Rationing of piston machines vibration

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Abstract
Existing documents in the field of piston machines vibration rationing, in particular standards VDI 2056, ISO 2372, ISO 10816-6, the draft standard ISO 10816-8, as well as commercial standards, do not provide diagnostics and a safe, fault free compressors operation. Moreover, the draft standard ISO 10816-8 is not intended to be used in monitoring systems, since it does not guarantee the compressors safe operation as well. In 2011 in Russia the industry standard STO 03-007-11 has been adopted; it allows to carry out a vibration analysis monitoring of the piston compressors crucial components and ensures the compressors safe operation.
The standard applies to stationary piston compressors, operating on explosive and harmful gases and sets the vibration standards for assessing their technical condition during operation and acceptance tests after mounting and repair.
The vibration parameters rates, specified in STO 03-007-11, are of advisory nature for all the machines which are not enumerated in the vehicles list, supplied in the standard appendix.
These rates can be adjusted according to resolutions of the enterprise responsible technical services as bringing the diagnosed equipment to the required reliability activities, guaranteeing safety and fault-free operation of the hazardous facilities equipment. The standard specifies the vibration parameters rates and prescribes their use for the arrangement of vibration monitoring, vibration analysis, technical condition monitoring and operational risks for stationary piston compressor units. This document determines the frequencies ranges of measurement for each vibration parameter and proposes to measure not only the mean square values of acceleration, velocity, displacement, but their amplitudes as well. The vibration rates are given for the five compressors constructive groups with unit capacities from 0,02 to 2 MW. The paper considers the standard STO 03-007-11 main points.

1. Introduction

Reduction of risks for technogenic accidents and catastrophes occurrence is inextricably connected with the development of monitoring and diagnostic systems for piston compressors of hazardous production facilities industries [(1)], which is constrained due to a total absence of a methodological framework in the field of piston machines vibration.

2. Review of regulatory and methodological documents

One of the first and fundamental developments in the field of absolute vibration levels (velocity amplitude) classification for piston machines in Western European 'Association of German Engineers' is the standard VDI 2056 (1964) [(2)]. These guidelines have been recognized and subsequently almost completely entered the ISO 2372 (1976) [(3)], approved

by the International Organization for Standardization. ISO 2372 proposes to regulate the velocity maximum root mean square values (v_{rms}), which have been measured at the most important units and machines areas (bearings housings, support feet and flanges).
VDI 2056 involves the equipment division by six types, according to capacity and kind of foundation. In ISO 2372 recommendations these types have been indicated as the following classes: I, II, III, IV, V, VI, and VDI 2056 has defined them as: *K*, *V*, *G*, *T*, *D*, *S*. The both standards equipment types, related to these classes – groups, completely coincide one with the other.
The regulated vibration parameters scale constitutes a number of velocity root mean square values (v_{rms}), defining various levels of the concrete class machine state, and differing at 1.6…2 times (from 4 to 6 dB).
In commercial standards (specifications) of DLI Engineering Corporation (1988) (at the present time - Azima DLI Company) vibrodisplacement
(peak-to-peak), velocity (amplitude) and vibration acceleration (*rms*) levels for piston machines have been increased by 8 dB compared to the levels for centrifugal machines of 'average' power.
Each state complies with a low and a high bound of the velocity levels. A frequency range with the vibrodisplacement constant is from 2.5 to 10 Hz. The frequency range with the velocity constant, characterizing the machine technical state, - from 10 to 1000 Hz.
In Ukraine the vibration rates standard for three classes of piston compressors (PC) has been approved (4). The standard normalizes:
- general rms of the compressor bearings housings velocity in the case of rigid fastening, mm/s;
- general rms of the compressor bearings housings velocity in the case of installation on vibroinsulators, mm/s;
- general rms of the compressor bearings housings vibroacceleration, m/s^2;
- general rms of the pipelines velocity mm/s;
- amplitude of the pipelines vibration displacement, μm.
Vibroacoustic oscillations rationing according to the bearings acceleration and velocity [(4)] does not ensure the completeness of *PM* units and parts technical state control.
VDI 2056, ISO 2372 classes V(*D*), VI (*S*) have been developed in ISO 10816-6 [(4)]. This standard provides guidance for evaluating the vibration state of eight classes of units over 100 kW with the components reciprocating motion, including piston compressors and internal combustion engines.
For evaluating the vibration state ISO 10816-6 sets the limiting rms for vibrodisplacement, velocity or vibroacceleration in the frequency range from 2 to 1000 Hz.
Measuring points: on the machine housing in three directions and three levels: a level of fastening to foundation, a shaft level, the housing upper point.
The standard [(4)] points out that PM housing vibration measuring and the machine technical state classification by the measurements results allow just to give a rough idea on the PM units strain and their vibration state.
Exceeding of the vibration limiting values, arised from the similar machines operating experience, is able to bring to damage of elements, which are mainly installed on the machine housing (turbine compressors, radiators, governors, filters, pumps), connecting elements (pipings) or measuring instruments (pressure sensors, temperature gages). The vibration level, able to bring to these elements damage, depends on their construction and the way of their fastening to the machine [(4, 16)].
The standard [(4)] describes that the main excitation constituents of reciprocating machines are concentrated in the frequency range from 2 to 300 Hz. However in the process of

vibration state estimation for the whole machine, including auxiliary equipment, being the machine functional part, it is necessary to take the vibration at the frequency range from 2 to 1000 Hz into consideration. In special cases the concerned parties can agree upon another frequency range of measurements. Since the broad band vibration includes several frequency components, it is impossible to establish a one to one correspondence between its parameters: root mean square and peak values (or between the root mean square value and the amplitude). Consequently, it is rather preferably to measure the root mean square values of displacement, velocity and acceleration within accuracy ± 10 % in the frequency range from 10 to 1000 Hz and within accuracy + 10 % and - 20 % in the frequency range from 2 to 10 Hz. These parameters can be received by means of a vibration sensor – a piezoaccelerometer. In such a case from the accelerometer output signal a velocity signal is received by dint of integration, and with the help of double integration - a displacement signal.

Established criteria are limited in use concerning the vibration estimation of the machine internal components and are of little use, for example, to detect the defects of valves, crank (CM) and slider-crank (SCM) mechanisms parts, the cylinder-piston group (CPG) components. Such defects detection requires the use of methods, going beyond the scope of ISO 10816-6 [5, 16].

VDI 2056 materials state that due to complexity of accounting and summation of forces, causing PM vibration, these groups machines are difficult to include in the proposed regulation scheme. It is marked that according to the statistics, even when the vibration velocity is in the range from 20 to 30 mm/s, the units reliability reduction have not been detected for certain classes of machines. As for piston machines with a high shaft speed, in the units, remote from the attaching point, the rms up to 50 mm/s can be registered, not bringing to breakage.

ISO 10816-6 [4] recommends to control the piston machines technical state by such vibration parameters as: acceleration, velocity, displacement. In this case, the term ‘intensity’ of vibration is used, which means the vibration parameters rms [5]. However, the measurement points on the PM housings, recommended by ISO 10816-6, exclude the technical state control of the cylinders parts and components.

In 2012 the ISO Committee prepared the draft standard ISO/CD 10816-8 [6] which established the procedures and principal guidelines for the mechanical vibration measuring and classification of the piston compressors units and systems. The vibration values have been determined, first of all, in order to classify the compressor vibration system and to avoid the weariness problem in such compressor units and systems as foundation, housing, damping devices, pipings and auxiliary equipment.

It is proposed to use the velocity rms - $\boldsymbol{v_{rms}}$ (mm/s) as the principal parameter in the frequency range from 2 to 300 Hz, but to control all the compressor parts the frequency range from 2 to 1000 Hz has been recommended. Frequencies, lower than 10 Hz, are recommended to use for the displacement rms - $\boldsymbol{d_{rms}}$ (mm). The vibroacceleration rms - $\boldsymbol{a_{rms}}$ (m/s^2) is recommended to measure in the frequency range from 2 to 1000 Hz.

1. On all anchor bolts of the compressor housing fastening.
2. At each extreme point of the compressor and on the housing between the cylinders.
3. On the cylinder head.
4. On the surge vessels at the compressor input and output.
5. On the pipings, which should be determined in the process of examination and adjusted with the compressor owners.

Appendix C of the standard ISO/CD 10816-8 [6] provides supplemental information on measurement of a crosshead vibration in the frequency range from 2 to 1000 Hz.

The standard states explicitly that the provided principal guidelines are not designated for the condition monitoring purposes. Furthermore, it has been admitted that the estimation

criteria have restrictions, connected with the evaluation impossibility of influence upon such vibration parameters of such problems as malfunctions of valves, cylinder-piston group (CPG) components, piston rings and other defects and failures of the internal units and components.
The standard has been developed for the piston compressors with the crankshaft rotational frequencies from 120 min^{1} to 1800 min^{1} inclusive without dividing them by classes according to capacity and rotational frequencies, thus naturally limiting its application.

3. Conclusions on the analysis of the existing regulatory framework

Methodologies for the technical condition estimation and diagnostics, as well as documents on PM vibration parameters rationing ignore the general principles of VA oscillations formation in PM and their properties:

1. A piston machine (whether it is a piston compressor or an internal combustion engine) is a complex gas-and-mechanical system and a powerful and multifactorial source of vibroacoustic signals, which has three statistically independent primary sources of vibroacoustic signals: instability of shifting and gyrating masses, gas-and-hydrodynamic processes, collisions and friction between the units and mechanisms elements and parts [7, 8, 9, 12];
2. Vibroacoustic oscillations parameters depend on propagation medium properties and intermodal connections [7, 8, 9, 12];
3. Vibroacceleration, velocity, vibrodisplacement and their parameters have the property of orthogonality [1, 7, 12, 17];
4. The above mentioned factors do not allow to use the existing vibration rates for the technical state objective estimation of the piston machines in general as well as of their separate units and parts, thus restricting their use for real-time condition monitoring of piston machines at hazardous production facilities of the first category [14] and in the spheres of application where safety is of great importance at the piston machines failure.

4. New developments in rationing of piston machines vibration

In 2011 Russian Scientific and Industrial Union ‘Risk management, industrial safety, control and monitoring’ (‘RISCOM’) has accepted the branch standard STO 03-007-11 [11], which allows to accomplish the vibroacoustic monitoring of the piston compressors main components and provides their safe operation. The standard has been evaluated and certified by the United compliance assessment system in the field of industrial and environmental safety, safety of energy supply and construction as a guidance document for non-destructive testing of the Russian Federation.
The content of this document is based on the results of long term theoretical and experimental research and over 15 years of experience in diagnostic and monitoring systems operation of more than 50 piston compressors with electric drive and unit capacity from 20 to 2000 kW, used in oil and gas industry in Omsk, Angarsk, Astrakhan, Achinsk, Burgas, Volgograd, Saratov, Syzran, Ukhta, etc. For compressing of explosive and foul gases the RF piston compressors are used: 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 and others, as well as the compressors, manufactured by such

companies as ‘Worthington’, ‘Nuovo Pignone’, ‘Neuman & Esser’, ‘Boge Kompressoren Bielefeld’ [1, 7, 8, 9, 12].

The standard applies to stationary piston compressor units, explosive and foul gases fired, and establishes the vibration rates for the technical state evaluation during operation and acceptance tests after mounting and repair, and applies to all engineered, re-manufactured and reconstructed, as well as existing stationary piston compressor units.

The standard specifies the vibration parameters rates and prescribes their use for the organization of vibration monitoring, vibration analysis, technical condition monitoring and operational risks for stationary piston compressors of hazardous facilities.

According to this document, it is recommended to measure the vibration (acceleration, velocity, displacement) of all vital compressor components, including the parts of the cylinder-piston group, the slider-crank and crank mechanisms, valves, bearings and others.

The rated values, established for the piston compressors, are as follows:

- the vibroacceleration rms (a_{rms}) in the frequency range from 10 to 3000 Hz;
- the velocity rms (v_{rms}) in the frequency range from 2 to 1000 Hz;
- the vibrodisplacement rms (d_{rms}) in the frequency range from 2 to 200 Hz;
- the vibroacceleration peak values in the frequency range from 2 to 10000 Hz;
- the vibrodisplacement peak values in the frequency range from 2 to 200 Hz.

The vibration rates are given for the five design groups of compressors with unit capacities from 20 to 2000 kW.

Selection of the frequency ranges for measuring and analysis of the vibration parameters is conditioned by the frequency ranges of vibroacoustic oscillations, which carry information on the piston compressor separate parts and components state [6, 7, 8, 11]. Picture 1 illustrates the vibroacceleration spectrum, obtained from the sensor, which is mounted on the compressor crank bearing. The spectrum shows that this unit the informative frequency range extends up to 5 kHz. And the spectrum in Picture 2, obtained from the sensor on the cylinder head in the axial direction, shows that the signal analysis should be carried out in the frequency range up to 10 kHz. Thus, the existing standards [2, 3, 4, 5, 6], in which the frequency range is determined up to 1000 Hz, limit not only the possibility of individual units state evaluation, but the possibility of their state danger evaluation as well, which increases the failure omission risk.

The compressor unit technical state is estimated according to the worst feature - any of the vibration parameters, reached the worst-case value.

The standard establishes four evaluations for the technical state:

- ‘GOOD’ (G). Admissible for acceptance tests after mounting or overhaul (midlife repair). Corresponds to a serviceable condition of the compressor unit and characterizes the high quality of repair and mounting works. To assess the quality of new productions mounting, it is appropriate to set ‘EXCELLENT’ technical state level, which corresponds to the vibration parameters, 30% below the levels required for ‘GOOD’;
- ‘TOLERABLE’ (t). Permissible for long-term operation. Characterizes the fully functional state of the compressor unit with the low probability of failure. When the level ‘’ is achieved, the speed of the vibration parameters change is monitored;
- ‘REQUIRES ACTIONS’ (RA) - WARNING. Admissible for short operation. The compressor unit technical state corresponds to ‘RA’, if the vibration parameter value exceeds the ‘RA’ level. Warns on the limiting state approaching, the presence of developing defects, gradual loss of efficiency and the failure probability increase. Used for maintenance and/or the planned repair withdrawal of the compressor unit. When passing to the state ‘RA’ it is necessary to provide maintenance works. If this does not lead the unit to ‘TOLERABLE’ state, it is necessary to bring it gradually to repair. In

exceptional cases, the further operation of the compressor unit is permitted, though it is necessary to control its vibration parameters changes not less than every hour;

- 'INTOLERABLE' (IT) - SHUTDOWN. Unacceptable for operation. The compressor unit technical state corresponds to the 'IT', if the vibration parameter value exceeds the 'IT' level. Characterized by the presence of developed defects or a high rate of their developing and the compressor unit attainment to the limiting or dangerous state with a high probability of failure. Used to stop the compressor unit and bring it to repair. When passing to the state 'IT', which is with a high probability caused by the unit, assembly or the whole compressor plant damage, it is necessary to take actions to withdraw the compressor unit from that state - up to an immediate shutdown and repair.

When equipped the hazardous facilities with the monitoring system, meeting the requirements [13, 14], current and medium repairs are carried out on the testimony and recommendations of the monitoring system, i.e. on the actual technical state of the compressor unit.

It is permitted to overhaul the compressor unit according to the technical state on the basis of the monitoring system indications for the complex of units after gaining a relevant experience at the enterprise.

5. Case history

Effectiveness of the vibration analysis monitoring applying, based on the proposed vibration rates, is proved by the vibration trends for different units. In the first case (Figure 3, case 1) a destruction of the valve springs without an inverse gas leakage has happened. In the second case (Figure 3, case 2) the trend shows changes in vibration with destruction of the piston compressor valve plate (Figure 4) with the inverse gas leakage from the charging cavity to the buffer capacity.

Conclusion

Thus, in Russia has been accepted the standard which due to the technical condition monitoring systems for hazardous facilities machinery allows to provide static and dynamic errors and the risk of the dangerous state omission not more than 5 %. As a result, for the first time the monitoring systems, based on the standard regulations [11], allow using the developed algorithms of the decision-making support expert system [7, 8, 9, 12, 17] to monitor the technical state of hazardous facilities piston compressors, providing their safe, trouble-free and resource-saving operation.

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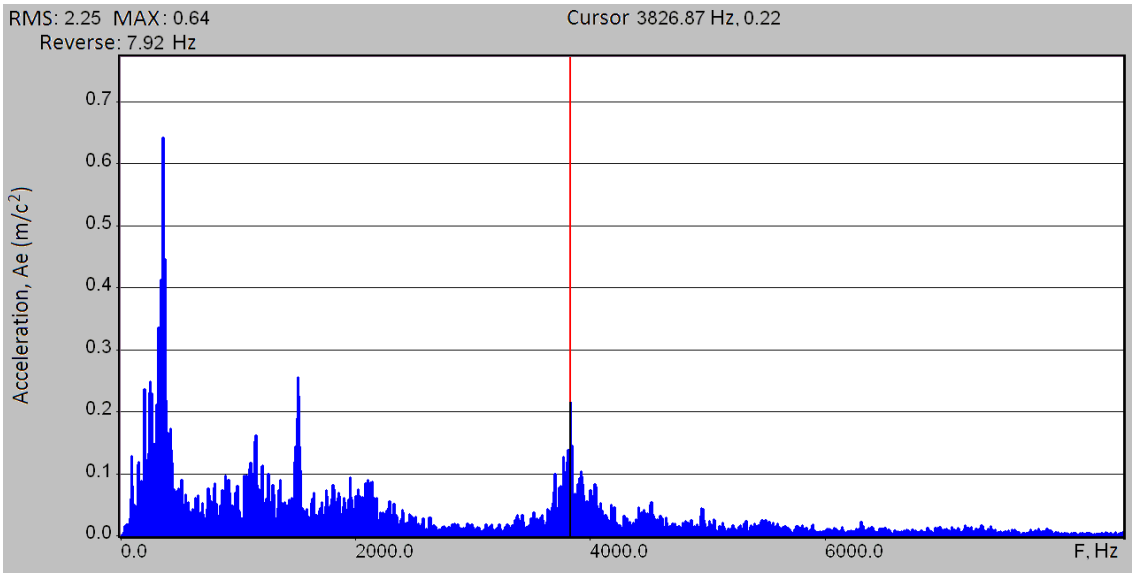

Figure 1. Vibroacceleration spectrum on the main bearing of the 2GM16-20/42-60 type compressor

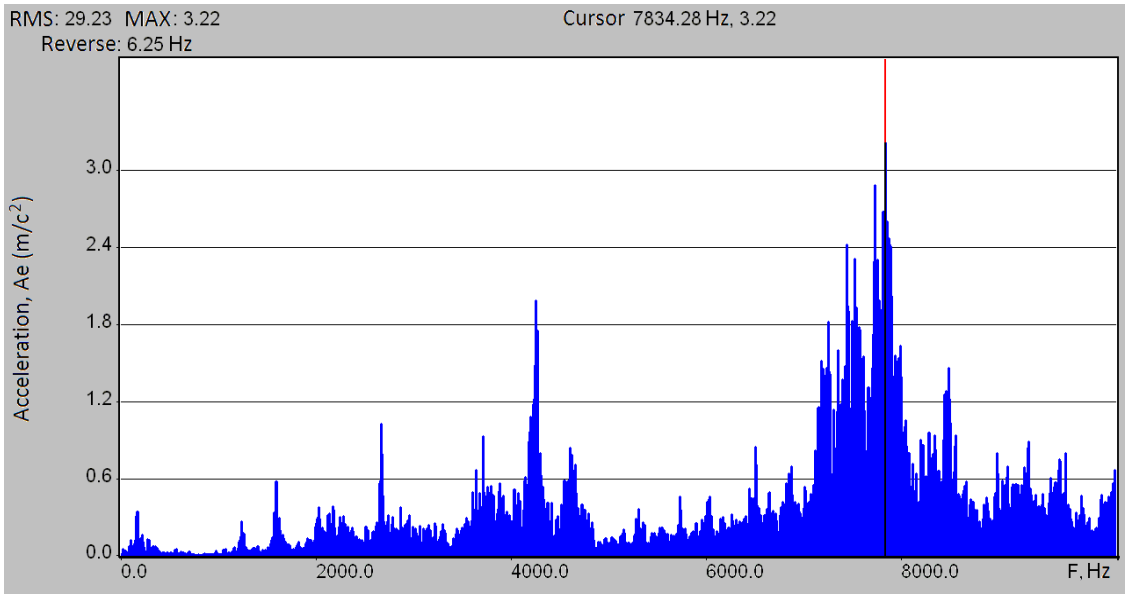

Figure 2. Vibroacceleration spectrum on the cylinder head in the axial direction of the 4GM16M-45/35-55 type compressor

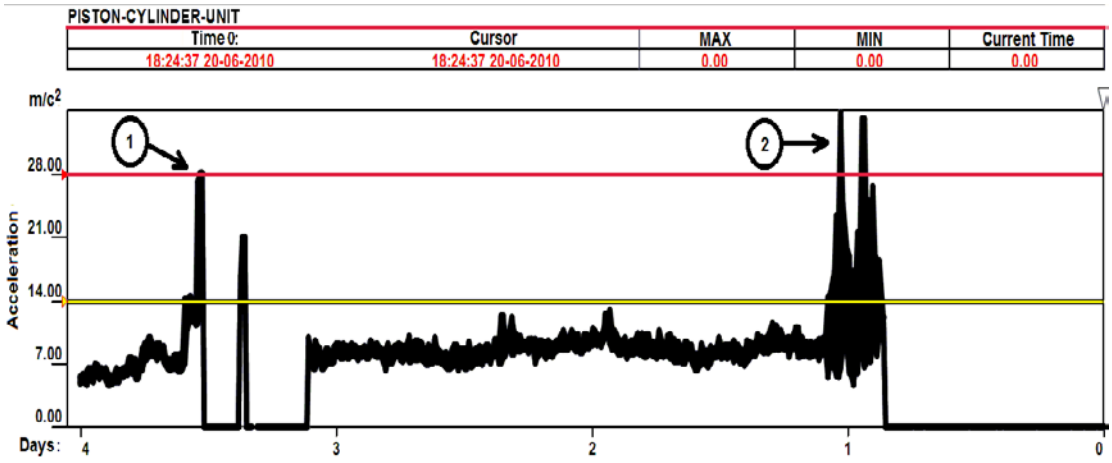

Figure 3. The cylinder vibration trend

Figure 4. Destructed valve plate of the piston compressor

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