Diagnostics of Rotary Vane Vacuum Pumps Using Signal Analysis and Processing Methods

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Abstract

Rotary vane vacuum pumps are devices widely used in various types of industries. A three-phase electric motor, which is a usual drive source in this group of devices, propels rotor, which is eccentric placed in the cylinder. The combination of this arrangement, between cylinder and rotor, with centrifugal force, forces the vanes to move out and into its slots milled in the rotor. As a result, the increase and decrease of the inter-vane volume occur, causing the air to be sucked into the pump. Due to improper exploitation, there is a possibility of a mechanical damage to the vane, and in some cases the vane can fall out of its groove, what leads to catastrophic failure. The article presents a new method for diagnostics of vanes, based on the observation and analysis of a pressure signal, generated by a rotary vane vacuum pump.

Keywords: vacuum pump, signal analysis, technical diagnostics

1. Introduction

Vacuum in industrial plants is produced using special designed vacuum pumps. There are a lot of different types of them, but rotary vane vacuum pumps are the most commonly used to produce, low vacuum (up to 1 mbar) and medium vacuum (up to 0.001 mbar). They can be found in various industries like pharmaceutical, food, chemical or even plastic processing. They are also used in pneumatic transport and in all kind of holding and moving operations of components during its production [1-3].

The group of rotary vane vacuum pumps can be divided to two separated categories – dry-running and oil-lubricated. Dry-running, also so-called “dry”, rotary vane vacuum pumps, use self-lubricated graphite vanes and they can operate with the capacity reaching up to 560 m^3/h and 100 mbar of maximum pressure. However oil-lubricated, so called “wet”, rotary vane vacuum pumps can operate with the higher capacity reaching even 1600 m^3/h and lower maximum pressure up to 0.1 mbar [2-4]. Technical data of selected pump models are presented in table 1.

Table 1. Technical data of selected oil-lubricated rotary vacuum pumps manufactured by BUSCH company [2]

Model	Nominal pumping speed [m^3/h]	Ultimate pressure [mbar]	Nominal motor speed [min^{-1}]	Weight [kg]
R5 RA0100 F	100	0.1	1500	73
R5 RA0302 D	300	0.1	1500	74
R5 RA0750 A	750	0.1	1200	670
R5 RA1000 B	1000	0.3	1000	1000
R5 RA1600 B	1600	0.3	1000	1330

These types of pumps, are usually built in the same way: electric motor permanently coupled with by the pump unit, which is flange-fitted to the oil-mist separator unit. A critical element of this kind of devices, is the pumps unit consisting of a cylinder, vanes, rotor, side covers with bearing supports, vanes and also inlet and outlet valves. The principle of operation of rotary vane vacuum pumps is illustrated in figure 1A.

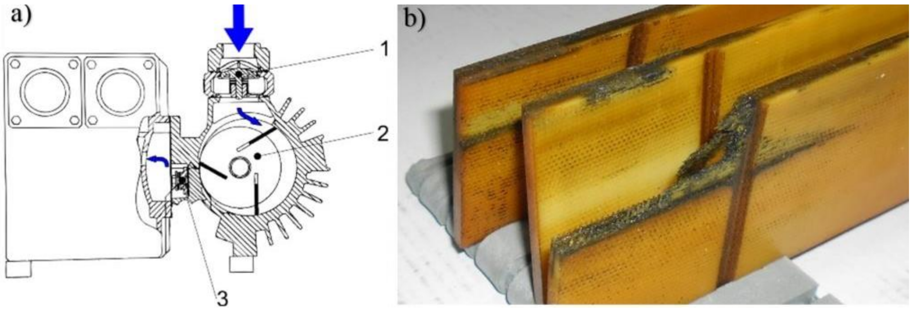

Figure 1. Principle of operation of oil-lubricated rotary vane vacuum pumps (a), and the view of a damaged vane (b) [1]

Electric motor, supplied by three phase current, generates torque, which is transmitted through the claw coupling to the rotor, (with milled slots for the vanes), setting it into the rotation movement [2-4].

The eccentric arrangement of the rotor in the cylinder, in combination with the centrifugal force, forces the vanes to move out and into the slots, what causes regular increase and decrease of the volume between the vanes, leading to suction, compression end exhausting the air into the oil-mist separator unit. Experience shows that properly operated and serviced rotary vane vacuum pumps can work for many years without showing significant wear symptoms [5, 6]. However even during normal exploitation, as a result of different random events, there may occur damages of the vanes, showed in the figure 1B, and sometimes even, as a result of its damage, uncontrolled displacement of the vanes, like falling out of its slot. Such situations leads to serious damage, which cost of repair is similar to the price of a new device. The examples of such damages are showed in the figure 2.

Figure 2. Examples of damaged pumps due to vane malfunction [1]

2. Rotary vane vacuum pumps diagnostics

At this moment, there are two methods of operational maintenance, of rotary vane vacuum pumps. The first one assumes regular inspections and repairs, which frequency is defined by the manufacturer – what often results in excessive costs and pauses in production. The second method, assumes only regular replacements of oil and oil-mist separators, and exploitation of device until a noticeable decrease in the quality of the generated vacuum. This apprenticeship is intuitively and practically much more risky and dangerous, in case of the pump malfunction, but sometimes, in some specific cases, it allows to reduce downtimes. In each of the described scenarios, it is necessary to turn off the pump, disconnect it from the vacuum system and transport it to an external service company. To date, no diagnostic methods are known to identify progressive damages without shutting down the device.

The new diagnostic method, is based on the registration and analysis of the pressure signal, generated by the rotary vane vacuum pump. The specificity of this sort of pumps, imposes restriction on the construction of the measurement system. The first major limitation is its cost. The capacity of the most common oil-lubricated rotary vane vacuum pumps is $100m^3/h$, and a price for such device is around 3500 EUR. For this reason, it was assumed that the cost of components, used to build the measurement system, cannot exceed 5% of the value of a new device of this type device. The second major limitation is the location of the pressure sensor. This sensor should be located as close as possible to the cylinder, behind the inlet filter, to eliminate the influence of inertia and leakage in vacuum system, and to protect it from damage by sucked gases, liquids and solid particles from the technological process. The third and last important limitation is the requirement of the signal recorder mobility, due to the required scope of application and user convenience.

The pressure value is measured at the pump inlet, directly in the suction port, by the analog pressure sensor, connected to the pump, by the short vacuum hose. Then the signal is filtered using a low-pass filter, and together with the signal describing the angular position of the rotor, it is sent to Raspberry Pi microcomputer with an analog-digital converter.

3. Research and results

Experimental studies were carried out on a test device, with a capacity of 100 m^3/h, with low wear rate. The measurement of pressure was carried out with a sampling frequency of 2048 Hz, while the rotor rotational frequency was ~25 Hz. During the tests, there was recorded the course of the pressure generated by the device, equipped with one damaged vane with low degree of its defect (a), with one damaged vane with high degree of its defect (b), with two damaged vanes with various degree its of defects (c), and equipped with undamaged vanes in conditions of lack of lubrication (d). Also the reference test, on the intact device, was performed (e).

The analysis of pressure signal, was carried out in time and in the frequency domain. In the time domain, the synchronous averaging and signal autocorrelation methods were used, while in frequency domain it was limited to spectrum analysis.

As a result of the synchronous averaging method, synchronized by the marked position of the rotor, an average time course of pressure was generated, for every individual state of the device. The coloured lines, which are shown in the figure 3a-e, present the pressure course during single rotations of rotor.

With an increase in the degree of damage of the vane, the chart shows increasing disorder. In the case of a heavily damaged vane, two inflection points are clearly visible, and in the case of a slightly damaged vane, there are visible three inflection points, and the shape of the graph is similar to the shape of an undamaged device. This phenomenon is directly related to the leakage through the edge of the vane. In the case of insufficient lubrication, much more pressure peaks are visible, what is related to the discontinuity of the oil film between the cooperating elements.

While analysing the graph of the normalized autocorrelation function , showed in the figure 4a-e it is possible to conclude about the condition of the vanes working in a vacuum pump. In the case of even small damage, a strong correlation can be seen only once per revolution, which in this measurement conditions is ~82 samples long. With the growing degree of damage to a single vane, the strength of this correlation decreases. In the case of efficient pumping, strong autocorrelation is visible 3 times per revolution, which is associated with the same operating conditions for all three vanes. In a situation where there is a lack of lubrication in the pump unit, a strong correlation occurs also 3 times per revolution, however, the shape of the autocorrelogram envelope is chaotic.

From the analysis of the amplitude spectra of the pressure signals generated by the rotary vane vacuum pump, shown in the figure 5a-e, it is also possible to detect damages of the vanes working in it. In the spectrum of the pressure, generated by an efficient pump, the frequency band of ~75 Hz dominates, which is related to the rotational frequency (25 Hz) of the rotor and the number of 3 rotating vanes. As the vane damage increases, the frequency band of ~25 Hz increase, which corresponds to the frequency at which the damaged vane passes by the suction port. In case of the insufficient lubrication, the pressure signal spectrum shows a significant increase in share of high-frequency components (over ~150 Hz), associated with the operation of moving elements (such as inlet and outlet valves), which are not directly related to the rotational frequency of the rotor.

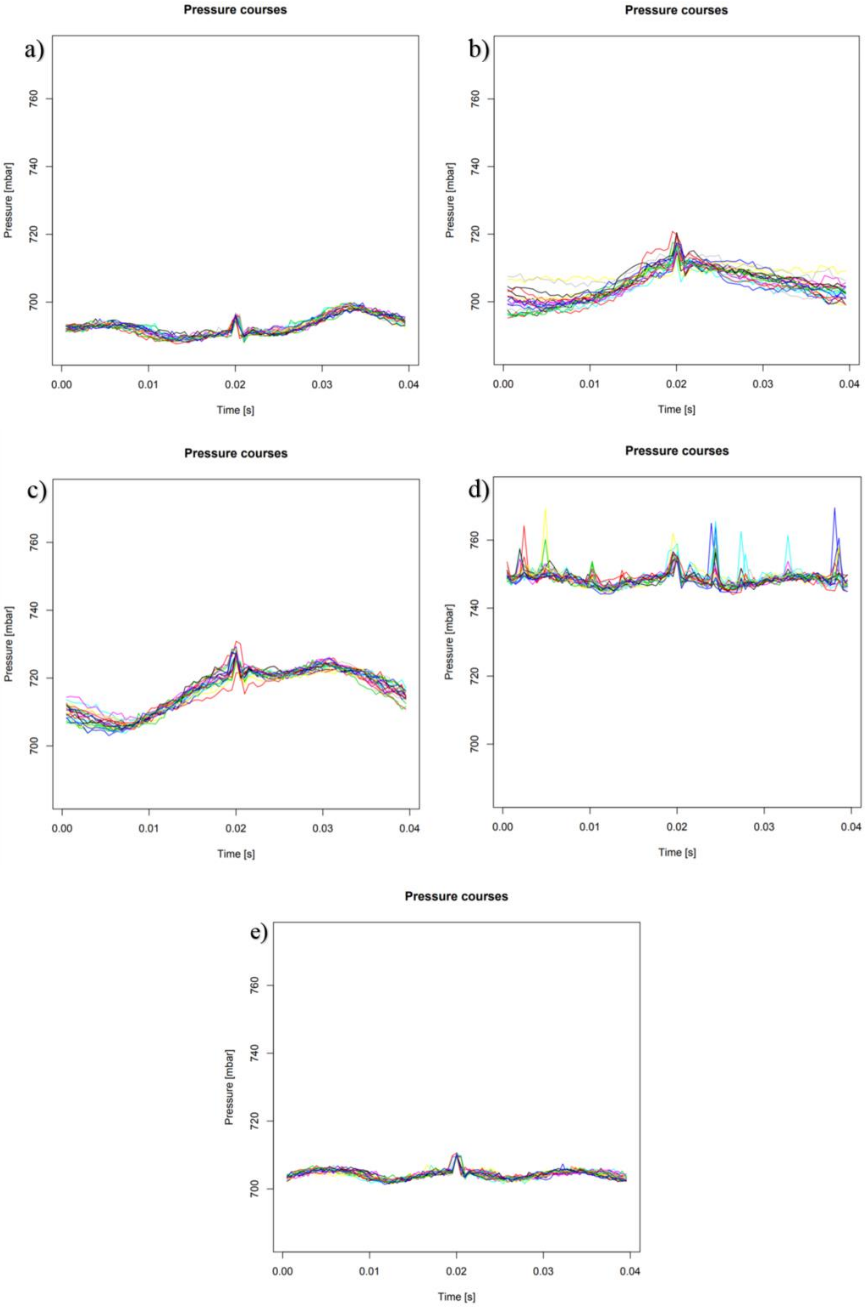

Figure 3. Time courses of the generated pressure signals
(see section 3)

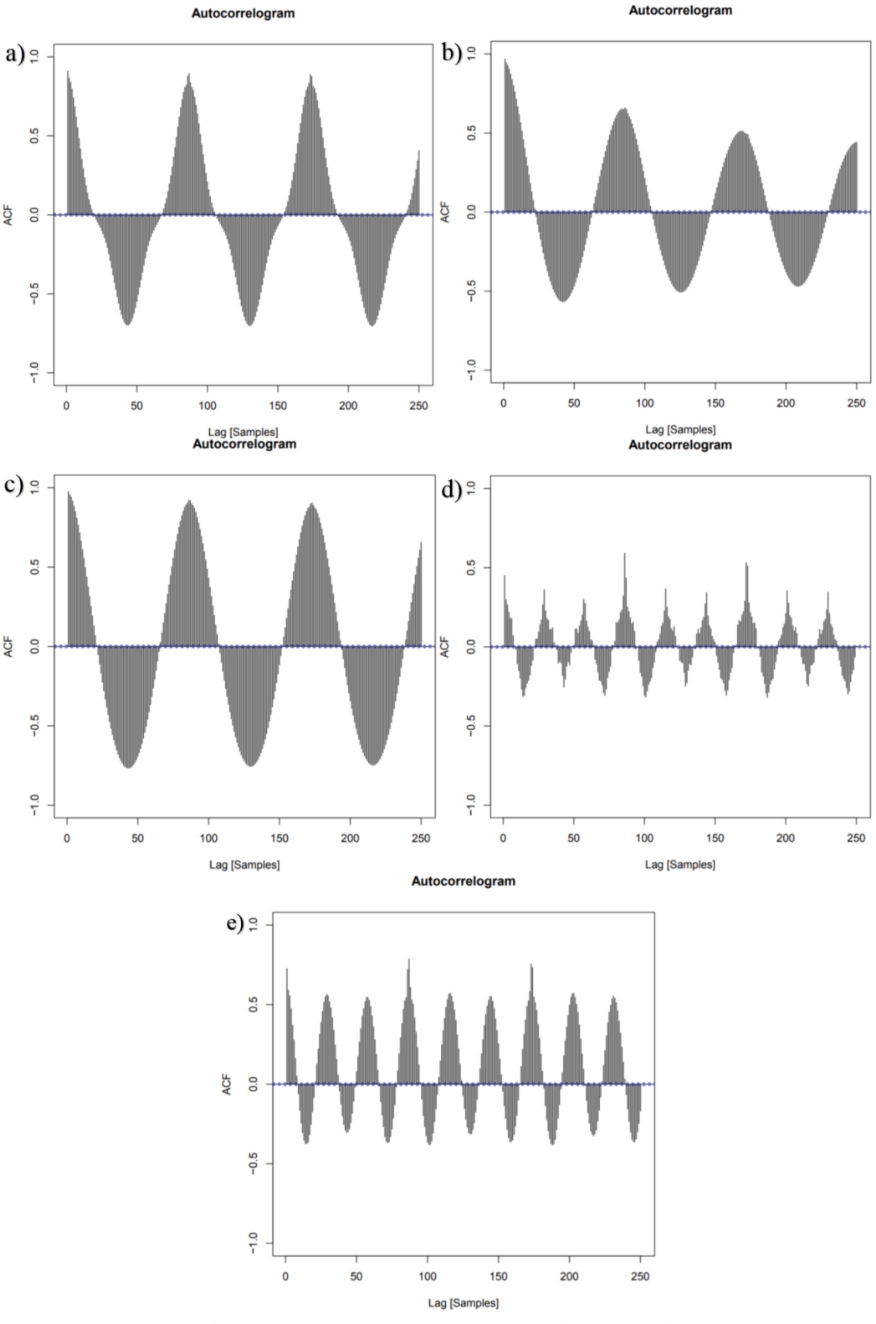

Figure 4. Graphs of the normalized autocorrelation function of the pressure signals (see section 3)

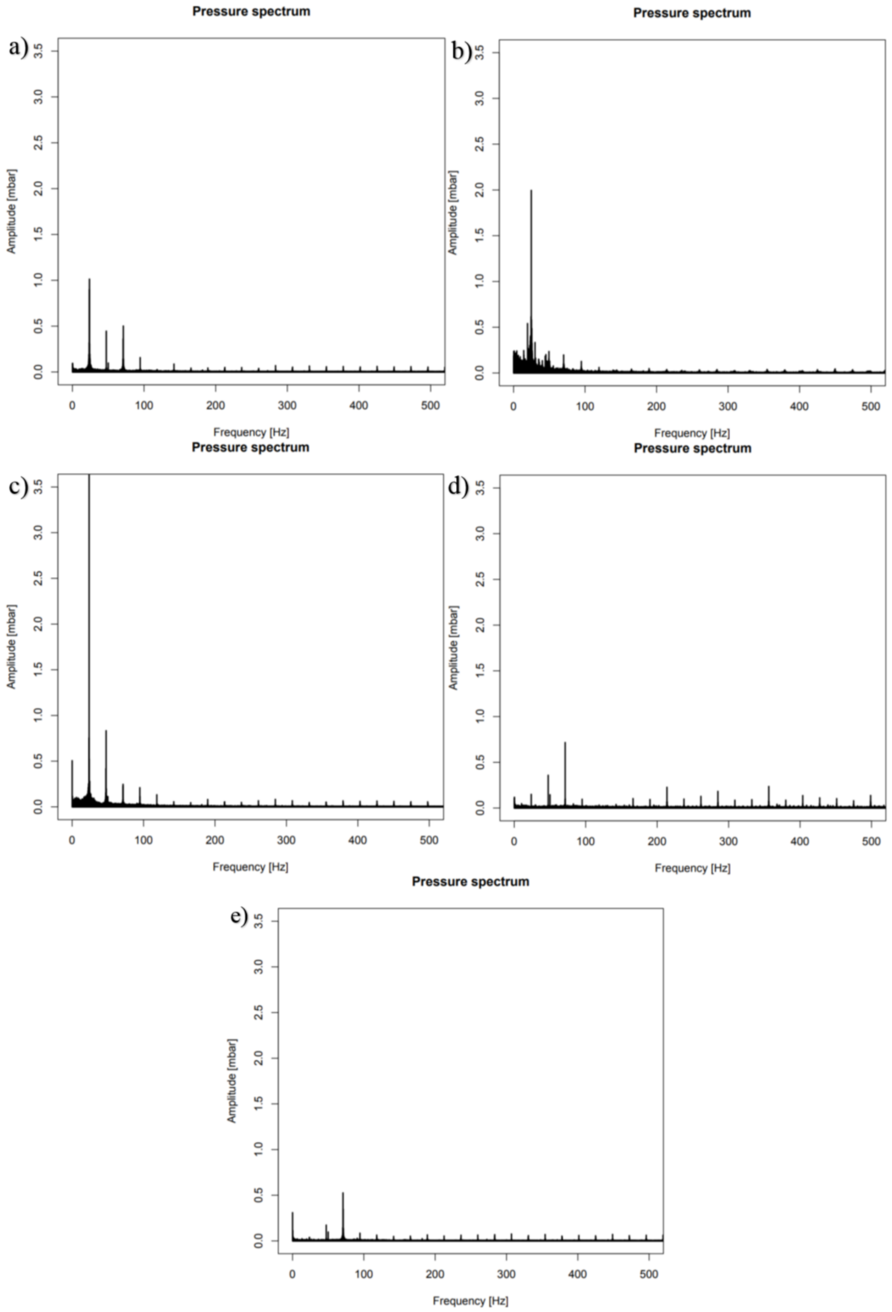

Figure 5. Amplitude spectra of the generated pressure signals
(see section 3)

4. Conclusions

Synchronous averaging of pressure signals, allows to detect damages and identify the degree of its advancement, what combined with information about the angular position of the rotor, allows to identify the damaged vanes.

Normalized autocorrelation function of pressure signals, allows detection and identification of the degree of vanes damages, as well as problems occurring in the lubrication system.

The use of spectral analysis allows the detection of both vane damage and problems with the lubrication system.

The presented method enables early detection of damages, leading to catastrophic consequences. It also allows to improve planning and managing maintenance of rotary vane vacuum pumps in the production company, by providing information about the current state of the working device.

All discussed diagnostics methods, are based on a comparison of the pressure signal, generated by the tested device, with the reference pattern obtain during the operation of the intact device. In the further work, an automatic reasoning system for the diagnostic process of the rotary vane vacuum pumps based on presented methods, will be developed.

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