

A particle velocity sensor to measure the sound from a structure in the presence of background noise

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The performance (or quality) of a product is often checked by measuring the radiated sound (noise) from the vibrating structure. Often this test has to be done in an environment with background noise, which makes the measurement difficult. When using a (pressure) microphone the background noise can be such that it dominates the radiated sound from the vibrating structure. However, when using a particle velocity sensor, the Microflown [1,2], near the vibrating structure, the background noise has almost no influence (it is almost cancelled) and the sound from the structure is measured with a good S/N ratio. The experimental results are explained in terms of the different boundary conditions at the surface of the vibrating structure for the pressure and the particle velocity.

1 Introduction

In this paper experiments are reported that show that for end of line control a particle velocity measurement is favorable compared to a sound pressure measurement.

In a production facility a high level of background noise with a diffuse character may be expected. In such environment low sound levels have to be measured that should discriminate good or faulty equipment. One can think of a gear box or a pump. If a bearing is damaged it generates a different noise than a proper working one.

One important reason that a measurement of the particle velocity is preferred above a measurement of the pressure is that close to the surface the particle velocity level caused by the vibration of the object under test is high compared to the sound pressure level [6]. The second reason is that in the background noise the particle velocity near the surface is reduced because the sound waves, belonging to the background noise, reflect to a rigid surface, where the velocity almost vanishes. Also the effect that the particle velocity sensor measures only one third of the reverberant field, while a pressure sensor measures the full reverberant field [4]. In a simple model discussed in section 3 these arguments are worked out.

2 Measurements

The measurement procedure consists of four steps.

To get a general idea of the problem at hand, step one is a simple sound pressure measurement in a silent environment. This measurement reveals the bandwidth of interest and gives an idea of the dynamic range of

the problem. In a silent environment it is often possible to discriminate between good and faulty equipment.

Step two is measuring the particle velocity (and sound pressure) close to the surface using this to create a particle velocity (or sound intensity) spectrogram of the object. This spectrogram shows the frequency response of all measurement points. It gives insight in the discriminating frequencies *and* measurement points of the good and faulty equipment.

The spectrogram is not so intuitively to interpret so therefore at a proper frequency bandwidth this picture is transformed in the acoustic picture, this is step 3. The acoustic picture reveals the best measurement locations to be able to discriminate between good and faulty equipment.

Step four is the acoustic check of the optimal location that is found by the acoustic camera. Good and faulty equipment are tested with a high level of background noise.

2.1 Step 1: general impression bandwidth/dynamic range

The equipment under study is a small pump that may be faulty. The aim is to discriminate between a good and faulty pump. The faulty pump has a damaged gear.

In a silent environment, at several places around both pumps (the good and the faulty one) the sound pressure is measured to get an overall impression on the frequencies of interest and the dynamic range (the difference in sound level of a good and faulty pump).

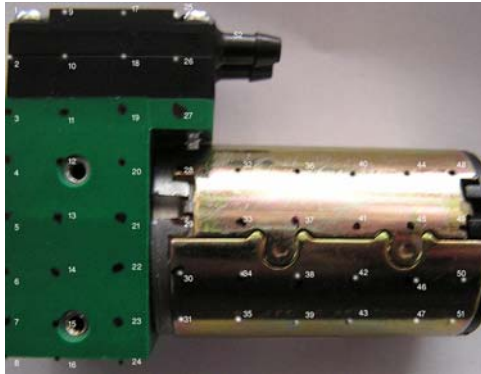


Figure 1: A photograph of the miniature pump with an electrical motor (the total length is 7.5cm). The numbers are the measurement locations.

The average of five pressure values is calculated. The result of the measurement is shown in Figure 2.

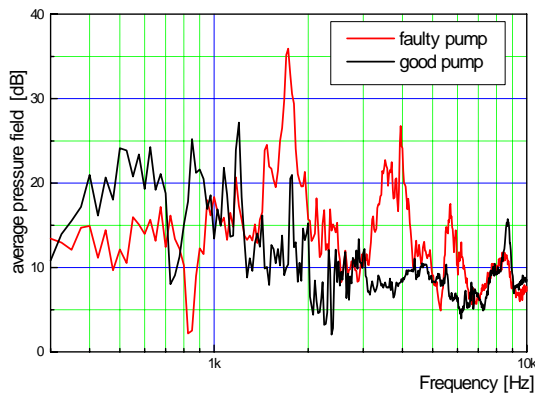


Figure 2: The average sound pressure (measured at several locations around the pump).

The black line shows the average sound pressure of a good pump and the red line shows the spectrum of a faulty pump. A useful bandwidth to discriminate is where dynamic range is large. Dynamic range is defined as the difference in spectrum between a good and a faulty pump. As can be seen, discriminating frequencies are found in the 1500Hz-2kHz bandwidth and the 3.5kHz-4.5kHz bandwidth. The dynamic range is in the order of 10dB-15dB which is not very high.

2.2 Step 2: The spectrograms of the object

From the general impression of the problem it was learned that the frequencies of interest are relative high so the lower frequencies ($f < 50\text{Hz}$) are not measured. This increases the measurement speed.

At the surface of the pumps the particle velocity is measured and the result is used to generate the spectrograms. These show the velocity field at all measurement points and at all frequencies in more detail, see Figure 3. At the x-axis the frequency is

given, the y-axis the measurement position (see Figure 1) and the color is a measure for the value of the autospectrum. Red is a high value, blue a low value.

It shows again that at 1.5kHz-2kHz ‘something’ is happening. An interesting detail is that the upper hole of a faulty pump (measurement point 12) generated less sound at higher frequencies. Also in the 3.5kHz-4.5kHz bandwidth differences between good and faulty are found.

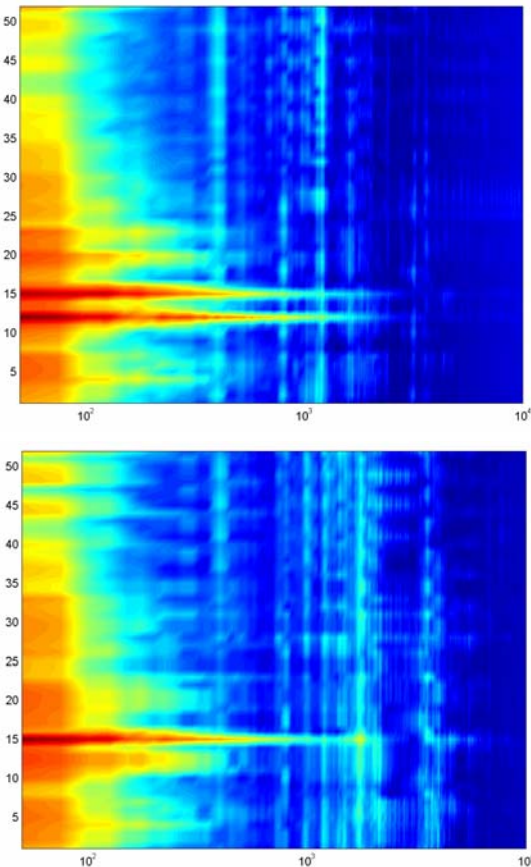


Figure 3: Spectrograms of the pumps. Upper the good pump and lower the faulty pump.

2.3 Step 3: The acoustic pictures of the object

At a specified bandwidth the data from the spectrogram can be extracted. The particle velocity in that specific bandwidth is integrated and the result is plotted ‘over’ the photograph of the pump. The result is a color map that represents the particle velocity field generated by the good and faulty pump, see Figure 4.

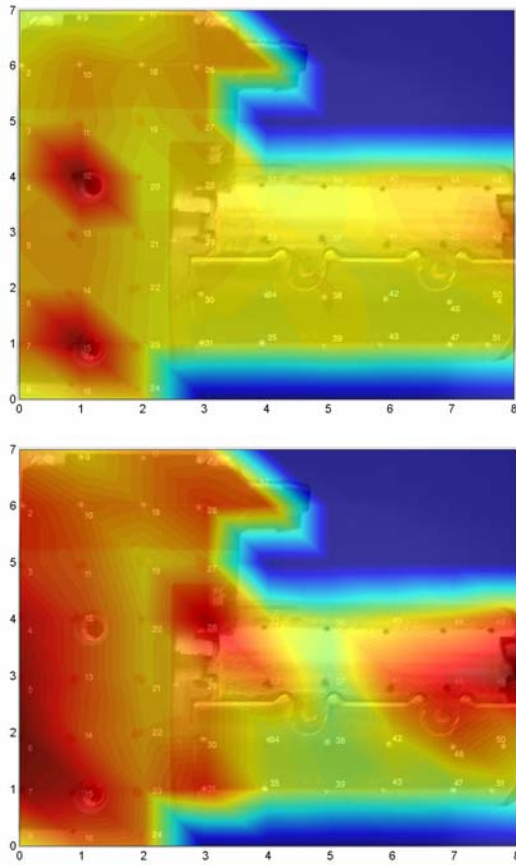


Figure 4: Acoustic particle velocity pictures extracted from the spectrograms at the 1.5kHz-2kHz bandwidth. Upper the good pump and lower the faulty pump.

As can be seen in Figure 4, the rear of the motor is the best position to detect if a pump is good or faulty.

2.4 Step 4: Acoustic test of the optimal location

A good and faulty pump is measured at the optimal location that is found by the acoustic picture both with and without a high level of background noise. At the test the background noise is so loud that a faulty pump cannot be heard at 20cm distance. Both pumps are measured with 3mm in front of the optimal location. Measurements were taken with a pressure microphone and a Microflown.

The result is shown in Figure 5 for the sound pressure measurement and in Figure 6 for a particle velocity measurement. As can be seen in Figure 5, the background noise is dominating the measurement for a sound pressure measurement, but when the measurement is performed with a Microflown, the background noise has almost no influence, see Figure 6.

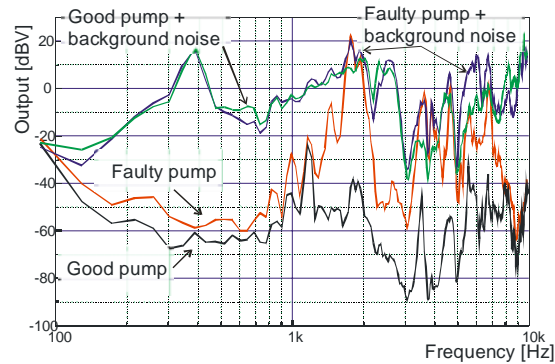


Figure 5: Sound pressure measurements at the optimal location. Black line good pump measured in a silent environment; red line faulty pump measured in a silent environment; green line good pump measured in an environment with background noise; blue line faulty pump measured in an environment with background noise.

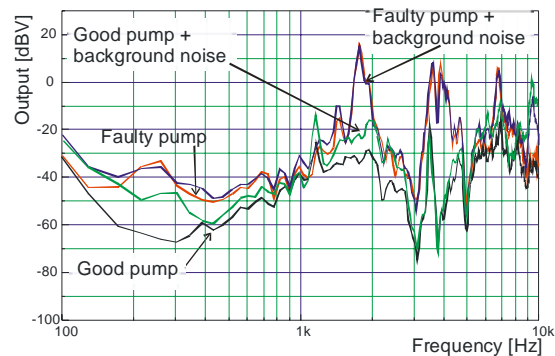


Figure 6: Particle velocity measurements at the optimal location. Black line good pump measured in a silent environment; red line faulty pump measured in a silent environment; green line good pump measured in an environment with background noise; blue line faulty pump measured in an environment with background noise.

The signals are recorded and can be listened to. The difference is remarkable.

3 Discussion and a simple model for explaining the results

In the following paragraphs a simple model is given that quantifies the effect that is shown above.

3.1 Sound of the motor and background noise at sensor positions

To compare the benefit of a velocity (u) measurement to the pressure (p) measurement, the ratio of their response is of relevance. The ratio is given by the acoustic impedance $z=p/u$.

Due to the motor, vibrations of the encapsulation appear which results in a radiation of sound outside the encapsulation.

Consider two examples of encapsulation configurations for which simple analytic expressions for the pressure and particle velocity are known: an on-axis circular piston with radius $r=a$ in an infinite baffle [3] and a sphere with radius $r=a$. Very near to the encapsulation the specific acoustic impedance z_m is given by:

$$z_m = \frac{P_m}{u_m} = \rho_0 c \left(1 - e^{-jka}\right) \quad (1)$$

for a piston on the axis and

$$z_m = \frac{P_m}{u_m} = \frac{\rho_0 c}{1 - 1/jkA} \quad (2)$$

for a sphere. (With $\rho_0 c = 415 \text{ Pa}\cdot\text{s/m}$, p_m is the sound pressure at sensor position and u_m is the particle velocity at sensor position normal velocity of the encapsulation, $k = 2\pi/\lambda$ is the wave vector and $j^2 = -1$). As abbreviation we will write for both cases $Z_m = \rho_0 c / (1 + 1/jA)$ with $jA = \exp(jka) - 1$ for the piston and $jA = jkr$ for the sphere. The term $1/jA$ is known as near field effects (evanescent waves), where p and u are not in phase, as they are in the far field $u = p/\rho_0 c$.

Consider the background noise as an incident-, reflected- and transmitted wave, which result in a (small) vibration of the encapsulation. The net force per unit area can be written as: $p_i + p_r - p_t$, where p_i , p_r and p_t are the sound pressures very near the encapsulation of the incident-, reflected- and transmitted wave. The p_t term is proportional to the local velocity of the encapsulation, u_b , and can be written for the two examples, as discussed above, as: $p_t = u_b \cdot \rho_0 c / (1 + 1/jA)$. The sum $p_i + p_r$ is just the pressure p_b at the sensor position.

The reaction forces are related to the mass per unit area, m , and to the stiffness and edge conditions of the encapsulation. The mass term is written as $j\omega m \cdot u_b$ with ω the angular frequency. The stiffness and edge condition force is in general proportional to the local displacements (elastic deformations) of the encapsulation and can thus be written as: $E u_b / j\omega$ with E a constant related to the elastic properties of the encapsulation. The expression for the force per unit area can thus be written as:

$$p_i + p_r = p_b = u_b \left\{ j\omega m + \frac{E}{j\omega} + \frac{\rho_0 c}{1 + \frac{1}{jA}} \right\} \quad (3)$$

The specific acoustic impedance at the sensor position is thus equal to:

$$Z_b = j\omega m + \frac{E}{j\omega} + \frac{\rho_0 c}{1 + \frac{1}{jA}} \quad (4)$$

3.2 Motor noise versus background noise at close to the motor

The relevant quantity for comparing the measured pressure and particle velocity of the motor noise and background noise is the ratio of the acoustic impedance of the emitted sound by the motor (Z_m) and the acoustic impedance of the background noise close to the motor.

$$\frac{z_b}{z_m} = \frac{j\omega m + E/j\omega + \rho_0 c / (1 + 1/jA)}{\rho_0 c / (1 + 1/jA)} \quad (5)$$

Comparing the first term with the last one and substituting $\omega = 2\pi \cdot 1000$, $m = 6.3 \text{ kg/m}^2$, $a = 5 \text{ cm}$, $A = ka \approx 1$, gives for the modulus of the impedance ratio:

$$\left| \frac{z_b}{z_m} \right| = \frac{\omega m}{\rho_0 c \sqrt{(1 + A^{-2})}} \approx 68 \quad (6)$$

It may well be that in our experiment the mass term is not dominant and that the stiffness and edge conditions also play an important role. In that case the ratio of the particle velocities and the pressures becomes even larger than the above value of 68 (37dB)! This simple model thus shows that $u_m/u_b \gg p_m/p_b$, and that measuring the particle velocities gives much better results than measuring the sound pressures.

3.3 The directional advantage

Also the directional characteristics of the sensors results in a higher value of the measured v/p ; the p -sensor detects the sound from all directions, whereas the Microflown detects only the particle velocity in one direction. Since it is expected that the background noise is a reverberant, diffuse sound field, only 1/3 is measured in the auto-spectrum of the u -sensor, while the p -sensor measures the full reverberant field:

$$\begin{aligned} \text{auto}(p) &= p_{rev}^2 \approx u_{rev}^2 (\rho c)^2 \\ \text{auto}(u) &= \frac{1}{3} u_{rev}^2 \approx \frac{1}{3} p_{rev}^2 (1/\rho c)^2 \end{aligned} \quad (7)$$

With $\text{auto}(p)$ is the auto-spectrum of p -sensor, p_{rev} and u_{rev} are the pressure and particle velocity of the reverberant sound field [4].

3.4 Solution for very low noise sources

If a p -sensor and a u -sensor are present near the encapsulation also the cross-correlation of these sensor signals can be determined. This cross-correlation is known as the intensity, of which the real part is equal to the energy flow through an area.

Using the above derived expressions for the impedances the real part of the time averaged intensity can be written as (8):

$$\operatorname{Re}(I) = \operatorname{Re}(p \cdot u^*) = \frac{pm^2}{\rho_0 c} + \frac{p_b^2 / \rho_0 c}{\left(\omega m - E/\omega - 1/A\right)^2 + 1}$$

Since $\omega m \gg \rho_0 c$ the second term containing the contribution of the background noise, is much smaller than the first term containing the motor sound. The advantage to use the intensity instead of the auto-spectrum of the particle velocity is not that the contribution of the motor sound should be stronger, on the contrary the real part of the cross-correlation ρ_{pc} is somewhat smaller, by the term $1/(\rho_0 c A)^2$, so about equal to the auto-spectrum of u . The advantage is that the signal to noise ratio, S/N, can be higher for the cross-correlation, since the noise of the p -sensor and the u -sensor are uncorrelated, and thus vanishes if a long time averaging has been done. When the phase difference between the p - and u -sensor is not very accurate calibrated a problem can arise in determining the real part of the cross-correlation, since the imaginary part of the cross-correlation is not small.

Another, better, alternative would be, to use two u -sensors close to each other and to determine the real part of the cross-correlation of the two sensor signals. The signal part of the cross-correlation between these two sensors is of course equal to the signal part in the auto-spectrum of one u -sensor, the noise (sensor noise) is, however, much lower than the noise of one sensor, because also the noise of the two u -sensors are uncorrelated.

It has been shown, [5] that in this case a large factor, e.g. 30 dB in the noise strength, could be realized.

4 References

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