Energy losses in magnetic contactless bearings on the base of high-Tc superconducting tapes

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Abstract. High-temperature superconducting tapes are very promising for application in rotary magnetic bearings owing to its excellent magnetic and transport properties as well as possibility to easy create magneto-levitation systems of various geometry. One of problem arising in the rotation superconducting bearings is the presence of the energy loss resulting from the magnetization hysteresis due to inhomogeneity of magnetic field from permanent magnets. In this report we present results theoretical studies of rotation losses in the model superconducting bearing based on commercial high temperature superconducting (HTS) tape. The bearing stator has a cylindrical shape and is made of a multilayer HTSC tape. The bearing rotor is made of permanent magnets located at the same radius relative to the axis of rotation. As a result of numerical calculations carried out in the framework of the critical state model, the rotor geometry was established, at which the value of energy losses was minimal.

1. Introduction
The using of a superconductor/permanent magnet in contactless bearings is promising not only because of the absence of friction forces in such bearings. The absence of direct mechanical contact between moving parts allows efficient use of magnetic bearings in high-speed technology: kinetic drives, gyroscopes, and similar devices (see, for example, [1]).

The manufacture of a superconducting rotor (stator) from a bulk high-temperature superconductor (HTSC) is a rather complicated technological task. First, the HTS material is quite fragile (in this case, it is YBCO perovskite). Secondly, a complex annealing mode is required to ensure uniformity of the superconducting properties of the material. An alternative to a bulk superconductor can be a dial-up superconductor consisting of stacks of HTS tapes [2]. Similarly, a stack of tapes can also be considered short-circuited coils made of HTS tapes, which can be used in various levitation applications. The use of HTS tapes instead of bulk materials has several advantages. The technology for creating a superconducting composite of arbitrary shape made from tapes is simpler. The superconducting characteristics of a stack of tapes are not inferior to bulk material [3]. In addition, HTS tapes have higher mechanical properties than bulk materials.

The manufacture of a magnetic rotor also presents a technological problem. A solid magnet of the desired shape and size should provide an axial symmetry magnetic field. An alternative to a solid magnet (as in the case of a superconductor) can be a dial-up magnet. The typesetting magnet means a
mosaic consisting of a large number of small magnets. Each element of the mosaic is a uniformly magnetized ferromagnet having the shape of a rectangular parallelepiped. The disadvantage of this mosaic is the heterogeneity of the magnetic field, especially noticeable at the junctions of neighboring elements. The inhomogeneity of the magnetic field can cause hysteresis magnetization reversal of the superconductor. The magnetization reversal of a superconductor is accompanied by energy dissipation (see, for example, the review [4]) and, therefore, the occurrence of a friction force in a bearing. The subject of this work is a theoretical study of the influence of the inhomogeneity of the magnetic field of a magnet on the friction force in a bearing, in which single-layer and multilayer rings formed from HTS tapes of the 2nd generation will be considered as a superconducting stator.

2. Experimental procedure
The bearing in question consists of a rotor and a stator. The division into "rotor" and "stator" is conditional. It is possible both the rotation of the internal shaft of the bearing with the fixed external part, and the rotation of the external part around the fixed internal axis. For definiteness, in the future, we assume the superconducting part of the bearing is a fixed stator, and the rotor is formed from a set of small permanent magnets. This choice is due, firstly, to the fact that it is technically easier to cool a stationary superconductor. The possibility of cooling allows us to neglect superheat superheating (otherwise thermodynamic instability may occur). Secondly, the rotating massive magnetic rotor around the internal superconducting axis is optimal for creating a gyroscope. Figures 1 and 2 show bearings with quadrilateral and octagonal rotors, respectively. In the following, the number of magnets in the rotor is denoted as $N_{\text{mag}}$ ($N_{\text{mag}} = 4, 8, 16$). For calculations, the following sizes of magnetic rotor are selected. The inner border of the rotor (the inner circle indicated by a broken line in Figures 1 and 2) has a radius of 20 mm for both quadrilateral and octagonal and sixteen-square rotors. The outer border of the rotor (the outer circle indicated by a broken line in Figures 1 and 2) has radius of 32.016 mm and 26.34 mm for the quadrilateral and octagonal rotors, respectively.

![Figure 1](image1.png)  
**Figure 1.** Bearing with a quadrangular magnetic rotor. Top down view.  
1 - superconducting stator. 2 - magnetic rotor. 3 and 4 are the outer and inner borders of the magnetic rotor.

![Figure 2](image2.png)  
**Figure 2.** Bearings octagonal magnetic rotor. Top down view.  
1 - superconducting stator. 2 - magnetic rotor. 3 and 4 are the outer and inner borders of the magnetic rotor.

The magnet thickness equal to 5 mm and the width of the magnets $dZ$ equal to 12 mm in the direction of the Z axis are also the same for all rotors. When choosing the tape parameters, we focused...
on quite promising in technical applications 12mm SuperOx tape. The magnetization of each magnet is considered homogeneous. If the density vector of the magnetic moment at a point in space with a radius vector \( \vec{r} \) is denoted \( \vec{m}(\vec{r}) \), the magnetic field induction vector at the point \( \vec{r} \) created by the magnet (which occupies volume \( V \)) has the following form [5]:

\[
\vec{B}(\vec{r}) = \mu_0 \int_{V} \left[ \frac{3\vec{n} \cdot (\vec{n}, \vec{m}(\vec{r})) - \vec{m}(\vec{r})}{|\vec{r} - \vec{r}'|^3} \right] d^3\vec{r}', \quad \vec{n} = (\vec{r} - \vec{r}')/|\vec{r} - \vec{r}'| \tag{1}
\]

The vector modulus \( \vec{m}(\vec{r}) \) was chosen so that the magnitude of the magnetic field induction of a separate magnet in the center of its surface was 0.3 T.

The usual thickness of the HTS tape is \( \sim 0.1 \) mm, so in this paper, just like in [3], we consider the stator winding thickness to be zero. We assume that the critical current density in a single-layer continuous HTS ring is equal to \( j_c \) in a two-layer - \( 2j_c \). The critical current density at the boundaries of adjacent rings perpendicular to the Z axis is zero. The coordinates Z of the boundaries of the stator rings coincide with the boundaries of the bipolar magnets of the rotor. These boundaries have coordinates \( Z=0, \pm d_2/2, \pm 2d_2/2, \pm 3d_2/2, \pm 4d_2/2, \) etc.

With a large number of magnets in the rotor (\( N_{mag} \gg 1 \)) and small width of HTS rings in comparison with their perimeter (\( d_p/ d_z \gg 1 \)) the stator curvature can be neglected and replace the problem of determining the density of superconducting current, set in cylindrical coordinates \( (\rho, \phi, Z) \) at \( \rho=R_s \) two-dimensional problem in the plane \( (p, Z) \), \( p=R_s\phi \). In this case the region of definition of magnetic field and current density is rectangle \(-d_p/2 \leq Z \leq d_p/2, -d_p/2 \leq \rho \leq d_p/2 \). The boundary conditions are periodic both in the angular variable \( p \) and in the variable \( Z \) (it is assumed that the rotor consists of an infinite number of rings of bipolar magnets adjacent to each other). Replacing a cylindrical problem with a flat one is justified by the fact that, firstly, the ratio \( dp / dZ = 8 \) is quite large, and secondly, from the practical side, rotors with a large number of magnets (\( N_{mag} = 8 \) and 16) are of the greatest interest. We consider the quadrangle rotor to qualitatively determine the dependence of the friction force of the bearing on the number of magnets. Moreover, it is for the quadrangular rotor that the effect of the nonuniformity of the external field (in the angular variable) on the distribution of superconducting currents is most pronounced.

The external magnetic field of the magnetic rotor in the stator was calculated by the formula (1) as well as in Comsol Multiphysics. The normal to the stator surface component of the magnetic field on this surface is shown in Fig. 3. The induction was determined for a quadrangular rotor.

The variation of the amplitude of the magnetic field \( (B_{max}-B_{min}) / (B_{max} + B_{min}) \) with the \( Z = 0 \) coordinate is 14.8%, 1.3%, and 0.2% for \( N_{mag} = 4, 8, \) and 16, respectively. The idea of using a nonuniform (periodic) external magnetic field is not new but the feature of this work is the calculation of the HTS tape in a weakly varying field, which, however, affects the superconductor for an unlimited number of periods.

We describe the field dependence of the critical current of a superconducting tape in the framework of a two-exponential model [6, 7], in which the density of surface currents of an HTSC film has the following form:

\[
j_c(B) = A_1 \exp\left(-|B| / \beta_1\right) + A_2 \exp\left(-|B| / \beta_2\right), \tag{2}
\]
The normal component of magnetic induction along surface on stator (distance from the magnets is 0 (blue), 1 (red) and 2 (green) mm).

with parameters \( A_1 = 12.9 \text{ kA/m} \), \( A_2 = 13.8 \text{ kA/m} \), \( \beta_1 = 0.08 \text{ T} \), \( \beta_2 = 1.92 \text{ T} \). The spatial grid step in the presented calculations is \( \delta h \sim 0.375 \text{ mm} \). The calculation was carried out within the framework of the model of the critical state of a superconductor originally proposed in [8], some modifications and applications of which are given in the review [4]. A detailed description of the formulation of the mathematical problem and the algorithm for numerical calculation for the field dependence (2) are given in publications [3, 9], and are not given in this paper due to cumbersomeness.

The mode of changing the external magnetic field was as follows: At the first stage, the magnetic field proportional to the rotor field without rotating the rotor monotonously increased from zero to the value determined by expression (1). Next, the rotor was rotated at 40 rotations (the number of rotations hereinafter referred to as \( N_{\text{mag}} \)). The corresponding density of superconducting currents was determined. One turn of the cylindrical configuration corresponds to the shift of the magnetic field in the plane problem with respect to the variable \( p \) by the magnitude of the period \( dp \). In this shift, the tangential component of the interaction force of the rotor field \( B \rho \) with the stator currents (friction force) \( f_p \) for one stator ring was determined from Ampere's law:

\[
f_p = \int_{-d_p/2}^{d_p/2} \int_{-d_z/2}^{d_z/2} B_{\rho} (p, Z) \cdot j_z (p, Z) dZ
\]

3. Results and discussion

The dependence of the friction force on number of rotor revolution the quadrangular stator (\( N_{\text{mag}} = 4 \)) is shown in Figure 4. The figure shows that the friction force is established in one turn. For rotors with a large number of magnets (\( N_{\text{mag}} = 8 \) and 16), the setting also takes place in less than two turns. In this paper, we are not interested in the nature of the transition processes. Therefore, we determine the
friction force by averaging this quantity from the third to the tenth turn. In the case of a quadrangular rotor ($N_{mag} = 4$), the friction force for a single-layer / two-layer stator is $0.013$ N and $0.0021$ N, respectively. In the case of an octagonal rotor ($N_{mag} = 8$), the friction force for a single-layer / two-layer stator is $2.01 \times 10^{-6}$ N and $1.25 \times 10^{-6}$ N, respectively. At $N_{mag} = 16$, the friction force for a single-layer / two-layer stator is $1.5 \times 10^{-7}$ N and $8.1 \times 10^{-8}$ N, respectively.

The characteristic density distribution of superconducting currents in the stator and the magnetic field of a quadrangular rotor is shown in Fig. 5. The upper part of the figure represents the lines of superconducting currents, the lower part represents the lines of the levels of the magnetic field of the rotor. This figure shows a fragment of a stator with a width of $2dZ$ (the central tape is surrounded on the top and bottom by the halves of adjacent stator tapes). When the rotor is rotated, the pattern is periodically shifted along the $p$ axis.

For a qualitative interpretation of the dependence of the friction force on the number of rotor magnets and turns of the HTS tape on the stator, it is convenient to present the stator as a system of interconnected magnetic pumps. Imagine each cell of the counting grid the size of the stator as an elementary magnetic pump. If we designate the rotor speed as a symbol, the pump frequency of each pump by the external alternating magnetic field will be equal (the phase of the field oscillations for cells with different coordinate $p$ will be different). The moment of the cell induced by the external field is $g \cdot \vec{n}_p \cdot h^2$ magnetic. In this expression $\vec{n}_p$ is the unit vector normal to the stator surface. The value of $g$ is the density of the magnetic moment related to the density of the surface currents $\vec{j}(p, Z)$ of the stator by the ratio $\vec{j}(p, Z) = \nabla \times (g \cdot \vec{n}_p)$ (see review [4] and literature to it). Figure 6 shows the dependence of the density of the magnetic moment of the cell with coordinates $p = 0, Z = 0$ on the magnitude of the magnetic induction of the rotor at this point. The upper curve corresponds to a single-layer, and the lower one to a two-layer HTS stator. Dependencies are given for one rotation of the rotor after passing through transients. The magnitude of the magnetic field at a given point varies from the minimum $B_{min} = 0.095$ T to the maximum $B_{max} = 0.128$ T.

![Figure 4](image.jpg)

**Figure 4.** The dependence of the friction force on number of rotor revolution the quadrangular stator.
Figure 5. Lines of superconducting currents (upper part of the figure) and level lines of the components of the magnetic field of a quadrangular rotor normal to the stator surface (lower part of the figure). One current line in the upper figure corresponds to the current 5A. One streamline in the lower figure corresponds to a magnetic field induction of 0.02 T.

Figure 6. The dependences of magnetic moment density in the point with coordinates $p=0$, $Z=0$ on magnetic induction for one turn of rotor: 1 – dependency for one-layer rotor, 2 – dependency for double-layer rotor. The arrays indicate the direction of moving along hysteresis curves.
On the section of the curve corresponding to an increase in the induction of the field from the minimum $B_{\text{min}}$ to the maximum $B_{\text{max}}$ value, the EMF of a varying field induces currents that reduce the density of the magnetic moment (the induced magnetic field is opposite to the inductive field). As a result, the magnetic moment is minimal at the maximum magnetic field. The shielding process is limited by the finite value of the critical current (otherwise, the shielding would be complete across the entire stator). When the magnetic field decreases from the maximum value at the initial stage, the electromotive force changes sign, and the current density at this point becomes less critical. With a further decrease in the field, the current density passes through zero and again its value reaches a critical value. The amplitude of the change in the magnetic field induction of the quadrilateral rotor on the stator surface reaches 14.8% of the average value. This change is sufficient for the first, in a single-layer stator, the magnetic moment of the unit cell to change sign (see Fig. 6, the upper curve), while the magnetic field is constant. Secondly, the smallness of the critical current with such a change in the field results in a radical reversal of the stator, which leads to a wide hysteresis loop (as a result, to energy dissipation and a large friction force). A two-fold increase in the critical current density in a double-layer stator blocks the process of magnetization reversal (see Fig. 6, lower curve). The area of the hysteresis loop decreases sharply, and as a result, the friction force decreases. Similarly, a significant decrease in the friction force due to an increase in the number of magnets is explained.

4. Conclusions
The calculations showed that the force of magnetic friction and the resulting energy losses are not an obstacle in the creation of a combined bearing, the rotor of which consists of more than 8 magnets, and the stator - of several short-circuited layers of HTS tape of 2nd generations. Experimental verification of the output, as well as analysis of the influence of other bearing parameters (eccentric position and misalignment of the rotor axis relative to the stator axis, defects in the HTS stator tapes, etc.) that can critically degrade its characteristics will be carried out separately. It should be noted that the considered configuration of the magnetic rotor and the superconducting stator of HTS tapes has a fundamental advantage compared to the bearings on bulk HTSCs, since it allows for almost unlimited scaling of the device.

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