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RESEARCH ON VIBROACTIVITY OF TECHNOLOGICAL EQUIPMENT BASED ON THE ANALYSIS OF DYNAMICAL PROCESSES AND SPECTRUM OF VIBRATIONS

This paper presents problems of technological equipment vibromonitoring. Mechatronic systems designed for monitoring and control of complex rotary machines can be implemented effectively only when alert or critical levels of the monitored parameters are well known and sources of parameter deviations can be determined.

Vibrodiagnostics is a powerful tool, which can be used for diagnosing of machine defects. However, in the case of complex rotary machines, it is very complicated to trace all sources of vibrations (e.g. internal defects). Therefore, attempts of vibration modeling are made aimed at evaluating the influence of various parameters on vibroactivity of a certain machine.

1. Introduction

Exploitation reliability and quality of technological equipment depend on equipment's vibroactivity [1]. Processes of degradation that take place during exploitation of the equipment, originate from various sources, and are accompanied by increased vibroactivity, temperature of various elements, changes of oil tribological properties and decreased quality or quantity of production. Many of modern rotary machines are equipped with complex mechatronic systems for monitoring and control of operating conditions. However, such

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systems can be applied effectively only in the cases where influence of various machine's elements and defects (which of monitored parameter they influence, and how it is done) on machine's condition is identified exactly [2], [3].

Therefore, the analysis of dynamical processes, modeling of various conditions and the analysis of vibrations are still essential tools for monitoring and control of complex rotary machines. These tools enable foreseeing potentially harmful situations, evaluating sources of vibrations, lowering influence of degradation processes and predicting reliability of technological equipment. Comprehensive analysis of possible defects, external effects and historical data should be performed before designing, implementing and tuning mechatronic systems of monitoring and control.

2. Object of the research

The object of this research is a complex technological machine (Fig. 1), composed of electric motor (0.8 MW), steam-fusion gas turbine-axial compressor, centrifugal compressor and mechanical reducer. All three rotors of this complex machine (electric motor, turbine and centrifugal compressor) rotate on sliding bearings (hydrodynamic elliptical bearings). Regular angular frequencies of rotors during their exploitation are between the first and the second natural frequencies of those rotors.

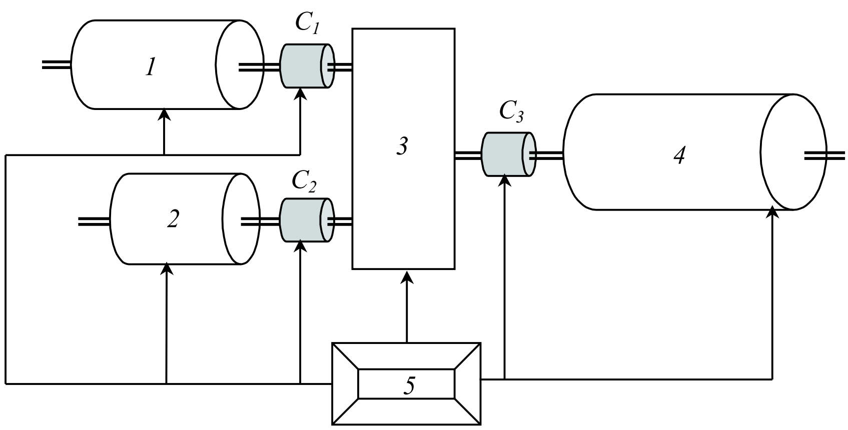

Fig. 1. GTT3 compressor. Here *1* – centrifugal compressor, *2* – electric motor-generator, *3* – gearwheel reducer, *4* – turbine-axial compressor, *5* – oil supply station, C_1, C_2 and C_3 – couplings between rotors

The problems of increased vibrations are especially crucial for the rotor of centrifugal compressor, because it has the highest speed of rotation. This rotor has two impellers with sets of blades. Experimental results of vibrations measurements performed on supports of this rotor and numerical modeling of its vibrations are discussed further. Dynamical model also includes the corresponding rotor of the reducer with its supports.

Table 1.

Characteristics of the compressor

Characteristic	Electromotor	Turbine-axial compressor	Centrifugal compressor
Nominal rotation, r/min	3000	5200	7500
First critical speed, r/min	1800	3110	3600
Mass of the rotor, kg	1490	2500	500

3. Experimental research

The analysis of experimentally measured spectral characteristics of rotor's supports vibrations showed that there were low-frequency components generated by unbalances, anisotropy of the rotor's structure, deviations of rotor's centering and so on. There are also high-frequency components generated by deviations of reducer's gearwheel positioning. These deviations are caused by defects of manufacturing and assembly of the gears. Therefore, measurements of vibrations were performed in quite a wide range of frequencies (0–7500 Hz), with an aim to gather more comprehensive data.

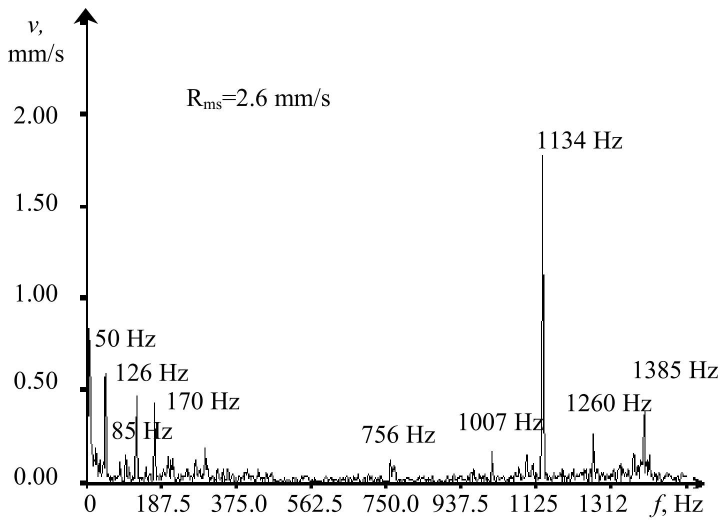

Fig. 2. Spectrum of the centrifugal compressor's bearing vibrations. Vibrations have been measured in the vertical direction. Exploitation conditions are in a regular range

Spectral analysis of vibrations of the centrifugal compressor's support adjacent to the coupling C_1 is presented in a form typical for this machine. Two cases are analyzed: when gap in compressor's sliding bearing is normal (0.3–0.5 mm, Fig. 2), and when gap is increased (0.7–0.9 mm, Fig. 3). The analysis shows that acceptable conditions of the machine exploitation exist only when gap the bearing is in a normal range. Spectral components of 50 Hz, 85 Hz and 126 Hz represent rotary speed of electro motor, turbine-axial compressor and centrifugal compressor. Amplitudes of these components show influence of rotors' unbalances or deviations of rotor centering. The 170 Hz component represents second harmonic of the turbine-axial compressor rotary frequency and is produced by anisotropy of the rotor's structure. High frequency components of 1007 Hz, 1134 Hz and 1260 Hz appeare in consequence of defects of the reducer's gearwheels and their assembling.

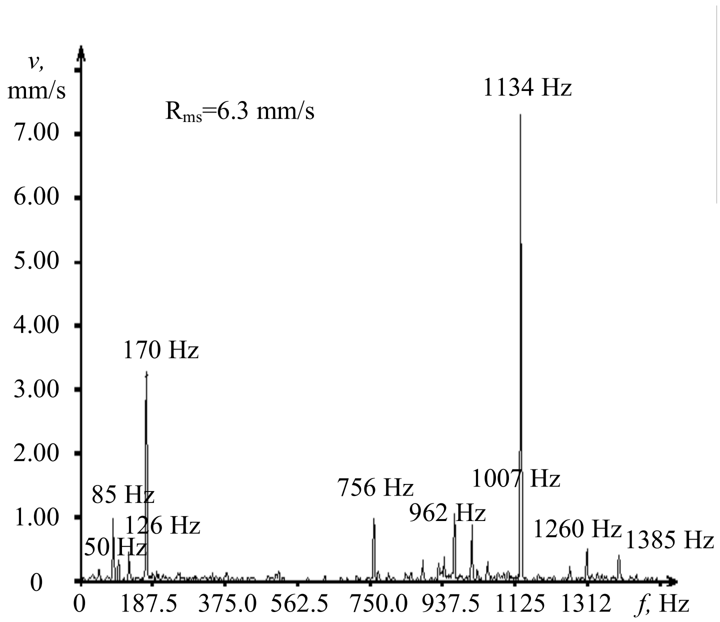

Fig. 3. Spectrum of the centrifugal compressor's bearing vibrations measured in the vertical direction. Gap in the bearing is increased

It has to be mentioned that changes of bearing's gaps and other parameters of certain machine's elements greatly influence vibroactivity of other elements (reducer, turbine and electro motor). For example, in the case when the gap in compressor's bearing is increased, vibrations of the reducer's bearing next to the coupling C_1 increase dramatically, and R_{ms} (mean-square value of vibration speed) reaches the value of 11.6 mm/s. In such a case, machine can not operate, and should be stopped for maintenance.

However, the data obtained experimentally by measuring vibrations of bearing supports are not always sufficient. For example, it is also important to know vibration of rotors' central points (between supports), because often amplitudes of vibrations are maximal there. Often it is impossible (like in the described case) to measure these vibrations experimentally, because the access to the most internal elements during machine's exploitation is impossible. Therefore, experimental results are not always sufficient enough for designing and tuning mechatronic monitoring and control systems. Such information can be obtained only by applying dynamical modeling.

4. Dynamical model

Dynamical equation of the compressor's rotor was derived applying the method of finite elements. The rotor of centrifugal compressor *GTT3* and the adjacent gear shaft of the reducer are divided into 18 elements, and analyzed as a system of flexible rotors (Fig. 4). Every element has 4 degrees of freedom.

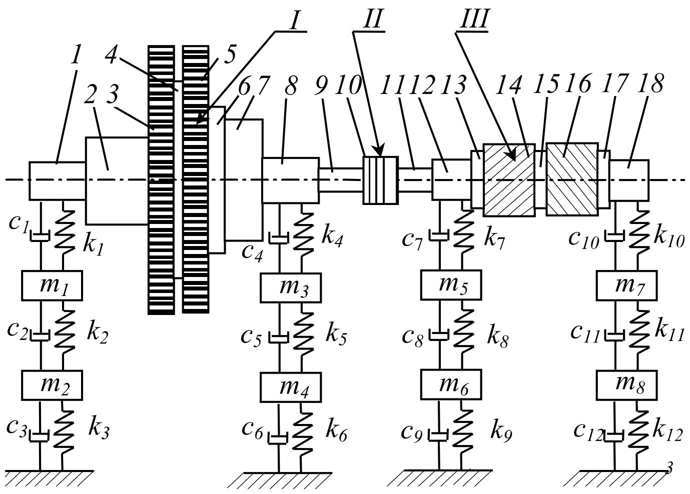

Fig. 4. Dynamic model of centrifugal compressor's and reducer's rotors: *I* – centrifugal compressor rotor, *II* – coupling, *III* – gear shaft with chevron gears, m_i, k_i, c_i – masses, stiffness and damping coefficients of rotor supports, *1 – 18* structural elements of rotors

Equation of forced vibrations of the modeled rotor is

$$(\mathbf{M} + \mathbf{M}')\,\ddot{\mathbf{U}} + (\omega\mathbf{G} + \mathbf{C})\,\dot{\mathbf{U}} + \mathbf{K}\mathbf{U} = \mathbf{F} \tag{1}$$

Here ***M*** is matrix of rotor masses; ***M'*** is matrix of masses characterizing rotation of the rotor's cross-sections around axes in a coordinate system; ***G*** is gyroscopic matrix; $\boldsymbol{C}$ is damping matrix; $\boldsymbol{K}$ is stiffness matrix; $\boldsymbol{U}$ is matrix of rotor elements displacements; $\boldsymbol{F}$ is matrix of forces affecting the rotor; ω is angular velocity of the rotor. Matrix $\boldsymbol{M}$ represents masses of beam elements and matrix $\boldsymbol{M'}$ allows evaluating rotation of their cross-sections.

The structure of matrix $\boldsymbol{F}$ depends on the type of exciting forces. Usually, these forces are caused by unbalances, anisotropy and deformations of certain rotors and their elements. The affecting forces can also be created by other sources of excitation: hydrodynamic processes in machine's sliding bearings, defects in rotors centering and assemblage, defects of gearwheels, etc. Detailed descriptions of dynamical model and structure of matrixes are presented in earlier works by the authors [4], [5].

Modeling of rotors dynamics gives amplitude-frequency characteristics of various elements. It allows evaluation of dynamics of rotor's elements and determining their condition that, because of the structure of the machine, can not be measured or monitored experimentally, or such monitoring would be very complicated (e.g. central part of the rotor and other internal elements).

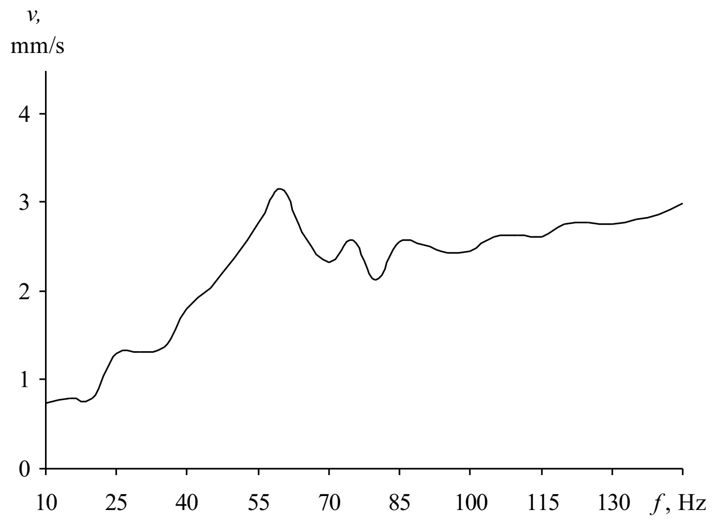

Fig. 5. Amplitude – frequency characteristic of the 4^{th} element vibrations

Amplitude – frequency characteristic of the compressor's rotor central element (4^{th} element) and reducer's rotor central element (15^{th} element) are presented in Figs. 5 and 6. It was assumed that vibrations are generated by rotor's unbalances.

The above graphs give information about dynamical condition of specific elements of the rotor, and such information can be obtained for any element described in the numerical model. The modeling can also be used to determine the sources of the vibration components that were measured experimentally. Therefore, the investigation helps finding critical frequencies, determining influences of various defects and their critical values, etc. It helps to predict machine's vibroactivity in certain conditions and the reliability of the machine during its exploitation.

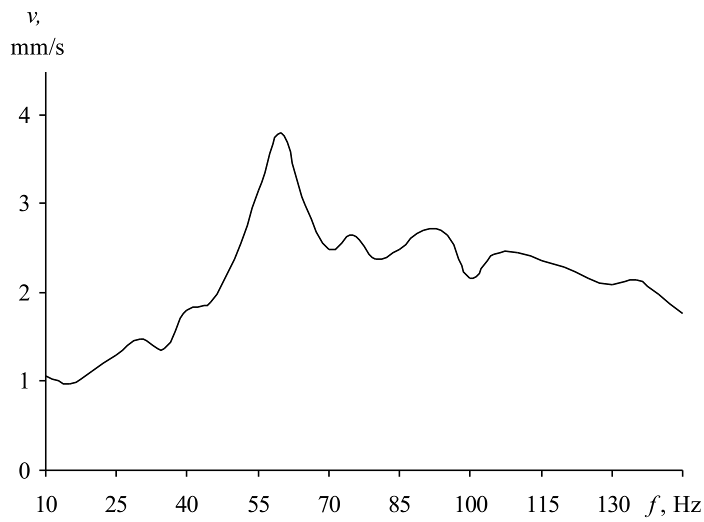

Fig. 6. Amplitude – frequency characteristic of the 15th element vibrations

The results of modeling together with experimental results (vibromonitoring, internal visual inspections, thermal monitoring and diagnostics of machine's tribological properties, etc.), technological parameters (quantity and quality of production) and historical data concerning defects and maintenance of a particular complex machine, can be used for modernizing the existing monitoring and control systems or for designing the new ones. The analysis results help to determine alert and critical levels of various monitored parameters, and are particularly important for modern systems.

5. Main results and conclusions

A thorough evaluation of machine's dynamical condition can be made through examining vibroactivity of technological equipment based on the analysis of dynamical processes and the spectra of vibrations, together with the modeling of dynamical conditions taking into account the data from monitoring of other parameters In this way, it is also possible to predict reliability of the examined technological equipment during its exploitation.

The presented dynamical model of complex rotary system helps to determine the influence of various defects and peculiarities of design on vibroactivity of the modeled system. The model is used for identification of defects in a real machine, and for planning maintenance activities.

The results of this research will be essential for the design, installation and tuning of modern mechatronic systems for machine monitoring and control.

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Badanie wibromechaniki sprzętu mechanicznego metodą analizy procesów dynamicznych oraz analizy spektrum drgań

S t r e s z c z e n i e

W pracy przedstawiono problemy związane z wibromechaniką (monitorowaniem wibracji, wibrotechniką) w urządzeniach technologicznych. Systemy mechatroniczne, projektowane do monitorowania i kontroli złożonych maszyn rotacyjnych, mogą być skutecznie implementowane jedynie wtedy, gdy poziomy zagrożenia lub krytyczne monitorowanych parametrów są dobrze znane, a źródła odchyleń parametrów mogą być wyznaczone.

Wibrodiagnostyka jest potężnym narzędziem, które może być użyte do diagnozowania uszkodzeń maszyn. Niemniej, w przypadku złożonych maszyn rotacyjnych jest bardzo trudno śledzić wszystkie źródła wibracji (np. wady wewnętrzne). Podejmuje się więc próby modelowania wibracji, co może służyć do oceny wpływu różnych parametrów na aktywność wibracyjną określonej maszyny.