APPLICATION OF SOUND ANALYSIS IN DIAGNOSING COLLECTOR MOTORS

Uroš Benko

Department of Computer Automation and Control,
Jožef Stefan Institute,
Jamova 39, 1000 Ljubljana, Slovenia
E-mail: uros.benko@ijs.si

Abstract: The sound of a motor is besides vibration and electrical properties a major important characteristic indicating motor's condition. Any deviation in sound implies high possibility of already present fault as well as an incipient and even an impending fault. The paper presents the results of the investigation the purpose of which is to use simple, yet effective signal processing tools to provide clear information about motors condition solely by employing sound analysis.

Keywords: spectral analysis, cepstrum analysis, motors, noise, fault diagnosis

1. INTRODUCTION

Tough competition and struggle among manufacturers of household appliances has implied steadily increasing quality of the products. The long-term result thereof is that in some sectors (e.g. washing machine manufacturing and car industry) there already are standards imposing strict requirements of device properties, while in other sectors (e.g. vacuum cleaner motors manufacturing) these standards and requirements seem to emerge very soon. However, quality assurance of the products is becoming more and more important task.

Sound emitted by rotating devices in many cases reflects the condition of a device. An important advantage of using sound as a basis for fault detection is its non-intrusive monitoring and easy installation.

Yang and Penman (2000) apply motor current and vibration sensing as a basis for feature extraction via artificial neural networks for bearing condition diagnosis. Gühmann and Filbert (1991) have treated the same problem via estimation of the current spectrum. Feature extraction based on residuals generated through the mathematical model of electrical and mechanical part has been addressed by Juricic et al. (2001).

The purpose of the paper is to investigate the potential of sound analysis in fault diagnosis of vacuum cleaner motors. It seems that very little attention if any has been paid to such a potentially relevant issue. The goal is to briefly introduce the results of sound signal analysis as the potential for fault diagnosis.

The paper is organised as follows. Section 2 provides a brief introduction of the experimental environment. Section 3 deals with the sound source analysis. Section 4 describes the design of experiments and signal analysis tools. Section 5 gives the experimental results of the sound analysis.

2. THE EXPERIMENTAL ENVIRONMENT

2.1 Vacuum cleaner motor

The central part of a vacuum cleaner is a universal collector motor with attached fan impeller. The fan rotates together with a rotor in order to fulfil the primary function, i.e. air suction. The nominal operating conditions of the motor are the following.

- applied voltage 230V 50Hz,
- 1.4 kW power,
- 33000 rpm (revolutions per minute) nominal speed
- life-span is ca 700 hours of effective operation.

2.2 Measurement equipment

The essential part of the experimental environment is the echo-free sound chamber. The walls of this chamber are made of sound absorbent material, which prevents sound reflection. The applied microphone has the frequency band between 20Hz and 20 kHz. The microphone is connected to the amplifier, which conditions the signal to appropriate voltage level in the range ±5V. An optical sensor attached to the motor is used to measure rotational speed. The signals are sampled at the frequency of 30 kHz, respectively.

3. SUMMARY OF SOUND SOURCES

The sound generated during rotation of the motor is contributed by three main sources:

1. time-varying electromagnetic forces causing electromagnetic noise,
2. airflow aerodynamics and
3. mechanical contacts.

3.1 Relationships among various sound sources

The sound pertaining to mechanical contacts and other mechanical malfunctions carries important information about condition of the motor. Experimental results show that such noise is noticeable only at low rotational speeds, i.e. below 2400 rpm. For rotational speeds from 2400 rpm upward the aerodynamic noise prevails over mechanical sources thus rendering fault detection almost impossible.

Figure 1 shows a comparison of sound source intensities for rotational speeds below 3000 rpm for both, fault-free and faulty motor.

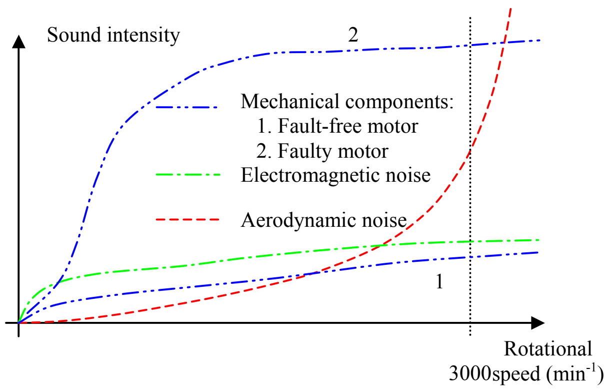

Fig. 1: Qualitative relationships among different sound sources.

4. DESIGN OF EXPERIMENTS

Faulty motors are classified into five groups:

- increased friction in brush-commutator contact,
- bearing fault,
- rotor imbalance,
- impact between fan and housing and
- howling (unpleasant sound).

4.1 Measurement scenario

It turns out that all faults except howling are detectable from sound signal recorded at a constant rotational speed, while detection of howling requires to scan the sound signal recorded across a wide range of speeds. Therefore, for diagnostic purposes the measurement is done according to velocity profile delineated in figure 2.

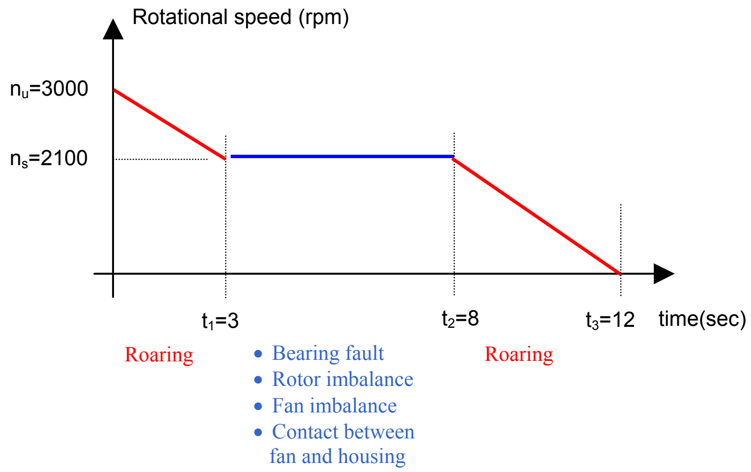

Fig. 2: Rotational speed profile that enables detection of all faults.

The values of time and velocity landmarks were chosen heuristically on the basis of thorough experimentation.

4.2 Tools

For feature extraction the following simple signal processing tools have been applied:

- Root Mean Square (RMS) of the sound signal,
- Power Spectrum Density (PSD) and
- Short Time Fourier Transform (STFT).

PSD of a signal is estimated by means of the periodogram. To decrease the variance of the PSD estimate and to prevent leakage[1] the techniques of windowing, window overlapping and averaging were employed.

Signals with time-varying frequency contents cannot be treated with the traditional Fourier Transform. In order to treat such signals and to provide time-frequency picture of a signal

[1] Leakage is the smearing of energy across the frequency spectrum caused by Discrete Fourier Transform of the frequencies that are not periodic within the time interval of signal.

Gabor (1946) introduced the STFT. Here, the signal x(t) is multiplied with a window w(t-τ) centred or localized around time τ and Fourier transform of x(t) w(t-τ) is computed. In practical cases one deals with discrete signals, hence the STFT is computed only for discrete values of ω, and for finite number of window positions τ. With STFT the time domain is mapped into the time-frequency domain.

During the experiments it was found out that sensor for rotational speed is actually redundant. With cepstrum analysis (Brüel & Kjaer, 1987) of the very sound signal it is possible to estimate rotational speed quickly and with satisfying precision. Figure 3 depicts complex cepstrum of the sound signal recorded at constant rotational speed. Time interval between two neighbouring peaks is actually the time of one rotor revolution.

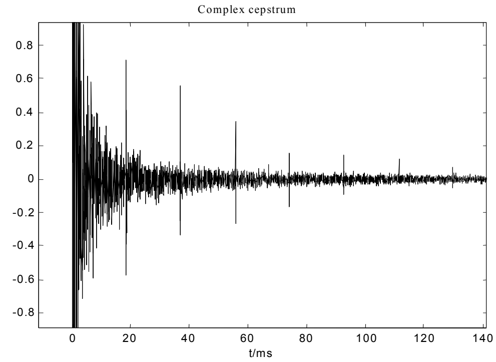

Fig. 3: Complex cepstrum of a sound signal.

5. EXPERIMENTAL RESULTS

It transpires that the sound of the motor is very unpredictable and variable phenomenon. Namely, PSDs computed from recordings taken during two consecutive experiments under same conditions can differ a lot. In PSDs still the same characteristic frequencies appear, but their magnitude can differ 100% or even more. Hence, for fault isolation one must use relative relations among components instead of their absolute values.

5.1 Fault-free motor

A fault-free motor is significantly less noisy than motors with faults. Components that belong to the sound of mechanical sources are scarcely noticeable. Electromagnetic noise (100Hz) prevails over all other sources (see figure 4).

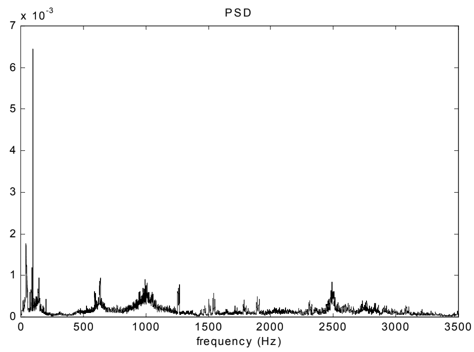

Fig. 4: Power spectrum density (PSD) of a fault-free motor.

5.2 Bearing fault

Fault in a rolling element bearing influence the sound of the motor in the specific way, i.e. it causes amplitude modulation of a sound signal. A modulation frequency is usually

$$f_m = \frac{f_S}{2} Z \tag{1}$$

or close to this frequency (f_S denotes a shaft frequency, i.e. a number of rotor revolutions per second and Z (Z=7) is the number of rolling elements) and the carrier frequency is some high frequency component which distinguishes for different motors. This tallies with the corresponding theory about rolling element bearing defects (Barron, 1996).

Figure 5 depicts PSD typical of motors with bearing faults. In this case the modulation frequency is approximately f_m=3.5f_S and the carrier frequency is 3770Hz.

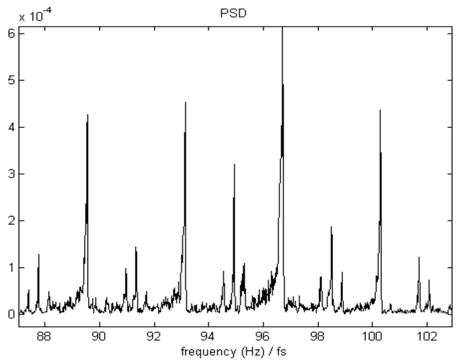

Fig. 5: PSD of a motor with a faulty bearing.

5.3 Howling

Motors labelled with the "howling" attribute produce an unpleasant sound, typically at lower rotational speeds. Howling itself is a manifestation of a fault in rotating parts (most likely improperly assembled bearing on the rotor shaft).

Different motors exhibit howling at different rotational speeds therefore an entire range of speed must be checked to detect this kind of fault. According to velocity profile (see figure 2) sections B1 and B2 are taken into consideration in signal processing. A sound signal recorded in these sections is nonstationary because the frequency content of the signal varies with time. In order to obtain the frequency content of the sound signal as a function of time, the Short Time Fourier Transform is applied.

Figure 6 depicts two power spectrum densities. The first PSD (a) belongs to a fault-free motor and the second (b) to a motor labelled with attribute “howling”. The difference between the sounds generated by such two motors is obvious. The sound of a fault-free motor entails “standard” components (reflecting electromagnetism, aerodynamics and brush commutator contact) while “howling” motor has highly increased power of frequency band between 9 kHz and 13 kHz. Moreover, the power of this frequency band is speed-invariant.

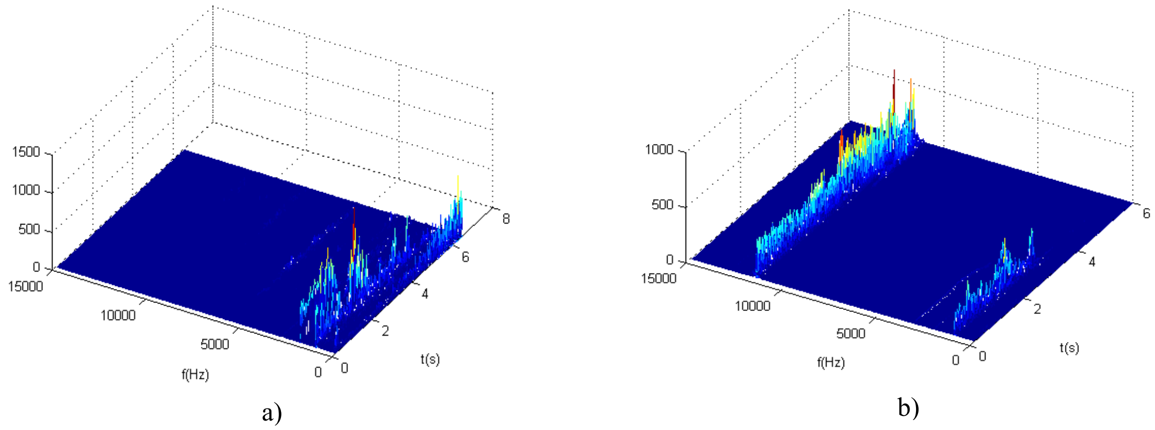

Fig. 6: PSD in time-frequency domain for (a) fault-free motor and (b) motor labelled with "howling" attribute.

5.4 Increased friction in brush-commutator contact

Commutator comprises 22 lamellas. In every rotor revolution brush slides over all of them and every impact between brush and lamella generates specific noise. In power spectrum this is presented with a peak at the frequency

$$f_i = f_S \cdot 22 \cdot i \qquad i = 1,2,3... \tag{2}$$

and its higher harmonics (i). Accordingly, the sound spectra are characterised by increased magnitudes of characteristic frequencies (equation 2). Figure 7 depicts the corresponding PSD. In this case only the magnitude of second harmonic frequency (i=2) is increased. Higher harmonics are not presented in figure because their magnitudes are rather weak.

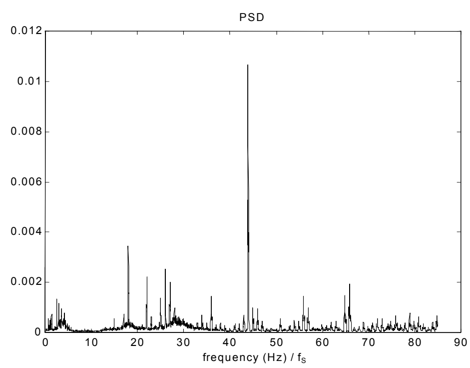

Fig. 7: PSD typical of motors with brush-commutator defect.

5.5 Impact between fan and motor housing

In some motors the fan impeller is improperly attached to the shaft. During rotation at low rotational speeds the fan shimmies and rubs against motor housing and adjacent parts, which also results in the emitted noise. As the rotational speed increases the airflow through the motor increases along with an air pressure at the input airflow port. High air pressure fixes the fan and prevents it from shimmying and therefore from rubbing against motor housing. Thus, for higher rotational speeds this noise literally disappears.

In sound of a motor this contact results in increased power of all frequencies in the frequency range between 3kHz and 8kHz (the energy is smeared over entire frequency band). Figure 8 depicts PSD typical of this fault.

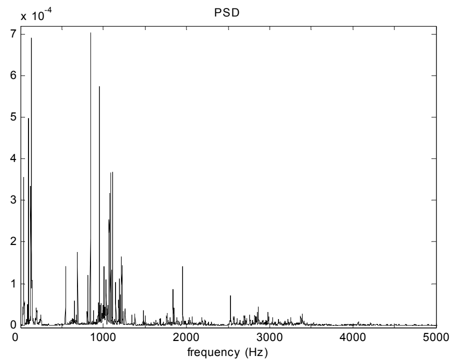

Fig. 8: PSD of a motor labelled as "impact between fan and housing".

5.6 Rotor imbalance

A motor with unbalanced rotor is subdued to increased centrifugal forces. These forces gradually bend its shaft, which brings on more intensive and irregular wear of motor parts that stay in contact all the time, i.e. brush, commutator, shaft and bearing. These parts are made of metal therefore their interaction result in high frequency noise. In power spectrum this reflects as the increased power of frequencies in the frequency range between 9kHz and 13kHz. Figure 9 depicts the PSD of a motor with unbalanced rotor.

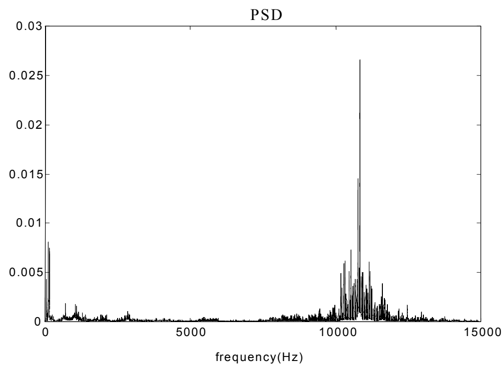

Fig. 9: PSD of a motor with rotor imbalance.

6. CONCLUSION

By using rather simple signal processing tools it is shown that sound actually carries important information about condition of vacuum cleaner motors. The results obtained on 68 motors, show that motors with mechanical faults generate specific sound, which can be easily distinguished from fault-free motors. Moreover, with sound analysis it is possible to clearly isolate motors labelled as “fault in brush-commutator contact” and most of the motors labelled as “bearing fault”. Other motors (e.g. labelled with attributes “howling” and “rotor imbalance”) emit rather similar sound and therefore cannot be reliably isolated from each other.

Acknowledgements

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