Technological assurance of reliability of centrifugal pumps for pumping biomass processing products based on adaptive dampers

O A Kolenchukov¹, E A Kozhukhov¹, E A Petrovsky¹, V V Bukhtoyarov¹,² and V A Kachaeva¹

¹Laboratory of Biofuel Compositions, Department of Technological Machines and Equipment of the Oil and Gas Complex, Siberian Federal University, 82/6, Svobodny Av., Krasnoyarsk, 660041, Russia
²Reshetnev Siberian State University of Science and Technology, 31, Krasnoyarskiy rabochiy pr., Krasnoyarsk, 660037, Russia

E-mail: olegandrenalin.ru@mail.ru

Abstract. In almost every mechanical system, moving mechanisms slide over stationary parts, creating friction and, as a result, unwanted energy losses. In engineering, sliding or rolling bearings are most often used as supports. However, any system can benefit from a greater reduction in friction between components. As will be shown in this article, the stability problem can be solved by blocking vibrations in the radial direction. The latest technological advances in the field of manufacturing magnetic materials make it possible to integrate magnetic bearings with permanent magnetization (hereinafter - MBPM) into a larger number of mechanical systems. This blocking of radial movement is carried out without the use of a mechanical sliding bearing, chosen for its simplicity and ease of integration. To facilitate the integration of the MBPM into the overall system of the device, it is important to know the mechanical properties of magnetic bearings, namely stiffness and damping, as well as the performance characteristics and limits of their operation. This article examines the possibility of using an adaptive damper in centrifugal pumps to ensure the technological reliability of the equipment. Alternating permanent magnets in the direction of their movement is the most optimal option, leading to large and smooth hysteresis loops of force-displacement. The proposed arrangement of magnets ensures the adaptability of the device with the determination of its optimal size, and also takes into account the edge and surface effects in the design of the damper. In addition, the article discusses theoretical and technical issues of levitation-free floating of bodies. Magnetic suspension can be used to study only those processes where mechanical connections are undesirable. The use of magnetic suspension for balancing centrifugal pumps during transportation of biomass processing products, supports of mixing devices in reactors in biomass processing reactors and other machine components opens up wide opportunities.

1. Introduction
The most modern methods of vibration diagnostics allow to determine up to 90% of defects at an early stage of their occurrence, for example, the method of spectral analysis of the envelope of frequency vibration, the method of shock pulses and frequency analysis [1-2]. However, these methods of
monitoring the diagnostics of the vibration state of centrifugal pumps require significant material costs. One of the ways to solve the reliability problem is the introduction of a system with MBPM [3-5].

The absence of mechanical interaction between the moving components of the device also makes it possible to effectively use MBPM in various technological equipment: in rotating parts of mixing devices in reactor lines for processing biomass (organic waste) by pyrolysis, kinetic storage, centrifugal pumps, turbo expanders, etc. [6-7].

The MBPM system in question is manageable, since there is no need for the system to function in order to maintain it in a stable (operable) state. The sources of the repulsive force in such a device are permanent magnets (or high-temperature superconductors) [8].

MBPM have a number of design and technological advantages:

- there is no power supply system;
- relatively low audible sound produced;
- no need for control systems;
- there is no need to control the position of the shaft;
- absence of vibration transmission to non-rotating machine elements in conditions of low radial stiffness;
- there are no requirements for the presence of a safety bearing.

2. Objects and methods of research

Let’s consider the process of implementing MBPM in centrifugal pumps. Wear of the bearing supports of centrifugal pumps (hereinafter referred to as CNP) is one of the main problems of stability in the spectrum of performance characteristics and leads to an increase in vibration, which subsequently causes the rotor to deviate from the stability position. In the future, this leads to the touch of the working organs of the central nervous system for the stuffing box seal (the base of the stuffing box seal) [9].

The imperfection of experimental installations and magnetization schemes, as a rule, leads to a deviation of the measured values from the theoretical values. The use of a numerical model of finite element methods (FEM) is also discussed in the authors' articles [10,11] in order to improve the accuracy of the results. In addition, experimental procedures for measuring stiffness and damping of passive, active or superconducting magnetic bearings are given in the literature [12-15]. Almost all of these techniques use a uniaxial weight sensor that measures the force generated in one direction, which leads to incomplete characterization. Although the experimental measurements are relatively accurate, a large number of analytical calculations are needed to fully analyze the state of the magnetic system.

2.1. Passive stabilization

Contactless support of rotary systems with magnetic levitation has a number of advantages. The concept of magnetic levitation without lubrication and friction is optimal for technological equipment in which high rotational speeds are desirable, the sealed design of the rotor from external environmental influences. In addition, passive magnetic bearing systems combine high reliability with relatively low complexity of manufacturing the bearing element (especially compared to active magnetic bearings). Passive stabilization can be achieved with superconducting materials, electrodynamic effect or the use of permanent magnetic bearings, but the general problem is the lack of damping. Electrodynamic and superconducting bearings introduce instability even in the supercritical mode [16-17].

2.2. Ensuring the manufacturability of magnetic materials

Permanent magnets are artfully constructed mixtures of phases designed to create a coercive force in the main component, which has favorable intrinsic magnetic properties Tc, Ms and Ku.

An actual approach, which has been studied for many years, is to create a two-phase nanocomposite from a soft phase with a high moment, an exchange associated with a solid phase with high anisotropy.

Another approach is to use shape anisotropy in aligned composites made of semi-solid materials. The best results were achieved with cobalt nanowires chemically grown using polyol and then aligned
Cobalt is a semi-solid material with $(BH)_{\text{MAX}} = 500 \text{ kJ/m}^3$ and $j = 0.45$, therefore, a significant anisotropy of the shape is necessary to turn it into a permanent magnet. The energy product of aligned nanowires, extrapolated to a density of 100%, is equal to 350 $\text{kJ/m}^3$.

Permanent magnets are, in fact, metastable structures that have a multi-domain ground state, which practically does not create a scattered field. Heating aggravates thermal instability, and magnets experience several types of flow losses during heating [12]. Firstly, these are reversible losses that are fully restored when returning to ambient temperature. They reflect the internal thermodynamic behavior of the material, and they cannot be avoided. Magnetic rigidity and coercive force naturally decrease with temperature due to the temperature dependence of $M_s$ and $K_1$. This is followed by irreversible losses associated with a change in the fully magnetized metastable domain structure at elevated temperatures. They can be cured by remagnetizing the material at ambient temperature. Finally, there are irreparable losses caused by changes in the chemical composition or microstructure of coexisting phases. Effects caused by oxidation or volatilization of rare earth elements belong to this latter category.

Manufacturers of magnets designed to work at high temperatures often practice conditioning their magnets at a temperature about 50K above the operating temperature range in order to eliminate irreversible losses so that the properties of the magnetic grid do not deteriorate further. Most rare earth magnets have a rectangular or cylindrical shape, with effective demagnetization coefficients given by formulas such as $1/(2n + 1)$ and $1/(4n/p1/2 + 1)$, where $n$ is the ratio of height to width.

The traditional method of increasing the coercive force of sintered Nd – Fe – B magnets is to partially replace Nd with heavy rare earth elements, such as Dy or Tb, to increase the anisotropy field of magnets, however, the increase occurs due to a significant decrease in $(BH)_{\text{MAX}}$ due to the ferrimagnetic characteristics of $(\text{DY/TB})_2\text{Fe}$.

Recently, several methods have been developed aimed at modifying grain boundaries, i.e., the concentration of Dy or Tb in the surface areas of grains of the Nd$_2$Fe$_{14}$ main phase by annealing sintered Nd – Fe – B magnets coated with micron particles TbFe3 for the preparation of sintered Nd – Fe – B magnets with Tb-enriched areas of the Nd$_2$Fe$_{14}$ grain surface after sintering. As a result, the magnets demonstrate a significant improvement in the coercive force without any obvious reduction in the residual magnetization and the maximum energy product [18].

Based on the approaches described above, it is possible to use new sintered Nd – Fe – B magnets with both high $H_{ci}$ and high $(BH)_{\text{MAX}}$, which may have a wider scope of application. Moreover, the new magnets containing less Dy or Tb will have low production costs compared to the current sintered Nd – Fe – B magnets. Excellent magnetic properties, in particular the gigantic coercive force, allow sintered Nd – Fe – B magnets to compete for wider application at elevated temperatures [19].

In addition, it is worth noting that terbium hydride has another advantage over terbium fluoride during processing. That is, hydrogen atoms in the particles are released as hydrogen gas when heated before the sintering process, so fluorine entering magnets with Tb will be absent. As a result, undesirable magnetic dilution with fluorine can be avoided, which will lead to a significant decrease in the residual magnetization and deterioration of the squareness of the demagnetization curve.

2.3. Factors affecting the magnetic force

Force indicators, determined by the magnitude and uniformity of the holding magnetic force, are the main characteristics of the MBPM. These indicators are influenced by many different factors, which can be defined into three main groups: operational, technological and constructive.

Operational factors include operating modes and operating conditions of the equipment.

Technological factors include the quality and accuracy of manufacturing and assembly of elements, reliability and quality of technical control of its parameters during and after manufacturing.

Design factors include the technology of manufacturing and assembly of elements, materials and other factors specified during design.
3. Results and their discussions

The control method has a significant impact on the design and technical performance of the MBPM. The main functions of the control system considered by the MBPM are to turn on, turn off the device, as well as the necessary regulation of magnetic energy (flow).

Let's depict the implementation of MPPM in the CNP in figure 1.

![Figure 1. Implementation of MBPM in the CNP: 1 – MBPM.](image)

In this case, a compensating (adaptive) method will be used, which consists in turning on a part of the magnetic elements during the movement of the magnetoelectric damping part of the MBPM from the position corresponding to the disabled state to the position at which the magnetic flux has the maximum value. Compensation control consists in parallel activation of magnets, starting from the edge of the device, then to the center of the axis of the device.

The damper device in question is an axial damper with a passive magnetic force regulator that performs the function of a magnetic support (figure 2).

![Figure 2. Adaptive damper: 1 - shaft; 2, 3 - permanent magnets; 4, 5 - cones; 6 - housing; 7, 8 - cups; 9 - groove [17].](image)

3.1. Ensuring the reliability of the MBPM

To study stability, we will use the Lyapunov function method. This method is used to study the stability of various differential systems and equations, so we will limit ourselves to considering an autonomous system [20].

We will introduce the following assumptions into the system [21]:

- magnets have the same brand and geometric parameters;
- angular and radial movements of the rotor are not taken into account;
- there are no external environmental factors.
The equation of motion of the central nervous system rotor along the OZ axis during a constant change in time has the form:

\[ m(a_z) = \sum F \]  

(1)

Consider the system equation of motion on the semi-axis OZ:

\[ m\left( \frac{dx}{dt} \right)^2 = \sum F(z) \]  

(2)

For the equation of motion along the OZ axis, the equality:

\[ m\left( \frac{d^3z}{dt^3} + \frac{d^2z}{dt^2} \right) = \frac{nB_\gamma \pi R^2}{\mu_0} \]  

(3)

Taking into account the displacement coefficient, the damping coefficient is defined as:

\[ I = \alpha z + \beta \frac{dz}{dt} \]  

(4)

Using similar suspension system transformations:

\[ \frac{d}{dt} \left[ b \left( \frac{dz}{dt} \right)^2 + \frac{a(z)^2}{2} + a_z \frac{dz}{dt} \right] = (a-b) \left( \frac{dz}{dt} \right)^2 + \frac{1}{m} \left( z - b \frac{dz}{dt} \right) \right] B r (2pRd_z) D_S^2 dt \]  

(5)

In the system under consideration, the structure of the senior terms of the expansion in the asymptote at infinity in time plays the main role in the stability property. In the left part of the differentiable expression (5) is a Lyapunov function, while its right part is its derivative. The left part is definitely a positive function, and the right part is its derivative with the opposite sign. Integrant function is a negatively defined function (differential equation without argument deviations). According to Lyapunov's theorem, this system will be stable.

4. Conclusion

Magnetic bearings with permanent magnets are characterized by high reliability in case of failures in the operation of the rotor of technological equipment and high reliability of the MPPM system itself. The introduction of MPM makes it possible to implement the principle of adaptability and increase the reliability of equipment in case of imbalance and high rotor vibrations. Sintered Nd – Fe – B magnets with modified grain boundaries (with enriched Tb) in the surface areas of the Nd₂ and Fe₁₄ phases have a wider scope of application, and also show the best technological characteristics with minimal material costs.

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