Temperature properties of passive magnetic bearing

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Abstract. The practical interest in passive magnetic bearings is due to the fact that they are not subject to wear and have insignificant dissipative energy losses. However, when the magnets are heated during operation, a reversible and irreversible decrease in the residual magnetization occurs and, consequently, the force of interaction between them changes. The thermal properties of passive magnetic bearings are adversely affected by the large demagnetizing fields from the coupled magnets. To predict the performance of passive magnetic bearings with regard to external temperature, an assessment of temperature changes in the bearing capacity of bearings with optimally shaped magnets is necessary. The optimum magnets were considered to be those with sizes, whose interaction force, reduced to a single volume of magnetic material, was the maximum. A magnetic system of two cylindrical magnets with equal radii and heights located coaxially or with some radial displacement was considered. The studies were carried out on cylindrical magnets made of $SmCo_5$ alloy, capable of maintaining magnetically hard properties at temperatures up to 250°C. It was confirmed that irreversible changes in the magnetic force for bearings with optimally sized magnets are close to each other. The destabilizing (radial) magnetic force at small radial displacements of one of the magnets also irreversibly decreased. A temperature of 250°C defines the upper limit of the temperature range for the normal operation of magnetic bearings with $SmCo_5$ magnets. It was found that as a result of the action of a demagnetizing field on magnets during heating, they develop a significant inhomogeneity of magnetization over the volume. After demagnetization of the magnets kept at a temperature of 260 °C, the force of their interaction reaches only 85 - 90% of the original, which is associated with microstructural changes in the magnets. Theoretically and experimentally, the numerical values of the temperature coefficients of changes in the bearing capacity and stiffness of bearings are determined.

1 Introduction

Passive magnetic bearings are the bearings in which the external load is compensated by the forces between permanent magnets. The advantage of such bearings over mechanical ones is that they are not subject to wear and have insignificant dissipative energy losses due to

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electromagnetic braking forces. Passive magnetic bearings are mainly used for unloading mechanical bearings or as a part of active electromagnetic suspensions [1-8].

Practical interest in passive magnetic bearings increased significantly after the creation of new power-consuming magnets based on the rare earth elements R-Co, Nd-Fe-B [9]. Specific bearing capacity of bearings with new generation magnets can reach 0.2÷0.4 MPa; the magnets are strong enough and can be used in conditions of high inertial forces. The magnetostatic interaction force of magnets depends on the magnetization in the second degree, so the force between Nd-Fe-B alloy magnets is about twice as high as that one between similarly sized R-Co alloy magnets. However, R-Co magnets can be used at temperatures up to 300°C, while the operating temperature of Nd-Fe-B mostly does not exceed 150°C.

When magnets are heated, there is a reversible and irreversible decrease in residual magnetization [10-13]. The reversible processes of changing the residual magnetization are due to the dependence of spontaneous magnetization on temperature as a result of a change in the thermal energy of the electrons compared to the energy of exchange interaction. Irreversible changes in residual magnetization are explained by changes in the structure of magnet materials, a decrease in the coercive force, and/or formation of reverse magnetization domains [12]. It is possible to partially restore the initial magnetization of magnets after temperature influences by their demagnetization. Thermal stabilization of magnets (artificial aging) is carried out at a temperature above the working temperature. The magnets can be partially restored to their original magnetization after temperature exposure by magnetizing them again.

Coefficients characterizing temperature changes for magnetically rigid materials are established and given in the reference literature. In some works [10, 13, 14], coefficients are obtained taking into account real operating conditions of products (magnets) made of these materials. In particular, the influence of internal magnetic demagnetizing fields on the magnetic state of magnets is taken into account.

In passive magnetic bearings, the magnets are affected not only by the internal demagnetizing field, but also by the heterogeneous demagnetizing field from the coupled magnets. Depending on the thickness of the magnets and their magnetization, the total demagnetizing field can approach the coercive force by magnetization. The influence of large demagnetizing fields on the temperature properties of magnetically passive bearings has not been studied and this does not allow predicting the performance of bearings with regard to external temperature.

The purpose of the work was to determine the temperature changes in the bearing capacity of bearings with optimally shaped magnets. Any passive magnetic bearings can be divided into pairs of interacting magnets and it is sufficient to know the temperature features of interaction of such pairs of magnets in order to predict the bearing operation as a whole. Since bearings use optimally sized magnets, it is with this factor in mind that the studies were carried out.

For advanced passive magnetic bearings, the permanent magnets capable to keep magnetically rigid properties at temperatures up to 250°C are necessary; therefore, in this work interaction of magnets from alloy $SmCo_5$ was studied.

2 Theoretical analysis

Let's consider a magnetic system consisting of two coaxially arranged cylindrical magnets with equal radii $R = R_1 = R_2$ and heights $H = H_1 = H_2$ (Fig. 1). In [11, 15], the dimensions of optimal magnets for passive bearings were determined.

For advanced passive magnetic bearings, permanent magnets capable of preserving magnetically rigid properties at temperatures up to 250°C are necessary, so in this work the interaction of magnets made of $SmCo_5$ alloy was studied.

In [11, 15] the dimensions of optimum magnets for passive bearings were determined. Magnets with such dimensions were considered optimal, the interaction force of which, reduced to a single volume of magnetic material, was maximum. It was found that cylindrical magnets with the following size ratio are optimal: H/R = 0.84, where H is the magnet height and R is the radius.

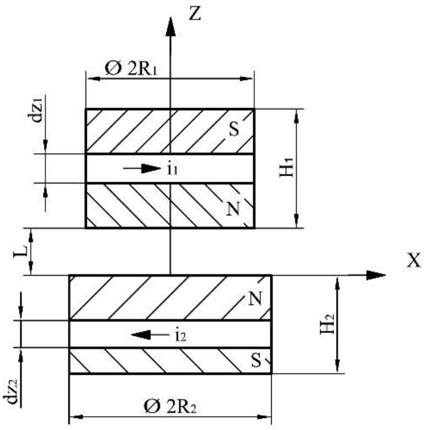

Fig. 1. Diagram of the permanent magnet arrangement.

The demagnetizing factor N for optimally sized magnets, determined by various analytical methods and finite element modeling, is N = 0.48÷0.53. The self-demagnetizing field in the magnet before heating can be considered as a first approximation a uniform, directed along the axis and equal to $H_N=NJ_r$, where J_r - is the residual magnetization, H_N is the component of magnetic field strength along axis z. This field leads to homogeneous changes of magnetization in magnets during heating.

The external demagnetizing field, for example, acting on magnet 1 from the side of the coupled magnet 2 has two components - axial H_z and radial H_r, and $H_z > H_r$. The effect of the radial component of the field H_r on the magnets is mainly reduced to small reversible turns of the magnetization vector. The axial component H_z at elevated temperatures stimulates demagnetization of the magnets.

The value of H_{0z} on the axis of a homogeneously magnetized magnet through the dimensionless parameter $m_2 = \frac{z_2}{R}$ can be expressed as follows:

$$H_z = \frac{J_r}{2}\left[\frac{1{,}2-m_2}{\sqrt{1+(1{,}2+m_2)^2}} - \frac{m_2}{\sqrt{1+{m_2}^2}}\right] \tag{1}$$

In this formula, J_r is the initial magnetization constant over the volume of the magnet. In first approximation, we can assume that the external demagnetizing field $H_e \approx H_{0z}$. After heating, the action of the magnetic field $H_e + H_N$ will reduce magnetization, but the field H_e and field H_N will still depend only on the parameter $m = \frac{z}{R}$. When exposed to increased temperature, the resulting demagnetizing fields cause interdependent rearrangement of the magnetic structure of the magnets. As a result, an inhomogeneous magnetization is established, but which, like the demagnetizing field, will have axial symmetry and depend on the m_2 coordinates. Therefore, after heating, the magnetization of the first magnet (Fig. 1) will also depend on this parameter and temperature T: $J_{Tr} = J_{Tr}\left(\frac{z_2}{R}, T\right)$. A similar dependence applies to the second magnet.

To calculate the interaction force of magnets, they can be represented as equivalent solenoids with variable current density $\frac{J_{Tr}}{dz} = i_1 = i_2 = i$. Formula describing the interaction of optimum magnets with variable magnetization is as follows:

$$F_z = \mu_0 R^2 \int_{-0.84}^{0} \int_{0}^{0.84} \frac{J_{\mathrm{Tr}}^2(m_1 - m_2)}{\sqrt{4 + (m_1 - m_2)^2}} \left[-E + \frac{2 + (m_1 - m_2)^2}{(m_1 - m_2)^2} N \right] dm_1 dm_2 = \mu_0 R^2 \omega, \quad (2)$$

where $m_1 = \frac{z_1}{R}$, μ_0 is the magnetic constant, E, N are elliptic integrals of the 1st and 2nd kind, respectively. It follows from formula (2) that:

$$\frac{F_z}{\mu_0 R^2} = \omega = const. \quad (3)$$

In formula (3) it is assumed that the clearance between the magnets tends to zero.

Then the reversible ε and irreversible η relative change in the forces of interaction of magnets during heating from temperature T_1 to temperature T_2 will depend only on the temperature, the properties of the magnet materials and will not depend on the absolute dimensions of the magnets:

$$\eta, \varepsilon = \frac{F_z(T_1) - F_z(T_2)}{F_z(T_1)} = \frac{\omega(T_1) - \omega(T_2)}{\omega(T_1)} \quad (4)$$

If the magnets when heated are not brought close together, but at a distance L, then the coefficients ε and η will depend on the parameter L/R. In order to confirm the theoretical conclusions and to determine numerical values of the coefficients characterising changes in the magnetostatic force, experimental studies were carried out.

3 Methodology of experimental studies

The studies were carried out on cylindrical magnets made of $SmCo_5$ alloy. Magnets were made using the same standard technology [16] and had the following characteristics: magnetization coercive force ❑$_J H_C$ = (1,3÷ 1,6) 10^6A/m, residual magnetic induction $\mu_0 J_r$= 0,78÷0,81T. The dimensions of the magnets were close to optimum - H/R≈0.84. For experimental researches, the device, which allowed to measure axial and radial (destabilizing) force of interaction of magnets located coaxially or with some radial displacement was used. The relative error in determining the magnetic force did not exceed 0.5%.

To determine irreversible changes in the normal interaction force of the $SmCo_5$ magnets, the samples were heated in air to a certain temperature in a thermo-cabinet, kept at this temperature for 5 hours, and then cooled down to room temperature. The temperature in the thermo-cabinet was maintained with an accuracy of 1°C. Preliminary experiments showed that a further increase in the time of thermal influence on the magnets does not lead to significant changes in irreversible losses. During exposure at elevated temperature, the magnets were positioned coaxially and brought together by their homonymous magnet poles. Thereby, each magnet was exposed to the maximum demagnetizing field of the coupled magnet. To determine reversible changes, the interaction force was measured at room and elevated temperatures.

4 Results of experimental research

The dependence of irreversible changes in the normal force η on the holding temperature is established, which is shown in Fig. 2. As might be expected, the irreversible force changes for the bearings with optimally sized magnets are close to each other. The destabilizing (radial) magnetic force also decreased irreversibly with small radial displacements of one of the magnets.

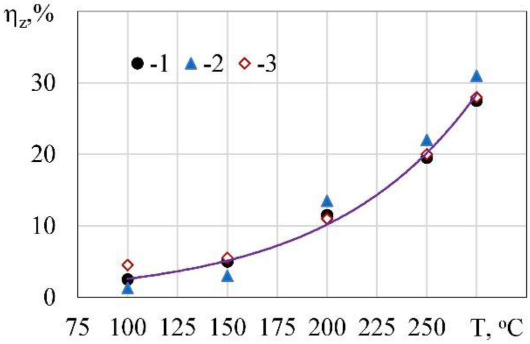

Fig. 2. Irreversible changes of magnetic force for different magnets: 1 - R = 7 mm, H = 5.9 mm; 2 - R = 9 mm, H = 7.5 mm; 3 - R = 5 mm, H = 4.2 mm.

It can be seen from the graph that at temperatures above 250°C, the value of η increases sharply. In fact, this temperature defines the upper limit of the temperature range of normal functioning of magnetic bearings with $SmCo_5$ magnets.

The studies have confirmed that the magnets exhibit significant inhomogeneity of magnetization over the volume as a result of the demagnetizing field when heated. For this reason, the magnetic induction of the field in the center of the opposite end faces differs by about 1.8 to 2 times in the magnets exposed at 260°C.

After demagnetization of the magnets, kept at 260°C, the strength of their interaction reaches only 85 - 90% of the original. The incomplete recovery of the force seems to be due to microstructural changes in the magnets.

With an accuracy acceptable for practical purposes, the bearing stiffness K_z (T_1) at temperature T_1 in the area of small clearances and radial displacements after holding at elevated temperature T_2 can be determined by the formula:

$$K_z(T_1) = K_{0z}(T_1)[1 - \eta(T_2)], \tag{5}$$

where $K_{0z}(T_1)$ is the stiffness before heating.

The reversible changes of magnetic force ε(T) were determined by formula (3). Before measurement, the magnets were thermostabilized at 260°C for ten hours.

Dependence of reversible changes of normal (lifting) force on temperature is shown in Fig. 3. It can be seen from the graph that the temperature coefficient of reversible changes of force $\frac{\varepsilon}{T_1 - T_2}$ in the temperature range from 20 to 250°C is equal 0,13/1°C. At other clearances the course of the curve shown in Fig. 3, does not change significantly.

If we assume that magnets at any temperature have a homogeneous magnetization, which is equal to the averaged magnetization of a real magnet, then the temperature coefficient of reversible changes is 0.065%/1°C. This value is approximately 1.5 times higher than for free magnets without the influence of external demagnetizing fields [16]. This difference is explained by the fact that reversible changes are determined not only by the temperature dependence of the fundamental characteristic of magnet materials - spontaneous magnetization, but also by the processes of reversible changes in the direction of the magnetization vector and displacement of domain boundaries.

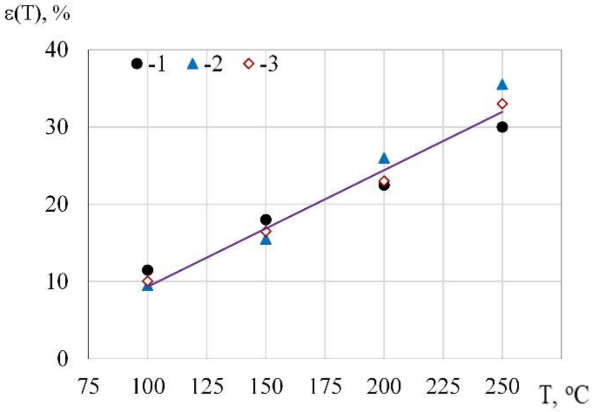

Fig. 3. Reversible changes of axial force depending on temperatures for different magnets: 1 - R = 7 mm, H = 5.9 mm; 2 - R = 9 mm, H = 7.5 mm; 3 - R = 5 mm, H = 4.2 mm.

The coefficients of reversible changes of the normal force and the corresponding stiffness of one-sided magnetopassive bearings are approximately equal to each other.

5 The conclusion

Thus, it is shown that the effect of elevated temperatures and demagnetizing fields on interacting magnets leads to a reversible and irreversible decrease in the power characteristics of magnetic bearings due to changes in the magnetic state of the magnet material.

The numerical values of temperature changes in the bearing capacity and stiffness of the bearings are experimentally determined, and the theoretical conclusion about the constancy of these coefficients for bearings with optimal magnet sizes is confirmed.

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