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Standardization in the sphere of vibrodiagnostic monitoring of piston compressors

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Abstract

The current Russian and the International standards in the field of standardizing parameters for piston machines vibration including piston compressors are reviewed. It is shown that the current standards do not meet safe operation requirements for piston compressors of hazardous production facilities. The Article describes the national standard of the Russian Federation "Condition monitoring and diagnostics of machines. Condition monitoring of hazardous industries. Vibration of stationary reciprocating compressor".

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Keywords: diagnosis; vibration; vibration diagnostics; monitoring; real-time monitoring; piston compressor; dangerous production; risk; standard

1. Introduction

Intensive introduction of monitoring systems of piston compressors operating at hazardous production facilities of petrochemical complex revealed the problem to ensure the normalization of the measured parameters used to control the technical state of the piston compressors. One of the major physical processes used in monitoring systems is a vibration.

The methodology of vibration machines parameters normalization is experimentally established fact: during normal machinery operation the vibration parameters of different machines are below certain values that can be used as borders [1]. Based on the newly identified function parameters of the probability distribution of instantaneous values of diagnostic features fault of piston compressors [2] there are developed [2] identified for the first time [3]

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dangerous regulatory and warning signs of diagnostic value for different types of piston compressors; and for the first time there are defined for a number of piston compressors sizes normalized values of vibro-acoustic signaling parameters for different states of machinery [3], [4], [5].

2. Study subject (model, process, apparatus, synthesis, experimental, etc.)

2.1. Analysis of the existing legal and procedural documentation

One of the first and fundamental developments of German engineers Union in the classification levels of absolute vibration (amplitude of vibration velocity) of piston machine (PM) is a standard VDI 2056 (1964) [6]. These recommendations have been recognized, and subsequently almost completely included in the standard ISO 2372 (1976 YG) [7], adopted by the International Organization for Standardization, which proposes to regulate the maximum value of the mean square value (RMS) vibration velocity vrms, measured on the most important areas and sites machines (bearing housings, flanges and foot supports) (Table. 1).

Table 1. Parameters of vibration measurements used in the standard.

Standard	Year	Criteria	Frequency band	Type of machines
VDI 2056	1964	d_{P-P} v_{RMS}	2.5 Hz to 10 Hz 10 Hz to 1000 Hz	K, M, G, T, D, S
ISO 2372	1974	d_{AMPL} v_{RMS}	2.5 Hz to 10 Hz 10 Hz to 1000 Hz	I, II, III, IV, V, VI
DLI Eng. Corp.	1988	$s_{P-P}, v_{AMPL}, a_{RMS}$	10 Hz to 1000 Hz	Piston machinery
ISO 10816-6	1995	$d_{RMS}, v_{RMS}, a_{RMS}$	2 Hz to 1000 Hz	1, 2, 3, 4, 5, 6, 7
ISO 10816-8	2014	$d_{RMS}, v_{RMS}, a_{RMS}$	2 Hz to 1000 Hz	Piston compressors 120 … 1800 min^{-1}

The VDI 2056 provided equipment division into six types, depending on capacity and type of foundation. The recommendations of ISO 2372 designated them as classes: I, II, III, IV, V, VI; and as a group VDI 2056: K, V, G, T, D, S. Types of equipment in both standards relating to these classes - groups are the same.

The scale of normalized vibration parameters is the number of RMS vibration values vrms, defining the different states of a particular class of machinery, and is characterized by 1.6 - 2 times (4 to 6 dB).

The commercial standards (classification) of DLI Engineering Corporation (1988) (now Azima DLI Company) vibro levels (peak-to-peak), velocity (amplitude), acceleration (RMS) for piston machines are increased by 8 dB compared with the levels for centrifugal machines of average capacity.

Each of them has corresponding lower and upper limits of vibration velocity levels. Frequency range from the constant vibration displacement is from 2.5 to 10 Hz frequency range with a constant level of vibration velocity, the technical status (TS) machines is 10 between 1000 Hz.

Ukrainian State Standard accepted standard rules for the three classes of vibration of piston compressors [8]. Standard rations are:

- RMS vibration velocity vrms of bearing housings of piston compressors in the case of rigid attachment, mm/s;
- RMS vibration velocity vrms of bearing housings for piston compressors when installed on vibration isolators, mm/s;
- RMS vibration acceleration arms of bearing housings of piston compressor, m/s2;
- RMS vibration velocity vrms of pipelines, mm/s;
- Scope vibro displacement of pipelines µm.

Rationing of vibro-acoustic oscillations to accelerate the speed and bearing only [8] does not ensure the completeness of monitoring the technical condition of assemblies and parts of piston engines.

Classes V(D), VI(S) of VDI 2056 standards, ISO 2372 are developed in ISO 10816-6 [5]. This standard provides guidance on the vibration state assessment of eight classes of units over 100 kW with reciprocating movement of their parts:

- Class 1 - balanced opposed gas piston compressors on the rigid base;
- Class 2 - gas multi-cylinder piston compressors on the hard ground and locomotive air compressors;
- Class 3 - single-cylinder gas piston compressors on a rigid base;
- Class 4 - has no analogues;
- Classes 5, 6 - industrial and marine diesel engines with a speed less than 2000 min-1;
- Classes 7, 8 - industrial and marine diesel engines with a speed of more than 2000 min-1.

The criteria for the classification of machine vibration with reciprocating movement are presented in Part 5 text ISO 10816-6. To assess vibration sets the standard limits values of RMS vibration displacement or vibration velocity or acceleration in the frequency range from 2 Hz to 1000 Hz.

Measuring points are: on the machine body in three directions at three levels - level attachment to the foundation level of the shaft, the upper point of the housing.

The standard [5] noted that the measurement of vibration body of piston machines and classification of the technical condition of the machinery on the results of these measurements make it possible to give only the roughest idea of the mechanical stresses in the nodes of piston engines and a vibrating state.

The standard states that the main components of the excitation machines reciprocating are concentrated in the frequency range from 2 to 300 Hz. However, when assessing the vibration state of the whole machine, including auxiliary equipment, which is a functional part of a piston machine, it is necessary to assume the vibration at least in the range of 2 to 1000 Hz. In special cases, it may be used by other bandwidth measurements. As broadband vibration contains many frequency components, it is impossible to install one correspondence between its parameters - RMS and peak values (or between RMS and scope). Therefore it is preferable to measure the rms displacement, velocity and acceleration to ± 10% in the range from 10 to 1000 Hz and with an accuracy of +10 and -20% in the range of 2 to 10 Hz. These parameters can be obtained by using one vibration sensor by integrating the accelerometer output signal.

Established criteria are of limited use in the evaluation of vibration nodes inside the machine and are of little use, for example, for damage valves, parts of the crank (crank), slider-crank (PCF) mechanism cylinder group (CPG). The detection of such damage requires methods that go beyond the scope of ISO 10816-6 [9].

The materials VDI 2056 indicated that because of the complexity of forces accounting and summation that cause vibration of piston machineries, machinery of these groups is difficult to include in the proposed scheme valuation. It is noted that, according to statistical data, even when the vibration velocity is of 20 to 30 mm/s for certain classes of machinery there were no evidence of reducing the machine units reliability. A piston machine with high rotational speed of the shaft remote from the attachment sites may be registered RMS vibration up to 50 mm/s, and thus there is no failure occur.

Since the ISO 10816-6 standards are only for points on the compressor housing and supports, at the level of vibration on the points of ISO 10816-6 the unbalanced force will influence rotating masses crank (crankshaft, connecting rod). At the same time when the sensor signal of the vibro-acoustic slide crosshead installed over the rod the vibroacoustic signal will be mainly influenced by unbalanced force of rotating masses CPM (crankshaft, connecting rod, slider, rod, piston), gas power is the cylinder clearances and connections KPM with more degree and CSV (except crosshead) - to a lesser degree. If vibroacoustic sensor signal is set at the cylinder head in the axial direction or in the radial direction near the valve, gas cylinder will have influence on the vibroacoustic signal strength, and ithis gap compounds parts CPG more. Therefore, vibration parameters measuring points on the body piston machine recommended by ISO 10816-6, eliminate state control technicals units and parts cylinder.

In 2014, the Committee adopted the ISO standard ISO 10816-8 [10] , which establishes the procedures and guidelines for the classification and measurement of the mechanical vibration of components and systems of piston compressors. Vibration values are determined primarily to the classification systems of vibration piston compressors and avoid fatigue problems in the compressor units and systems, i.e. basement, compressor housing, damping devices, piping and auxiliary equipment.

As the basic parameter proposed to use RMS vibration vrms (mm/s) mainly is from 2 to 300 Hz, but to control all parts of the compressor is recommended to choose a range from 2 to 1000 Hz. At frequencies below 10 Hz it is recommended to measure also RMS of vibro displacement drms (mm). Vibration arms (rms in m/s2) should measure a range from 2 to 1000 Hz.

The standard defines five types of measurement points in the vibration directions X, Y, Z:

- all anchor bolts fastening the housing fastening of the compressor;
- At each point of the compressor and on the body between the cylinders;
- on a cylinder head;
- to the buffer reservoir (pulsation bottle) at the inlet and outlet of the compressor;
- pipeline, to be determined in the survey and agreed with the owners of the compressor.

As information in Annex C of ISO standard 10816-8 [10] the data on the measured vibration of the crosshead range from 2 to 1000 Hz is reviewed.

It should be noted that the standard states that "given the guidelines are not intended for the purposes of state monitoring." In addition, it is recognized that the evaluation criteria have limitations related to the inability to assess the impact on the parameters of vibration problems such as failure of valves, CPG parts, piston rings and other defects and faults internal components.

The standard is designed for piston compressors with engine speed from 120 to 1800 min-1, inclusive, without dividing them into classes in terms of power and frequency of rotation, which naturally limits its use.

2.2. Disadvantages of existing regulatory and procedural documents

As the methodology for assessing the technical condition and diagnosis, as documents on the normalization of vibration parameters of piston machines do not assume the basic principles of vibro-acoustic oscillations in piston machines and their properties:

- piston machine, be it a piston compressor or an internal combustion engine is a complex gas-mechanical system that has three powerful and multifactor nearly statistically independent main sources of vibro-acoustic oscillations [1] , [2] , [11] , [12] , [14]: imbalance of moving and rotating masses of gas-hydrodynamic processes of collision and friction between the elements and parts of assemblies and mechanisms, informative frequency range which significantly exceeds the range defined in the above-mentioned documents (see. Table. 1);
- options of vibro-acoustic oscillations depend on the properties of the propagation medium of vibro-acoustic vibrations and harshness of cross-site connections [1] , [2] , [11] , [12] , [14] ;
- acceleration, velocity, vibro and their parameters have orthogonal property [1] , [2] , [11];
- these factors do not allow the use of existing norms of vibration piston machines for objective assessment of how the machine as a whole and the state of some of their components and parts, which generally does not allow the use of these standards for monitoring piston machines in real time, hazardous production facilities of the first category [13] , [14] and also piston machines in the application areas, where security at failure piston machines play determining role.

3. Regulatory documents of the Russian Federation

3.1. Review of regulations and standards

In 2011, the Scientific-Industrial Union "Risk management, safety, control and monitoring" (RISCOM) has adopted industry standard SRT 03-007-11 [3] , which allows the parameters of vibration signals to monitor the status of the piston compressors basic units and ensure safe operation of piston compressors. The standard has been evaluated and certified in a single system of conformity assessment in industrial and environmental safety, safety in the energy and construction as a guidance document for the non-destructive testing. Similar provisions are included in the standard vibration SRT 03-002-12. "Reciprocating Compressors of oil refining, petrochemical and chemical industries. Maintenance, technical supervision, inspection, rejection and repair " [4] prepared by a team of authors of LLC "VNIKTI Neftehimoborudovaniye" return of the document "General specifications for repair of piston compressors" 1985

On the basis of the standards [3] , [4] there was developed in November 11, 2014 and approved by GOST R 56233-2014 "Condition monitoring and diagnostics of machines. Monitoring of hazardous production equipment. Vibration of stationary reciprocating compressors" with the date of entry into force December 1, 2015 [5].

4. Results and discussion

4.1. Research and experimental base of standards

The content of standards [[3], [4], [5]] is based on the results of many years of theoretical and experimental studies, and more than 20 years of experience in operating of diagnostic systems and real-time monitoring "COMPACS®" [2], [17] more 70 piston compressors with electric drive with a unit capacity of 0.02 to 2 MW, used in petrochemical (NHC) complexes and factories in Omsk, Angarsk, Astrakhan, Achinsk, Burgas, Volgograd, Saratov, Syzran, Ukhta and other cities and to compress explosive types of harmful gases such as: domestic-piston compressors 205VP-16/70; 305GP-20/8; 2M10-11/42-60; 2GM16-20/42-60; 4GM10-28/43-56; 4M16M-45/35-55; 4GM16M-45/35-55; 4GM16-22/17-37; 4M16-22,4/23-64; 2GM2,5-6,2/38-46S; 5G-600/42-60; 4SGV et al., As well as imported - VDSV-30/30/20/20x16 (Worthington); 4HF/2 Series HF (Nuovo Pignone); 2TV2 (Neuman&Esser); RV 288-35 (BOGE KOMPRESSOREN BIELEFELD) [1], [2], [11], [12] and [14].

The values of vibration parameters were derived from the statistical processing of the monitoring results of these parameters, statistical methods of decision-making and the results of fault detection and repair of reciprocating compressors [2], [14].

The main advantage of statistical pattern recognition methods is the possibility of simultaneous consideration of various physical features or mechanisms of formation, since these methods operate with dimensionless quantities - the probability of their occurrence in various states of the system. Among the methods of technical diagnostic method based on the generalized Bayes formula, it occupies a special place because of its simplicity and effectiveness. However, this method has one significant drawback - rare signs of depression, which is unacceptable in the case of monitoring the status of hazardous production facilities. In terms of real production method Wald (Sequential Analysis) also provides safe operation in connection with the possibility of exceeding the range of diagnosis [13].

Methods of statistical solutions, such as the methods of minimal risk, a minimum number of erroneous decisions, minimax, Neyman-Pearson, maximum likelihood, allow to choose a decision rule based on the optimality conditions, such as the condition of minimal risk, minimize one of the errors of diagnosis for a given level [2], [13] and [14].

In general, based on the totality of vibration parameters, each method with a certain probability characterizes the state of the object being diagnosed, it is necessary to construct the decision rule the selected set of vibration parameters would be assigned to one of the possible states (diagnoses). In the particular case it is necessary to choose one of two diagnoses (differential diagnosis, or dichotomy), for example, be in good condition and a fault condition. To identify the statistical characteristics of vibration parameters each vibration parameters for each state of approximated distribution function based on a representative sample, numbering a few thousand values for each state [2], [14]. Then the methods of statistical solutions for each vibration parameters determine limit value, which is a given probability of failure and the risk of missing shared object state diagnostics. As a result, values of the parameters were obtained by vibro-acoustic signal, separating the technical state of the piston compressors of different sizes and frequencies of rotation [3], [4], [5].

4.2. Application area

Standards [3], [4], [5] are applied to stationary piston compressors operating in hazardous and noxious gases of the 1st and 2nd classes of danger, and establishes standards for vibration assessment of their technical condition and the operation of the acceptance test after installation and repair of all designed, manufactured and newly reconstructed, as well as to existing stationary piston compressors.

4.3. Controlled components and parts

This standard defines and prescribes standards for vibration parameters for organizing their use vibration monitoring, vibration diagnostics, condition monitoring, and the risk of exploitation of stationary piston compressor units of hazardous industries. According to this document, it is recommended to carry out the measurement of vibration (acceleration, velocity, displacement) of all vital compressor units, including mechanisms or parts of piston group, crank and slider-crank mechanism, main bearings, valves, etc., in the direction of positioning sensors action force vectors forcing impacts of each monitored node.

Selecting a location of absolute vibration sensors on the cylinder in the installation of valves or valves on the main bearing on the compressor housing, over the piston rod, as well as control the relative movement of the rod are determined by agreement with the owner of the compressor unit on the basis of the status of the compressor, the stability of the technological mode, gas composition and other conditions.

4.4. Standardized Options

As the normalized parameters for piston compressors are installed:
- RMS acceleration a_{rms} in the frequency band from 10 to 3000 Hz;
- RMS vibration v_{rms} in the frequency range from 10 Hz to 1000 Hz;
- RMS vibration displacement d_{rms} in the frequency band from 2 to 200 Hz;
- Peak values of acceleration a_{ampl} in the frequency band from 2 to 10,000 Hz;
- The peak value of vibration displacement d_{ampl} in the frequency band from 2 to 200 Hz.

The amplitude values of acceleration a_{ampl} controlled both the cycle of a piston compressor, and in specific times when opening/closing the valves, changing the direction of the main effects of forcing power piston machine: the amplitude of the vibration acceleration, respectively, after TDC a_{atd1} (top dead center) (TDC) to TDC a_{atd2}, and lower dead point a_{atd1} (bottom dead center) (BDC) BDC after a_{atd2}, at the opening of the first (front to back cover) suction valve a_{asv1} (suction valve) (SV), at the opening of the second SV a_{apv2} , at the opening of the first (low to cover) the discharge valve a_{asv1} (pressure valve) (PV), at the opening of the second PV a_{apv2} (Fig. 1).

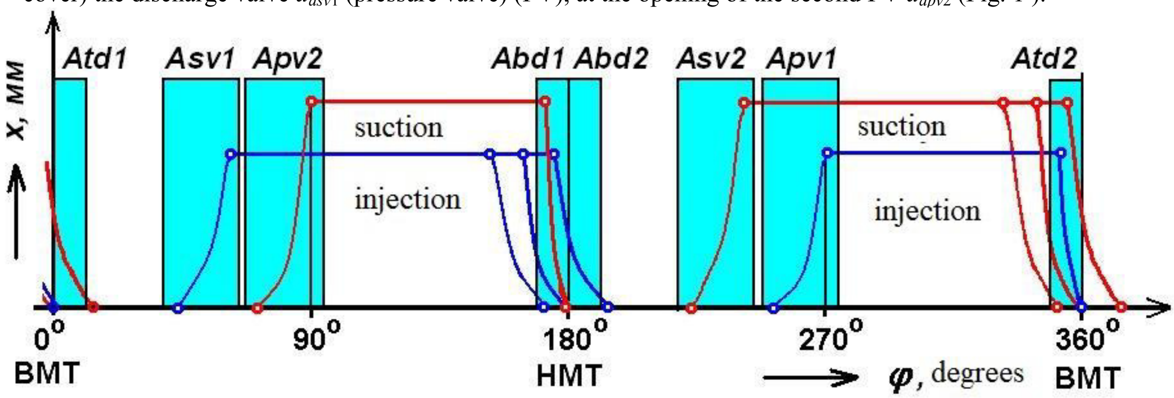

Fig. 1. Cyclogram of working piston compressor (the dependence of the height of the valve plate lift on the angle of shaft rotation).

Standards for vibration sensor mounted on the cylinder head in the axial direction, are for the six design groups compressors with an output range from 0.02 to 2 MW (Table.2 - 4).

Table 2. The mean square value of acceleration, velocity and displacement.

Zones	167 min^{-1}			300 min^{-1}			375 min^{-1}			500 min^{-1}			750 min^{-1}			1000 min^{-1}		
	a_{rms} m/s^2	v_{rms} mm/s	s_{rms} µm	a_{rms} m/s^2	v_{rms} mm/s	s_{rms} µm	a_{rms} m/s^2	v_e mm/s	s_{rms} µm	a_{rms} m/s^2	v_{rms} mm/s	s_{rms} µm	a_{rms} m/s^2	v_{rms} mm/s	s_{rms} µm	a_{rms} m/s^2	v_{rms} mm/s	s_{rms} µm
«The axial direction of the piston»																		
A/B	2.8	2.8	7,1	9	0.9	5.6	7.1	0.9	8.7	9	2.8	11.2	8.7	2.8	14	11.2	3.6	18
B/C	3.6	3.6	14	14	1.8	18	14	1.8	18	14	4.5	24	14	5.6	28	18	7.1	36
C/D	7.1	7.1	28	28	3.6	36	28	3.6	36	28	8.7	56	28	11.2	56	36	14	71

Table 3. The amplitude of the acceleration and movement of a few revolutions.

Zones	167 min^{-1}		300 min^{1}		375 min^{-1}		500 min^{-1}		750 min^{-1}		1000 min^{-1}	
	a_{ampl}, m/s^2	s_{ampl}, µm	a_{ampl}, m/s^2	s_{ampl}, µm	a_{ampl}, m/s^2	s_{ampl}, µm	a_{ampl}, m/s^2	s_{ampl}, µm	a_{ampl}, m/s^2	s_{ampl}, µm	a_{ampl}, m/s^2	s_{ampl}, µm
«The axial direction of the piston»												
A/B	11.2	36	18	24	24	24	24	18	24	24	36	36
B/C	18	56	28	36	45	36	45	36	45	45	56	56
C/D	36	112	56	71	90	71	90	71	90	90	112	112

Table 4. Amplitude of acceleration for different phases of the cycle.

Zones	a_{atd1}, m/s^2	a_{asv1}, m/s^2	a_{apv2}, m/s^2	a_{abd1}, m/s^2	a_{abd2}, m/s^2	a_{asv2}, m/s^2	a_{apv1}, m/s^2	a_{atd2}, m/s^2
«The axial direction of the piston», 1000 min^{-1}								
B/C	45	45	56	56	56	45	56	45
C/D	90	90	112	112	112	90	112	90

4.5. Justification of the frequency range of vibration parameters

Selecting frequency bands measurement and analysis of vibration parameters is due to the frequency bands of vibro-acoustic oscillations, carrying information on the status of individual components and parts of piston compressors [2], [11], [12] and [14]. Fig. 2 shows the spectrum of acceleration obtained from the sensor, which is mounted to the crank bearing of the piston compressor. The spectrum indicates that this node extends the frequency range of informative up to 5 kHz. A spectrum in Fig. 3 obtained from the sensor to the cylinder head in the axial direction, shows that the signal analysis should be carried out in the frequency range up to 10 kHz.

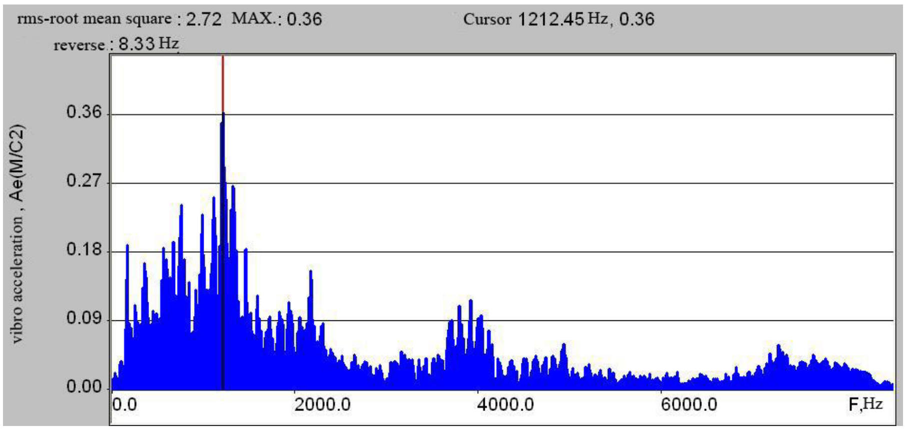

Fig. 2. The range acceleration Ae on main bearing piston compressor type 2GM16-20/42-60.

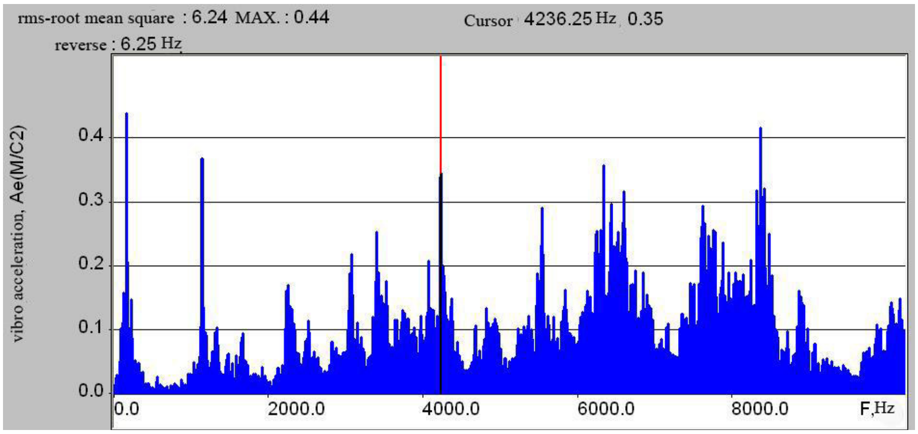

Fig. 3. The range of acceleration Ae on the cylinder in the axial direction of the piston compressor type 4M16M-45/35-55.

The above examples are not unique to the national school of compressor machines, but also for foreign developers and manufacturers of very well-known brands. Fig. 4 shows the signal obtained from the sensor to the cylinder head in the axial direction of the piston type compressor JGT/2 of Ariel company, which is specially designed for use in petrochemical industry for compressing hydrogen indicating that RMS acceleration in the range from 10 kHz to more than 50 m/s2 and peak amplitude 300 m/s2. Such a value of acceleration exceeds the limit values specified in national regulations [3], [4], [5]. The main energy of the signal is concentrated on vibrations at frequencies above 1 kHz (Fig. 5). In the frequency range up to 1kHz rms it does not exceed 3 m/s2, and the peak value is 11 m/s2 (Fig. 6).

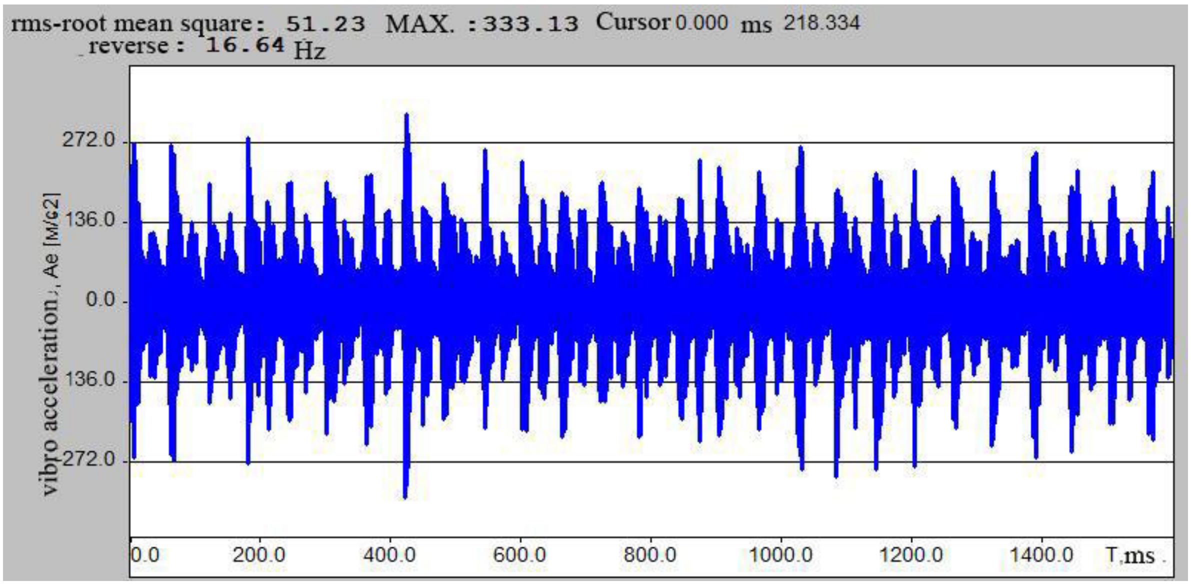

Fig. 4. Signal acceleration A_f on the cylinder in the axial direction of the piston compressor type JGT/2 Ariel companyin the range up to 10 kHz.

Thus, the existing regulations [6], [7], [8], [10], where the range of frequencies is up to 1000 Hz; is determined, to a large extent they do not only limit the possibility to assess the technical condition of individual units, but also the possibility of risk assessment of their condition, which increases the risk of missing rejection, as well as a significant impact on the safe operation of piston compressors.

4.6. State Criteria

According to [3], [4], [5] the technical condition of the compressor unit is estimated by a worst-case basis: any one of the vibration parameters, reached the worst-case value.

The standard establishes four technical condition assessments:

- "Good" (G). Recommended for acceptance tests after installation or major (middle) repair. Conforms good condition of compressor unit and is characterized by high quality repair and installation works;
- "Permissible" (P). Recommended for long-term operation. It characterizes the fully operational status of the compressor unit at a low probability of failure. Upon reaching the P control the rate of change vibration parameters;
- "Requires action" (RA) - a warning. Is recommended for a short operation. The technical condition of the compressor unit corresponds to RA, if the value exceeds the level of vibration parameters "RA". It warns of the approach to the limit of technical condition, the presence of developing defects, gradual loss of efficiency and increase the probability of failure. Used for maintenance and/or the planned withdrawal of the compressor unit in for repair;
- "Invalid" (I) - Stop. It is unacceptable in the operation. The technical condition of the compressor unit corresponds to I, if the amount of vibration parameters exceed the level of I. Characterized by the presence of defects developed a high rate of development and the achievement of a compressor installation limit any dangerous condition with a high probability of failure. It is used to stop the compressor unit and display it in for repair.

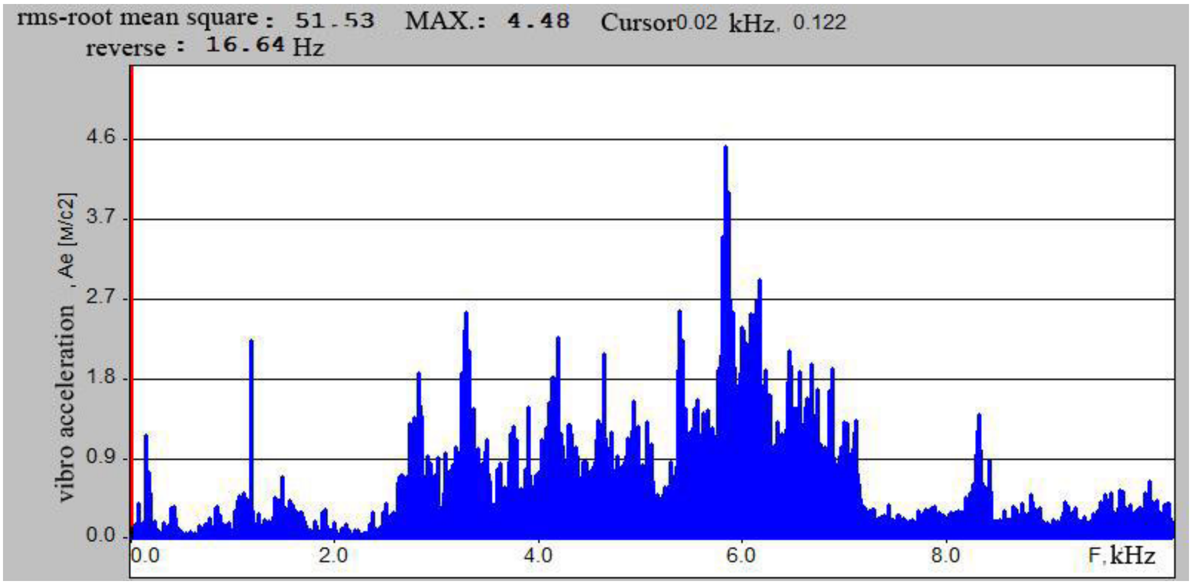

Fig. 5. The range of acceleration A_f on the cylinder in the axial direction of the piston compressor type JGT/2 Ariel company.

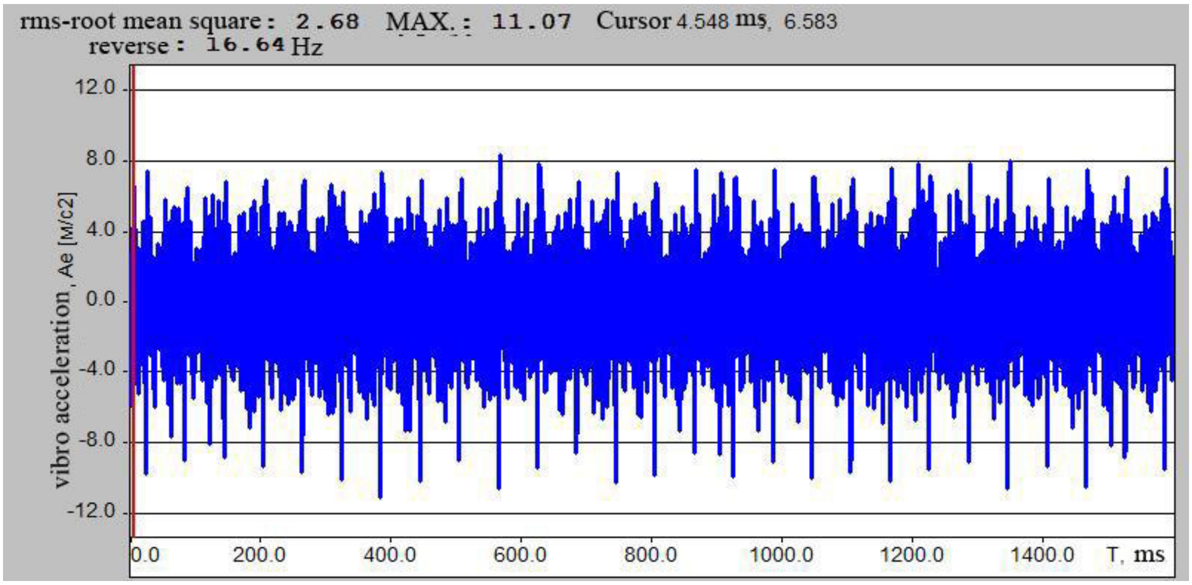

Fig. 6. The signal acceleration A_f on the cylinder in the axial direction of the piston compressor type JGT/2 Ariel company in the range up to 1 kHz.

When switching the machinery into a state of "Invalid" it means a high probability of damage caused by the unit, the unit or the entire compressor installation, one must perform all actions for the removal of the compressor unit of this state until the immediate stop and repair.

When switching the unit to the state "requires action" it is necessary to perform maintenance. If this does not set into a state of "permissible", it should be planned to bring it in for repair. In exceptional cases, the further operation of the compressor unit, thus it is necessary at intervals not less frequently than once per hour to control the change in its vibration parameters.

When complex machines of hazardous production is equipped with monitoring system of their technical condition, meeting the requirements of [15], [16], current and average repairs are carried out on the data and recommendations of the monitoring system, i.e. on the actual technical state of the compressor unit.

It is allowed to carry out overhauls compressor unit on a technical condition on the basis of the data of the complex monitoring system of units after the acquisition of relevant experience in the enterprise.

5. Conclusion

Thus, Russia today has adopted regulations that allow, together with the monitoring systems of machinery of hazardous industries, meet the requirements of [15] , [16] , [18] and relate to the first-class system, to ensure the value of the static, dynamic and the risk of errors crossing the dangerous condition not more than 5%. As a result, for the first time in the world the monitoring system based on regulatory data standards [5] makes it possible with the help of developed algorithms of automatic expert decision support system [2] , [11] , [12] , [14] to monitor the technical condition of piston compressors of hazardous industries and to ensure their safe, trouble-free operation of resource-saving.

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