Actuators of active tribotechnical systems of the rotor-bearing type

L Savin¹, D Shutin¹, A Kuzavka¹

¹Department of Mechatronics and International Engineering, Orel State University,
Naugorskoe sh. 29, Orel, Russia, 302020

E-mail: rover.ru@gmail.com

Abstract. The article describes the perspectives of using active bearings in rotor-bearing systems. The principal scheme of a mechatronic tribotechnical system and classification of actuators used in such system are shown. Piezo actuators are considered from the point of view of use as actuators in active bearings. The comparative characteristics of different types of actuators

1. Introduction

Bearings in rotating machinery are a large class of tribotechnical systems. Fluid-film bearing are a very complex system from the point of view of tribology because different types of friction can appear during their operation. In addition to wear caused by friction, vibrations also appear in rotor-bearing systems due to different reasons including nonlinear properties of the lubricant film. Rotor oscillations increase friction and wear, lead to lead to the failure of the important parts of the machine. So, improving dynamic characteristics of rotor-bearing systems, including reducing vibrations level, is actual engineering problem. This problem is being solved in different ways. The classic way is investing in constructive and technological solutions in fluid-film bearings. However, the process of improving bearings this way often meets some physical limits, and even small improvements may take a lot of resources. The other way is integration of informational and control systems in bearings. This way is becoming more popular due to the development of electronic, computing and other technical means necessary for the implementation of such systems. So, improving the hardware characteristics by lead to new results in developing modern rotor-bearing systems in recent decades [1].

Actuators are one of the most important elements of such systems. Actuators transform the input signal (electrical, mechanical, pneumatic, hydraulic, etc.) into the output signal acting on the controlled object. Active fluid-film bearings are rather complex systems so the characteristics of the used actuators must meet rather strict requirements.

2. The principle of operation of a typical tribotechnical system of the rotor-bearing type

The way how active control is implemented in fluid-film bearings is illustrated in [2]. The shown method is the simplest one to be implemented and is perspective for application in rotating machinery. In such systems control is implemented by changing the lubricant pressure in the feeding chambers of a hybrid (combined hydrostatic and hydrodynamic) bearing. Such active bearings usually are a closed-
loop control system containing sensors, controller, intermediate devices and actuators. The control signal is generated in the control loop that is external with respect to the structural design of the bearing. The typical scheme of such mechatronic bearing is shown in the Figure 1.

**Figure 1.** Common scheme of an active tribotechnical system of the rotor-bearing type.

3. **Classification of actuators**

In mechatronic bearings the rotor is usually a control object. The controlled coordinates describe the position of the rotor in the bearing. At the same time, the rotor’s coordinates themselves are not as important for the machine’s operation as its complex characteristics, such as oscillations amplitude, power losses due to friction. These characteristics are obtained using the data describing the position of the rotor in the bearing, size and shape of the rotor’s trajectory.

The control signal produced by controller is transmitted in a control loop to the actuators and changes that way the parameters of operation of the rotor-bearing systems in the required manner.

**Figure 2.** Classification of actuators of tribotechnical systems of the rotor-bearing type.
There are several approaches to creating the mechanical control action in fluid-film and gas bearings:

a) changing the geometry of the gap between the rotor and the bearing. The geometry of the gap is usually changed due to the movable elements of the bearing. Such elements are driven by actuators. The example of such bearing is shown in [12];

b) changing the parameters of supply of lubricant. This process is usually implemented by special controlling devices (throttles, pressure controllers) mounted in supply tracts [13];

c) combined actions obtained by joint using of the approaches mentioned above [14-16].

Active bearings in which the mentioned approaches are implemented are equipped by different types of actuators. The most commonly used types of actuators in fluid film bearings are described below.

1. The mechanical actuators with electromagnetic drive. Such actuators are rather cheap and simple. However, such actuators are often limited in performance due to high inertial properties of moving parts. It makes it more complicated to use these actuators in rotor-bearing systems with direct control of the rotor position at high rotation frequencies. Mechanical actuators with electromagnetic drive are more applicable in systems with indirect rotor position control, e.g. when the damping or stiffness of the whole bearing are controlled.

Mechanical actuators with electromagnetic drive can have different types of impact on the parts of the bearing. In some systems it is direct mechanical impact on the moveable parts of the bearing, e.g. in active tilting-pad bearings [17]. In other cases the considered actuators are a part of a device that regulates other parameters that are used for controlling the rotor-bearing systems. The example of such a device is a servovalve controlling the lubricant pressure [13].

2. The mechanical actuators with piezo drive. Such devices transform the input electrical signal into the output mechanical force or displacement due to the inverse piezoelectric effect [18]. There are different types of piezoactuators [19-21], some of them are shown in the Figure 3.

Figure 3. The most commonly used types of piezoactuators.

Piezoactuators have sufficiently better performance comparing to the category described above and very low inertial properties, so they can be used in high-speed rotating machinery with direct control of the rotor position in the bearing. However, piezoactuators are also limited in the possible range of mechanical displacement which is tens or hundreds of microns for simple batch piezoactuators. It limits application of piezoactuators in some cases.
When piezoactuators are used for having the direct impact on the moveable parts of the fluid-film bearing, the limited displacement range makes it impossible to use them in bearings with large geometric dimensions. In such bearings the required ranges of displacement of the moveable parts that provide the appropriate control action range exceed the possible actuator’s displacement range. Its increase by using mechanical transmission are usually not justified due to the performance decrease caused by the inertial properties of the transmission elements and the appearance of concomitant negative effects such as backlashes and increased friction.

Bimorphous piezoactuators provide larger displacement range than batch piezoactuators but rather low generated mechanical force that is not enough in many cases for moving the parts of the bearing with the required dynamic characteristics.

3. The electromagnetic actuators. They are not actuators in the direct sense of this term. Electromagnetic actuators generate the electromagnetic field. In turn, it leads to appearance of the force action on the rotor-bearing parts due to different physical effects, such as magnetorheological effect. Such systems have almost unlimited performance but have a limited range of applications in tribotechnical systems.

A common unified evaluation of the various drives is not possible due to some reasons. First of all, actuators solve different technical problems in different types of bearings. Besides, different types of actuators are at different stages of development [20]. The table 1 presents the comparison of individual properties of the actuators in tribotechnical systems.

4. Hydraulic and pneumatic. Devices of this category mechanically change the parameters of a tribotechnical system by transforming the energy of liquid or gas flow. Pneumatic and hydraulic have rather simple design and good force-to-size ratio.

However, hydraulic and pneumatic systems have substantially limited frequency range, so using them in active bearings, especially with direct rotor position control, is also limited. Actuators can be based on hydraulic, pneumatic cylinders, hydraulic motors, compressors, as well as special types of drives in which mechanical movements are caused by a change in the pressure of a liquid or gas [10,11].

4. Comparison of actuators in rotor-bearing systems

Table 1. Comparative characteristics of the properties of the executive mechanisms of tribotechnical systems.

| Properties            | Electromagnetic actuators | Hydraulic and pneumatic actuators | Piezo actuators          |
|-----------------------|---------------------------|-----------------------------------|--------------------------|
| Benefits              | Simple transfer function  | High force-to-size ratio          | Simple transfer function |
| Drawbacks             | High mass                 | Transfer function                 | Relatively long design   |
|                       | Relatively low generated  | depends on pneumatic-hydraulic    | Expensive high-voltage   |
|                       | force                     | dynamics                          | amplifier                |
| Frequency range       | Good                      | Satisfyingly                      | Excellent                |
| Displacement range    | Good                      | Excellent                         | Insufficient             |
| Rrigidity             | Insufficient              | Good                              | Excellent                |
| Force-to-size ratio   | Satisfyingly              | Good                              | Good                     |

Despite a number of drawbacks, piezo actuators are highly promising in terms of using them in active fluid-film bearings. This is facilitated, in particular, by high dynamic characteristics of piezo actuators that are very essential in view of the current tendency to increase the rotational speed of rotating machinery to increase its power-to-weight ratio. High-performance active bearings can
provide long service life, reliability and safety such equipment. In addition, piezo actuators have a number of additional advantages that are essential for use in active bearings:

- almost unlimited resolution: piezo actuators convert electric power directly to mechanical, they provide movement in subnanometric ranges. This property is useful when correcting the clearance geometry between the rotor and the bearing housing;
- the response rate in microseconds;
- the absence of a magnetic field, the action of actuators is based on electric fields. They do not generate magnetic fields, nor are they affected by such. This is especially important when used in equipment that should be proofed from electromagnetic interference;
- low energy consumption in static state regardless of the external load magnitude, even under the influence of large loads, actuators do not consume energy. It allows developing energy-efficient rotor-bearing systems in which power losses are reduced by active control [18], and energy consumption of a control system is lower than energy savings due to reduced friction;
- there is no wear of piezo actuators because their operation is based on the dynamics of the solid;
- ability to work in extreme conditions, piezo actuators do not require lubrication, and piezoelectric effect is present even at low and cryogenic temperatures. It allows using piezo actuators in bearings with cryogenic lubrication, e.g. liquid oxygen, hydrogen, etc.

5. Application of piezo actuators in rotor-bearing systems
Let’s consider the examples of using of piezo actuators in fluid-film bearings and gas bearings that operate mostly on the same principles as fluid-film bearings.

The paper [22] presents an active foil bearing where piezo actuators pull and push the foil and influence the rotor behavior that way. The bearing is used in small-sized gas turbine engines, centrifugal compressors, turbo expanders, aerospace auxiliary units, conventional vehicles. The scheme of the bearing is shown in the Figure 4.

![Figure 4. Foil gas bearing.](image)

The devices described in [23, 24] also contain piezo actuators. In [23] the deflections of each individual corrugation of the circular corrugated element are directly proportional to the change in the magnitude of the current in the circuit. It allows monitoring the deflections and change the stiffness of the circular corrugated element (and the rigidity of the whole bearing as well) by increasing the current
(Figure 5 (a)). In [24] the control is implemented in a similar way, but the deflections are obtained by means of the foils (Figure 5 (b)).

![Figure 5](image1.png)

**Figure 5.** Gas bearings with piezo actuators: (a) – single-foil bearing with the circular corrugated element; (b) – multi-foil bearing.

Piezo actuators are also used in the device described in [25]. The bearing differs from the foil bearings described above by usage of bimorphous piezo elements that consist of the foil and the piezo element (Figure 6).

![Figure 6](image2.png)

**Figure 6.** Multi-foil gas bearing with bimorphous elements.

Piezo actuators are used in active bearings in combination with other actuators as well. Such systems are described in [15, 16].

One of the main problems solved by active bearings is reducing the unwanted rotor movements during operation of the rotor-bearing system. The rotor position in the bearing is described by the coordinates of its center in the coordinate system based on the bearing. A certain position of the rotor is chosen as the setpoint of the control system. The control system minimizes the deflection of the rotor from the setpoint. The structure of a two-loop control system of a journal active hybrid bearing is
described in [2] and shown in the Figure 7. SP is a device determining the setpoint, C is a converter, CT is a controller, A is an amplifier, RBU is a rotor-bearing unit, FB is a feedback loop, SV is a servovalve changing the pressure of the lubricant. The main drawback of the servovalve is its low dynamic properties. Using piezo actuators instead of the servovalves with electromagnetic drive allows obtaining much better dynamics of the system.

Figure 7. Structure of the control system of an active journal hybrid bearing.

6. Conclusion
Development of modern piezo actuators results in new developments in tribotechnical systems. The presented active mechatronic bearings use various ways of using piezo actuators in such systems. The combination of known physical phenomena (piezoelectric effect, electromagnetism, hydro- and pneumo-mechanics, etc.) into integrated system contributes to the appearance of modern devices which are actively introduced into mechatronic rotor-bearing systems.

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