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Sensors and Measuring Systems in the Diagnostics of Mechatronic Rotating Systems

***Abstract**. Diagnostic tools capable of inspecting the technical condition of the machine and its bearing operating parameters on-line are essential to ensure adequate reliability of the machine. Therefore, the acquisition and real-time processing of measurement data on the dynamic state of the rotating system is vital.*

***Streszczenie.** Dla zapewnienia odpowiedniej niezawodności maszyny niezbędne są narzędzia diagnostyczne umożliwiające kontrolę stanu technicznego maszyny i parametrów funkcjonowania jej łożysk w trybie on-line. Kluczowe znaczenie ma zatem pozyskiwanie i przetwarzanie w czasie rzeczywistym informacji pomiarowych dotyczących stanu dynamicznego układu wirującego. (**Czujniki i systemy pomiarowe w diagnostyce mechatronicznych układów wirujących maszyn**).*

Keywords: sensors, measuring systems, magnetic bearing, diagnostics.
Słowa kluczowe: czujniki, systemy pomiarowe, łożysko magnetyczne, diagnostyka.

Introduction

In many areas of technology, also in mechanical engineering, there are more and more devices whose design is possible through the integration of the mechanical, electrical, electronic, specialized measurement instrumentation, control systems and they require appropriate computer software. These devices are called mechatronic systems.

To ensure adequate reliability of the machine, diagnostic tools capable of inspecting the technical condition of the machine and its bearing operating parameters in the *on-line* mode are needed [2]. The acquisition and processing of the real-time measurement information related to the dynamic state of the rotating system is therefore crucial.

An example of the unconventional solution for the bearing, for which the diagnostic software has been designed, is a mechatronic system of an active magnetic bearing. The active, digitally controlled magnetic bearing is an interesting alternative in the design of modern machines, whose task is to implement the technological processes related to the fulfillment of the specific requirements (work in a very low or very high temperature, chemically aggressive environments or in vacuum) [7, 8].

The magnetic suspension of machine rotors is a qualitatively different technology in comparison with conventional bearing solutions [1]. Its characteristic feature is a non-contact levitation of the machine rotor in a magnetic field generated by the automatic control system that allows one to control the dynamics of the rotor during its motion.

The paper presents a methodology for the collection, preparation and storage of the measurement data for the diagnostic base of the unconventional rotating system with an auxiliary active magnetic bearing. The results of the effects of the designed diagnostic system, which supervises the proper operation of a mechatronic rotating system of the machine through the interface using the measurement data obtained from sensors installed in the magnetic bearing, are presented.

Test stand

A model test stand, for which the diagnostic system was built, is a horizontal, flexible shaft, supported by two roller bearings mounted on both ends (Fig. 1).

An auxiliary active magnetic bearing system is mounted between the bearing and the right end of the shaft. The active magnetic bearing operates as an auxiliary cross bearing modifying the dynamic properties of the shaft line [3, 7, 8].

Structurally, the shaft is a thin-walled tube made of duralumin with an outer diameter of 80mm and wall thickness of 2.1mm. The drive was an electric motor with variable speed, which is connected to the shaft through the flexible membrane coupling. The mass of the rotating system - 4.85 kg, the length of the shaft line - 1923 mm.

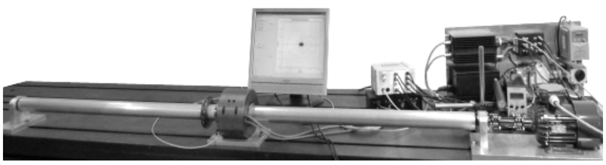


Fig. 1. Test stand of the rotating system with an active magnetic bearing

Concept of the diagnostic system

The design specificity of the real object - a long flexible shaft transmitting power - poses special requirements associated with the design of the diagnostic system, which supervises the work of an active magnetic bearing, the correct functioning of the rotating system and the effectiveness of a transverse vibration control flaccid shaft at the same time. These conditions cause that the input elements of the diagnostic system are an integral part of the system of the active shaft vibration control [2].

The diagnostic system is designed to analyze and interpret the measurement data collected during operation of the machine rotating system with a magnetic bearing [3].

The source of measured signals for a database of the diagnostic system are the sensors installed in the magnetic bearing, which are a necessary part of the modules to control the operation of the bearing. Additional measurement systems measure current values in the windings of the electromagnets of the bearing and the frequency of rotation.

The measurement data available in the control system of the bearing are collected from the sensors:

• movements of the shaft in the axes X, Y,
• currents in the windings of the electromagnets I_{XT}, I_{XB}, I_{YT}, I_{YB},
• the frequency of rotations n

They are transmitted by a specially configured interface that provides acquisition of these data for the diagnostic system [4, 5, 6].

The operation of the diagnostic system is possible in two modes: *on-line* and *off-line* and the software gives the test functions in two phases of work of the mechatronic rotating system:

• suspending phase of the shaft in the magnetic bearing - implemented option – SELF-DIAGNOSTICS,

• after starting the drive of the rotating system - implemented option - DIAGNOSTICS of OPERATION

In each phase of the object operation the user has an access to the option ANALYSIS, which in an *off-line* mode allows one to choose a presentation form of the recorded data and their analysis as: waveforms, a decrement of damping, a phase portrait, a trajectory test, FFT analysis and identification of the magnetic reaction force (Fig. 2).

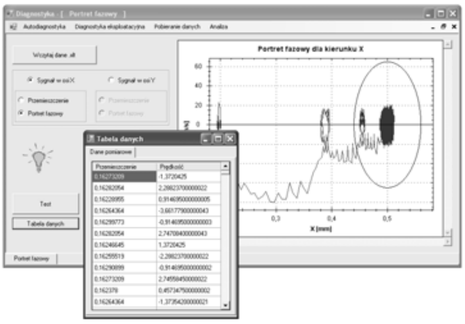
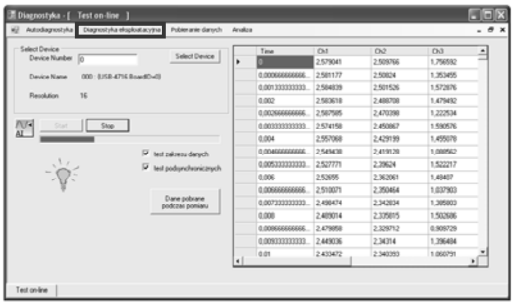


Fig. 2. SELF-DIAGNOSTICS – *off-line* mode – Phase portrait – Suspension of the shaft - a positive test result

An option - *on-line* TEST allowing for automatic execution of the measurements in real-time, data analyzing and generating the information to the user about the status of the diagnostic object is very important from the point of view of the operation (Fig. 3).



Rys. 3. DIAGNOSTICS of OPERATION – *on-line mode – Start-up* – a positive test result

Diagnostic database

The designed diagnostic system requires an access to the measurement data generated by the diagnosed object. This has been achieved by designing an additional device that allows for the acquisition and recording of these data to enable their analysis with the dedicated diagnostic packages.

For collection and registration of the data necessary for the diagnostics of mechatronic rotating systems, a portable *USB-4716 Advantech* module equipped with a USB interface that provides adequate speed and accuracy of the data transmission in the measurement applications was used.

The device is equipped with a 16-bit digital-to-analog converter, which, together with multiplexer systems, a programmable amplifier and a FIFO memory includes 16 analog voltage inputs with the common ground, with configurable input ranges from ± 625mV to ± 10V.

It also has two voltage analog outputs with the selected range from four options: ± 10V, ± 5V, 0-10V, 0-5V, 8 digital inputs and outputs (TTL compatible) and an event counter with a capacity of 16 bits. The USB module does not require any additional power source. Terminals for connecting all I / O signals are placed on the unit.

However, due to the low input resistance of the USB module, appending the input signals resulted in the charging of the signal source and interferences in their transmission. Each measurement channel has therefore been equipped with a set of emitter duplicates built on high-class operational amplifiers which eliminate the interactions of the measuring inputs. Additionally, isolated outputs reduce the impact of interference from the entrance paths and do not impact on the transmission quality of the diagnostic signals.

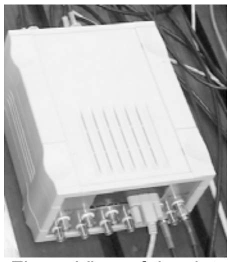


Fig. 4. View of the data collection module

Figure 4 shows a view of the data collection module with the external connector for a computer managing these data.

The interface prepared in this way allowed the transmission of the diagnostic data into a computer, where the diagnostic functions can be carried out.

The realization of these functions was possible after preparation and testing of the appropriate software, which was conducted in several stages.

Data storage

The producer of the USB module supplies the drivers allowing for a free use of the device in our programs written in *Visual Basic, Visual C ++, Visual C #, Delphi, C ++ Builder* and *LabVIEW* (only for operating systems *Windows 2000/XP/Vista*). Before connecting the module to the computer, a device manager was installed (*Advantech Device Manager*), a controller and a package *dll*.

The letterhead package of dll libraries extends a range of functions allowing for the access to the module, for example, in the simplest case, to perform a single analog measurement, use the function: select the device, its opening, download the analog value for which the number of the channel and the input range is the parameter. In case of the necessity to scan the analog inputs with high frequencies, the structure of the program becomes more extensive.

For the data archiving the corporate *Wavescan* application which allows one to save data to a text file and to generate a graphical waveform (Fig. 5) is used.

The corporate *Wavescan* application did not fulfill, however, of the required assumptions for the proposed diagnostic system and the direct use for archiving the data proved to be less effective due to the preparation of the data and their further analysis.

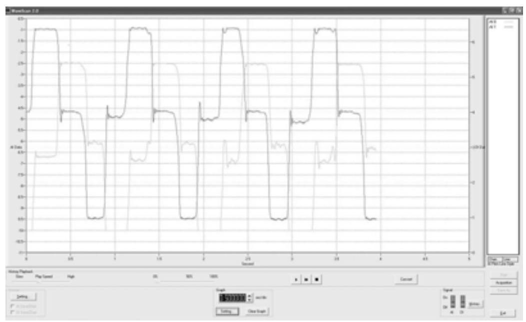


Fig. 5. Sample waveform from *Wavescan*

The measurement data in the Wavescan application are saved automatically to a *wsp* file and can be read out only by this application. The next step is to convert and save them to an *xlt* file, whose format allows one to load these data in *Microsoft Office Excel* files. This recording method significantly lengthens the procedures and, therefore, a very important stage of work was to design a dedicated application for archiving data with the saving possibility in a *xlt* format directly used in the author software.

This eliminates the need to use the *Wavescan* application to provide the required operation speed of the diagnostic system, which allows one to use packages in the *on-line* option and any hardware for the diagnostic analysis of the rotating system.

These conditions caused that the own Diagscan application for the data archiving, which is implemented in the prepared diagnostic software, was designed. For this purpose, a set of *ActiveX* functions from the *ActiveDAQ* package, provided by equipment producer, was used.

Collecting and recording of the analog data could be carried out after implementation of the *axAICtrl* function for proper communication of the diagnostic application with the used *4716-USB* interface in the diagnostic program.

On the basis of the *axAICtrl* function, a program for the data downloading from the measurement channels and recording them for the later operation analysis of the rotating system with the magnetic bearing in the ANALYSIS option was prepared.

Optymalization of the data collection parameters

From the point of view of the proper functioning of the diagnostic system, a very important stage of work was a suitable choice of the input data parameters needed for the analysis. A series of preliminary experimental tests, which allowed one to check at what settings: a sample rate, a number of collected samples, a range of the input data, the results of analysis satisfy of the founded requirements, was made.

Data collection

At the beginning of the work with the system, the user selects the DATA COLLECTION and gains access to a dialog box allowing one to define the device (*Select Device*) and define the data collection parameters (Fig. 6): a number of measuring channels (*Start Chanel, Chanel Number*), *Data Count* and *Sample Rate.*

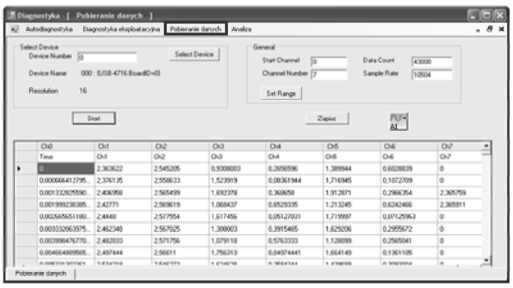


Fig. 6. Dialog box to define the data collection parameters

The ability to define the data collection parameters can be matched to varied needs of the user and the object because the system is adapted to cooperate with various variants of test stands of rotating systems with an active magnetic bearing.

In the first column of the recorded file, the time of measurement execution, which is calculated on the basis of the declared sampling frequency is saved. Subsequent columns contain the data recording of the shaft displacements *X*, *Y*, currents in the windings of the electromagnets I_{XT}, I_{XB}, I_{YT}, I_{YB}, and the frequency of the rotating shaft *n*.

The Start option begins the data registration procedure which can be saved to a *xlt* file (*Save* option). We can refer to them from all other levels, available in diagnostic modules. The recording format is also directly read by *Microsoft Office Excel*.

The package COLLECTION OF DATA can also be used optionally, when the operator wants to record all the measurement data transmitted to the diagnostic system through the SELF-DIAGNOSTICS or DIAGNOSTICS of OPERATION package. They are used for an *off-line* analysis of rotating system parameters in various phases of its operation.

Calibration of the measuring channels

Waveforms of the registered quantity in the designed diagnostics system: the displacement of the shaft in the steering axes *X*, *Y* and currents in the windings of each electromagnet I_{XT}, I_{XB}, I_{YT}, I_{YB} were the basis for the development of other forms presenting the results: a decrement of damping, a phase portrait, a trajectory, a force of the magnetic response. Thus, the faithful registration of their waveforms *on-line* and the ability to play *off-line* was required for correct operation of the diagnostic system. Measuring channels of the displacement in both axes of control and currents in the windings of the bearing electromagnets had to be calibrated for this purpose.

The objective of the calibration was to determine the real relationship between the voltage values measured by the data acquisition module prepared to work with the diagnostic system and the displacement setpoint values which are within the range of the magnetic bearing clearance. Displacement sensors of the bearing journal were installed in a special holder and standard values of this displacement were applied with a micrometer screw. The output voltages were recorded in the measuring channel through the prepared module of the data collection to keep the calibration conditions comparable with the path of the data transmission during normal operation of the bearing system and realization of diagnostic functions. In the control bearing system in two axes *X* and *Y*, two of the same type eddy current displacement sensors from *Bently Nevada* company are working.

Figure 7 shows a block diagram of the carried out calibration methodology for the displacement sensors.

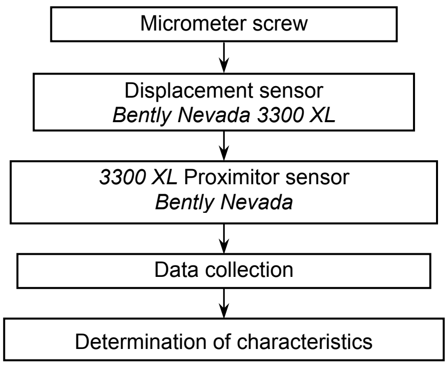


Fig. 7. Calibration methodology for the displacement sensors

As a result of the calibration, displacement-voltage characteristics determined for the two measuring channels used in diagnostics of the magnetic bearing were obtained:

Control axis X $x = -0.28U + 1,19$

Control axis Y $y = -0.29U + 1,22$

The equations of these characteristics were introduced into the appropriate procedures of the diagnostic software, which gave real displacement values recorded by the diagnostic system expressed in millimeters.

For the measurement of currents in the windings of the electromagnets, LEM Hall Effect transducers which produce an output voltage signal are used. The calibration of the current measurement paths have revealed that the conversion ratio is equal to unity, and, thus, the dependence current - voltage is of the form:

$I = k\ U_i$, dla $k = 1A/V$.

Verification of the correctness of the waveform registration

After an introduction of procedures for processing characteristics, obtained through measuring path calibration of the displacement in the axes *X*, *Y* and currents in the windings I_{XT}, I_{XB}, I_{YT}, I_{YB} into the program, the verification of the registration correctness of their waveforms has been made.

Figure 8 shows a verification of the displacement waveforms recorded for the X and Y axis. At the same time the waveforms were recorded with the diagnostic system (upper part of the figure) and the measuring system *LMS TestXpress* (lower part of the figure), while maintaining the same conditions of registration.

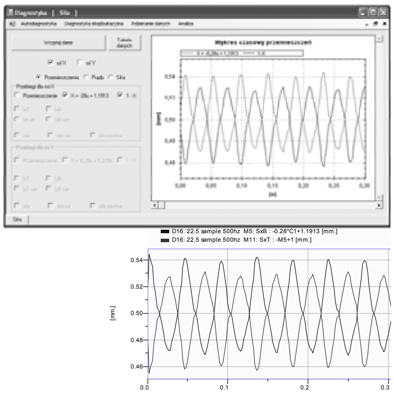


Fig. 8. Verification of the displacement waveforms for the X axis

Figure 9 shows a verification of the trajectory waveform for the rotating system with an active magnetic bearing consisting of displacements for the X and Y axis.

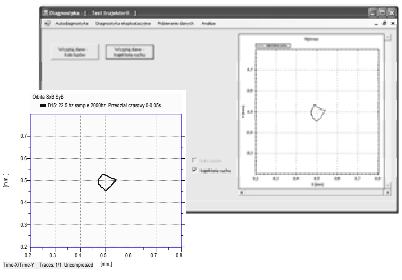


Fig. 9. Verification of the trajectory waveform

The samples of the displacement and trajectories waveform registrations confirm the correctness of the developed measurement procedures used in the designed diagnostics system.

This allowed for an implementation of the subsequent diagnostic procedures in the designed system for analyzing a damping decrement, a phase portrait, FFT and a magnetic reaction force.

Conclusions

The designed diagnostic software includes software packages to perform a variety of complex procedures, which are responsible for the *on-line* diagnostics of the correct operation of the magnetic bearing both in the stationary and rotating system. It also provides an ability to analyze, in an *off-line* mode, data automatically saved into memory and associated with untypical behavior of the system. The key problem is to collect data from the measuring paths of the displacement in the X and Y axes and the currents in the windings I_{XT}, I_{XB}, I_{YT}, I_{YB}, which determine the proper operation of the system.

To develop this system, advanced IT technologies that allow for integration of mechanical and electronic components and specialized measuring equipment were used.

The diagnostic system, designed, built and tested on real objects, gives wide possibilities to analyze the proper operation of the mechatronic rotating system using options SELF-DIAGNOSTICS and DIAGNOSTIC of OPERATION, in various stages of work:

- Suspension of the shaft in the bearing,
- Start-up,
- Shut-down,
- Operation at the nominal frequency of rotation.

The laboratory stands, where diagnostic tests were performed, were built in the scale of real rotating systems. They have their practical applications such as:

- turbomachinery diagnostics with active magnetic bearings
- control of flexible shaft vibrations of the machines using an auxiliary magnetic bearing
- magnetic damper exploitation designed for secure crossing of the critical frequency by long flexible shafts of the machines.

The designed diagnostic system is very important if a decision to use such a solution in the industrial machine is made.

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