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Monitoring and diagnostics of special-purpose turbomachines

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Abstract: In the operation of special-purpose turbomachines, diagnostic tools are necessary. They enable control of the machine technical state and its operation parameters in the on-line mode. The acquisition and processing of the measurement data in real time is crucial as they are indicators of the machine functioning under various operating conditions. The paper presents two types of computer designed diagnostic tools to monitor in real time the dynamic and thermodynamic parameters of special-purpose turbomachines. The first one monitors the dynamics of the rotating system with an active magnetic bearing, the second - monitors the instant value of polytropic efficiency of the compression process, which was designed for the industrial machine.

Keywords: turbomachinery; monitoring; diagnostics; magnetic bearing; polytropic efficiency

1 Introduction

1.1 Contemporary diagnostics systems of machines

Due to the requirements related to the reliability of modern machines and devices, advanced measurement techniques are widely applied as a base of modern diagnostic tools. For this reason, the machinery operation increasingly becomes an interdisciplinary area of knowledge, and requires the involvement of experts from various scientific disciplines (mechanics, automation, computer science, electronics).

Implementation of unconventional technical solutions in the industrial practice requires effective diagnostics to ensure the reliability and safety of the machine operation [1, 2]. For this reason, it is necessary to design diagnostic systems which allow one to control the machine technical condition and parameters of its operation in the

on-line mode. The acquisition and processing of the measurement data in real-time, which are indicators of the machine functioning under various operating conditions, is therefore crucial. The proper technical evaluation of the operational risk in special-purpose turbomachines requires experience, knowledge and understanding of the rules determining the correct operation of its individual components.

1.2 Rotating system with an active magnetic bearing

Searching for new solutions of machines with special technological requirements has caused an increase in designers' interest in the technology of untypical support of rotating shafts of machines. Bearings and supports, in which an untypical principle of operation or a working medium for the given field of application is used, are referred to as unconventional bearings or unconventional supports, respectively.

An example of an unconventional solution to the bearing node is a mechatronic system of an active magnetic bearing. The system of active, digitally controlled magnetic bearings, whose task is to implement the technological processes involved in meeting specific operational requirements (operation in a range of very low or high temperatures, in chemically aggressive environments, or in the vacuum) [3–7] provides an interesting alternative in the design of modern machines.

The magnetic rotor suspension technology in machines is qualitatively different if compared with conventional bearing solutions. Its characteristic feature is non-contact levitation of the machine rotor in the magnetic field generated by an automatic control system, which allows for controlling dynamics of the rotor during its motion.

1.3 Aim of study

In this study the results of the effects of computer-designed diagnostic tools to monitor the proper operation of a specific group of special-purpose turbomachinery in real-time are presented. The first part of the paper describes a diag-

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nostic system which was designed for the laboratory rotating system with an active magnetic bearing. The designed system uses vibration control of the rotating system to analyze the correctness of its operation. The second part presents a diagnostic system designed for the industrial machine to monitor the instantaneous value of polytropic efficiency for the compression process. This system will be used in the future to develop diagnostic software for turbines operating in Organic Rankine Cycles (ORC).

2 Description of the experimental method

The diagnostic system to control the proper operation of unconventional magnetic bearings was designed for the laboratory test stand (Figure 1), whose rotating shaft is a thin-walled tube made of duralumin with the external diameter equal to 54 mm and the 2 mm wall thickness, supported in two roller bearings mounted on both ends. Between these bearings, there is a system of active magnetic auxiliary support. It is driven by an electric motor, controlled by an inverter and connected to the shaft by a flexible coupling membrane. The mass of the rotating system is 4.85 kg and the length of the shaft – 1923 mm [8–10].

2.1 Diagnostic system for the rotating system with a magnetic bearing

The diagnostic system was designed to analyze and interpret the measurement data collected during the operation of the rotating machine system with magnetic bearings.

Figure 1: Test stand of the rotating system with a magnetic bearing.

Figure 2: System management scheme.

The source of the measured signals for the database of the diagnostic system are sensors installed in the magnetic bearing, which are a necessary part of the modules to control the operation of the bearing [8].

The measurement data, available in the control bearing system, are collected from the sensors of: the shaft displacement in the control axes X , Y , the currents in the windings of electromagnets I_{XT} , I_{XB} , I_{YT} , I_{YB} , the frequency of rotations n .

They are transmitted through a properly configured interface that provides the acquisition of these data for the diagnostic system.

The operation of the diagnostic system is possible in two modes of operation: on-line and off-line and the software allows for the realization of test functions in two work phases of the mechatronic rotating system, namely:

- in the phase of the shaft mounted in a magnetic bearing – *Self-diagnostic package*;

- after the start up of the drive system - *Diagnostics of operation* package.

In each functioning phase of the object, the user has access to the options which in the *off-line* mode allow one to choose the form of presentation of the recorded data and their analysis as:

- *Timing – Decrement – Phase portrait;*
- *Test of trajectories – FFT – Force (of the magnetic reaction).*

The options for the automatic measurements in real-time (on-line), their analysis and the user-generated information about the state of the diagnostic object are very important from the standpoint of operation.

2.1.1 Self-diagnostic package

The *Self-diagnostic* package checks *on-line* the readiness of the rotating system with a magnetic bearing to run the drive and generates automatically the information for the operator to allow an operation test with the drive running to be conducted.

To assess the correct functioning of the rotating system in the first phase of the work, that is, when the magnetic bearings and the suspension of the shaft are activated, a procedure which consists in control of the shaft displacement in each axis of control and an analysis of the logarithmic damping decrement, has been developed. This happens in an automatic cycle in the real work time of the object, when the elements of the bearing control system are working. The end of the test will generate the information about the object status and the possibility (or its lack) of transition to the next stage (Figure 3a, b).

After obtaining the information about the correct state of the system after running the bearing (Figure 3a), its efficiency is evaluated through an analysis of the shaft vibration when the impulse signal is applied (Figure 3b).

2.1.2 DIAGNOSTICS OF OPERATION package

Obtaining the ready signal at the stage of *Self-diagnostics* allows one to start the drive of the rotating system and to register the data in different operation phases in the *on-line* mode:

- start-up,
- shut-down,
- work with a nominal frequency of rotations – a subsynchronous frequency analysis,

- passing the critical frequency – a subsynchronous frequency analysis.

During each phase of operation of the rotating system, the *on-line* control of displacement values of the shaft, current values in the windings of electromagnets and subsynchronous components (based on the FFT analysis) is conducted. The data on unusual behavior of the system are automatically saved to a file and can be analyzed *off-line* using the *Analysis* package. In this package, the user of the system has an option to choose a type of the analysis.

The *on-line* test controls the values of shaft displacements and currents in the real time of the operation of the rotating system with the magnetic bearing during the start-up, shut-down or works with a nominal frequency of rotations, and examines the subsynchronous components on the basis of the FFT. The user of the system has an option to choose a type of the analysis in the form of: waveforms, a decrement of damping, a phase portrait, a motion trajectory of the shaft, an amplitude spectrum analysis and an analysis of the magnetic reaction force.

The analysis of the spectral amplitude – a subsynchronous test – is possible due to the *FFT* module, which checks the presence of significant values of subsynchronous components. They are an important symptom of an appearance of self-triggered vibrations of the rotating system (Figure 5).

Unstable conditions of the system operation were determined experimentally, and the identification of the significant subsynchronous component will be indicated on the graph by changes in the stripe color and recording the results in a table.

Figure 6 shows a sample assessment of the phase portrait for the rotating shaft, available in the *Analysis* option.

The proposed procedures of the specialized diagnostic software dedicated to rotating systems with an active magnetic bearing allow for automatic execution of measurements in real-time, their analysis, and generation of the information for the operator about the state of the machine in different phases of its work. It is very important from the viewpoint of safe operation and increasing the reliability of this type of unconventional solutions of rotating machine systems. An important feature of the designed diagnostic system is an open architecture that allows for modifications and extension of the number of the analyzed parameters.

The laboratory test stands, where the diagnostic tests were performed, have their practical applications:

- to control the vibration of a long flexible shaft of the industrial machinery by an additional magnetic support - safe crossing of the critical frequency,

Figure 3: Readiness assessment of the rotating system to start the drive a) shaft suspension, b) providing the forcing impulse signal.

Figure 4: Diagnostics of operation – on-line test – start-up a) proper functioning of the system b) negative test result, displacement limits exceeded for the axes X and Y – data saving to a file.

Figure 5: Identification of subsynchronous components.

Figure 6: Phase trajectory of a movement of the rotating shaft, frequency: 25.5 Hz Ω – area of the acceptable displacement.

- in the operation of an active magnetic support as a damper - the drive transmission system for the rear rotor of the helicopter [5, 9].

3 Process compressors - monitoring of the polytropic efficiency

An example of the diagnostic system which supervises the correct functioning of the special-purpose turbomachine in real-time is the software to monitor the polytropic efficiency of the process compressor functioning in the chemical and petrochemical industry. The polytropic efficiency of the process is the most effective indicator of machine operation under different operating conditions and at variable load.

Due to the complexity of the installation and the time-variable gas composition, development of a system for continuous monitoring of efficiency for this type of industrial machinery causes certain difficulties in developing a reliable method to monitor the instantaneous polytropic efficiency of the energy-intensive compression process. These prerequisites were an assumption to design a calculation algorithm of the polytropic efficiency realized between two points of the installation in which the measurement of thermodynamic parameters of the input (T_1 – static temperature, p_1 – static pressure) and the output (T_2 – static temperature, p_2 – static pressure) is made. On the basis of this algorithm, a program for visualization, mon-

itoring and optimization of the process efficiency was developed, which results in certain economic effects.

3.1 Algorithm of calculations and its visualization

A block diagram of the algorithm, which allows one to calculate and visualize the polytropic efficiency of the compressor on the basis of the knowledge of the gas composition and current values of the pressure and the temperature on the machine suction and discharge, is shown in Figure 7.

To calculate the polytropic efficiency of the thermodynamic process in turbomachines, a series of auxiliary calculations based on the equations and data contained in the literature [11] should be performed. The calculation algorithm has been developed for a mixture of gases consisting of seven basic components occurring in the industrial processes under consideration (ethylene, nitrogen, argon, methane, carbon dioxide, oxygen and ethane), whereas the molar composition of the gas can be varied.

The program starts with downloading the molar gas composition and checking if the sum of its shares is equal to 100%. By pressing the START button, the cyclic data downloading of the suction temperature T_1 [K], the discharge temperature T_2 [K], the suction pressure p_1 [bar], the discharge pressure p_2 [bar] starts. The loaded data are stored to a file in the correct order. These data are periodically updated by an external measuring system, thus it contains only the information corresponding to the current state of the machine there.

Figure 7: Block diagram of the diagnostic algorithm.

Figure 7: Cont.

Figure 8: Program for visualization of the machine polytropic efficiency.

The next step of the program operation is to analyze the downloaded data and to interpret the results in a graphical and text form, which is performed in each cycle of the program functioning. The results in a graphical form are shown on two graphs on the visualization screen as: Maximum and Polytropic efficiency (Figure 8).

The first of them is represented by means of a bar graph. It shows a relationship of the current measurement and the attained values of the maximum efficiency. The second graph presents 10 efficiency values obtained in the subsequent cycles of calculations, with the current one shown as a dot, in a linear form.

All the data presented on graphs are available in the text form as well, in order to facilitate their interpretation by the user. The obtained maximum efficiency of the process is saved and recorded in the first table Maximum polytropic efficiency, whereas the table for the last 10 measurements and the polytropic efficiency of the process calculated on their basis is placed below.

After stopping the monitoring procedures of the polytropic efficiency, there is an option to record the results to enable their further analysis.

4 Summary

Most of the bearings used in industrial rotating machines (turbines, flow compressors and centrifugal pumps) are hydrodynamic, have different designs and use oil as the working medium. It is a very popular technology for bearings in machines.

However, increasingly, specific functional conditions exclude an application of oil as the working medium for bearings and, as a consequence, lead to a search for an "oil-free" technology.

An interesting alternative for the "oil-free" technology development is a use of the turbomachinery working medium as the bearing lubricating medium [12–15]. Turbomachines, built according to this design concept, eliminate a number of elements, which are troublesome in operation and often unreliable (e.g. clutches, transmissions and seals).

This concept allows one to:

- increase the overall efficiency of the machine from a few to several percent, which is associated with a reduction in losses accompanying the functioning of a typical oil system;
- simplification of the design and shortening of the machine shaft by elimination of some seals;
- maintain the absolute cleanliness of the working medium for circulations;
- build a "hermetic" machine without the rotating shaft end situated outside of the body in the case of using a motor integrated with the rotor or an electricity generator.

This paper demonstrated that the previous experience related to the design and structure of dedicated diagnostic systems can play the role of foundation for generation of diagnostic algorithms to control the proper operation of special-purpose process turbomachines. The use of unconventional working medium for the machine bearings

required an assessment of the reliability and certainty of the machine operation in different conditions of its operation. Implementation of the proposed diagnostic system was of predominant importance for this type of rotating machines to reduce the risk of exploitation.

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