New diagnostic signs of the technical condition of piston compressors on the basis of characteristic function of the vibroacoustic signal

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Abstract. Topical issues of formation of the system elements of diagnostic signs of malfunctions and defects of piston compressors are considered in the paper. Diagnostic signs are formed on the basis of parameters of vibroacoustic signal. Vibration sensors are installed on various units of the piston compressor. Usually sensors are installed on the cylinder in the axial direction, on the compressor valves, on the crosshead, on the main bearing. Today, there are effective ways to assess the condition of components and parts of piston compressors on the parameters of the vibroacoustic signal, which are developed by the authors of this work. Diagnostic signs are based on statistical parameters of vibroacoustic signal such as the root-mean-square value of vibroacoustic signal, quantile of instantaneous values of vibroacoustic signal, spectral invariants the vibrating acoustic signal envelope. The first two groups of diagnostic traits are formed on the basis of statistical processing of signals for different types of machines. Thus, these features can only be used for a certain type of piston compressors. The appearance of faults and the degree of their hazards are estimated by the spectral inversion of the envelope of vibroacoustic signal regardless of the type of the machine. To increase certainty and reliability of diagnostics in this work it is suggested to use the size of module characteristic function of instantaneous values of vibroacoustic signal at the specified parameter characteristic function. Given that the module of the characteristic function varies from 0 to 1, it can be assumed that the value of the characteristic will not depend on the absolute value of the signal and, accordingly, on the type of machine. In this case, the characteristic function of the vibroacoustic signal is used, which is obtained at certain intervals by the angle of rotation of the crankshaft of the piston compressor in the region of the lower and upper dead points. Using probabilistic-statistical decision-making methods and the probability density functions of the modulus of the characteristic function, which are determined for different states of compressor nodes, the boundary values of the modulus of the characteristic function are obtained. Thus, the authors managed to get a diagnostic sign of faults and defects, which does not depend on the absolute value of the vibration acoustic signal. Thus, it is possible for the authors to first obtain a diagnostic feature of faults and defects on the basis of probabilistic characteristics of the vibration-acoustic signal, which is independent of absolute value of vibroacoustic signal.

1. Introduction
Investigation of dependence of parameters of various characteristics of diagnostic signal and, in particular, vibroacoustic, from technical condition of machines and mechanisms is the actual problem of technical diagnostics. The revealed new regularities allow to make formation of the system of informative diagnostic signs for expansion of independent component of a vector of parameters of vibroacoustic signal of machines and mechanisms that increases reliability diagnostics and solves the actual problem of vibroacoustic diagnostics [1–9].
The author suggested phenomenological model of the structure of vibroacoustic signal of the machine containing mechanisms of centrifugal and reciprocating types in the form of a mixture of periodic and noise components with mutually modulated components, allowed to offer orthogonal components of vibroacoustic signal as informative diagnostic signs [10]. And the use of laws of formation of vibroacoustic signals made it possible to form a system of defining criteria of faults, containing not only a system of informative components, but also their standard values [10, 11].

2. Problem statement

The purpose of the development of diagnostic features based on the parameters of the vibroacoustic signal in coherent selection is to increase the reliability of diagnosis by applying the parameters of the characteristics of vibroacoustic oscillations invariant to the value of the signal.

To achieve this goal, it is necessary to conduct a study of diagnostic signs of defects and malfunctions of assemblies and parts of a piston machine using a coherent (synchronous peak) selection of the vibroacoustic signal based on the cyclogram of the piston machine operation.

The task is solved by determining parameters of vibroacoustic signals, received from different units of piston machine at intervals of time by angle of turn of shaft c taking into account cyclogram of piston machine operation. In this case, it is necessary to define probabilistic characteristics of diagnostic signs. Then it is necessary to determine the normative values of diagnostic signs which make it possible to separate the technical states of the object of diagnosis.

3. Theory

In the basis of the health monitoring of piston compressors of potentially hazardous productions are normative values of parameters of vibroacoustic signal [11–14].

Development and commissioning of GOST R 56233 [14] largely dispelled the uncertainties in the normalization of the vibration parameters of piston compressors and provided adequate and reliable control and monitoring of the vibration state of machines [11, 13].

It should be noted that there is also ISO 20816-8-2018 [15], which, however, is not intended for the monitoring of piston compressors. In addition, this document defines the values of vibrations at individual points of the machine, among which there are no most dangerous and critical in terms of their failure [3, 10].

Thus, in this standard [15] it is stated that “ISO 20816-8 gives general guidelines for the evaluation of machine vibration by measurements on nonrotating parts. It establishes procedures and guidelines for the measurement and classification of mechanical vibration of reciprocating compressors. In general, this part of ISO 20816 refers to vibration of the main structure of the compressor, including the foundation, pulsation dampers and attached pipe system. The guidance values given for these vibrations are defined primarily to classify the vibration and to avoid problems with auxiliary equipment mounted on these structures.”

It should be noted that “the vibration values are defined primarily to classify the vibration of the compressor system and to avoid fatigue problems with parts in the reciprocating compressor system, i.e. foundation, compressor, dampers, piping and auxiliary equipment mounted on the compressor system. The guidelines are not intended for condition monitoring purposes” [15].

The scope of ISO 20816-8 ends with the phrase: “However, this part of ISO 20816 is not intended to be applied for condition monitoring purposes”.

Thus, the standard GOST R 56233 de facto and de jure is the only regulatory document in the world that provides the regulatory framework for vibration-based diagnostics monitoring of piston compressors of hazardous industries.

According to GOST R 56233, the following criteria for assessing the condition of piston compressors are used:

- root mean square (RMS) acceleration $a_{RMS}$ in the frequency range from 10 to 3000 Hz;
- RMS velocity $v_{RMS}$ in the frequency range from 10 to 1000 Hz;
- RMS displacement $d_{RMS}$ in the frequency range 2 to 200 Hz;
- peak values of acceleration $a_{AMPL}$ in the frequency range from 2 to 10,000 Hz;
- peak values of displacement $d_{AMPL}$ in the frequency band from 2 to 200 Hz.
One of the criteria for evaluating the state of piston compressors is such a statistical evaluation of a vibroacoustic signal as the quantile value $d_{\text{AMPL}}$ [9, 11, 16], which in GOST R 56233 are called the amplitude values of vibration acceleration $d_{\text{AMPL}}$. These parameters are controlled both for the cycle of operation of the piston compressor, and at the characteristic points in time when opening / closing the valves, changing the direction of the main forcing forces of the piston machine.

The following notation and sequence of analysis of the vibro-acoustic signal are used (figure 1) [10, 11, 14]:

- $\text{Asv}_1$ – peak value of vibration acceleration (A) at the moment of opening of the 1st (closest to the cover) of the suction valve;
- $\text{Asv}_2$ – peak value of vibration acceleration (A) at the moment of opening of the 2nd (closest to the crosshead) suction valve;
- $\text{Apv}_1$ – peak value of vibration acceleration (A) at the moment of opening of the 1st (closest to the lid) pressure valve;
- $\text{Apv}_2$ – peak value of vibration acceleration (A) at the moment of opening of the 2nd (closest to the crosshead) pressure valve;
- $\text{Atd}_1$ – amplitude value of vibration acceleration after the top dead center (TDC);
- $\text{Atd}_2$ – amplitude value of vibration acceleration up to TDC;
- $\text{Abd}_1$ – peak value of vibration acceleration to the bottom dead center (BDC);
- $\text{Abd}_2$ – peak value of the vibration acceleration after BDC.

![Figure 1](image.png)

**Figure 1.** Sequence diagram of the operation of the compressor and the characteristic intervals of the angle of rotation of the shaft, on which are formed the vibroacoustic vibrations

Increased dynamic loads due to the occurrence of hydraulic shocks initiate an increase in the impact energy in the interaction of parts in the increased gaps in the interfaces of components and parts of the crank-slider mechanism. In this case, depending on the location of the increased gaps, shocks occur either immediately after the passage of the dead point mechanism ($\text{Atd}_1, \text{Abd}_2$), which is associated with the choice of gaps in the progressively moving nodes (rod, piston fastening), and before the passage of the dead point ($\text{Abd}_1$) – the choice of gaps in the upper or lower connecting rod heads (figure 2) [8, 9, 11, 13].
However, it is especially dangerous for parts of the crank-slider and crank mechanisms to condensate, which leads to complex precession of the shaft or sleeve, reducing the lubricating layer up to dry friction (figure 2), which is quite clearly reflected in the implementation of the waveform vibroacoustic signal.

Quasideterministic processes along with generally accepted statistical characteristics as a distribution function or probability density and their parameters, such as standard deviation, kurtosis, and quantile, can be characterized by other statistical characteristics. These characteristics are uniquely related to the distribution functions, and therefore reflect and describe all the properties of a quasideterministic or random process. These functions, first of all, include the characteristic function [17–19].

Since in practice the signals with a finite number of instantaneous values are analysed, the result of the definition of the value of the characteristic function on a limited set of sample data is referred to as evaluation and to denote \( \theta(v)_* \).

The estimation of the characteristic function is found by the formula:

\[
\theta(v)_* = \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{N} \exp[jv x_i]
\]  

(1)

where \( x_i \) – instantaneous values of realization of vibroacoustic signal; \( v \) – real parameter of the c.f.; \( N \) – the volume of sample values; \( j \) – the imaginary unit.

Using Euler’s formula, it is possible to get expressions for estimations of actual and imaginary parts of the characteristic function:

\[
\theta(v)_* = \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{N} \cos[v x_i] + j \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{N} \sin[v x_i] = A'(v) + B'(v)
\]  

(2)

Since the characteristic function module in a wide range of variation of the characteristic function parameter \( v \geq 0 \) varies from 1 to 0, which is a natural physical standard of the “good” and “bad” state of the mechanism, known with mathematical precision, this characteristic is chosen as an estimate of the technical condition mechanism:

\[
|\theta(v)| = \sqrt{A^2(v) + B^2(v)}
\]  

(3)

The characteristic function \( v \) parameter begins from 0, for all values of the characteristic function module \( |\theta(v)| \) and tends to zero at degradation of the technical condition of the mechanism at the fixed value of the characteristic function module, i.e. at emergence and development in it of malfunctions.

4. Experimental results

The experimental data were realizations of the waveform vibroacoustic signal obtained from the vibration sensors of the monitoring system [1, 2, 3, 8], which were installed on the cylinder of a piston.
compressor. From the signals accumulated during several months of waveform signals received from the start of operation of the compressor to its stop for average repairs, 128 signals with a duration of five full revolutions of the crankshaft were selected. Each waveform signal realization allowed to form five data sets for each interval Atd1, Atd2, Abd1, Abd2, which amounted to 640 sample implementations of signals for each interval. Each implementation was a series of instantaneous sampled values of a vibroacoustic signal. For each interval Atd1, Atd2, Abd1, Abd2, five sets of each signal were calculated characteristic function.

Estimates of the probability density functions of the characteristic function modulus for a given parameter for an ensemble of samples of instantaneous values of a sampled vibroacoustic signal at intervals Atd1, Atd2, Abd1, Abd2 revealed a unique correlation between the characteristic function module for a given parameter and the quantile of vibration accelerations at specified intervals (Figures 3 - Figures 6).

**Figure 3.** The dependence of the module of the characteristic function on the value of the acceleration quantile at the level of 0.97 on the interval Atd1

**Figure 4.** The dependence of the module of the characteristic function on the value of the acceleration quantile at the level of 0.97 on the interval Abd1
quantile at the level of 0.97 on the interval Abd1

Figure 5. The dependence of the module of the characteristic function on the value of the acceleration quantile at the level of 0.97 on the interval Abd2

Figure 6. The dependence of the module of the characteristic function on the value of the acceleration quantile at the level of 0.97 on the interval Atd2

Table 1. The results of calculations of the boundary values of signs

| Interval - criterion | $P_{EA}$ | $P_{UD}$ | $R$     | $|\eta_{0}(v)|$ | $P_1$ | $P_2$ |
|----------------------|----------|----------|---------|-----------------|-------|-------|
| Abd1 – minimax       | 4.27⋅10^{-4} | 4.61⋅10^{-4} | 8.88⋅10^{-4} | 0.46               | 0.48  | 0.52  |
| Abd1 – Neumann-Pearson | 6.28⋅10^{-4} | 3.54⋅10^{-5} | 6.64⋅10^{-5} | 0.44               | 0.97  | 0.03  |
| Abd2 – minimax       | 9.97⋅10^{-4} | 9.21⋅10^{-4} | 1.92⋅10^{-3} | 0.53               | 0.52  | 0.48  |
| Abd2 – Neumann-Pearson | 2.82⋅10^{-3} | 3.53⋅10^{-3} | 2.86⋅10^{-3} | 0.56               | 0.97  | 0.03  |
| Atd1 – minimax       | 1.37⋅10^{-3} | 5.00⋅10^{-4} | 1.87⋅10^{-3} | 0.33               | 0.73  | 0.27  |
| Atd1 – Neumann-Pearson | 2.51⋅10^{-4} | 1.86⋅10^{-5} | 2.53⋅10^{-3} | 0.35               | 0.97  | 0.03  |
| Atd2 – minimax       | 4.94⋅10^{-4} | 2.61⋅10^{-4} | 7.55⋅10^{-4} | 0.22               | 0.65  | 0.35  |
Estimates of the probability density functions of the modulus of the characteristic function for a given parameter for an ensemble of samples of instantaneous values of a sampled vibroacoustic signal at intervals Atd1, Atd2, Abd1, Abd2 formed the basis for determining the limiting values of the modulus of the characteristic function separating the states of piston compressors.

Using the tested algorithms of probabilistic-statistical methods of decision-making for estimations of functions of distribution of diagnostic characteristics [17–19], the mathematically justified choice of boundary values of the module value was made. Characteristic functions for vibration acoustic signals at the investigated intervals (figure 7, 8, table 1).

For example, the dependences and graphs of the probability density of a diagnostic sign (modulus of the characteristic function with the parameter of the characteristic function \(v=0.2\)) for the state “Unacceptable” (UA) [11, 14] (curve 1), “Action required” (AR) [11, 14] (curve 2) of the Abd2 interval. Using the probabilistic-statistical decision-making methods, the minimax criterion and the Neumann-Pearson criterion, the risk curves of an erroneous solution are obtained.

The curve of risk (3) received by a minimax method at the equal prices of false alarm and the admission of malfunction and also the boundary value of sign (4) separating states on Abd2 interval is given in figure 7. The curve of risk (3) received by Neumann-Pearson’s method at the equal prices of false alarm and the admission of malfunction and also the boundary value of sign (4) separating states on Abd2 interval at importance coefficient for the probability of the admission of malfunction equal 1 is given in figure 8.

Calculation results of boundary values of diagnostic signs on the basis of the module of characteristic function |\(\theta(v)\)| are given in table 1 at \(v=0.2\) for four intervals of Atd1, Atd2, Abd1, Abd2.

In the course of calculations sizes of probabilities of false alarm \(P_{FA}\) and the admission of defect or malfunction (undetection probability) \(P_{UD}\), size of risk of wrong decision-making of \(R\), boundary value of diagnostic sign |\(\theta_0(v)\)| which divides conditions of an object at the received sizes of probabilities of \(P_{FA}\), \(P_{UD}\) and risk of decision-making \(R\) are received.

Considering the reliability of the obtained experimental data, a priori probability of the correct diagnosis when calculating by Neumann-Pearson’s method is accepted at the level of \(P_1=0.97\), and wrong – \(P_2=0.03\). When using a method of a minimax a priori probabilities were specified in the course of calculations.
Conclusion
The conducted researches allowed to determine boundary values of the module of characteristic function of instant values of vibroacoustic piston compressors of a signal for the set intervals by a compressor shaft angle of rotation. The diagnostic signs of malfunctions and standard sizes invariant to the size of an initial signal, on the basis of parameters of characteristic function of a vibroacoustic signal are for the first time received.

Statistical data processing allowed to receive probabilistic characteristics of instant values of a vibroacoustic signal for the set intervals by angle of turn of piston compressors shaft. The specified intervals are located in the field of the top and bottom dead points of the piston position. Parameters of characteristic function of instantaneous values of vibroacoustic signal have been studied. Boundary values of the characteristic function module, which separate technical condition of diagnosed machine components into "Good" ("Action required") and "Bad" ("Unacceptable") were defined.

Thus, for the first time, diagnostic signs of malfunctions have been obtained on the basis of the probabilistic characteristics of the vibration-acoustic signal and the normative values are invariant to the value of the original signal.

The proposed diagnostic signs should be used primarily in the real-time health monitoring systems of reciprocating compressors of explosive fire-hazardous facilities [3, 4, 5, 8, 9].

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