VIBRATION ANALYSIS OF VACUUM CLEANER MOTORS

Dejan Tinta

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

Abstract: Vacuum cleaner motor is a device consisting of a universal electric motor and a fan impeller that makes air flow in vacuum cleaners. In this paper a fault diagnostic system for vacuum cleaner motors is presented. The core of the system are four modules for feature extraction. The first one is based on the mathematical model of the device, the second one estimates quality of commutation while the third and fourth one rely on vibration and noise analysis respectively. Features generated by these modules from measured signals are used for fault isolation by using an approximate reasoning method. An excerpt from the diagnostic system i.e. the module for feature extraction based on vibration analysis is described in the sequel.

Keywords: vacuum cleaner motor, fault detection, vibration measurement, vibration analysis.

1. INTRODUCTION

The manufacturers of vacuum cleaner motors tend to purchase (almost) 100% fault-free devices by lowest prices. This demands for well-organised process of quality assurance during the manufacturing cycle. This paper addresses a family of vacuum cleaner motors manufactured by company Domel, which is a recognised European producer. The quality assurance in Domel consists of two segments. Firstly, several standard automated tests are performed on most critical components during assembly (e.g. rotor balance, high-voltage test etc). As the matter of fact, those tests are able to reveal defects on the level of components only. That means that some errors occurring during assembly process might become visible not earlier than on the end product. Therefore a thorough and in-depth analysis of the condition of the end product is very important. Currently the end test entails only manual measurements of vibrations, sound inspection and visual checks. The rest of the quality assurance process relies on a statistical procedure for quality control of finished series. This segment takes a rather high amount of work and, consequently, costs. Therefore, it is hoped that a way to reduce costs is to employ thorough end tests able not only to reveal defective motors but also to isolate the root cause. Thus the operators will have the opportunity to take immediate corrective actions on assembly line. Similar ideas, though with different realisation, have been applied by Yang and Penman (2000), c.f. also web page of Schenk, Albas et al. (2000).

Vibration measurement is one of possible approaches that can be utilized for end test of the vacuum cleaner motors. Namely, the vibration signal is the carrier of information about different faults on the motors. Furthermore the vibration also indirectly affects the lifetime of the motors. Finally the vibration causes the noise, which is disturbing for users.

The purpose of this paper is to describe a prototype design of a diagnostic system for vacuum cleaner motors. The core of the system consists of four modules for feature extraction and a module for fault isolation via approximate reasoning. The paper is organized as follows. Short description of the vacuum cleaner motor is given in the second section. Experimental environment for measuring different quantities on the motors is described in the third section. The fourth section introduces the diagnostic system structure. An excerpt from the diagnostic system i.e. the module for feature extraction based on vibration analysis is explained in the fifth section.

2. THE DESCRIPTION OF VACUUM CLEANER MOTOR

Vacuum cleaner motor is a single-phase commutation motor whose construction and working principle are the same as in DC motors. It is also referred to as universal motor because it can run under AC and DC voltage supply. Owing to the fact that stator and rotor windings are serially connected and therefore the load current flows also through the excitation windings, the largest motor torque is achieved. This electric motor has a big start up torque. The main weak point is commutation, i.e. problems of sparking and brush wear, which seriously affects the device lifetime.

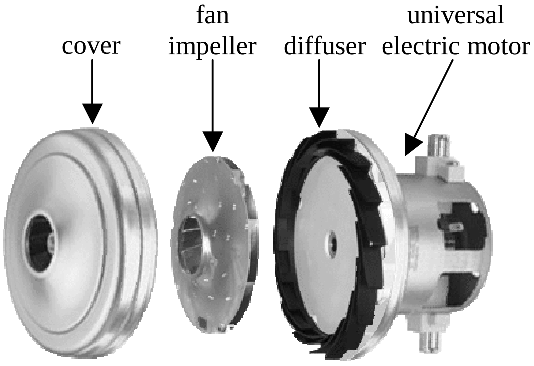

Fig. 1. Components of the vacuum cleaner motor

Main parts of the vacuum cleaner motor are shown in Figure 1. Fan impeller with nine shovels mounted on motor’s shaft generates airflow through the hole in the cover. The diffuser directs then the airflow through the orifice between stator and rotor in order to cool the motor. The nominal rotational speed of those motors is $550s^{-1}$.

3. EXPERIMENTAL ENVIRONMENT

Experimental environment consists of three parts: power supply, signal adapter and personal computer with Burr-Brown PC card PCI-20041C for data acquisition (see Figure 2).

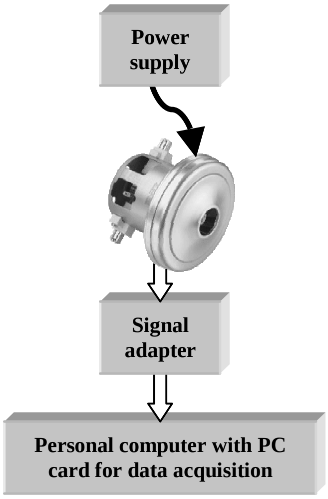

Fig. 2. Experimental environment

The experimental environment enables measuring of the following physical quantities on the vacuum cleaner motors: supply voltage, current, voltage on brushes, vibration, noise and revolutions.

The supply voltage and voltage on brushes are adjusted to the voltage level ±5 V and galvanically isolated. The current is measured as a voltage drop on the precise resistor. A piezoelectric sensor is used for the vibration measurements. Its output is proportional to vibration acceleration. Namely, the piezoelectric responds to the force, which equals the product of the measured vibration acceleration and seismic mass in the sensor. The noise is acquired by means of a condenser microphone in an anechoic chamber that prevents reflection of the sound and smoothes disturbing noise from environment. So the microphone perceives only the noise from vacuum cleaner motor. Rotational speed is measured with an infra-red sensor, which detects a black mark on the motor's shaft.

4. DIAGNOSTIC SYSTEM STRUCTURE

The architecture of the algorithmic part of the diagnostic system is depicted in Figure 3. There are four feature extraction modules that operate on data obtained during motor operation under a pre-specified velocity profile. These modules blend methods of signal processing and parity equations.

The first module makes use of a semi-physical mathematical model of the motor, which relies on power conservation laws. Discrepancy between measured and predicted values reflect fault either in electrical or mechanical part.

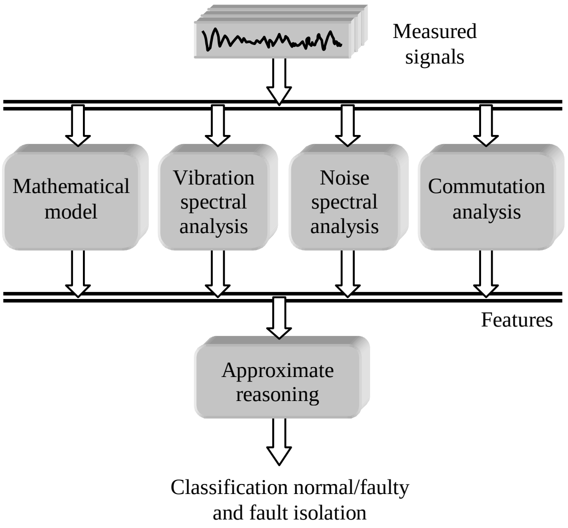

Fig. 3. Structure of diagnostic system

Module based on noise spectral analysis detects modifications of noise power spectra caused by rubbing between static and rotating parts of the motor or defected bearings. The relevant sound recordings are done at lower rotational speed of the motor in order to avoid the influence of aerodynamic component contributed by fan impeller. The mechanical and electromagnetic noises are dominant under this measurement conditions (Benko, et al., 2002).

Commutation substantially impacts the motor lifetime. Commuted collector current induces high voltage peaks, which generate sparking between collector and brushes. Increased sparking causes increased wear of brushes. Commutation analysis is based on non-linear signal processing of emitted radio-frequency noise (Petrovčič, et al., 2002). The histogram of the resulting signal allows for clear distinction between motors with normal commutation from those with increased sparking.

In order to isolate eventual faults on the basis of partial evidences received from each feature extraction module the Transferable Belief Model (TBM) is employed (Rakar and Juričić, 2002; Shing and Jang 1993). The output is a list of most likely faults accompanied by a degree that express confidence in the diagnostic results.

5. VIBRATION ANALYSIS

In order to get useful information from vibrations signal one has to yield proper insight in the underlying mechanisms. Figures 4 and 5 illustrate what happens if amounting of vibration sensor and data acquisition are performed in a merely routine way. Firstly, nothing can be seen from displaying data in time domain. Even motors in good and bad condition hardly show any difference. Moreover, even if measurements are repeated on the same motor under the same measurement conditions, and results are observed in the frequency space, obvious differences occur! The main reason lies most likely in small dimension of the motor and light mass so that a change in initial condition results in different vibration records.

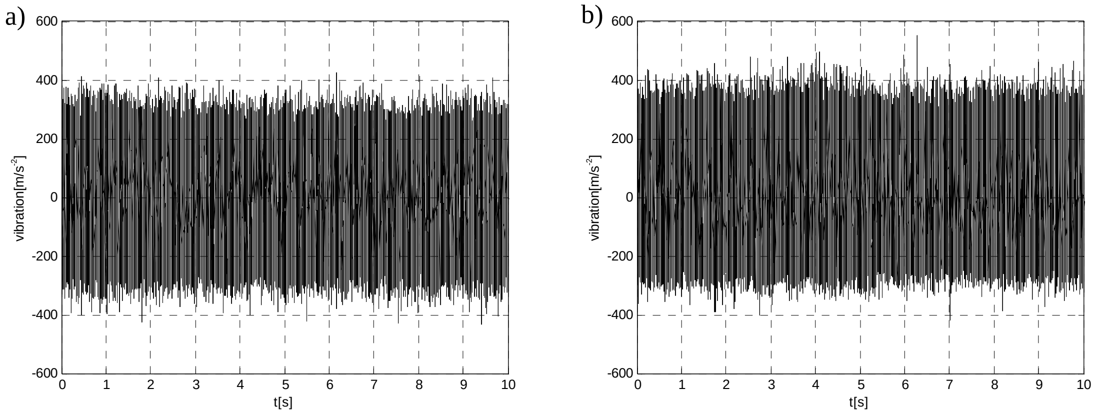

Fig. 4. Vibration signals of: a) normal vacuum cleaner motor, b) faulty vacuum cleaner motor

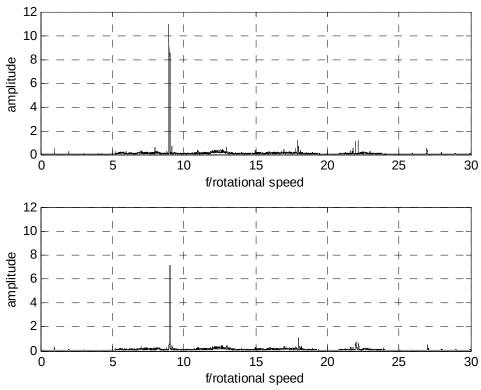

Fig. 5. Two vibration spectra obtained on the same vacuum cleaner motor (motor is fault-free)

Consequently, a more detailed study of vibration origins is required. Indeed, vibrations originate from several sources:

- fluctuating motor torque (due to AC supply),
- mass imbalance, which manifest as shaking of the entire motor (imagine rotor as a giro) and waves in housing (due to impulses caused by shaft hitting bearings, c.f. Figure 6),
- impulses caused by changes in direction of air velocity (air pushed by fan impeller through the diffuser changes the momentum) and
- impulses provoked whenever the collector lamella hits the brush during the commutation cycle.

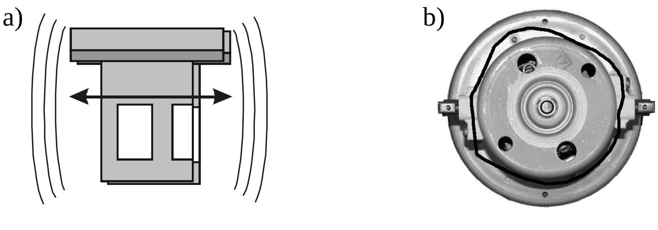

Fig. 6. Manifestation of vibration sources: a) shaking of the whole motor, b) waves on housing

The first source can be seen at frequency 100 Hz (c.f. power density spectrum in Figure 7). It arises from time varying motor torque, which fluctuates with the frequency 100 Hz. Magnetostriction also contributes to that component. Namely it causes widening and contracting of material due to alternating magnetic field in the motor. Both components disappear as soon as DC supply is employed.

The largest frequency component is at $9 \cdot f_0$ (f_0 stays for number of revolutions per second). It originates from air strokes produced by nine shovels of fan impeller. Because of very high rotational speed these air strokes are so big that this frequency component dominates in the vibration signal.

The fourth component appears at $22 \cdot f_0$ as there are 22 lamellas of collector. It results from slight jumps of brushes each time a lamella passes by. Unfortunately, no relationship between this component of vibration signal and condition of motor commutation was found out.

Obviously, the third and fourth components appear irrespective of motor condition, i.e. they are default due to motor construction.

The most important frequency component, which reflects motor condition, appears at the rotating frequency f_0. Eccentricities in any of the rotating parts, bad bearing and mounting faults reflect in this component. Consequently it is one of the features used for vacuum cleaner motor classification.

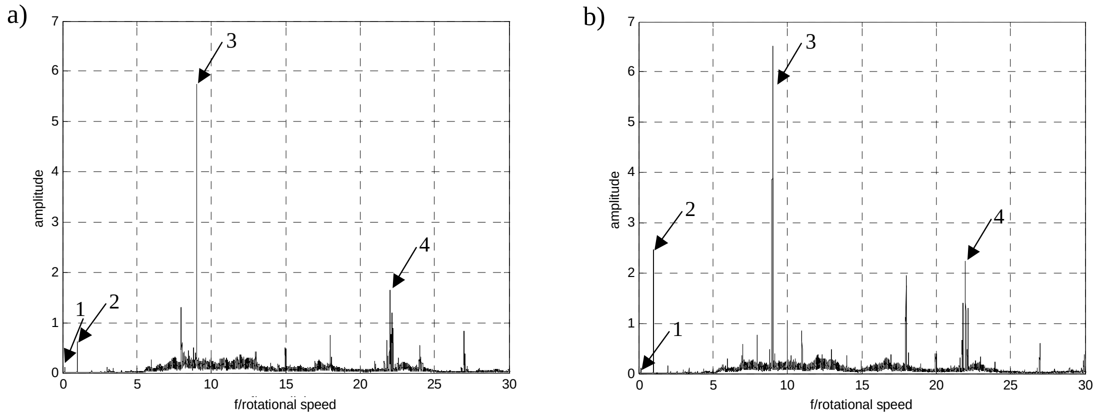

Fig. 7. Vibration spectra of: a) normal vacuum cleaner motor, b) faulty vacuum cleaner motor. Important components of the spectrum are originated by: 1 - fluctuating motor torque and magnetostriction, 2 - unbalanced rotating parts, 3 - air strokes produced by fan impeller and 4 - brush-collector contact. The component at rotational speed of the motor (2) is used as a feature for the vacuum cleaner motors classification.

One of the issues in vibration-based diagnosis is sensor position. It has been shown by a very detailed study that vibrations spread from cover of the motor to other parts of the housing. Therefore the vibration signal is not only composed of shaking of the whole motor (see Figure 6a) but also of waves in housing (see Figure 6b). These waves have knots and peaks (see the black curve in Figure 6b) the positions of which vary from motor to motor. These positions also depend on rotational speed of the motor. Fortunately, what all motors have in common are four knots on the contacts between stator and housing. This observation holds true irrespective of the rotational speed. Given the fact that shaking reflects imbalance in the rotating parts, the most appropriate position of vibration sensor turns to be any of the four contacts between stator and housing. Thus the influence of waves on stability of the extracted feature and repeatability of measurements is minimized.

The computational aspect of calculating spectra is also important. A spectrum is calculated as mean value of seven spectra obtained by using discrete Fourier transform of the signal. Time segments are weighted with Hanning window. Two-thirds overlap of time records is used to avoid loss of data and thereby possible loss of valuable information. If the time records would not overlap, parts of the signal would not be included in the average. Averaging of spectra is applied to eliminate the noise.

6. CONCLUSIONS

The prototype of diagnostic system for fault detection on vacuum cleaner motor is presented in the paper. A motor is first run shortly under a proper velocity profile. From the analysis of six acquired signals with different algorithms for feature extraction almost all the faults can be uniquely isolated. In some cases even multiple faults can be recognised.

Module based on vibration spectral analysis is described in detail. The origins of different vibration components are revealed and the vibration measurement conditions are defined.

One of the problems to address in the future regards threshold selection and diagnostic system calibration. Thresholds of features namely have essential influence on diagnostic accuracy and sensitivity of the system. The concept of anthropocentric design will be applied for that purpose. So the user should on the base of his own experience choose the proper threshold values according to his concrete needs.

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