A case study for a superconducting magnetic bearing optimization

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Abstract

Superconducting magnetic bearings have high potential use in flywheel energy storage systems. In these systems, the rotor stability is one of the most challenging issues and it is closely related to the rotor's levitation configuration. We have investigated the effect of various levitation configurations on the levitation force and stability of the rotor. A case study is introduced to discuss the optimization of the bearing, via arraying permanent magnets and superconductors in certain configurations. The force calculations are performed by using frozen image model based on the Amperian current approximation. It was determined that the optimum levitation of the rotor strongly depends on the superconductor and permanent magnet configurations in the bearing.

1. Introduction

The use of bearings is essential for all types of machines. Bearings are used as a mechanical component to transfer the power via moving certain parts in the bearing mechanism. The transfer of power is provided by utilizing the small frictional force in the bearings, which makes them rotate easily. Magnetic bearings are used in numerous industrial applications, such as electrical power generation, compressors, turbines, turbo pumps, motors and generators, maglev trains, and flywheel energy-storage systems (FES). A detailed literature is given in [1].

In general, a bearing is an element that executes desired motion and reduces friction between relatively moving parts in the machine mechanism. The bearing may provide both linear and rotational motion. Bearings are generally classified as contact and non-contact types. Contact bearings are the most commonly used, such as plain rubbing bearings, ball bearings and roller bearings. In non-contact bearings, there is no direct physical contact between the bearing and the load. Non-contact systems can be operated at much higher speeds than using conventional mechanical bearings. Non-contact bearings such as air bearings and magnetic bearings are already being used in industrial applications.

Magnetic bearings have no physical contact and they require active control. Magnetic bearings having active control systems are called as active magnetic bearings. Active-controlled electromagnetic levitation systems have become a mature technology and offer many advantages. High stiffness and adaptive control built in are the major advantages, while high cost and complexity-reliability issues are serious concern. Magnetic bearings generally have very low drag, do not require any lubrication and there is no physical contact between the spindle and the bearing. Active magnetic bearings are used in a number of applications such as energy storage flywheels, high-speed turbines and compressors, pumps and jet engines. Active magnetic bearings may offer a strong controlled stiffness but require a sophisticated high frequency feed-back control loop which may complicate the electronics.

Passive magnetic bearings on the other hand do not require any lubricant and they can be used in vacuum. Passive magnetic bearings are contactless devices, which consists of permanent magnets (PM) on the rotating shaft and the stator. Since no active components such as actuators, coils or power electronics are needed in the passive bearings, they can be produced cheaply. Superconducting magnetic bearings are in the class of the passive bearings which use PMs and high temperature superconductors (HTS) combination.

Superconducting magnetic bearing provides near friction-free system for FES application. A flywheel is a rotating mass, which stores energy in the form of kinetic energy. The flywheel can be thought as a mechanical battery that has a certain amount of energy stored in its system depending on its rotational velocity and its moment of inertia. An electric motor is used for maintaining the continuous rotating motion of the rotor during the energy storage. The stored energy can be retrieved by slowing down the flywheel via a decelerating torque and providing the kinetic energy to the electrical machine, which is used as a generator. A schematic description of the superconducting FES system is shown in Fig.1. The control mechanism of the electricity storage system comprises two major subcomponents: energy storage and power conversion electronics. In flywheel storage systems, the power conversion system is a bidirectional process that allows the DC to flow to the load after it is converted to AC and vice versa to charge the battery or flywheel.

A typical superconducting magnetic bearing consists of a disk PM on the rotor, a ring PM on the shaft and a combination of a cylindrical bulk superconductor and a ring shaped PM on the base [2]. The picture of the superconducting bearing is shown in Fig. 2. Force between the PM on the rotor and that of the shaft are in attractive configuration, while on the other hand the force between the PM on the rotor and that of the ring PM on the base are in the repulsive configuration. The force between the PM on the rotor and the superconductor in the base is in the field cooling configuration, which means that the net force between the rotor PM and superconductor is zero at the equilibrium position. More technical properties of the bearings can be found elsewhere [2].

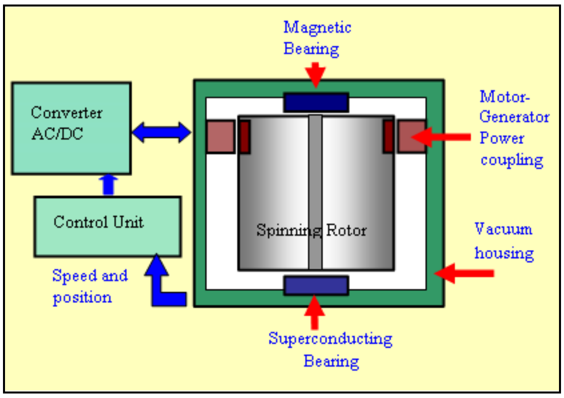

Fig. 1. Superconducting flywheel energy storage system.

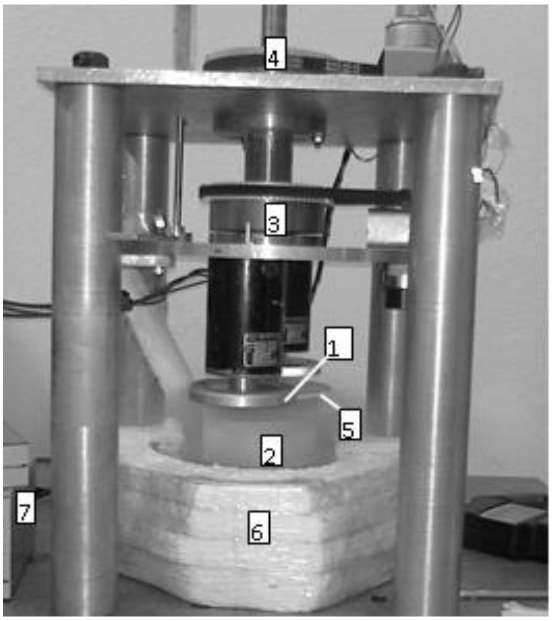

Fig. 2. Superconducting bearing components. 1: Driving PM discs, 2: Rotor, 3: Lift motor mechanism, 4: Setup motor, 5: Copper disc, 6: HTS (YBCO) inside a Liquid Nitrogen Tank.

The load-carrying capability of the bearing configuration introduced in this study is analyzed in terms of the vertical force on the rotor as a function of its vertical displacement. The vertical stability mechanism is evaluated by determining the stiffness on the rotor as a function of the vertical displacements. The forces on the rotor are determined by using MATLAB for various design configurations based on the considerations of the cooling procedure of the superconductors. The force between the PM components are determined in terms of the Amperian current approximation [3] and the force between the PM and superconductor are determined in terms of the frozen-image model (FIM) [4]. The optimization of the force on the rotor and its stability can be achieved by considering the geometrical properties of the bearing components, such as size, shape and magnetization values of the PMs, size of the superconductor, and configuration of the components.

2. Force and stability modeling for the rotor in the bearing mechanism

The force between superconductors and PMs are modeled with various methods. Some of these include the magnetization model by Brandt [5], the Maxwell-stress tensor model by Moon [6], and the critical-state model by Navau et al [7]. The realistic method to evaluate the forces requires the configuration and the hysteresis in the superconductor. Utilization of a particular method may not lead accurate results, depending on the assumptions and constraints. When the hysteresis is not taken into account, Amperian current approach is one of the most realistic methods to evaluate the forces between HTSs and PMs, with the consideration of FIM [3]. FIM is successfully implemented for various cases of levitation applications [8].

Magnetic fields produced by PMs are identical to those produced by electrical currents. The force between two circular current loops can be calculated under various configurations, which can be implemented for PMs. In this study, circular loops are considered that are coaxially positioned relative to each other, and they are free to move in vertical and lateral directions. As shown in Fig. 3, a PM is positioned in the rotor, a superconductor disk in the base, a ring PM in the shaft and another ring PM in the base.

The PM configuration given in Fig. 3 can be modeled as the interactions between the individual current carrying loops given in Fig. 4. To calculate the force, the magnet is divided into sub-layers and represented by surface currents I_1. Then, the surface currents are assigned for each sub-layer according to their magnetizations. This approach is known as Amperian current approximation [3]. The same procedure is also applied for the ring permanent magnet (RPM). For the case of the interaction between the PM and HTS the FIM is taken into account [4].

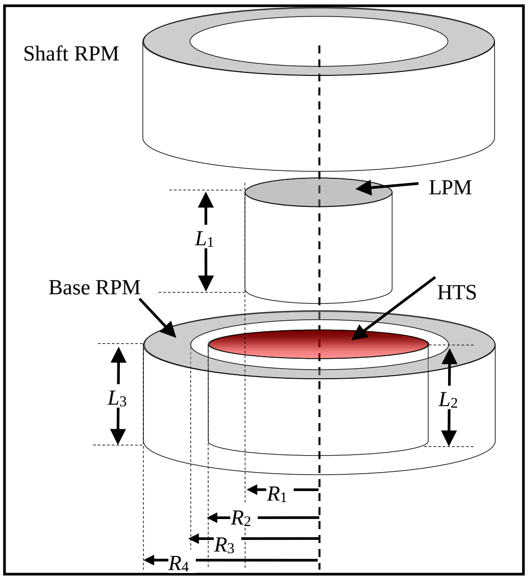

Fig. 3. Bearing configuration: Coaxially levitated permanent magnet (LPM) below the shaft RPM and over the Bulk HTS-RPM base.

When a HTS is brought near a PM, the interaction force is formed in terms of the cooling procedure of the superconductor with the consideration of FIM. In zero field cooling (ZFC), the PM produces its diamagnetic mirror image below the HTS top surface, while in field cooling (FC), two images appear: one is the diamagnetic mirror image and the other is the frozen image. The diamagnetic mirror image moves when the PM moves so that its lateral position equals that of the PM and its vertical height below the HTS surface equals the height of the PM above the surface. Once formed, the frozen image does not move. The magnitude of the magnetic moment of the frozen image is exactly equal to that of the PM so that there is no net force upon field cooling.

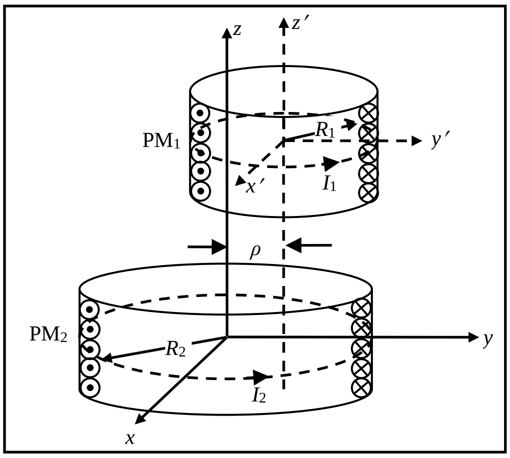

Fig. 4. Two coaxially aligned PMs (PM_1 and PM_2), shifted in horizontal direction. The PMs are modeled as circular surface current loops having radius R_1 and R_2 and each current loops carrying current I_1 and I_2, respectively.

As shown in the configuration given in Fig. 3, the bearing consists of a superconducting disk and ring PM in the base, a disk shaped PM in the rotor and a ring shaped PM in the shaft. The configuration for the interaction between PMs can be seen in Fig. 4, which can be implemented both on the force calculation between only PMs or between the PMs and superconductors. For the case of PM-superconductor interaction the configuration given in Fig. 4 is modified in terms of FIM. The frozen image implementation can easier to be understood by using magnetic moment representation, depicted in Fig. 5. In this figure, z is measurement height, m^{PM} is magnetic moment of PM, m^d is diamagnetic image, m^f is frozen image. r_f is the distance between frozen image and new location of PM and r_d is the distance between the new location of the PM and its diamagnetic image.

By implementing the frozen image concept on the geometry of the two circular conducting loops carrying the current shown in Fig. 4, the force between the loops can be obtained analytically. We assume that the first loop has current I_1 with radius R_1, the second loop has current I_2 with radius R_2, z as vertical distance between the loops, then the vertical fore (F_z) as a function of vertical distance between the loops is [3]:

$$F_z = \frac{\mu_0 I_1 I_2 z}{[(R_1+R_2)^2+z^2]^{1/2}}\left[\frac{R_1^2+R_2^2+z^2}{(R_1-R_2)^2+z^2}E(k)-K(k)\right] \qquad (1)$$

where, K and E are first and second types of elliptical integrals, respectively, with an argument of $k^2 = 4R_1R_2/[(R_1+R_2)^2+z^2]$.

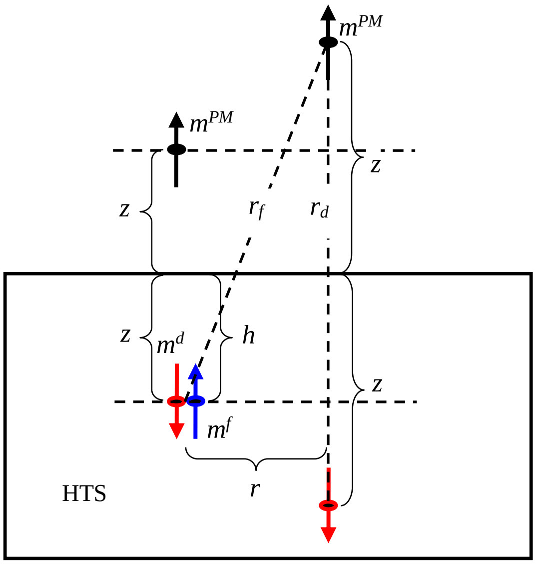

Fig. 5. Frozen image configuration: h is FC height, z is measurement height, m^{PM} is magnetic moment of PM, m^d is diamagnetic image, m^f is frozen image. r_f is distance between frozen image and new location of PM, r_d is the distance between diamagnetic image and new location of the PM, respectively.

The interaction force between the PM and HTS is provided by the superposition of the magnetic field from the PM, the source of the frozen image (due to trapped flux in the HTS), and the diamagnetic mirror image (due to the screening currents in the HTS) [3]. In this case, in order to calculate the vertical force between the PM and the HTS, the current circulation direction in the PM is selected to be same as that of the frozen image in the HTS, while it is the opposite for the diamagnetic image.

The stiffness in the vertical direction can be obtained by direct derivation of the force equation given in Eq. 1. In this case the vertical stiffness, which is defined as the negative derivation of the force with respect to the corresponding direction, is given by [8],

$$K_z = (\mu_0 I_1 I_2 z^2 / a_3^{3/2})\left[b_1 K(k) - b_2 E(k)\right] \qquad (2)$$

where

$$a_1 = R_1^2 + R_2^2 + z^2 \qquad (3)$$

$$a_2 = (R_1 - R_2)^2 + z^2 \qquad (4)$$

$$a_3 = (R_1 + R_2)^2 + z^2 \qquad (5)$$

$$b_1 = (a_2 a_3 - a_1 z^2)/a_2 z^2 \qquad (6)$$

$$b_2 = \frac{2a_2a_3z^2 - 2a_1a_2z^2 + a_1a_2a_3 - 2a_1a_3z^2}{a_2^2 z^2} - \frac{1}{k-1} \qquad (7)$$

Eq. 2 provides an analytical expression for the stiffness as a function of the vertical displacement for a particular cooling height. This equation is utilized according to the FIM for a bearing configurations consisting of the PM-HTS and the PM-HTS-RPM.

3. Results and Discussion

In this study we investigated the levitation of the rotor of the bearing based on three cases. In case 1, the rotor PM is levitated by using the combination of the base and shaft PMs. In case 2 and 3, the rotor PM is levitated by using the combination of the base and shaft PMs together with the use of superconductor in terms of cooling heights 5 and 10 mm, respectively. The levitation is achieved for each case in terms of certain conditions regarding the geometrical properties called as model 1, 2, 3, 4 and 5. The parameters for each model are given in Table 1. For every model, rotor PM radius is 22.5 mm, base ring PM outer radius (OR) is 29.25 mm and inner radius (IR) is 24.75 mm.

Table 1. Bearing configurations.

Case	Model	Shaft PM (mm)	FCH(mm)
1	1	-	-
1	2	R=29.25 (Disk)	-
1	3	OR= 29.25, IR= 13.5	-
1	4	OR= 29.25, IR= 18	-
1	5	OR= 29.25, IR= 24.75	-
2	1	-	5
2	2	R=29.25 (Disk)	5
2	3	OR= 29.25, IR= 13.5	5
2	4	OR= 29.25, IR= 18	5
2	5	OR= 29.25, IR= 24.75	5
3	1	-	10
3	2	R=29.25 (Disk)	10
3	3	OR= 29.25, IR= 13.5	10
3	4	OR= 29.25, IR= 18	10
3	5	OR= 29.25, IR= 24.75	10

Eq. 1 and 2 are used to calculate the force and stiffness on the rotor PM, respectively. In the calculation of the force the flux density of the PMs are determined as 1.32 Tesla. The distance between the base and the shaft PM is considered as 40 mm, which is the most effective distance for the force interaction under the bearing configuration. All of the PMs have the height of 20 mm. Since the height of the rotor PM is also 20 mm, regardless of its field cooling height the rotor PM can move about total of 20 mm up and down respect to its equilibrium position.

The force calculation is performed for three cases. As indicated in Table 1, there is no superconductor in the bearing configuration. Case 1 is only considered to investigate the effect of the vertical force on the rotor, which is provided by base and shaft PMs. Case 1 cannot provide stable levitation of the rotor because of the absence of the superconductor in the bearing configuration. Case 2 and 3 use the superconductor to strengthen the levitation force and provide stable levitation for the rotor.

To investigate the levitation for optimum condition the force calculation is performed for various conditions for each of the cases. These various conditions are named with models as indicated in Table 1, where each of the case consists of different bearing parameters related to the PM geometry. For instance, the bearing does not have shaft PM particularly in Model 1 for any of the case. For the model 2, the shaft PM is in the disk shape, with a radius of 29.25 mm. For the models 3, 4 and 5, the shaft PMs are in ring shape with the outer radius of 29.25mm. The inner radius of the ring PM for Model 3, 4 and 5 are 13.5, 18 and 24.75 mm, respectively.

Fig. 6 shows the vertical force (or levitation) on the rotor of the bearing for Case 1 for different models. As it is expected, there is no stability condition for the rotor PM since there is no superconductor in Case 1. This is easily seen in Fig. 7 that the stiffness on the rotor is small in the mid region in between the base and shaft PMs. The levitation force is minimum when there is no shaft PM in the bearing (Model 1). The levitation force is maximum when the shaft PM is in disk shape (Model 2). For Models 3, 4 and 5 the shaft PMs are formed as ring shape. As the inner radius of the ring PM is increased the levitation force is reduced. However, as shown in Fig. 6, the force variation as a function of displacement is most stable for Model 5.

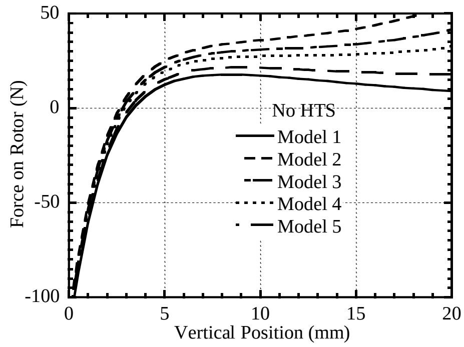

Fig. 6. Levitation force on the rotor PM for Case 1.

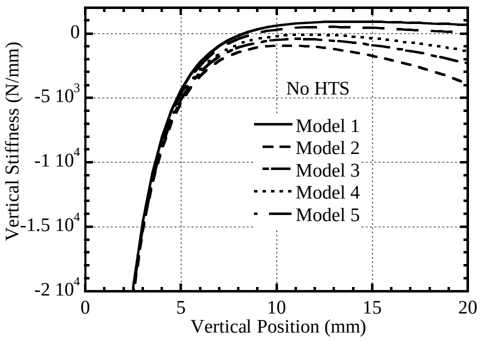

Fig. 7. Vertical stiffness on the rotor PM for Case 1.

Fig. 8 shows the vertical force (or levitation) on the rotor of the bearing for different models for Case 2, where the field cooling height is 5 mm. As it is expected, there is strong stability condition for the rotor PM since there is superconductor in Case 2. This is easily seen in Fig. 9 that the stiffness on the rotor is high in the mid region in between the base and shaft PMs. The levitation force is minimum when there is no shaft PM in the bearing (Model 1). The levitation force is maximum when the shaft PM is in disk shape (Model 2). For Models 3, 4 and 5 the shaft PMs are formed as ring shape. As the inner radius of the ring PM is increased the levitation force is reduced. However, as shown in Fig. 8, the force variation as a function of displacement is most stable for Model 5.

As shown in Fig. 10 and 11, when we increase the field cooling height of the rotor PM to 10 mm, which is Case 3, the levitation force and stiffness is decreased compared to the Case 2. Because of the model configurations provided for the bearing the levitation force was not reduced very much as the field cooling height is increased from 5 mm to 10 mm. This result indicates that the optimization of the bearing mechanism can be improved with the consideration of the parameters given in Table 1.

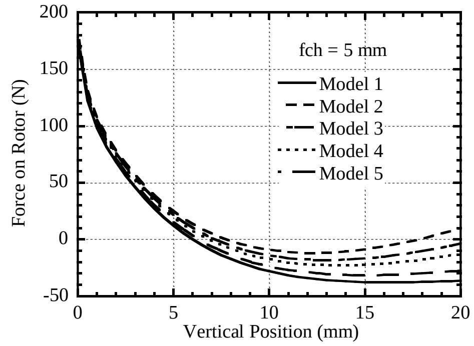

Fig. 8. Levitation force on the rotor PM for Case 2.

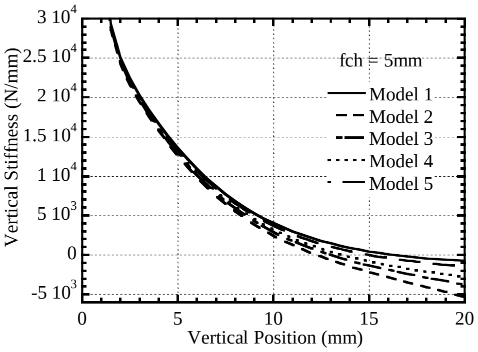

Fig. 9. Vertical stiffness on the rotor PM for Case 2.

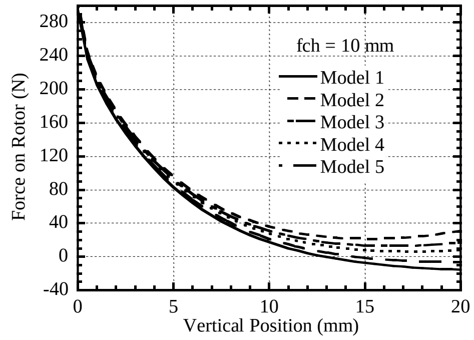

Fig. 10. Levitation force on the rotor PM for Case 3.

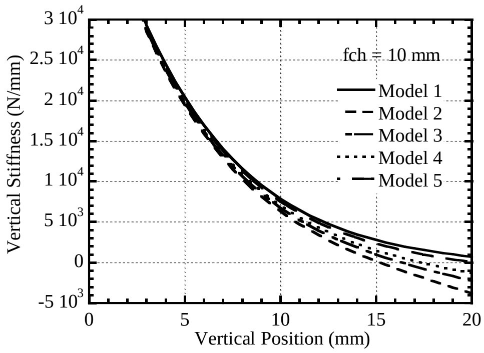

Fig. 11. Vertical stiffness on the rotor PM for Case 3.

4. Conclusion

The proposed superconducting magnetic bearing in this article consists of a disk-shaped PM in the rotor, ring shaped PM on the shaft and a combination of a bulk HTS with a ring PM in the base. The ring PM is positioned around the bulk HTS as a levitator. To analyze the load-carrying capability of the proposed configurations, the vertical force on the rotor as a function of the vertical displacement according to the cooling procedure of the superconductors are investigated by using an Amperian current approximation based on FIM. According to the results of the analysis, the proposed design provides greater levitation force at large levitation heights, as well as a higher stiffness for the stability. The overall results also indicate an optimized bearing system that provides a clearance advantage for the bearing with a quick and effective calculation for various design considerations.

5. References

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