System of vacuum mechanisms failure prediction based on outgassing flows dynamic

E A Deulin, V P Mikhailov and R O Emelianenko
Bauman Moscow State Technical University, 105005, Moscow, Russia

E-mail: deulin@bmstu.ru, mikhailov@bmstu.ru

Abstract. We simulated a vacuum system in order to diagnose vacuum mechanism failure with the goal of estimating dynamic properties of pumps (time to achieving desired pressure in the presence of rapidly varying flows, precision of dynamic pressure maintenance), determining maximum recordable impact frequency of rectangular gas flow pulses when detecting the mechanism state and predicting time to failure. The following parameters are usable for diagnostics: frequency and magnitude of outgassing flow oscillations in the mechanism, residual pressure fluctuations in the vacuum chamber.

The method of diagnosing failure of mechanical components of vacuum equipment that we present [1] is based on frequency analysis of outgassing flow. It entails the following difficulties: detecting the outgassing flows in the working chamber which are released by various mechanism components and decoding the signals recorded. There are several factors contributing to this: outgassing flows are small and only noticeable in ultra-high vacuum; due to evacuation, the outgassing flow being measured decreases in magnitude and alters its shape; properties of equipment performing measurement and signal discretisation affect measurement accuracy; fluctuations of base pressure in the vacuum chamber affect measurement results.

Figure 1 shows the layout of our vacuum system for mechanism failure prediction.

![Figure 1. Layout of the vacuum system for mechanism failure prediction.](image-url)
It comprises the mechanism undergoing diagnostics 1, a vacuum chamber 2, a vacuum pump 3, a pulsating piezoelectric leak valve 4, a thermocouple vacuum gauge 5, ionization 6 and thermocouple 7 vacuum gauges, and an ionization vacuum gauge 8.

Let us consider a bellows-sealed rotary feedthrough as an example of a mechanism undergoing diagnostics (figure 2), comprising an intake eccentric shaft 1, a case 2, bellows 3, the first, second and third vacuum ball bearings 4, 5, 6, a takeoff eccentric shaft 7. Rotation of the takeoff eccentric shaft 7 leads to outgassing flows $Q_1$, $Q_2$, $Q_3$ being released from the friction assemblies of the first, second and third vacuum bearings.

![Figure 2. Layout of a bellows-sealed rotary feedthrough.](image)

Figure 3 shows an example of signal summing for the case of outgassing flows released by a mechanism operating in a vacuum and random fluctuations of the total pressure $P$ as a function of time. It clearly demonstrates the difficulty of decoding the operating vacuum chamber pressure signal that responds to the start and stop moments. Linking this signal to the original signal of the bearing rotation frequency requires employing the scientific methods shown below.

![Figure 3. Operating pressure in the vacuum chamber as a function of the start–stop working process of a vacuum mechanism drive equipped with ball bearings.](image)

In practice, the problem of vacuum signal diagnostics involves theoretically reconstructing the magnitude and shape of the initial outgassing signal, knowing which enables us to diagnose the "health" of the mechanism under consideration. A convenient tool for reconstructing the original outgassing flow signal is a pulsating piezoelectric leak valve 4 (figure 1), which has an advantage in the form of being able to create small pulsating gas flows simulating mechanism outgassing pulses with the frequency up to $10^4$ Hz and flow magnitude up to $10^2$ m$^3$Pa/s.

Consider an example solution to the diagnostic model problem using a pulsating piezoelectric leak valve 4 (figure 1). We assume that the pulsating piezoelectric leak valve 4 simulates a pulsating outgassing flow released by a vacuum mechanism, for example, a gear, a ball bearing or others. The top plots in figure 4 represent signals originating from the gas flow generated in the vacuum chamber by the piezoelectric leak valve pulses at various frequencies; the plots below show the variations in the vacuum...
chamber pressure. Comparing the pressure variation curves obtained while letting in the gas flows generated by the piezoelectric leak valve shows that it is possible to solve the problem facing the developers of the diagnostic system. To elaborate on the ways of solving this problem, consider the plot in figure 4 that shows input and output signals resulting from varying the input gas flow signal frequency from 0.1 to 1 Hz, for the evacuation rate of 0.05 m$^3$/s and the vacuum chamber volume of 0.04 m$^3$.

![Figure 4. Example curves for the externally introduced flows $Q$ and pressure signals $P$ under investigation for input signal frequency $F_1 = 0.1$ Hz (a) and $F_2 = 1$ Hz (b).](image)

The difficulty in using frequency analysis for decoding the vacuum chamber flow signal stems from the difficulty of separating the spectra of outgassing flows released by different components of the mechanism. This happens because of "signal smearing", which is a reduction in pressure signal magnitude due to the chamber volume and evacuation rate.

Let us now conduct a dynamic simulation and consider the functional flow block diagram of our diagnostic system (figure 5) using failure prediction of the bellows-sealed rotary feedthrough (the layout of which is shown in figure 2) as an example. When the intake shaft rotation is $X$ (figure 5), the outgassing flows $Q_1$, $Q_2$, $Q_3$ released from the friction assemblies in the ball bearings 1, 2, 3 sum and form the total vacuum mechanism 4 flow $Q$. This flow enters the vacuum chamber 5 that has the volume $V$, which is being evacuated at the rate $S_0$. As a result the vacuum chamber pressure $P$ increases. The ionisation pressure gauge 6 records the pressure $P$ by converting it to ionic current $I$. The ionic current signal $I$ enters the analogue-to-digital converter 7, gets converted to a digital representation of the voltage $U$ and analysed in the control computer 8.

Gas balance in the chamber 5 is described by the equation [2]:

$$Q = P S_0 + V \frac{dP}{dt},$$

where $Q$ is the total flow in the vacuum chamber; $P$ is the vacuum chamber pressure; $V$ is the vacuum chamber volume; $S_0$ is the evacuation rate.
It is possible to transform equation (1) into a lag element equation by dividing both sides by $S_0$ and obtaining the following factors: $T = V / S_0$, which is the vacuum system time constant, $k = 1 / S_0$, or the vacuum system gain:

$$T \frac{dx_t}{dt} + x_2 = k x_t,$$

where $x_1$ is the input signal affecting the system; $x_2$ is the output signal (system response); $T$ is the system time constant; $k$ is the system gain.

**Figure 5.** Functional flow block diagram of the vacuum system for mechanism failure prediction.

The input signal for the vacuum chamber 5 is the outgassing flow $Q$, and the output signal (the system response) is the vacuum chamber pressure $P$. Let us take the Laplace transform of the equation 2, that is, replace the operation of differentiation with respect to time by a Laplacian $S$. Let us determine the transfer function of the vacuum system:

$$W_v = \frac{x_2(S)}{x_1(S)} = \frac{k}{TS + 1}.$$  

(3)

The vacuum system under consideration is a dynamic system described by the lag element transfer function [4–8]. The ionisation pressure gauge 6 consists of an ionisation transducer and an electronic unit comprising a microammeter that records the ionic current. Let us determine the transfer function of the ionisation transducer. Writing down the ionisation transducer equation:

$$P = \frac{I}{K},$$

(4)

where $I$ is the ionic current in the transducer; $K$ is the ionisation transducer constant, we arrive at the following ionisation transducer transfer function resulting from the equation 4:

$$W_i = \frac{I(S)}{P(S)} = K.$$  

(5)

Therefore, the ionisation transducer is an amplifying circuit with the gain $K$. This transducer is practically inertialess, since the time it takes for the ions to move in response to the voltage from the anode mesh to the ion collector is approximately 0.05 ms. It is these ions that generate the ionic current that assists in determining the vacuum chamber pressure $P$. A microammeter measures the ionic current over approximately 10 ms. If the signal frequency from the piezoelectric leak valve gas flow or the contact friction zone in the test mode does not exceed 10 Hz, this measurement time may be disregarded as well.

Let us determine the time constant $T$ and gain $k$ of our vacuum system ($V = 4 \cdot 10^{-2} \text{m}^3$, $S_0 = 5 \cdot 10^{-2} \text{m}^3/\text{s}$): $T = 4 \cdot 10^{-2}/5 \cdot 10^{-2} = 0.8 \text{ s}$, $k = 1/5 \cdot 10^{-2} = 20 \text{ s}/\text{m}^3$. If the duration of a rectangular gas flow pulse is at least 0.8 s, then the pressure pulse is shaped as an aperiodic signal, as shown in the figure 4a. For the duration of a rectangular gas flow pulse that does not exceed 0.8 s, the pressure pulse is shaped as a saw-wave signal with its magnitude reduced (figure 4b). Therefore, dynamic properties of a vacuum system constrain the frequency and duration of gas flow pulses generated by a precision piezoelectric leak valve 4 (see figure 1) or friction zones in the vacuum mechanism. It is possible to
run vacuum mechanism diagnostics at higher frequencies, but the pressure signal oscillation magnitude will decrease with frequency, which will make diagnostics harder and create an erroneous impression that the mechanism is failing. Calibration of the vacuum system for mechanism failure prediction in the test mode takes place as follows: the piezoelectric leak valve 4 (see figure 1) assigns the frequency and duration to the rectangular gas flow pulses which correspond to the frequency and duration of outgassing in friction assemblies of the vacuum mechanism; the oscillation frequency and the shape of the vacuum chamber pressure 2 signal are recorded using the ionisation transducer 8, and the data captured contributes to decoding the outgassing flow signal for the vacuum mechanism.

Gas exchange theory [3] states that mechanically induced desorption happens when surfaces are no longer in contact, therefore it is important for a diagnostic system to account for the fact that outgassing in friction assemblies occurs in time with vacuum mechanism surfaces coming into contact. It means that a square wave is the signal shape providing the closest match for simulating outgassing flows from kinematic pairs of vacuum mechanisms in operation. The diagnostics model presented may be used for all types of vacuum systems. In this way we arrive at the following conclusions: 1) we show that the dynamics of outgassing flow and pressure variations is affected by the processes happening in zones of contact friction and the vacuum system properties; 2) analysing the dynamic model of a vacuum system enables us to reconstruct the outgassing flow, which represents the "health index" of the mechanism; 3) dynamic properties of a vacuum system constrain the frequency and duration of gas flow pulses generated by a precision piezoelectric leak valve or friction zones in the vacuum mechanism; 4) it is possible to run vacuum mechanism diagnostics at higher frequencies, but the pressure signal oscillation magnitude will decrease with frequency, which will make diagnostics harder.

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