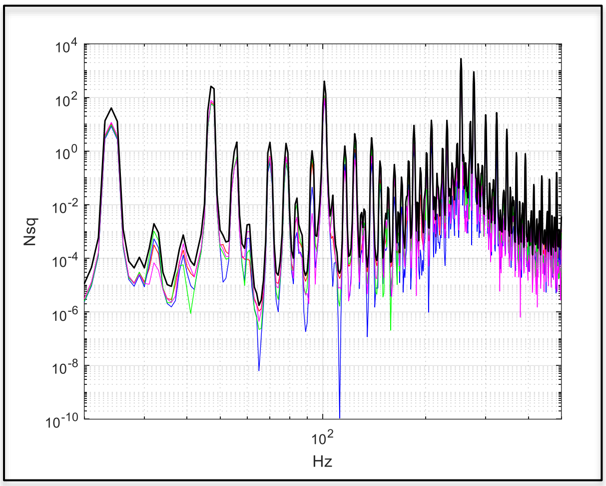

Figure 5. Pump mounts blocked force squared and sum-square (black line).

The tonal characteristic is again indicated with little difference between blocked forces. Figure 6 shows results for the fan. Similar to the fan free velocity and fan point mobility spectra, there are significant differences between the mount pair at the flexible end of the fan base and the rigid end.

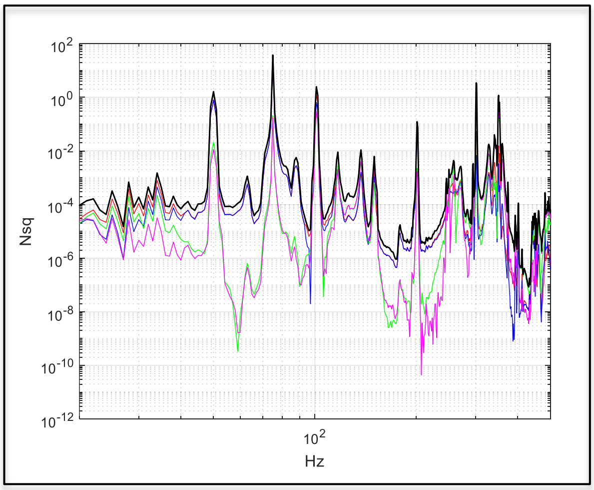

Figure 6. Fan mounts blocked force squared and sum-square (black line).

3. Reception plate power

The transmitted power **P** from a source of free velocity $\mathbf{v_f}$ and mobility $\mathbf{Y_S}$ into a receiving structure of mobility $\mathbf{Y_R}$ is given by

$$\mathbf{P} = \mathbf{v_f}^{T} (\mathbf{Y_S} + \mathbf{Y_R})^{-1T}\mathbf{Re}(\mathbf{Y_R})(\mathbf{Y_S} + \mathbf{Y_R})^{-1*}\mathbf{v_f}^{*} \quad (2)$$

In this example of sub-structuring, i.e. where the source and receiver quantities are obtained separately, prior to fictively combining them, equation 2 will be termed the mobility method and provides narrow-band powers for comparison with approximated values using the RPM. To obtain the source quantities using the RPM, the machine of interest is assumed attached to a reception plate [3, 4]. The transmitted power P_{trans}, through all contacts with the reception plate, is calculated from equation 2. If the reception plate is thick, i.e. of lower mobility than the source, then the source is characterized by the sum square of the blocked force over the contacts [4]

$$F_{bRPM}^{2} = P_{trans} / \mathrm{Re}\ (Y_{thick}) \quad (3)$$

If the reception plate is thin, such that the mobility is much higher than the plate mobility, then the source is characterised by the sum square free velocity over the contacts

$$v_{fRPM}^{2} = P_{trans} / \mathrm{Re}(\ 1/Y_{thin}) \quad (4)$$

3.1. Receiver mobilities

The two reception plates were: a high mobility plate of 1mm perforated mild steel in a 2m x 1m clamping frame, and a low mobility 20mm aluminium plate (2.12m x 1.50m) supported by visco-elastic pads. The test plate was a framed notched plate of 11mm aluminium of size 2.18m x 1.56m. Figure 7 shows the mobilities of the sources and receivers.

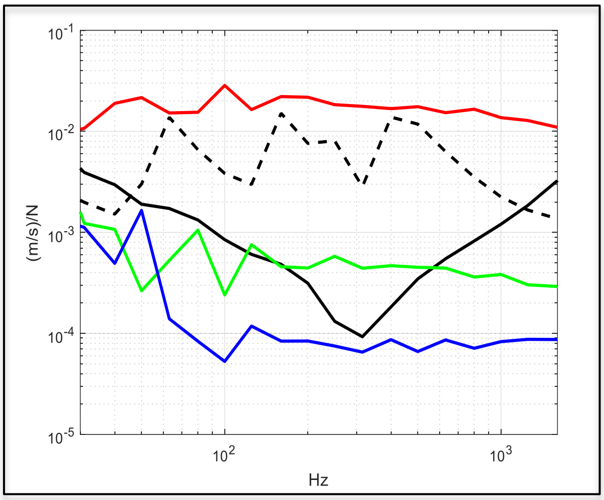

Figure 7. Pump mobility (black), fan (dashed); reception plates: thin (red), thick (blue); test (green).

The source mobilities are average magnitudes over the contact points, the receiver mobilities are spatial averages over the contact points at four pump locations and two fan locations. Results are shown in 1/3 octaves for ease of comparison. The low mobility reception plate requirement of equation 3 is achieved by the 20mm thick aluminium plate, except for the pump at 315Hz. The high mobility reception plate requirement of equation 4 is achieved by the perforated steel plate, except for the fan at 63Hz, 160Hz and 400Hz. For the purposes of verification, the transmitted powers from the sources into the test plate were calculated by the mobility method and compared with powers obtained from RPM source quantities.

4. RPM quantities

4.1. RPM free velocity

Figure 8 shows the directly measured sum square free velocity of the pump and the RPM estimate, obtained from attaching the pump to the thin perforated reception plate, and from equation 4. The reduced frequency range of 20-500 Hz is shown for clarity. The tonal maxima are captured within 5 dB, with a 1 Hz resolution.

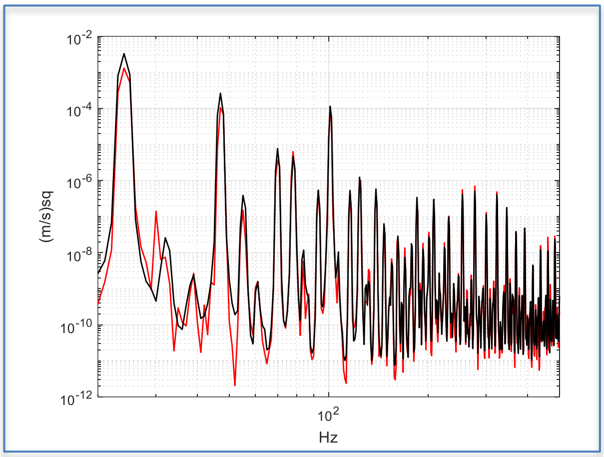

Figure 8. Pump sum squared free velocity: measured (black), by the RPM (red).

Figure 9 shows the directly measured sum square free velocity of the fan and the RPM estimate. The tonal maxima are captured within 10 dB. This is because of the greater variation of free velocities, over the contacts (see Figure 2), when compared with the pump (see Figure 1).

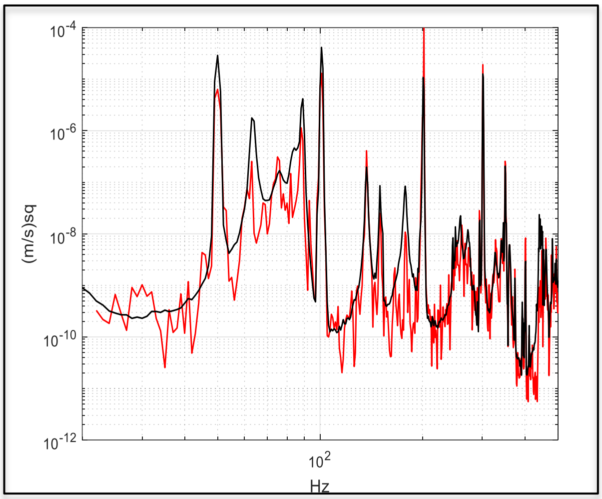

Figure 9. Fan sum squared free velocity: measured (black), by the RPM (red).

4.2. RPM blocked force

Figure 10 shows the sum square blocked force of the pump, obtained from matrix inversion (see equation 1), and by the RPM estimate, obtained by fictively attaching the pump to the 20 mm aluminium reception plate (equation 3). The tonal maxima are captured within 5 dB, except at 50Hz. Figure 11 shows the sum square blocked force of the fan. The tonal maxima are captured within 5 dB, except at 50 Hz.

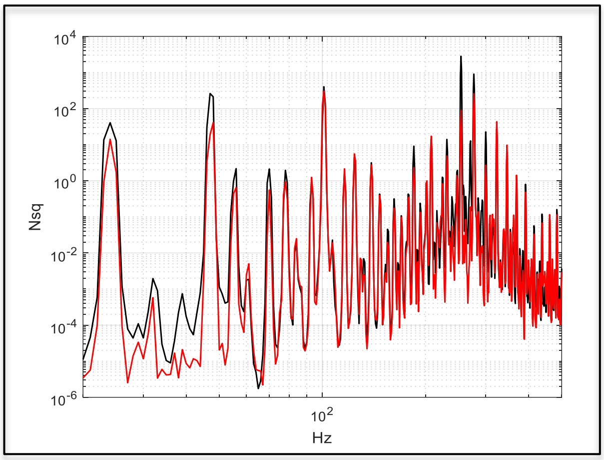

Figure 10. Pump sum squared blocked force: matrix inversion (black), by the RPM (red).

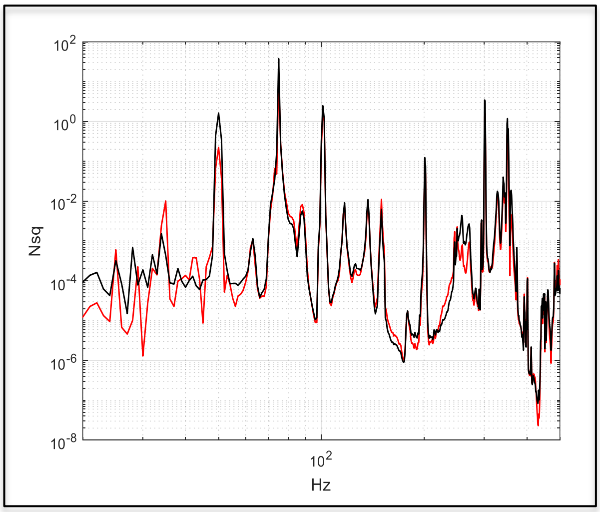

Figure 11. Fan sum squared blocked force: matrix inversion (black), by the RPM (red).

4.3. RPM source mobility

A single equivalent source mobility is calculated from the RPM free velocity and blocked force

$$Y_{RPM} = \sqrt{v_{fRPM}^2 / F_{bRPM}^2} \tag{5}$$

Figure 12 shows the directly measured average magnitude of point mobility over the four mounts of the pump and the RPM estimate (red line) from equation (5). Also shown (blue line) is for the directly measured free velocity. The RPM estimates fluctuate within 10 dB of the measured value, with similar trends.

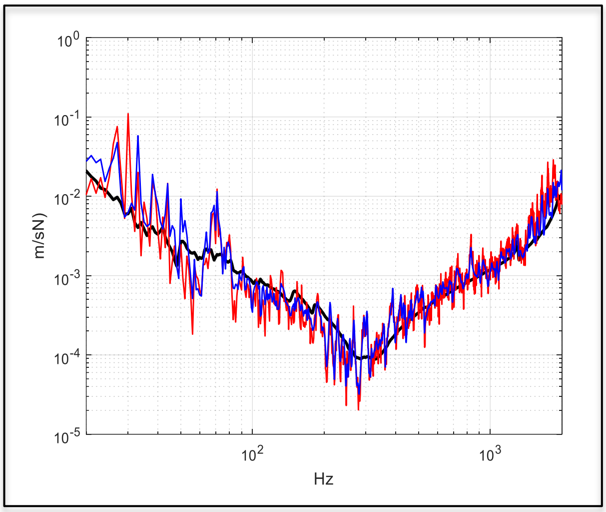

Figure 12. Average pump mobility: measured (black), RPM (red), RPM with measured free velocity (blue).

Figure 13 shows the mobility of the fan. There is a greater discrepancy because of the greater differences in point mobility over the mount points.

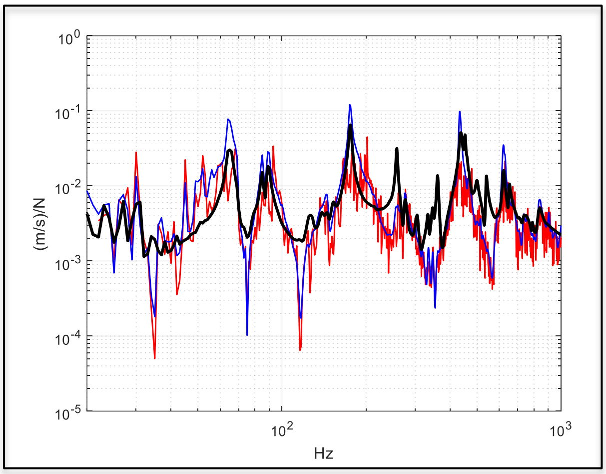

Figure 13. Average fan mobility: measured (black line), RPM (red), RPM with measured free velocity (blue).

4.4. RPM power into test plate

The RPM estimates of source data were used to calculate the transmitted power into the test plate. For this, the test plate mobility was reduced to the spatial averages of magnitude and real part of point mobility, required in

$$P_{RMS} = v_{fRPM}^2 \,\mathrm{Re}(Y_{TRPM})/(Y_{SRPM}{}^2 + Y_{TRPM}{}^2) \qquad (6)$$

Figure 14 shows the RPM estimated pump power into the test plate, compared with the mobility method calculation according to equation 2. Also shown is the RPM estimate using measured free velocity. The power maxima are captured within 5 dB, except at 50 Hz, and irrespective of whether the free velocity was measured directly or by the RPM. Figure 15 is for the fan on the test plate The RPM power estimate gives discrepancies of up to 10 dB.

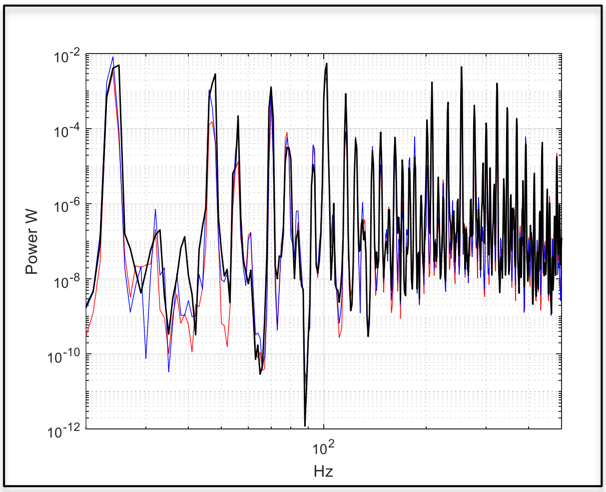

Figure 14. Pump power into test plate: mobility (black), RPM (red), RPM with measured free velocity (blue).

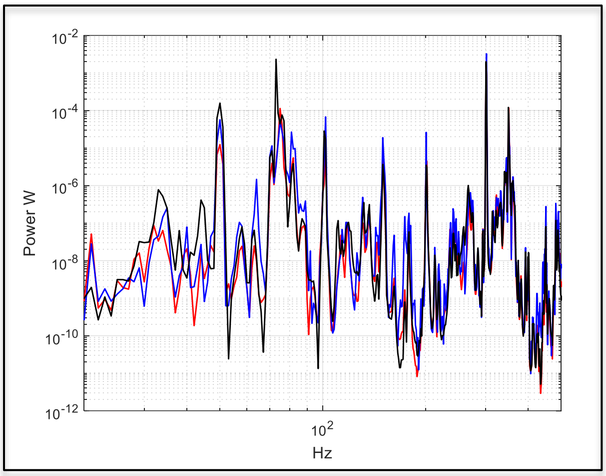

Figure 15. Fan power into test plate: mobility (black), RPM (red), RPM with measured free velocity (blue).

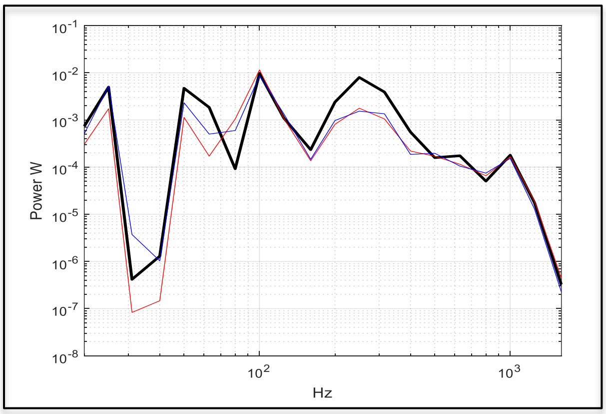

Figure 16. 1/3 octave pump power into test plate: mobility (black), RPM (red), RPM with measured free velocity (blue).

Figure 16 and 17 re-present the results of Figure 14 and 15, respectively, in 1/3 octaves. The frequency range is increased to 20 Hz – 1600 Hz, to show the high-frequency components. Overall, the agreements are within 10 dB.

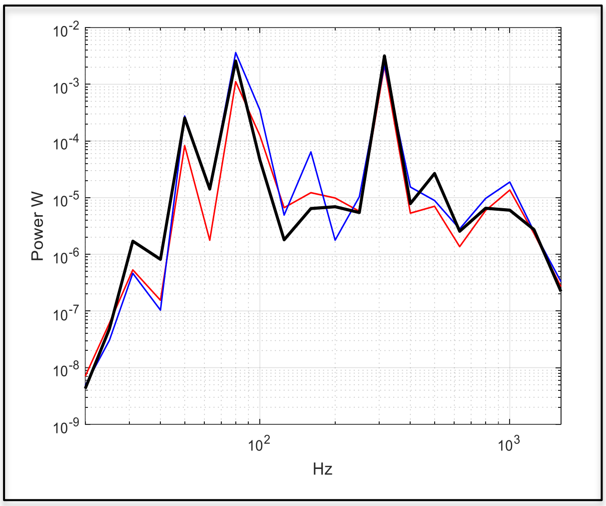

Figure 17. 1/3 octave fan power into test plate: mobility method (black), RPM (red), RPM with measured free velocity (blue).

5. Concluding remarks

For laboratory testing of structure-borne sources, the sum square free velocity and sum square blocked force are required for sources connected through multiple contacts to plate-like receiver structures. The source mobility, in the form of the average point mobility, is obtained indirectly from the square root of the ratio of sum square free velocity and sum square blocked force.

The sum square free velocity and average source point mobility can be measured directly, or by the reception plate method (RPM). In this paper, the RPM was used to obtain source quantities of tonal sources as narrow-band data.

Two sources were considered: a compact air pump of symmetrical construction; and a fan on a composite base with a flexible end and rigid end. In both cases, either direct measurement of the free velocity or by the RPM can be used. This gives a practical choice in the laboratory, depending on which is more convenient.

The RPM provides a practical way of obtaining the blocked force, when compared with the mobility method, which requires measurement of free velocity and source mobility and matrix inversion.

The blocked force could be obtained directly by inserting force transducers at the contacts between sources and low-mobility reception plate, but this could alter the contact conditions and introduces greater measurement effort.

The tonal maxima in pump free velocity were captured by the RPM within 5 dB of the true value. For the non-symmetric fan base, the tonal maxima were captured within 10 dB. For the blocked force of the pump and fan, tonal maxima were captured within 5 dB.

For the pump and fan powers into the test plate, the maxima were captured by the RPM within 10 dB, irrespective of whether the free velocity was measured directly or by the RPM.

So far, the powers were obtained from measurements of the separated sources and receivers and then calculating the transmitted power by the mobility method. It remains to measure the transmitted powers directly.

Acknowledgements

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