Controlling the characteristics of the hybrid bearing by means of an electromagnetic actuator

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Abstract. The increase in the power and efficiency of the newly developed rotating mechanisms is inextricably linked with the growth of their rotation speeds and the overall level of vibration. Gas-dynamic foil bearings have a higher priority for use in high-speed mechanisms due to their practically unlimited maximum speed, the absence of an additional lubrication system, low friction power losses, etc. However, increased friction and low load-carrying capacity during the start-stop period is a problem for the further application of gas-dynamic foil bearings. The hybrid bearing studied in this work includes a rolling-element bearing, a gas-dynamic foil bearing and actuators. The hybrid bearing studied in this work includes a rolling-element bearing, a gas-dynamic foil bearing and actuators. Actuators allow during operation to switch from one type of bearing to another, as well as to control the radial gap of the gas-dynamic foil bearing, changing the dynamic characteristics of the hybrid bearing. The new designed hybrid bearing was manufactured and tested on a rotordynamic test rig in this study. A theoretical model of the hybrid bearing rotor system was built and demonstrated by the experiment results.

1. Introduction

The stability of the rotor-bearing system is one of the most important performance indicators of equipment with rotary motion. This affects the reliability, efficiency and safety of the unit [1, 2].

There are a lot of researches to improve stability and reduce vibration in rotor bearings. Bearings with variable geometry [3, 4] allow changing the dynamic characteristics of the bearing and reducing the vibration level of the unit. Bearings with active lubrication control [5-7] increase the stability of the rotor system. Bearings with a magnetorheological fluid [8-10] can ensure the stability of the rotor system by adjusting the viscosity of the lubricant. Bearings with controlled piezoactuators [11-13] can actively balance the rotor by close-loop controller. Combinations of gas-dynamic foil bearings with active magnetic bearings or electromagnetic actuators [14-16] can reduce the wear of the foils by creating a larger radial gap when the foil is bent under the influence of an electromagnetic field. The results of the presented studies demonstrate the ability to reduce vibration by applying a control action and demonstrate the ability to stabilize the hybrid bearing system.

In this paper consider the dynamic characteristics of a hybrid bearing with controlled characteristics. The influence of the control action by means of actuators on the dynamic characteristics of the bearing was studied experimentally.
2. Hybrid bearing and test rig

Figure 1 shows the schematic view and photo of the hybrid bearing with controlled characteristics. The hybrid bearing consists of the housing 1 there is a pair of radial rolling-element bearings 2. A gas-dynamic foil bearing is mounted in the rolling-element bearings. The gas-dynamic foil bearing consists of a sleeve 3 inside of which are mounted eight foils 4. A rotor 5 is installed in the gas-dynamic foil bearing. The electromagnetic actuator 6 installed in the housing allows to control radial gap of the gas-dynamic foil bearing. To lock the inner ring of the rolling-element bearing during the start-stop period, a piezoactuator 7 is installed.

![Schematic view and photo of the hybrid bearing.](image)

**Figure 1.** Hybrid bearing with controlled characteristics: a) schematic view: 1 – housing; 2 – rolling-element bearing; 3 – sleeve; 4 – foils; 5 – rotor; 6 – electromagnetic actuator; 7 – piezoactuator; 8 – proximity probe; b) photo of the hybrid bearing.

In Figure 2 the overview of the test rig is presented. The rotor system consists of a rotor 6 with diameter of 40 mm, resting on a pair of hybrid bearings 4. The rotor is coupled to an ELTE TMPE3 3 electromotor with a maximum rotational speed of 24,000 rpm. Perpendicular to each other two displacement sensors AP2100-C-051 are mounted in the bearing housing. Data from these sensors is acquired using National Instruments NI cDAQ-9178 chasse module and analog input module NI-9205. An AU02 torque hammer with an AC21 force sensor is also connected to the analog input module. The hammer acts as a source of disturbance in the study of the dynamic characteristics of the hybrid bearing. The filtering of the input signals for each channel is carried out with an eleventh order Butterworth low-pass filter and a cutoff frequency of 100 Hz.

The second information-measuring system is represented by a portable vibration analyzer Bruel & Kjaer PULSE 3560C. This system includes two Deltatron 4507-001 piezoelectric accelerometers mounted vertically and horizontally on the bearing housing and an MM0024 photoelectric tachometer.
In Table 1 main parameters of the test rig elements are presented. The same parameters are used for modeling below.

| Element                  | Parameter       | Value  |
|--------------------------|-----------------|--------|
| Rotor                    | Diameter        | 40 mm  |
|                          | Length          | 575 mm  |
|                          | Mass            | 4.5 kg  |
|                          | Inner diameter  | 55 mm  |
| Rolling-element bearing  | Outer diameter  | 80 mm  |
|                          | Width           | 13 mm  |
|                          | Diameter        | 40.2 mm |
|                          | Width           | 72 mm  |
| Foil bearing             | Max. radial gap | 100 μm |
|                          | Foil thickness  | 100 μm  |
|                          | Number of foils | 8      |

3. Mathematical modelling and results

Figure 5 shows a dynamic model of the combined support. The rotor vibrates under the influence of imbalance forces, mass and simultaneously acting reactions of rolling and sliding bearings, which are presented in the form of linear springs and dampers.

In the process of operation of the hybrid bearing, three modes can be distinguished:
1. Acceleration, in which the voltage across the electromagnetic actuator and the piezoelectric actuator is zero and the main load is carried by the rolling-element bearing.

2. Transition from rolling-element bearing to gas-dynamic foil bearing. When the transient rotation speed is reached, voltage is applied to the actuators, as a result of which an electromagnetic force arises, which bends the foils and at the same time the inner ring of the rolling-element bearing is locked.

3. The main operating mode, in which the rolling-element bearing speed is zero, the main load is taken by the foil gas-dynamic bearing, and the voltage change on the electromagnetic actuator allows to adjust the radial gap and change the dynamic characteristics of the unit.

The main interest is operating mode, which is associated with operation on a gas-dynamic foil bearing with a controlled gap. The stiffness and damping coefficients of the hybrid bearing will be determined by the following relationships:

\[
K_{x}^{HB} = K_{xx}^{FB} + K_{xy}^{FB}, \quad K_{y}^{HB} = K_{yx}^{FB} + K_{yy}^{FB}
\]

\[
B_{x}^{HB} = B_{xx}^{FB} + B_{xy}^{FB}, \quad B_{y}^{HB} = B_{yx}^{FB} + B_{yy}^{FB}
\]

The calculation of the stiffness and damping coefficients of the lubricating layer of a foil gas-dynamic bearing can be performed by one of the methods based on a linear formulation, where the reactions of the lubricating layer are presented as linear functions of the rotor center displacement:

\[
R_{x}^{FB} = R_{x}^{FB} - K_{xx}^{FB} \Delta X - K_{xy}^{FB} \Delta Y - B_{xx}^{FB} \Delta X - B_{xy}^{FB} \Delta Y,
\]

\[
R_{y}^{FB} = R_{y}^{FB} - K_{yx}^{FB} \Delta X - K_{yy}^{FB} \Delta Y - B_{yx}^{FB} \Delta X - B_{yy}^{FB} \Delta Y
\]

The reactions of the lubricating layer in projections on the axes of the coordinate system can be represented as:

\[
R_{x}^{FB} = \int_{0}^{L} \int_{0}^{\pi D} p \cdot \cos \alpha dx dz; \quad R_{y}^{FB} = \int_{0}^{L} \int_{0}^{\pi D} p \cdot \cos \alpha dx dz
\]

where \( p \) – pressure in the lubricant layer.

The main equation for determining the pressure field is the Reynolds equation, generalized to the case of a two-dimensional flow of a viscous compressible lubricant:

\[
\frac{\partial}{\partial x} \left( \frac{\rho h^3}{\mu K_{x}} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial z} \left( \frac{\rho h^3}{\mu K_{z}} \frac{\partial p}{\partial z} \right) = 6 \frac{\partial}{\partial x} (p U h) + 12 \rho V
\]

where \( U \) and \( V \) - circumferential and radial velocities of the surface points of the shaft; \( K_{x} \) and \( K_{z} \) - the turbulence coefficients in the directions of turbulence; \( \rho \) and \( \mu \) are the density and viscosity of the fluid accordingly; \( h \) – radial gap.

In the GNU Octave mathematical modeling environment, a program was written that allows, according to the given geometric and physical parameters of the hybrid bearing, to determine the stiffness and damping coefficients depending on the voltage applied to the electromagnetic actuator (Figure 4).
A series of experimental studies included a study of the assessment of the influence of the voltage of an electromagnetic actuator on the dynamic characteristics of a hybrid bearing and comparison with the results of a calculating experiment. A natural experiment consisted of accelerating the rotor to the nominal speed, followed by a vertical hit on the open part of the rotor with an AU02 torque hammer, followed by recording and processing the amplitude of the rotor oscillations with AP2100-C-051 converters with finding the stiffness and damping. Figure 5 shows the results of comparing experimental data with a calculating experiment on the stiffness and damping coefficients for different states of the electromagnetic actuator.

Comparative analysis of calculating and experimental results showed the discrepancy between the results by no more than 15%. The results show that with an increase in the rotor speed, the rigidity of the hybrid bearing increases with practically unchanged damping. When voltage is applied, a drop in stiffness and damping is observed, which is explained by an increase in the radial gap of a foil gas-
dynamic bearing and, as a consequence, a decrease in the reaction of the gas lubricating layer. The nature of the dependence of the stiffness coefficient on the voltage applied to the electromagnetic actuator indicates a smooth change in the stiffness and damping of the combined support, which makes it possible to reduce dynamic loads. The mechanism for changing the radial gap and controlling the dynamic characteristics of the hybrid bearing allows to achieve the effect of transition through the critical frequencies of the rotor during its operation, which makes it possible to ensure such a value of the spectrum of natural frequencies so that they do not coincide with the current value of the rotational speed of the rotor.

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