IN-DEPTH FAULT DIAGNOSIS OF SMALL UNIVERSAL MOTORS BASED ON ACOUSTIC ANALYSIS

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Abstract: The traditional techniques for assessing end quality of electrical motors rely on techniques such as vibration analysis, analysis of electrical current and parity relations between electrical and mechanical quantities. However, for certain types of small universal motors these techniques fail to provide reliable diagnosis for a set of incipient mechanical faults (impact between rotating surfaces). The aim of this paper is to present a complementary approach based on acoustic analysis, which results in unambiguous and reliable diagnostic classification. The underlying case study refers to the fault detection and isolation of vacuum cleaner motors in the framework of quality assessment at the end of the production line. The main contributions of the paper are as follows. First, a detailed analysis of sound sources is performed and a set of appropriate features is suggested. Second, for the purpose of fault detection efficient signal processing algorithms are presented, which enable detection and isolation of faults with mechanical origin and faults with aerodynamic origin. Third, a prototype version of a test rig is designed and applied on a set of test motors. Finally an excerpt from diagnostic system performance evaluation obtained from a vast experimental study is provided.

Keywords: sound analysis, fault detection, electrical motors, Hilbert transform, signal processing.

1 INTRODUCTION

Fault diagnosis of electrical machines – and rotating machinery in general – is a vast subject that has been thoroughly studied and numerous applications have resulted thereof. The most widely used diagnostic means employ traditional techniques such as vibration analysis, analysis of electrical current and model-based parity relations (see Edwards et al. (1998) for a broad overview). These techniques proved useful in most of the cases in which various DC and AC drives, including universal motors were employed. Indeed, vibrations and current signal bear rich information about tiniest defects in mechanical parts such as imbalance, bearings, impacts etc. In this paper attention will be focused on a family of small universal motors with serially connected stator and rotor windings. For these types of motors these techniques fail to provide reliable diagnosis of all relevant defects. Therefore, this paper attempts to provide a complementary approach, which is based on *acoustic* analysis. The ideas are demonstrated on a case study dealing with diagnosis of vacuum cleaner motors at the end of the production line. Indeed, various faults can occur during the assembly process such as insufficient balancing, improperly built-in bearings, missing contacts on commutator bars, deformations on fan impeller etc. These faults manifest in different ways, most notably in increased vibrations, unfamiliar sound, intensive sparking and howling. Therefore, a thorough test is required in order to gain a clear indication about tentative fault sources. In order to study the problem in depth, a prototype version of the diagnostic system has been developed.

Similar motivation, though with different realisations, has been reported by several other authors. For example, the system produced by (Schenk, 2002), make use of vibration analysis, statistics and analytical redundancy based on the mathematical model. Similar approaches were utilised by (Vogelsang&Benning, 2003) and (Albas et al. 2002), but none of them employs sound analysis. Moreover, the diagnostic sensitivity of those systems to some incipient mechanical faults is questionable. What makes the system presented in this paper distinctive is utilisation of the sound analysis as a non-contact means for detection of mechanical faults. Actually, alternative means such as electric current analysis and vibration analysis did not prove useful in our case. For example, faulty bearing in this particular motor cannot be efficiently detected from the motor current signal. The serial connection between the rotor and the stator windings of the motor results in high electric inductivity, which strongly attenuates higher-frequency components of the current signal. That is why any change in load, which should reflect in the current variation, remains unseen. This is not an issue in motors with permanent magnet, where faulty bearings can be successfully detected by motor current analysis (Vetter et al., 1994). Vibration analysis also falls short of expectations for two reasons. Firstly, in vibration measurement the vibration sensor should be placed as close as possible to the vibration source (e.g. faulty bearing), because magnitudes of vibrations decrease quickly with the distance from the source. In large machines, with large bearings, it is not a problem to mount a piezo sensor on the bearing housing. It is even simpler to direct the beam of a laser vibrometer to any point but, unfortunately, such a solution is (still) rather expensive. The dimensions of the motor represent an additional constraint in the case of the vacuum cleaner motor described below. This motor is rather small and the sensor can reach only one bearing while the other bearing lies within the construction and is inaccessible. Another problem related to vibration analysis is that during lower rotational speeds the bearings provoke very weak vibrations, which cannot be detected by a vibration sensor, whilst during higher speeds the airflow of the fan impeller strikes the housing and provokes housing vibrations, which prevail over vibrations originating from bearings. On the contrary, faulty bearings produce significant sound. Owing to the motor structure, the motor cover performs as a kind of resonator, which amplifies the sound from bearings and thereby makes the sound a representative means for fault detection.

Main parts of the vacuum cleaner motor are shown in Figure 1. The fan rotates together with the rotor in order to fulfil the primary function, i.e. air suction. The diffuser serves to direct the airflow through the orifice between stator and rotor in order to cool the motor. The motor operates at a nominal speed of 38000 rpm.

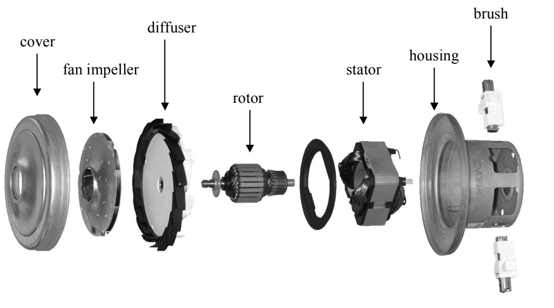

Figure 1: Components of the vacuum cleaner motor.

The paper is organized as follows. In the second section a detailed description of the sound analysis module is provided and in the third section a structure of the diagnostic system along with a summary of the diagnostic system performance presented.

2 SOUND ANALYSIS

2.1 *Sound Sources*

Sound generated during motor rotation originates from three main sources:

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

In the motor under investigation, the contribution of the first source can be neglected. Indeed, electromagnetic sound does not provoke or indicate any kind of fault. More attention needs to be paid to airflow and mechanical contacts. In order to detect faults originating from mechanical sources, the motor must run at low rotational speed, whereas detection of aerodynamic faults requires higher rotational speeds.

2.2 *Mechanical Faults*

The most usual mechanical faults in the underlying motor are bearing faults and rubbing between the rotating and static parts. Both of these two faults have common characteristic, i.e. the emitted sounds contain high frequency repetitive bursts (see Figure 3 and Figure 4). In the case of bearing fault, the frequency content of bursts lies between 2.5 kHz and 3.5 kHz, whereas in the case of rubbing fault this frequency is much higher and lies between 10 kHz and 15 kHz. For the purpose of fault detection, one has to infer the repetition frequency of bursts. In the case of a bearing fault, the bursts repetition frequency depends on the geometry of bearings, rotational speed and exact location of the fault within the bearing. For a given motor these frequencies read as follows:

- cage defect: $0.37 f_0$,
- outer race defect: $2.6 f_0$,
- inner race defect: $4.4 f_0$,
- ball defect: $1.77 f_0$,

where f_0 denotes the rotational speed of the motor. In motors with rubbing, this frequency is usually f_0 and $2f_0$. This can be explained by the fact that in most cases rubbing occurs in one or two particular angular positions of the rotor, which in terms of frequency response means once or twice per rotor revolution. Since the frequency contents of bursts and the bursts repetition frequencies differ for these two faults, these two faults can clearly be distinguished.

In order to detect motors with such faults, the bursts repetition frequency must be evaluated. The signal with repetitive bursts can be treated as amplitude modulated signal where the bursts repetition frequency corresponds to the modulation frequency, and the frequency content of bursts to the carrier frequency. Detection of bursts repetition frequency can therefore be done by using envelope analysis. (Randall, 2002) has shown that detection of repetition frequency of bursts from the signal envelope is much more robust to variations in rotational speed than detection from the raw signal itself. The envelope is obtained by amplitude demodulation (2) realized with Hilbert Transform (HT) (Randall, 1987). Basic principles of HT are summarised in the sequel.

2.2.1 *Hilbert Transform*

The Hilbert transform of a time function $x(t)$ is an integral transform defined as (Boashash, 1992)

$$H\{x(t)\} = \tilde{x}(t) = p.v.\frac{1}{\pi}\int_{-\infty}^{+\infty} x(\tau)\frac{1}{t-\tau}d\tau = \frac{1}{\pi}x(t) * \frac{1}{t} \quad (1)$$

where p.v. denotes the Cauchy principle value of the integral (Hildebrand, 1949). The signal $x(t)$ and its Hilbert transform $H\{x(t)\}$ yield the analytic signal[1] in the following way

$$z(t) = x(t) + jH\{x(t)\} = |z(t)|e^{j\phi(t)} \quad (2)$$

If $x(t)$ is a monocomponent signal[2], the amplitude of an analytic signal $|z(t)|$ represents the instantaneous amplitude or signal envelope while the phase of the signal $\phi(t)$ equals the instantaneous phase. Let us remind that the instantaneous frequency *IF* can be derived from the instantaneous phase in the following manner

$$IF(t) = \frac{1}{2\pi}\frac{d\phi}{dt} \quad (3)$$

In the ideal case *IF* is constant and can be referred to as the carrier frequency. It turns out that in our case *IF* can be treated as constant without any loss of information.

The Hilbert Transform can be effectively applied as a demodulation technique. Moreover, if a signal is monocomponent, the transform inherently selects the higher frequency of the signal as the *IF* and the lower frequency as the envelope without prior knowledge about the signal. This renders construction of the signal envelope possible even if the exact value of the carrier frequency is not known. This approach is also utilised in our case, where carrier frequency varies from motor to motor.

The interested reader is recommended to refer to the tutorial (Boashash, 1992), which provides the details about the Hilbert transform.

2.2.2 *Detection of Bursts Repetition Frequency*

In order to detect motors with bearing faults and motors with "rubbing"[3], the procedure depicted on Figure 2 is employed. The original sound signal is firstly passed through two parallel bandpass filters. Filter A serves to isolate the part of the signal excited by faulty bearing, whereas Filter B isolates the sound emitted by possible rubbing. Filtered signals are then processed by a module, which performs amplitude demodulation by means of Hilbert Transform (2). The outcomes of this module are two envelopes. The first envelope corresponds to the bearing fault and the second to the rubbing fault. The envelopes are then passed through the filters, which isolate only the frequencies characteristic for bearing fault and rubbing fault. The RMSs of these signals serve as the features for bearing fault and rubbing fault, respectively.

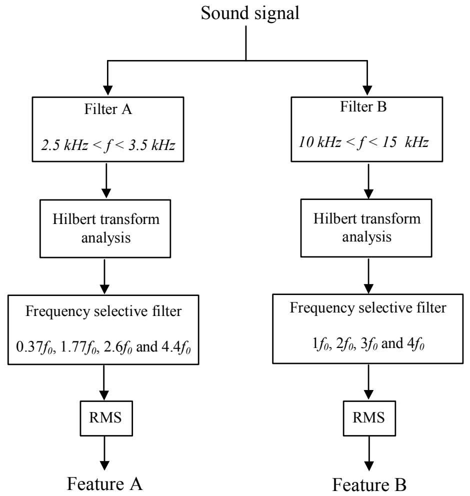

Figure 2: Procedure for detection of mechanical faults

To demonstrate how the procedure works, two signals are compared step by step and results are depicted in figures 3 and 4. The first signal belongs to a motor with a faulty bearing (inner race defect) while the second one belongs to the motor with a rubbing fault. Figure 3 presents the first sound signal (raw signal) and two envelopes extracted from that signal and Figure 4 presents equal plots for the second signal.

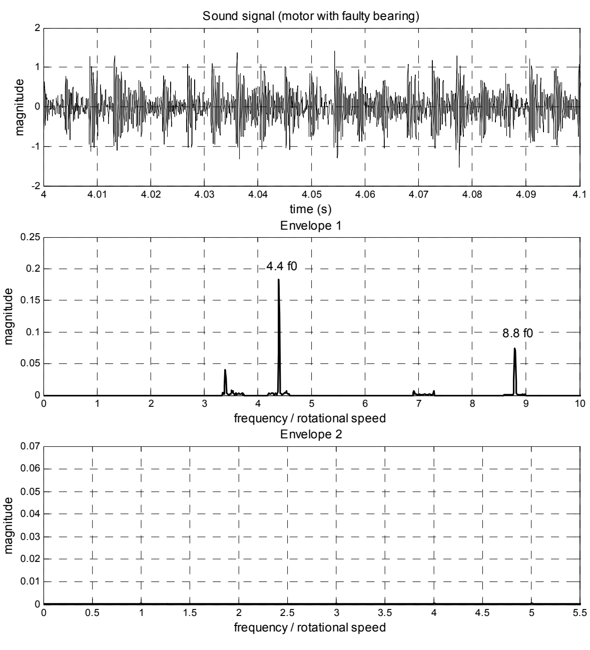

Figure 3: Envelopes of a motor with bearing fault extracted by means of procedure presented in Figure 2.

[1] Analytic signal is a signal, which satisfies Cauchy-Riemann conditions for complex signals (Kreyszig, 1999).

[2] Monocomponent signal is a signal in which the amplitude of only one frequency component varies as a function of time (Boashash, 1992). In terms of frequency domain, monocomponency means that the spectra of amplitude $|z(t)|$ and phase $\phi(t)$ of a signal are non-overlapping.

[3] "rubbing" is a label for occasional/continuous contact between cover and fan impeller (see Figure 1)

It is obvious from Figure 3 that motor with bearing fault exhibits peaks in power spectrum characteristic of bearing fault (envelope 1), while no power content can be seen from the envelope 1 in case of a motor with rubbing (Figure 4). On the contrary, envelope 2 of a motor with rubbing fault (Figure 4) has spectral peaks characteristic of rubbing fault, whereas no content can be seen in envelope 2 of a motor with bearing fault (Figure 3).

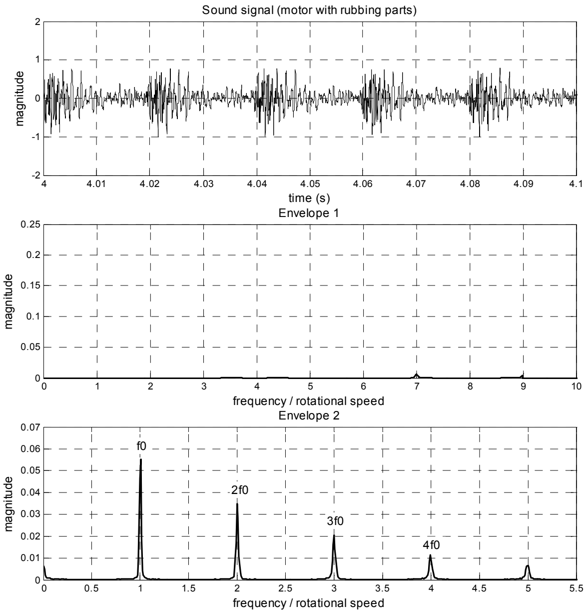

Figure 4: Envelopes of a motor with rubbing fault extracted by means of procedure presented in Figure 2.

2.3 Faults With Aerodynamic Origin

In nominal operating conditions most of the emitted sound is due to aerodynamics. This is characteristic of such type of rotating machines. This sound depends on the geometry of the fan impeller, and rotational speed. The higher the rotational speed, the greater is the sound intensity.

Even slight deviations in geometry of the fan impeller can substantially affect the sound, making it rather unpleasant and annoying. The deviations, which are the most impairing in this particular type of motor are as follows:

- sharp edges of the fan impeller, and
- improperly manufactured or assembled shovel.

Sharp edges at high rotational speeds imply whistle sound, whereas improperly manufactured or assembled shovel brings motor to howling.

It was found out that such faults imply increased power density at the frequencies $kN_S f_0$, k=1,2,.. and $kN_C f_0$, k=1,2,… N_S=9 is the number of shovels and N_C =17 is the number of compartments in the diffuser. The important fact here is that these frequencies alone do not cause the annoying noise. One can easily compute that at the rotational speed of f_0=550 Hz, the higher harmonics $34f_0$ and $36f_0$ are 18700 Hz and 19800 Hz respectively, and they even exceed the upper frequency limit of the audible range of human ear. In fault-free motors the power of the sound signal is concentrated at the frequencies $9f_0$, $18f_0$, $27f_0$ and $36f_0$, which are caused by the rotating fan impeller (see Figure 5a). In the case of a motor with fan impeller defect most of the power is concentrated around $17f_0$ and $34f_0$ (see Figure 5b). This is due to irregular airflow through the diffuser. In such a case, the annoying noise is caused by the interplay of two pairs of frequencies ($17f_0$, $18f_0$) and ($34f_0$, $36f_0$). This is called the beating phenomenon.

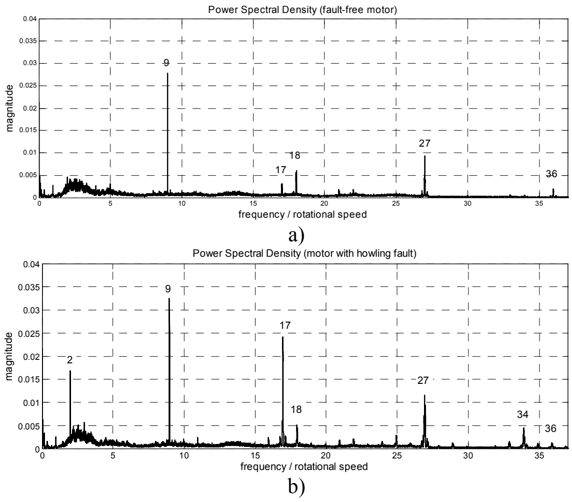

Figure 5: Power spectral density of a) sound signal from a fault-free motor sound signal, b) a sound signal from a faulty motor.

2.3.1 Beating Phenomenon

Beating is a periodic pulsation of the loudness of a sound at a rate equal to the frequency difference between the nearly coincident harmonics. This means that if the signal comprises the frequencies of $17f_0$, $18f_0$, $34f_0$ and $36f_0$ a human ear can perceive this as two frequencies, i.e. f_0 and $2f_0$. Whether or not beating is heard depends upon the amplitude of the harmonics in question and a variety of other factors whose discussion is beyond the scope of this work. Owing to the great power of the frequencies $17f_0$, $18f_0$, $34f_0$ and $36f_0$, the power of pulsating frequencies f_0 and $2f_0$ is large as well. This is actually what we perceive as the annoying noise caused by the deformed fan impeller.

To present the beating graphically, let us show a graph of two superposed sinusoids whose frequencies are close. Indeed, it is easy for our visual system to extract a convincingly pulsating shape from such graphs (see Figure 6).

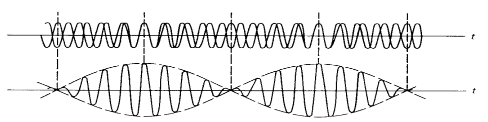

Figure 6: Beating phenomenon

The procedure for detection of such a fault (see Figure 7) is rather simple.

The sound signal passed through a band of four narrow bandpass filters with central frequencies positioned at the frequencies of $17f_0$, $18f_0$, $34f_0$ and $36f_0$. After filtering the two ratios are evaluated (see Figure 7), which also serve as the features. If any of the two features exceeds the threshold, the motor is labelled as faulty.

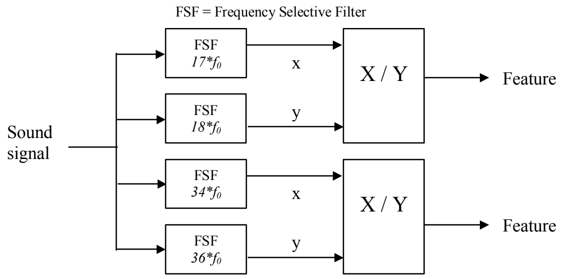

Figure 7: Procedure for detection of aerodynamic faults

3 EVALUATION OF THE SYSTEM PERFORMANCE

3.1 Prototype Diagnostic System

The structure of the prototype system is depicted in Figure 8. The system is built around an anechoic chamber in which a motor is mounted for test.

During a short test a motor is driven along a pre-specified velocity profile. The velocity controller controls the rotational speed. For the sake of a complete diagnosis six different signals are sampled during the experiment, i.e. vibrations, sound, rotational speed, supply voltage, current and voltage on brush contacts.

The recorded signals are then processed by feature extraction modules that employ classical vibration analysis, commutation analysis, check of parity relations and sound analysis. The features obtained therefrom serve as inputs for the reasoning module (Rakar et al., 1999).

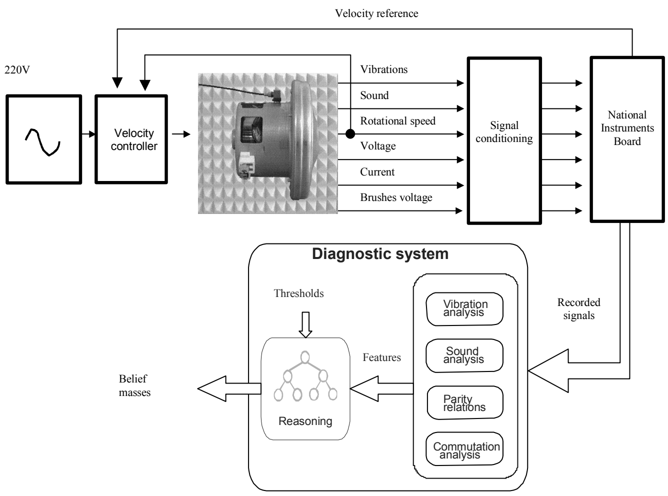

Figure 8: The structure of the prototype system.

Sound is acquired by a microphone mounted in the interior of the anechoic chamber. The applied microphone has a frequency range between 20 Hz and 20 kHz and a voltage/sound pressure sensitivity of 10 mV/Pa. The sound signal, as well as other signals needed for the diagnosis, is passed through an anti-aliasing filter with cut-off frequency of 18 kHz. One can easily see that 34^{th} and 36^{th} harmonics of rotational speed, which are important for detection of aerodynamic faults exceed the cut-off frequency. However, attenuation of these frequencies has no effect on fault diagnosis since the feature is defined as the ration of these two frequencies. After filtration the sound signal is amplified by 50 dB or 40 dB depending on the signal level. The sampling of the signal is done at the sampling rate of 40 kHz.

At the end of the test-cycle the diagnostic system returns a list of most likely states of the motor. It should be noted that the system is able to isolate multiple faults as well. The results of the test are stored in a database, which allows the user to retrieve past records, analyse trends in quality parameters and appropriately re-tune the diagnostic system.

3.2 Results of experiments

3.2.1 Feature uncertainty

The motor itself exhibits complex dynamics. Consequently, features obtained from repetitive tests performed on one and the same motor fluctuate. Standard deviations of the fluctuations of features divided by full range of related features are used as a measure for feature uncertainties. These uncertainties are 5%, 6% and 8% for bearing fault, rubbing fault and aerodynamic fault respectively. This is sufficiently low for good diagnostic resolution.

3.2.2 Sensitivity

High sensitivity of a feature versus a fault, along with low uncertainty of a feature, is important for high diagnostic resolution. Most faults in the motor are by nature difficult to describe in quantitative terms (e.g. damaged bearing, howling, sparking). Consequently, sensitivity cannot be expressed as a ratio between change in the feature value and change in the fault magnitude. Instead, the domain of possible feature values obtained both from healthy and faulty motors can serve as an indication of sensitivity. An example in Figure 9 shows results obtained on a series of 13 motors with faulty bearing and 10 motors with flawless bearing. Obviously, the proposed feature enables clear separation between faulty and non-faulty classes. Similar is the case with other features.

3.2.3 Robustness

Insensitivity of the features vis-à-vis disturbances has been thoroughly analysed. Features based on sound analysis are insensitive to temperature but are highly sensitive to errors in rotational speed, implying variations in feature values of almost 1 % per revolution. The influence of disturbances can be minimised if the sensor of rotational speed is regularly calibrated.

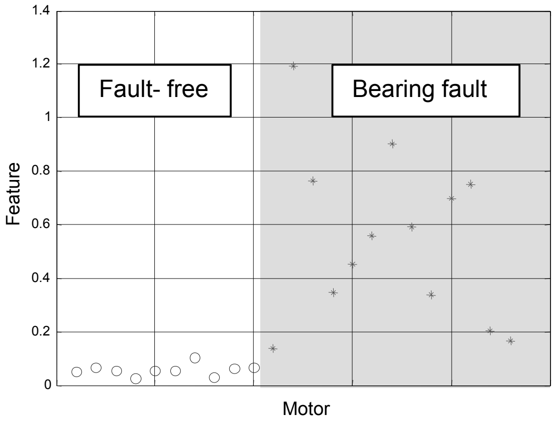

Figure 9: Range of feature values reflecting bearing condition obtained on a set of motors labelled as fault-free and a set of motors suspected of problems with bearing (labelling is done by operators "by hand").

3.2.4 Accuracy

Accuracy refers to the capability of the diagnostic system to hold suspect on the *true* fault. In classical instrumentation the "true" (or rather, reference) response is taken to be that of the etalon device. In our case, the operator's judgements represent etalon. Then, technically, tuning the diagnostic system to the reference "system" is a matter of adjusting thresholds on the generated features. Unfortunately, the operator's judgements happen to be non-uniform in some "grey" cases in which a defect is not particularly obvious. This problem is alleviated by a learning procedure built into the system, which adjusts the accuracy on the basis of features obtained on the set of motors with reference quality and sets of defective motors.

4 CONCLUSIONS

The paper presents a part of a diagnostic system prototype for vacuum cleaner motors based on sound analysis. An attractive advantage of sound analysis is that the measurement requires no contact with the motor. In addition, it is shown that with procedures based on sound analysis it is possible to isolate motors with a bearing fault, motors with intermittent harsh noise emitted due to rubbing of different surfaces and motors that emit unpleasant noise due to deviation in the geometry of a fan impeller. It is worth highlighting that alternative means such as current analysis and vibration analysis did not prove useful in our case. On the other hand, unfamiliar sounds generated by a deformed fan-impeller are not reflected in current or vibration at all. For that purpose a novel approach based on sound analysis was developed, although the techniques above have been motivated by diagnostic problems encountered in universal motors with serially connected windings.

The next step of the project will focus on implementation of the proposed ideas on the assembly line, which will take additional R&D effort.

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