Frequency band averaged data for prediction of structure-borne sound power from mechanical installations in buildings

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Summary

Structure-borne sound transmission is a more complicated process than airborne sound transmission, but practitioners seek methods of prediction for the former, which are as straightforward as for the latter. In this paper a description is given of measurement and calculation procedures where the source activity (the velocity of the source when resiliently supported) and the mobility, and receiver mobility are measured and assembled as third octave values. As a further step in data reduction, single values of free velocity, source mobility and receiver mobility are measured directly, or indirectly using the reception plate method (RPM). Comparisons are made between measured source powers into a selection of plate-like receiver structures and RPM estimates. The findings point to the limitations of simplified methods, specifically the uncertainties likely as a result of reducing the measurement and computational effort.

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1. Introduction

To obtain the structure-borne transmitted power from a vibrating machine into a structural element, three quantities are required in some form: source activity (either the free velocity or the blocked force); source mobility; receiver mobility.

The three quantities can be measured directly, or indirectly using a reception plate method. To reduce the measurement and calculation effort, it is proposed that all quantities are frequency band averaged values, e.g. in 1/3 octave bands; further that the three quantities are expressed as equivalent single values.

To obtain the source quantities, the reception plate method (RPM) requires the machine to be attached to a reception plate and operated under otherwise normal conditions [1]. The machine power, through all contacts with the reception plate, is calculated from the plate parameters as [2]:

$$P_{source} = \omega\, \eta\, M \left\langle v^2 \right\rangle \qquad (1)$$

The mean-square plate velocity $\left\langle v^2 \right\rangle$ is recorded using accelerometers distributed over the plate surface. The loss factor η of the plate of mass M is obtained by the decay method [3]. Alternatively, the plate can be calibrated with a shaker and in-line force transducer to give the ratio of the known input power to mean-square plate velocity [4]. Replacing the shaker with the source under test, then gives the required power:

$$P_{source} = \left\langle v_{source}{}^2 \right\rangle P_{cal} / \left\langle v_{cal}{}^2 \right\rangle \qquad (2)$$

If the reception plate is thick, such that the source mobility is much higher than the plate mobility, then the source can be characterised by a single quantity, related to the sum square blocked force over the machine supports [5]. In this case, the source power into a thick plate of known mobility Y_{Req} is:

$$P_{source} = F_{beq}^2 \operatorname{Re}\left(Y_{\mathrm{Req}}\right) \qquad (3)$$

If the reception plate is thin, such that the source mobility is much lower than the plate mobility, then the source can be characterised by a single equivalent quantity, related to the sum square free velocity over the contacts [5]. Here, the source power into a thin plate of known mobility is:

$$P_{source} = v_{feq}^2 \ \mathrm{Re}(1/Y_{\mathrm{Req}}) \tag{4}$$

To summarise, the required source quantities can be obtained from any two of the measured quantities: sum square free velocity, sum square blocked force, average source point mobility.

These quantities can be measured directly, of obtained indirectly, using the reception plate method (RPM).

2 Experimental implementation

The RPM was experimentally implemented. At the same time, the required source quantities were measured directly, for comparison, all as 1/3 octave values. Two sources were considered: a compact air pump and a fan unit with a plate base.

The two reception plates were: a high mobility plate of 1.5mm perforated mild steel, in a 2m x 1m clamping frame; a low mobility 20mm aluminium plate (2.12m x 1.50m), resiliently supported on six visco-elastic patches.

The following were directly measured:

1. Free velocities as sum square magnitudes
2. Average magnitude of point mobility over the source contacts.
3. Sum square blocked forces of the sources.

The following were measured for the RPM:

4. Structure-borne powers from the pump and then fan, into the two reception plates, using the power substitution method (Equation (2)).
5. F_{beq}^2 and v_{feq}^2, using Equations (3) and (4), respectively, were compared with the directly measured values: $\sum_i^N F_{bi}^2$ and $\sum_i^N v_{fi}^2$.
6. Single equivalent source mobility [6] from:

$$Y_{Seq} = \sqrt{v_{feq}^2 / F_{beq}^2} \tag{5}$$

7. RPM estimates were compared with directly measured powers into a: clamped plate of 11mm aluminium; 13mm ribbed Perspex plate.

3 Instrumentation

The main components of the experimental set-up are an inertial driver, with in-line force transducer, and small accelerometers, shown in Figure 1.

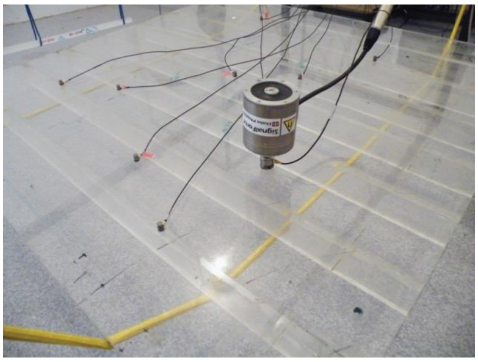

Figure 1: Inertial shaker with in-line force transducer..

The shaker and accelerometers measured:

1. Pump and fan point mobility magnitude $|Y_{Si}|$.
2. Reception plates point mobility, as real part $R(Y_{Ri})$ and magnitude $|Y_{Ri}|$.
3. Shaker power $P_{shaker} = R(F_c^* v_c)$, the real part of the cross-spectrum.
4. The remote accelerometers registered the plate velocities $\langle v^2 \rangle$ as auto-spectra.

4 Free velocity by RPM

The sources were glued to the perforated plate, the pump is shown in Figure 2.

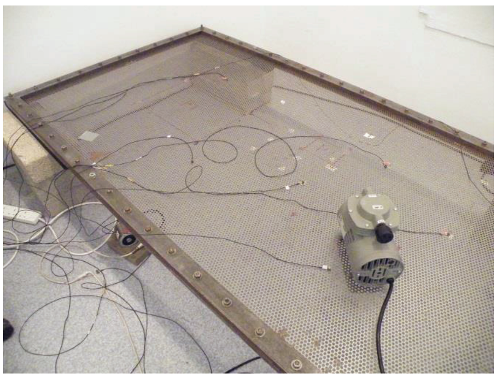

Figure 2: Air pump attached to the perforated plate

The source powers were measured by power substitution. Figure 3 shows the power calibration at three locations and as an average.

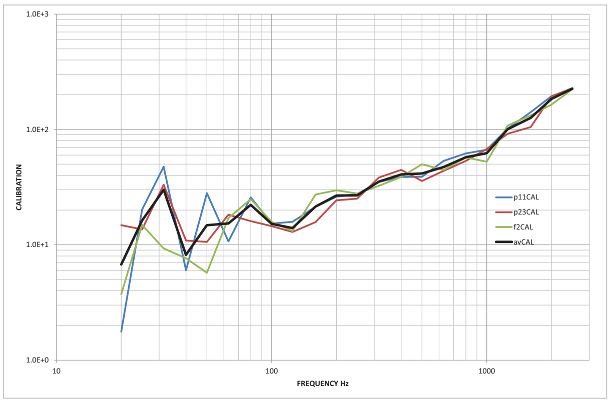

Figure 3: Perforated plate power calibration

Figure 4 shows the average real part of plate impedance $R(z_{\mathrm{Re}q})$, for the RPM free velocity.

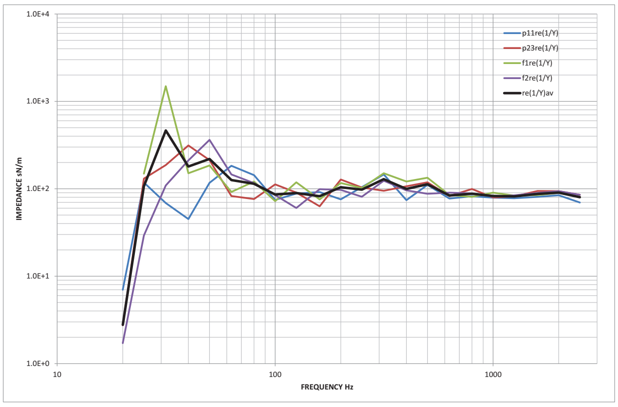

Figure 4: Average real part of point impedance of perforated plate.

Figures 5 and 6 show the measured and RPM sum square free velocities, of the pump and fan.

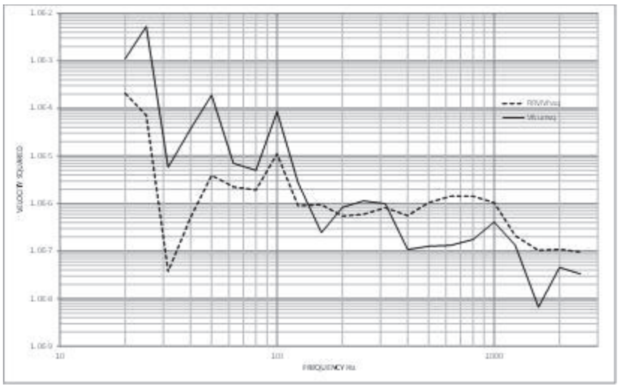

Figure 5: Sum square free velocity of pump: Solid line, directly measured; dashed line, by RPM.

The agreement is within +/-10 dB for the pump, for frequencies above 80 Hz. Below this frequency, the RPM gives an underestimate due to rocking motion at some frequencies.

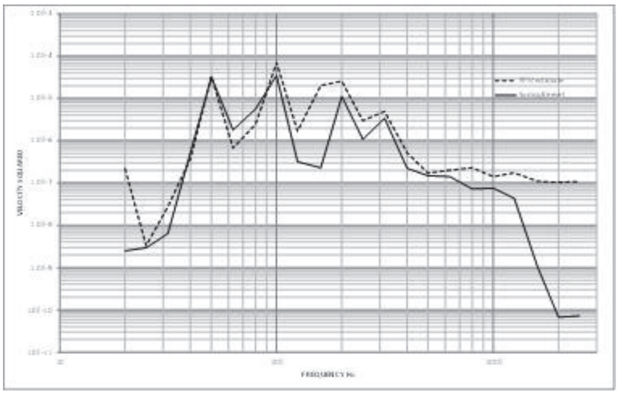

Figure 6: Sum square free velocity of fan: Solid line, directly measured; dashed line, by RPM.

The agreement is within +/- 5 dB for the fan unit. The contacts are at greater distances than for the pump and the contact forces behave independently.

5 Blocked force by RPM

The RPM blocked force requires the power of the test sources to the low-mobility 20mm aluminium plate, using the power calibration (Figure 7) and real part of plate mobility (Figure 8).

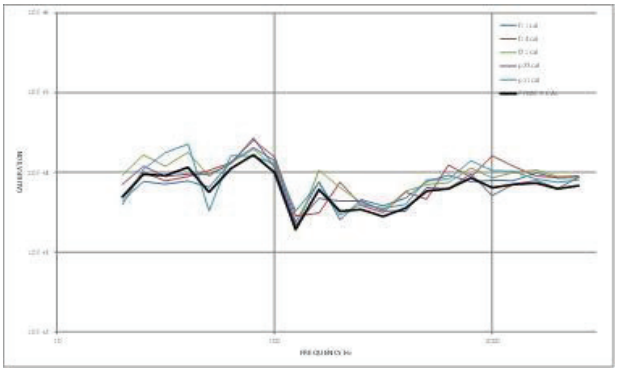

Figure 7: Power calibration of 20mm plate.

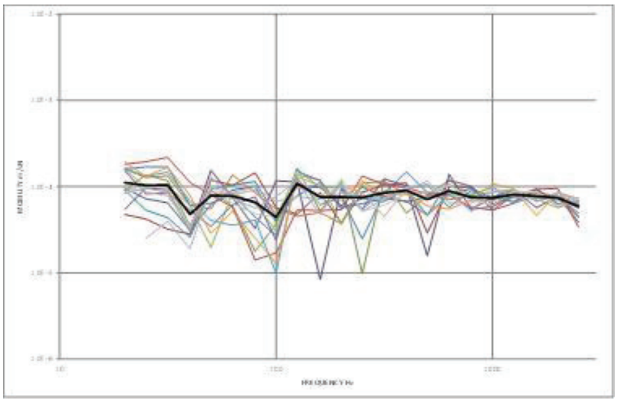

Figure 8: Real part of point mobility of 20mm plate.

Figure 9 shows the pump sum square blocked force, by direct measurement and RPM; also the RPM estimate of the pump on isolators.

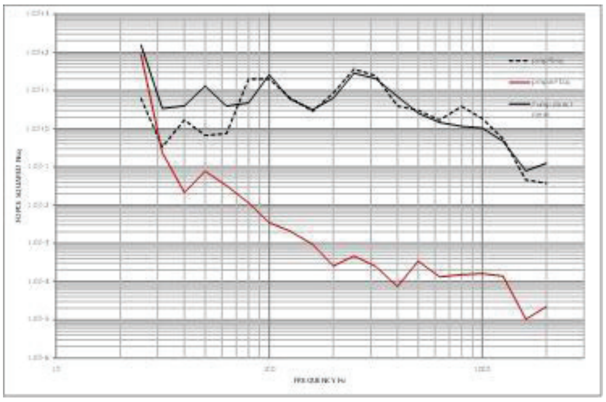

Figure 9: Pump sum square blocked force: measured (solid); RPM (dashed); RPM pump on isolators (red).

Figure 10 shows the fan sum square blocked force.

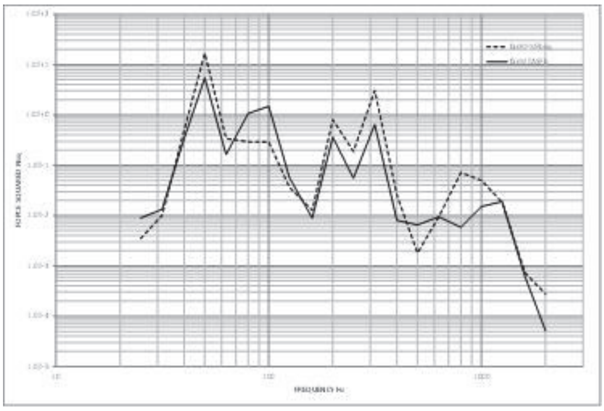

Figure 10: Sum square blocked force of fan: direct measurement (solid line) and RPM (dashed).

The RPM estimate of blocked force of the pump is within +/- 3 dB of the directly measured value, above 80 Hz, with a negative discrepancy of 10 dB, below 80 Hz, again due to rocking motion at some frequencies. The RPM estimate for the fan is within +/- 5 dB, except at 800 Hz.

6 Source mobility by RPM

Shown is the measured average point mobility, with the RPM estimate, from Equation (5), for the pump in Figure 11, and for the fan in Figure 12.

The RPM estimate of pump mobility is within +/-5 dB of the measured value. The point mobility varies relatively little over the contacts.

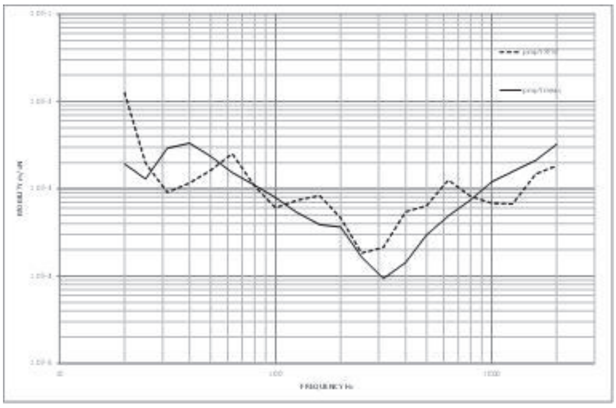

Figure 11: Average magnitude of pump point mobility: black line, direct measurement; dashed line by RPM.

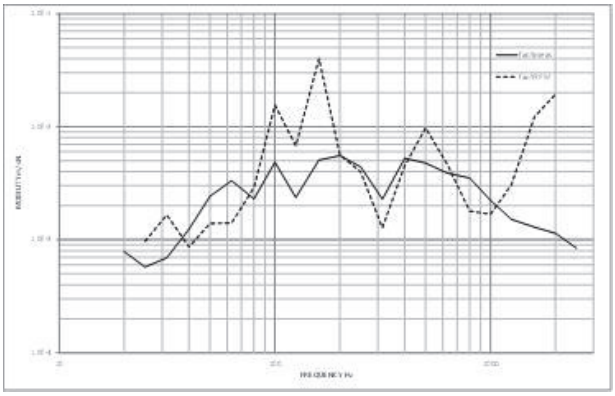

Figure 12: Average magnitude of fan point mobility: black line, direct measurement; dashed line by RPM.

For the fan, the RPM gives an estimate within +/- 10 dB of the measured mobility, but the ‘signature’ has not been captured, because of large differences in point mobility, over the contacts.

7 Installed power by RPM

The RPM was used to calculate the powers, for the pump and fan, when attached to two other structures. The first was a framed notched plate of 11mm aluminium of size 2.18m x 1.56m. Notches at the edges give a rotationally compliant thickness of 3mm. the second was a 13mm Perspex plate, with dimensions 1000mm x 1000mm. The ribs are of dimension 50mm x 13mm, at 120mm centres.

The structure-borne powers of the sources, when attached to the plates, were measured directly using power substitution. The RPM estimate of power is given by:

$$P_{source} \approx v_{feq}^2 \, R\left(Y_{\mathrm{Re}q}\right) / \left(\left|Y_{Seq}\right|^2 + \left|Y_{\mathrm{Re}q}\right|^2\right) \quad (6)$$

As with the equivalent source mobility, the receiver plate mobility was measured as the spatial average real part of the point mobility and spatial average of the magnitude. The measured and RPM estimated powers from the pump and fan are in Figure 13 and 14, respectively.

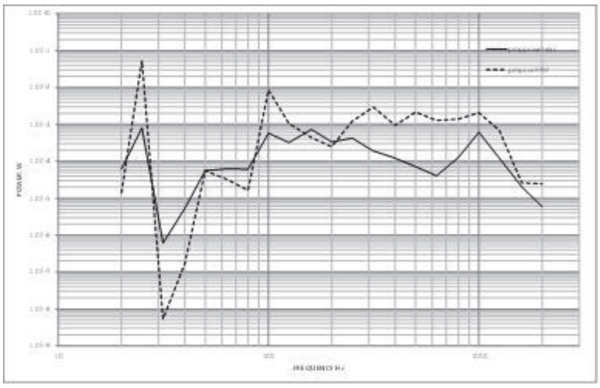

Figure 13: Measured pump power into 11mm plate (solid line) and RPM estimate (dashed).

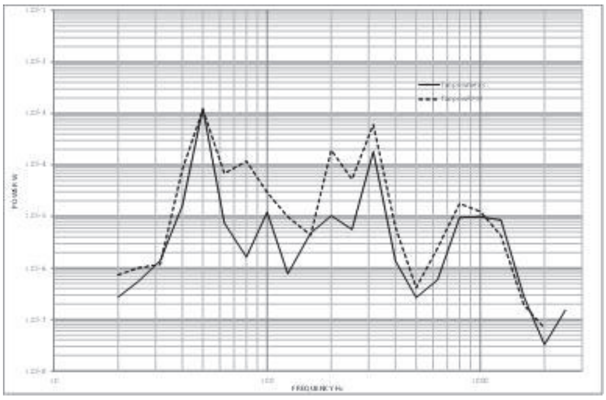

Figure 14: Measured fan power into 11mm plate (solid line) and RPM estimate (dashed).

Figure 15 shows the measured and RPM powers from the pump on isolators.

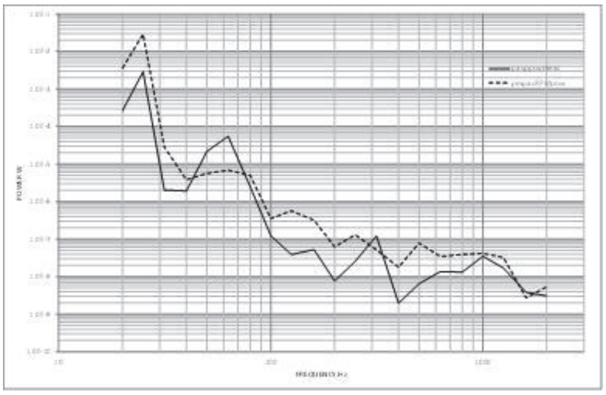

Figure 15: Measured pump power, on isolators, (solid line) and RPM estimate (dashed).

In all cases, the level difference between measured powers and RPM estimates are within +/-10 dB.

The RPM was used to predict the power from the pump when attached to the ribbed Perspex plate. Figure 16 shows the pump, rigidly attached to the ribbed plate (left), and (right) when on isolators.

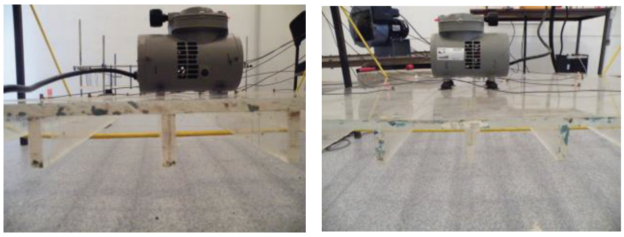

Figure 16: Ribbed Perspex plate with left, pump attached, and right, with pump on isolators.

Figures 17 and 18 show the measured and RPM estimated powers from the rigidly connected pump and isolated pump, respectively.

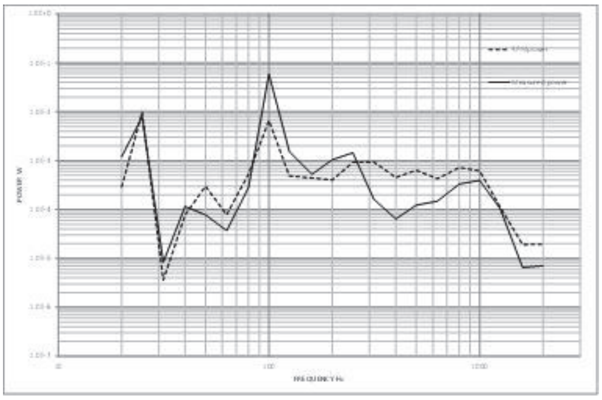

Figure 17: Measured pump power into ribbed plate (solid line) and RPM estimate (dashed).

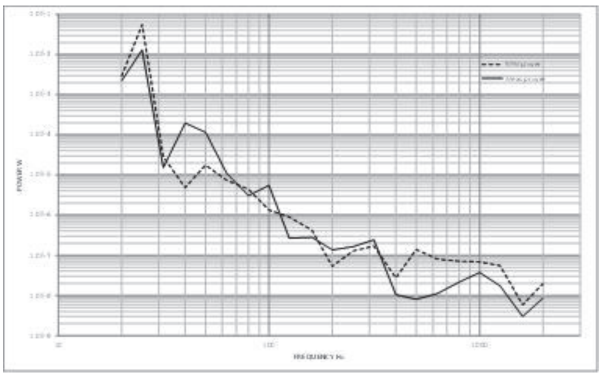

Figure 18: Measured pump power with isolators (solid line) and RPM estimate (dashed).

Overall, the RPM estimate is within 10 dB of the measured powers.

8 Concluding remarks

In seeking an approach for laboratory testing of structure-borne sources, the sum square free velocity and sum square blocked force have been identified as candidate independent quantities for sources connected through multiple contacts to plate-like receiver structures.

Also required is the source mobility, in the form of the average point mobility, which is obtained indirectly from the square root of the ratio of sum square free velocity and sum square blocked force.

Along with the free velocity, it provides the two source quantities required for calculating the structure-borne power to other plate-like structures.

The sum square free velocity and sum square blocked force can be measured directly, or by the two-stage reception plate method (RPM), i.e. by measuring the source power when attached to a high mobility plate and low mobility plate, respectively. The measurements and calculations are in one-third octave bands.

For a compact source such as the pump, the RPM estimate of sum square free velocity was within +/- 10 dB of the measured value, above 80 Hz. Below this frequency, the RPM underestimates the free velocity by 20 dB. The pump is in rigid-body motion and rocking motion will give reduced power into the plate at some frequencies.

For an extended source, such as the fan, the RPM estimate is within +/-5 dB of the measured value and the contact forces can be assumed to behave independently.

For the pump, the RPM estimate of sum square blocked force was within +/- 5 dB of the measured value, above 80 Hz, with an under-estimate of 10 dB, below 80 Hz, again due to rocking motion at some frequencies.

For the fan, the estimate is within +/- 5 dB of the measured sum square blocked force.

For the resultant estimate of source mobility, the RPM was within +/- 5 dB of the measured average, for the compact pump, and within +/- 10 dB for the fan.

For the transmitted power into a third structure, the 11mm aluminium plate, from the pump, the fan and the pump on isolators, the RPM estimate is within +/-10 dB the measured power.

For the transmitted power from the rigidly attached pump and isolated pump, into a fourth structure, the ribbed 13mm Perspex plate, the RPM estimate is within +/- 10 dB of the measured power.

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