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STRUCTURES FOR HIGH TEMPERATURE SUPERCONDUCTING MAGNETIC BEARINGS

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Abstract

As a technology, superconductivity has had a great contribution to the advancement of medical science, electronics, astronomy and transportation. With the improvements in the field of superconductivity, the discovery of new materials with better properties, commercialization of these materials, and regarding the importance of rotary equipment in major industry, trends in research and development of superconducting magnetic bearings is broadened day by day. High efficiency compared to the cost of manufacturing and maintenance of these bearings as well as the increasing need to economic save in key industry, could reinforce the tendency to use these bearings instead of conventional bearings. Superconducting magnetic bearings have various structures, all of which can be used for various applications. In recent decades efforts have been made to design new structures for specific applications. In this paper a general review of magnetic bearings' history as well as their existing structures is investigated and the theoretical and experimental results have been presented for a studied bearing system.

Keywords: Superconductivity, Magnetic Bearing, Levitation

1. INTRODUCTION

Bearing systems come in linear and rotary types [1]. The principal function of a bearing is to allow the relative motion of two machine parts with a minimum of resistance, wear, noise, friction, and heat generation. Conventional bearings have some advantages and disadvantages. The meeting point of such bearings is friction which decreases their efficiency. Researches have been done to reduce the friction and energy loss of bearings, and therefore increase their efficiency. Inventing the magnetic levitation and introducing magnetic bearings was a great step towards that goal.

This bearings support moving parts without physical contact and permit relative motion with very low friction and no mechanical wear. Magnetic bearings support the highest speeds (almost 500000 rpm) of all kinds of bearing and have no maximum relative speed, without any need for lubrication. Moreover, they can damp the vibrations during rotation and control the shaft's position precisely. They have a wide range of applications such as power generation, oil refinement, centrifuges, pumps, and any applications where isolation from pollution is needed.

The discovery of superconductivity opened the door to development of science and technology. At the first, there were only low temperature superconductors, needing very low temperatures (about the temperature of liquid helium) to remain superconductor. This was a great issue which had impeded the progress of superconductivity and its applications. In 1986, with the discovery of high-temperature superconductors at the temperature of liquid nitrogen (77 K), a huge amount of activity and excitement was generated among scientists [2, 3].

Superconductors can levitate on permanent magnets and vice versa, without any need for control systems. Therefore superconductors have a great potential to be utilized in applications related to levitation. Here, superconducting magnetic bearing was invented. This type of bearings have been utilized not only in rotary systems such as electric machines and flywheels which is the main issue of this paper, but also in magnetic levitated (MAGLEV) transportation systems. The modern development of magnetic levitation transportation systems, known as Mag-Lev, started in the late 1960s as a natural consequence of the development of low-temperature superconducting wire and the transistor and chip-based electronic control technology. In the 1980s, Mag-Lev had matured to the point where Japanese and German technologists were ready to market these new high-speed levitated machines. (see Fig. 1).

Fig. 1. Photograph Of Japanese Superconducting Mag-Lev Vehicle; Rated Speed 500 km/hr [4].

2. HISTORY

Levitation, whether an illusion caused by a stage magician, or a permanent magnet (PM) stably levitating over a bulk high-temperature superconductor (HTS), such as the system shown in Figure 2, often leaves the viewer with a sense of awe. In the case of the PM/HTS system, the levitation also provides a tactile and visual indication of many of the basic phenomena associated with HTSs. From its equilibrium position, if one pushes the PM in Figure 2 up, down or sideways, or tries to tilt it, a restoring force returns the PM to its initial position. If one pushes the PM hard enough, its equilibrium position can be changed to almost any orientation or the center of mass of the PM can be moved to a new equilibrium position. If the PM is a cylinder with a relatively symmetric magnetic field, it readily rotates about its axis of symmetry. Even before the discovery of the first HTS [4], the ability of superconductors to provide levitation was well established. The first stable levitation that involved a superconductor was reported in 1945 [5, 6], with the levitation of a small PM over a concave lead disk. In this experiment, the superconductor was the stator and the PM was the levitated part or rotor. By 1953 levitation of a small superconducting lead sphere in a coil structure and attempts to measure rotational drag on the superconducting rotor were reported [7].

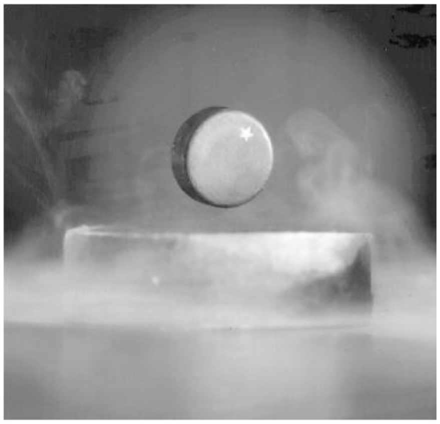

Fig. 2. Pm (With Star) Stably Levitated Over Hts. The Pm Levitates With Passive Stability, Rotating Freely While Maintaining Position [4].

Early studies all involved the use of low-temperature superconductors (LTSs). The early investigation of HTS levitational phenomena was accompanied by early interest in their use as bearings, and small stable rotors with rotational speeds> 100,000 rpm were soon demonstrated [9-11]. This interest arose from the advantages of no contacting surfaces without an active feedback system, ability to operate in a vacuum, and potential for extremely low rotational drag. In addition, the inconvenience of refrigerating the HTS was deemed more tolerable than that for LTS. Other advantages of HTSs were their relatively simple fabrication and use in bulk form and a much higher magnetic field before onset of flux jump instabilities. Earlier proposals and experiments in superconducting levitated bearings began in the 1950s and 1960s. For example, Harding and Tuffias [12] (1960) built a levitated niobium sphere at liquid helium temperatures (4.2 K) for a superconducting gyro. However, the necessity to work with liquid helium discouraged further work in superconducting bearings.

C, W. Chu of the University of Houston and co-workers in 1987 discovered a new, higher-temperature superconductor, yttrium-barium-copper oxide (YBCO) [8]. Bulk YBCO was found to have a low current density, and early samples were found to be too brittle to fabricate into useful wire. However, from the very beginning, the hallmark of these new superconductors was their ability to levitate small magnets. In the past few years, the original technical obstacles of YBCO have gradually been overcome, and new superconducting materials such as bismuthstrontium-calcium-copper oxide (BSCCO) have been discovered. Higher current densities for practical applications have been achieved, and longer and longer wire lengths have been produced with good superconducting properties [4]. After the discovery of YBCO in 1987, many laboratories around the world began to build prototype high-temperature superconducting bearings for temperatures near that of liquid nitrogen (78 K). One of the early prototypes was built at Cornell University in 1987, and it was spun up to 10,000 rpm. A later version in 1988 (Figures 1-14 and 1-15) levitated a 5-g rotor with two YBCO journal bearings up to speeds of 120,000 rpm. Subsequently, the levitation of small rotors (10 g) with speeds of 500,000 rpm (havc been reported by Allied Signal Corporation in 1992, and larger rotors of 1-10 kg on thrust bearings have been rotated to speeds of 5000-30,000 rpm at other laboratories.

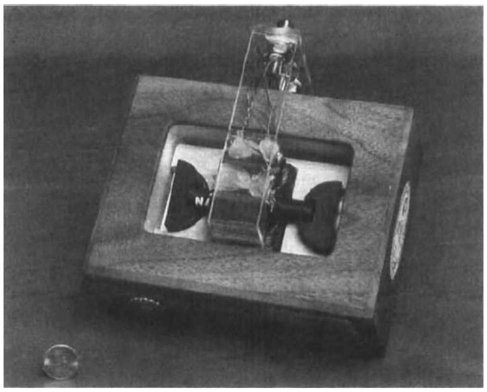

Fig. 3. Photograph Of A Prototype Passive Magnetic Bearing Using High-Temperature Superconducting Material, Yba,Cu,O, (50,000-120,000 Rpm) At Cornell University

Initial application programs by several companies in the United States (e.g., Allied Signal Corp. and Creare, Inc.) have focused on small levitated turbines for small cryocoolers for long-time space applications. These applications have natural cryogenic environments, and the bearing lifetimes of 5-15 years without maintenance gives superconducting bearings a potential advantage over conventional rolling elements or gas bearings.

According to the paper published in 2004 [14], the equilibrium position of a superconducting levitation device is determined not only by the geometry and electromagnetic properties of its components, but also by the cooling process of the superconductor. In this work the dependence of the equilibrium positions upon the cooling process is studied. Using the critical state model and the principle of magnetic energy, different diagrams of this type are calculated. The results show that for a given levitation system, which cooling process improves the capabilities of the system. In 2005 [15], the rotational speed degradation, which cuts down the stored energy, occurring in the PM rotors was considered as one of the most significant problems for the practical use of the SMBs. It is caused mainly by the Lorentz force due to the inhomogeneous magnetic field. . In this study, various shapes of the SC stator are tested to smooth the magnetic field and decrease the energy loss. Using our calculation method, it was found that the power loss of a changed bulk will be reduced by about 50% than the normal shape. Another paper in 2005 [16], developed a magnetic levitating transporter, which was composed of the HTS bulks and permanent magnets. To accomplish the design of a real levitation system, the influence of permanent magnet arrangement on levitating characteristics is investigated through measurements and numerical simulation. In order to enhance the levitation and guidance performance of the levitated high temperature superconductor (HTS) bulk over the permanent magnet guideway (PMG), it is necessary to optimize the design of the guideway [17]. First of all, a three dimensional (3D) model of the guideway was built up, through which the influence of the air gap across the guideway on the magnetic field was studied. It was found that the magnetic field 10 mm above the guideway is roughly uniform in the length direction. . Since generally the levitation gap between the vehicle body and the guideway surface is more than 10 mm, it is possible to simplify the HTS-PMG interaction model from 3D to 2D. Subsequently the levitation and guidance forces of the superconductor with different kinds of permanent magnet guideways were calculated in the 2D model. , the numerical results indicated that the HTS-PMG system is optimum when the width ratio between PMG and HTS is between 1.005 and 1.105. Strasik et. al [18], investigated the detailed characteristics of a 5-kWh/100-kW flywheel energy-storage system (FESS) utilizing a high-temperature superconducting (HTS) bearing suspension/damping system. This bearing system consists of three rings of radially polarized permanent magnets separated by ferromagnetic steel pole pieces. The steel rings both “turn” the flux in the axial direction so that it will have a high gradient within the adjacent superconductor, and serve as support surfaces for the mechanically weak permanent magnets. In the stator component of the HTS bearing, YBCO is utilized as the HTS material. In 2009, a paper was submitted by Deng et al [19], in which a double-axial superconducting magnetic bearing system was proposed for a flywheel energy storage system (fig. 4). The double SMB system is a vertical structure which is mainly composed of three parts: support platform, SMBs and driving module. The upper and lower axial SMBs are fixed at two ends of a vertical shaft, respectively, which are used to suspend and levitate the shaft. At the middle of the shaft, an inductive motor is mounted to drive the SMB. Both stators are composed of seven single-domain melt-textured YBCO bulks. The corresponding rotors are made of several stacked cylindrical axialmagnetized NdFeB permanent magnets (PMs).

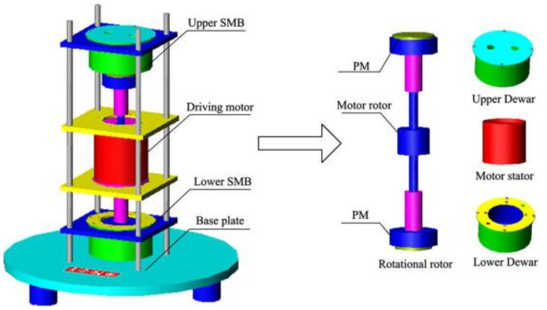

Fig. 4. Schematic View Of The Double-Axial Smb System

In 2009, some papers were published which studied the geometry and cooling conditions of HTS bulks. [20]-[22]. Lin et al [23], delivered a paper in 2010. To increase the efficiency of the transmission mechanism, this paper introduces one HTS magnetic helix transmission mechanism, which is composed of a magnetic bolt and an HTS nut. This paper also introduces the basic characteristics of the mechanical helix transmission mechanism. In the article written by Morandi et al [24] in 2011, the levitation performance of a magnetic bearing, is experimentally investigated. In this paper an MgB_2- based superconducting bearing is investigated both numerically and experimentally. the stator is made of a hollow cylinder and the rotor is made of a stack of ring like permanent magnets with soft magnetic steel interposed in order to form a magnetic circuit for the channeling of the flux. In this paper a numerical model is developed and validated against the experimental results.

In the paper published in 2012 [25], the damping for the SMB with superconducting coil is compared with the SMB without superconducting coil. In 2013, a group of scientists studied the geometrical characteristics of SMB [26]. In 2014, for the optimal structure of permanent magnet rotor, 3 topologies were presented and their magnetic field characteristics were analyzed [13, 27]. For effective cooling of YBCO bulks, a thermal model of the superconductor magnet stator using alumina shims was set up and its temperature distribution was analyzed. The result shows that the structure of the stator in which alumina shims were put between the neighboring YBCO bulks is better than that without alumina shims, and the temperature of YBCO bulks in the structure is lower. Cansiz and Yildizer [28], designed and simulated a high temperature superconducting magnetic bearing with various design considerations for a flywheel system. The design of the bearing consists of a rotor with 7.5 kg mass. By using non-contact torque mechanism, additional forces in the bearing are considered via electromagnetic and electrodynamic levitations, which in turn improved the bearing characteristics in levitation and operation speed (up to 70 Hz). Although the use of wires and thin films in superconducting bearings has been investigated somewhat, most of the current efforts involve the use of bulk HTSs. The current material of choice for superconducting levitation is Y–Ba–Cu–O (YBCO) and the rare–earth Ba– Cu–O analogues (RE–Ba–Cu–O where RE denotes the rareearth elements Nd, Sm, Eu, Gd, Dy, Ho, Er, Tm, Yb, Lu, La).

3. BEARING DESIGNS

In the most common configuration for a basic HTS bearing design, the PM is levitated and free to rotate while the HTS is held stationary. This is mostly due to the convenience of cooling the HTS in boiling liquid nitrogen or by a good thermally conductive contact with a cold source. To maximize the levitation pressure in a PM/HTS system, one may increase the magnetic field at the bottom of the PM by making the PM cylinder taller. This has the disadvantage of increasing the levitated mass and cost of the PM. A more acceptable design uses nested rings of PMs with alternating vertical polarity and includes a shunt of soft-ferromagnetic material on top of the rings [29]. Several studies have addressed the optimization of these designs [30], [31].

In practical HTS bearings, the low levitational pressure available in the interaction between the PM and the HTS is often augmented by various hybrid schemes in which interactions between pairs of PMs provide the bulk of the levitational force. These methods are sometimes termed magnetic biasing. Three of these augmentation methods are shown in Fig. 5. Figure 5(a) shows augmentation in the form of an Evershed-type design [33]. Here, the levitated rotor consists of a levitation PM, below which hangs a rigid rod with a smaller stabilizing PM on the bottom. The levitation PM of the rotor experiences an attractive force toward the stator PM immediately above it. This system is statically stable in the radial direction but unstable in the vertical direction.

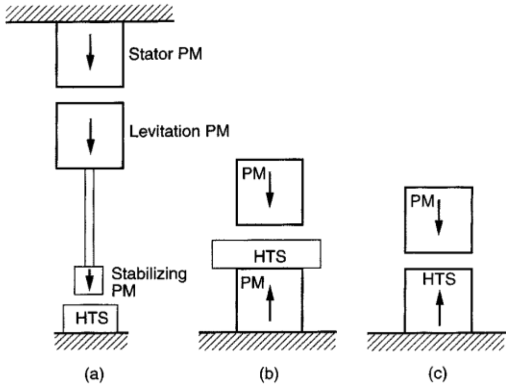

Fig. 5. MAGNETIC BIASING METHODS TO IMPROVE THE LEVITATIONAL PRESSURE IN HTS BEARINGS: (A) EVERSHED-TYPE DESIGN WITH ATTRACTIVE-FORCE AUGMENTATION, (B) REPULSIVE-FORCE AUGMENTATION AND (C) TRAPPED-FIELD AUGMENTATION. [32]

The gap between the levitation PM and the stator PM is adjusted in such a manner that the attractive force between the pair of magnets is just less than 100% of the rotor weight, so that the rotor would tend to fall. The remainder of the weight is provided by the interaction between the stabilizing PM and the HTS; this interaction also supplies sufficient stiffness for vertical stability and some additional radial stability. Fig. 5(b) shows augmentation in which a stator PM is placed below the HTS and acts in repulsion with the levitated PM [34]. Here, the PM/PM interaction is vertically stable but horizontally unstable. Because the minimal separation distance between the two PMs is limited by the thickness of the HTS, the amount of augmentation in this particular configuration is somewhat limited. Various combinations of attractive-force and repulsive-force hybrids have been devised [34], [35].

Another method to augment the levitation pressure is to use trapped fields in the HTS [36], as shown in figure 5(c). To create trapped flux, the HTS is usually field cooled in the presence of an external electromagnet or superconducting magnet. Alternatively, large pulsed fields can be applied after the HTS is cooled, although this method is the less effective of the two at trapping flux. The reported trapped fields are usually the maximum value measured at the surface of the HTS after the magnetizing fields have been removed. The average magnetization of the cylindrical HTSs is significantly less than these maximum fields. Trapped fields that are significantly >1.0 T have been reported at 77 K, and fields of up to 10 T have been reported at lower temperatures [36], [37]. The diameters of high-performance melt-textured HTSs are currently limited to a maximum of ≈100 mm. A large bearing system will thus need an array of superconductors [38].

One of the advantages of noncontact in magnetic bearings is elimination of overheating as the determining factor for the maximum speed of the bearing. Instead, the speed of the bearings tends to be limited by the mechanical strength of the rotating bearing components. PMs and HTSs are brittle and exhibit low mechanical strength, both of which lead to structural failure under sufficiently large centrifugal forces. These materials can be radially banded by materials with greater tensile strength, however, designs that allow for high velocities at the bearing perimeter require a careful balance between mechanical strength and the requirements of the magnetics [39]. An alternative design to the conventional PM/HTS system is the mixed-μ bearing [40], shown in figure 6.

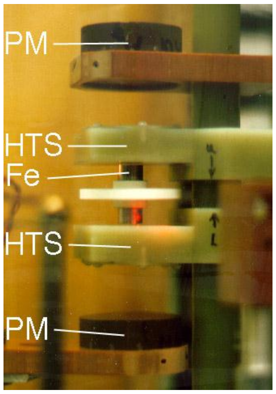

Fig. 6. MIXED-μ HTS BEARING.

In this bearing, a soft ferromagnetic cylinder (Fe) ($\mu r > 1$), where μ is the relative magnetic permeability) is levitated in attractive levitation between two PMs and stabilized by two HTSs ($\mu r < 1$), one HTS placed between the rotor and each of the PMs. The PM pair induces a magnetization in the Fe, which experiences a levitation force that depends on the gradient of the applied magnetic field from the PMs. For stabilization, the magnetization induced in the Fe produces diamagnetic images and trapped flux in the HTSs. In figure 6, the HTSs are housed in nonmetallic cryochambers, the lower PM is mounted on a movable stage and the Fe cylinder is surrounded by a ceramic disc-type rotor. The PMs shown in figure 6 are approximately identical, and, in this case, to obtain a net upward force, the distance between the upper PM and the rotor must be less than the distance between the lower PM and the rotor.

One advantage of this design is that the rotor can be made of a material with high tensile stress, such as steel, and its maximum rim velocity should be significantly greater than that for a rotating PM or HTS. A second advantage is that losses in the HTSs are not affected by inhomogeneities in the PMs. The primary contribution to a changing magnetic field near the HTSs is due to radial oscillation of the rotor. To date, the mixed-μ bearing has displayed the lowest rotational loss of any HTS bearing tested in laboratories. Disadvantages of the mixed-μ design include a stability that is weaker than the stability of the PM/HTS configuration and difficulty in scaling the design to larger sizes. Several researchers have investigated the possibility of combining HTS bearings with active magnetic bearings and with eddy current dampers [41], [42]. Another design possibility is the levitation of a bulk HTS with a stationary coil that is either an electromagnet or, preferably, a superconducting magnet [43]. A major advantage of this approach is a higher levitation pressure. A further advantage is that azimuthal homogeneity of the magnetic field produced by a coil can be much higher than that attainable in a PM; therefore the potential for extremely lowloss bearings exists. To take advantage of the homogeneity, it would be necessary to hold the energizing current of the coil constant in time to prevent changes in levitation height. The main disadvantage of this approach, when compared with levitating a PM, is that much lower temperatures are required and the levitated HTS must be cooled over long periods of time. Up to now, several structures for superconductor magnetic bearings have been proposed, all of which could be classified into different categories. The following section deals with the conventional classifications of SMBs.

3.1. Passive, Active, and Hybrid (Passive-Active) SMBs

SMBs are classified into three distinct groups according to the system they utilize to generate magnetic field and control the position of rotor.

3.1.1. Passive SMBs

The main difference between passive and other bearings is the absence of coils and control currents to adjust the precise position of rotor. As shown in figure 7. The magnetic field of a passive bearing is generated by permanent magnets and rotor is levitated by a passive magnetic force. These bearings have many advantages over those bearings using electromagnets. Firstly, using passive SMBs is really economical, because of elimination of control system which handles the rotor's position. Without using the control system, fewer components would be used. However, apart from the economic advantages, this situation may cause some problems. The most important issue is that in passive SMBs there is no active control which could lead to instability.

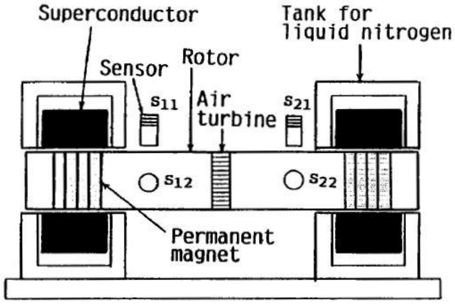

Fig. 7. Schematic Illustration Of The Passive Superconducting Bearing. In This System, Permanent Magnets Are Utilized To Produce Magnetic Field

Using permanent magnets leads to not using power supplies. Passive bearings are like mechanical bearings which do not need any control systems. Further advantages of passive SMBs are as follows: simple structure, very low cost of fabrication compared to other SMBs, and low level of loss. The quality of passive SMB is dependent on PM's material, its magnetization, the dimensions of superconducting bulks, and the air-gap's height. Passive SMB has some disadvantages. First of all, there would be not any control over the shaft's position because of elimination of control systems. Therefore, a weak damping would be available for shaft's vibrations. Moreover, this type of SMB has a low load capacity and low magnetic stiffness. Passive SMB is compatible with all the mentioned applications for SMBs. However, for applications where the precise control of shaft's position is required, this kind of SMB would not be a good choice.[44]-[47].

3.1.2. Active SMB

After fabricating passive SMBs, efforts have been done to fabricate the more advanced and controlled type of SMBs and prototypes of active SMBs were made. Nowadays, active bearings have many applications in the industry. The main feature of active magnetic bearing is the electromagnet in which the control current is running. Therefore, the required magnetic field to levitate and support the rotor in the desired position is generated. It is obvious that to control the precise position of rotor, one should utilize appropriate control systems. Ongoing dramatic improvements in Digital Signal Processors (DSP) – faster performance, integration of important peripheral features, and cost reductions – have further boosted commercial attractiveness of active magnetic bearings. The magnetic bearing system is open loop unstable and therefore feedback control is needed for the stable levitation of rotor. This function is commonly achieved by a controller which controls rotor position based on the data transmitted from the position sensors. The controller supplies equal and opposite currents to opposite magnet poles to provide stabilizing force to rotor [48]-[51].

3.1.3. Hybrid SMBs

Passive magnetic bearing features very little loss due to no current, but has no active control ability and low damping stiffness. Active magnetic bearing, on the contrary, has better control ability and a high stiffness characteristic, but high power loss because of the existence of the biased current. Therefore, more attention is paid to the permanent magnet biased hybrid magnetic bearing, which combines the merits of passive and active magnetic bearings. In hybrid-type SMB system, the passive bearings are considered to be dominant for suppressing the rotor displacements, and the active bearings assist them to suppress the rotor displacements. Fig. 8 indicates a schematic illustration of a typical Hybrid SMB. Hybrid bearings are more complex than active and passive bearings. However, this type of bearings consume less power and need smaller power amplifiers, compared to active bearings. Moreover, hybrid bearings have greater magnetic stiffness than passive bearings and show a better control abilities [51].

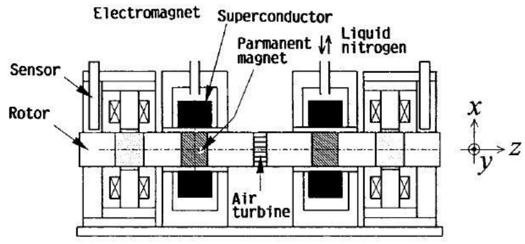

Fig. 8. SCHEMATIC ILLUSTRATION OF THE HYBRID-TYPE SMB SYSTEM

3.2. Radial, Axial, and Mixed (Radial-axial) superconducting magnetic bearings

According to the applied load, SMBs are divided into three groups.

3.2.1. Radial bearings

In a radial bearing the load force is perpendicular to the rotational axis. A typical PM/HTS radial bearing configuration could consist of a rotating shaft with PM discs mounted as endcaps, and the shaft assembly supported by HTS bushings that completely or partially surround the PMs at both ends of the shaft assembly. The arrangement shown in figure 9 is an example of a radial bearing. These bearings should not resist rotation. Otherwise the efficiency of system would decrease.

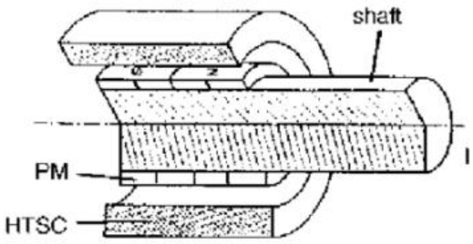

Fig. 9. SCHEMATIC OF A TYPICAL RADIAL SMB

3.2.2. Axial SMBs

In an Axial bearing, the major load force is in the direction of the rotational axis. If an axial load be applied to the shaft, radial bearing would not be able to stop the shaft's displacement. Therefore, in such cases an axial bearing is needed. As shown in figure 10. The magnetic field generation system and the position of superconductor bulks in axial SMB is different to that of radial ones.

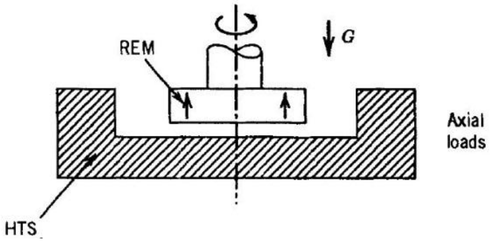

Fig. 10. THE ILLUSTRATION OF A TYPICAL AXIAL SMB

3.2.3. Mixed SMBs

In some applications, bearing system should sustain both radial and axial loads. As a result, a bearing system which is a combination of radial and axial bearings should be designed. This type of bearing is named mixed (radial-axial) bearing. This king of bearing could somehow address the problem of radial displacements in radial SMBs.

4.CONSIDERED BEARING SYSTEM

The considered bearing system has a PM rotor and a HTS stator. The PM rotor consists of an aluminum shaft, PM rings and iron shims. The system is shown in Fig. 11, where the stator has HTS cylinders shaped like doughnuts, embedded at two ends of the stator. Due to the Meissner effect, when the magnetization of PM cylinders is axial, the levitation force would be radial.

A. Concentrating forces

The radial concentrating force in rotational bearing systems may be calculated through the Lorentz equation, which is the force between the screening current and the external magnetic field, and is calculated from (1).

$$F_r = \iiint_{V_{SC}} (J_{SC} \times B)\, dV \tag{1}$$

Where, dV is the differential volume, V_{sc} is the HTS volume, J_{sc} is the super-current density distribution, and B is the total magnetic flux density at the HTS position. Because the total magnetic flux density is resultant of the magnetic flux density due to PMs, B_{PM}, and the magnetic flux density due to the HTS, B_{sc}, the radial force would be as (2).

$$F_r = \iiint_{V_{SC}} (J_{SC} \times B_{PM})\, dV + \iiint_{V_{SC}} (J_{SC} \times B_{SC})\, dV \tag{2}$$

And, since the cross product of J_{sc} and B_{sc} is zero, (3) is achieved.

$$F_r = \iiint_{V_{SC}} (J_{SC} \times B_{PM})\, dV \tag{3}$$

The external field due to PMs, B_{PM}, is obtained from FEM simulation results. Regarding the structural symmetry, the radial force of (3) is equal to zero, however, the total radial force, which acts as the concentrating force on the shaft, would be the sum of the differential force magnitudes on the shaft.

$$F_{concentrating} = \iiint_{V_{SC}} |J_{SC} \times B_{PM}|\, dV \tag{4}$$

the super-current density is approximated by the critical current density of the HTS cylinder, J_c, according to the Bean model [52].

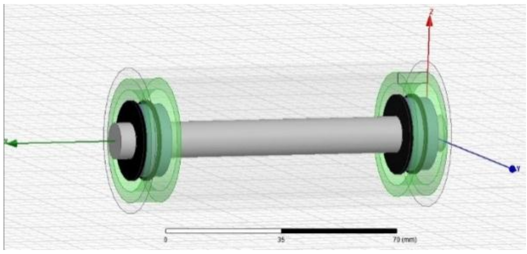

Fig. 11. Simulated System

5. TEST SETUP

A prototype bearing system has been fabricated with the cooling chambers, the permanent magnets and the shaft as in Fig. 12. The superconducting cylinder and discs are fabricated out of YBCO powders through the casting method. The vertical displacement in the shaft has been measured by measuring the difference in height of the shaft from the ground before and after superconductor cooling. As shown in Fig. 13, the vertical displacement, ε, would be calculated from (5).

$$\varepsilon = H_1 - H_2 \tag{5}$$

Where, H_1 is the height of the shaft from the ground before the superconductor cooling, and H_2 is the height of the shaft from the ground before the superconductor cooling.

Fig. 12. The Fabricated Prototype (a) Stator Inside The Cooling Chambers, (b) Rotor: Shaft And Pm Rings.

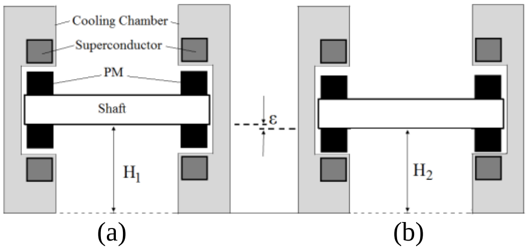

Fig. 13. Measurement Of The vertical Displacement, (a) Balanced Position, (a) Levitated Position

The overall weight of the shaft with the PM rings is measured as 120 gr, equal to the restoring force of

1.2 N. Some external weights have been applied on the shaft to simulate different displacement forces. With the aid of the external weights, the displacement force has been increased up to 200 gr, equal to 2 N, for the system. The simulation results and the experimental results are shown in Fig. 14, for the studied system.

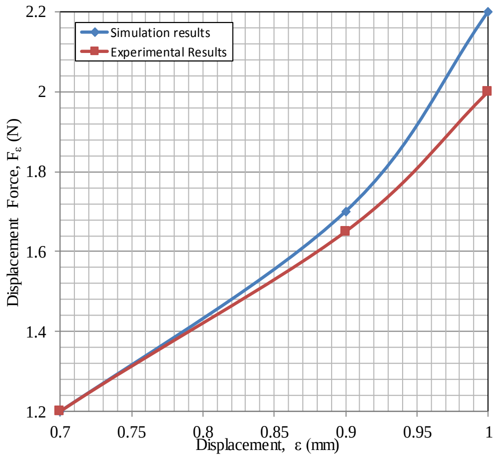

Fig. 14. The Simulation And The Experimental Results For The Considered System

The maximum error of the simulation results relative to the experimental data is deduced to be around 3 percent. This shows the good consistency between the practical and the theoretical data. According to Fig. 14, the restoring force of 1.2 N predicts the displacement for the considered system as shown in Table III, due to the simulation results. The experimental measurements have resulted in the displacement as also shown in Table I, for the considered case.

Table I. Comparison Between The Theoretical And Experimental Results

Theoretical Displacement (mm)	**0.7**
Experimental Displacement (mm)	**0.7**
Concentrating Force (n)	**3.215**
Superconductor Volume (mm^3)	**5843.36**

The calculation result for concentrating forces and the volume of the HTS material in the considered system are also shown in Table I.

6. APPLICATIONS

Because superconducting levitation is versatile over a wide range of stiffness and damping, it has been suggested for numerous applications [9]. Superconducting bearings, like magnetic bearings, do not require a lubricant; this could be a major advantage in harsh chemical or thermal environments. In addition to the early applications considered for low temperature superconductors mentioned in the introduction, such as electric motors and gyroscopes, our increased understanding of the hysteretic behaviour of HTSs has suggested new possibilities. The availability of HTS bearings that are so nearly friction-free naturally leads to their consideration for flywheel energy storage [38]-[51]. Flywheels with conventional bearings typically experience high-speed idling (that is, no power input or output) losses of the order of ≈1% per hour. With HTS bearings, it is believed that losses as little as 0.1% per hour are achievable. Electric utilities have a great need for efficient diurnal energy storage, such as flywheels. With modern graphite fibre/epoxy materials, the inertial section of a flywheel rotates with rim speeds well in excess of 1000 m s−1 and achieves energy densities greater than those of advanced batteries. The kinetic energy in a (large) Frisbee-sized flywheel with this rim speed is ≈1 kW h, and a person-sized flywheel could store 20–40 kWh. HTS bearings are particularly interesting for cryogenic turbo pumps. Liquid hydrogen, which is typically pumped at a temperature of ≈30 K, seems the most likely candidate, but liquid oxygen is also a possibility, if materials with critical temperatures higher than that of YBCO can be used in HTS bearings. The tribological properties of mechanical bearings at cryogenic temperatures are poor, and experience with rocket engines indicates that the bearings of turbopumps are one of the most life-limiting components. Other applications for HTS bearings in which a cryogenic environment already exists include cryogenic turbine flow metres and cryocoolers for space or terrestrial use [4]. Another application for which a cryogenic environment naturally exists is the use of HTS bearings in a lunar telescope. The drive mechanism of the telescope must be capable of exceedingly fine steps and repeatability, and it must survive and operate in the cold temperatures of the lunar night. The low magnetic drag of an HTS bearing has suggested its use as a sensitive detector of gas pressure [53]. The possibility of using low-loss superconducting bearings in sensitive gyroscopes has long been recognized. The hysteretic nature of HTSs has suggested their use in docking vehicles in space. Hysteresis is also important in the potential use of HTS as torque couplers and vibration dampers. Apparently, the first successful vacuum tunneling experiment, which eventually led to the development of the scanning tunneling microscope, was made possible by suppression of vibrations with the use of a superconducting bearing. Although this article has focused almost exclusively on rotating HTS bearings, similar physics applies to linear HTS bearings [54-56]. The stable levitational force suggests application in magnetically levitated conveyor systems in clean-room environments, where high purity requirements mandate no mechanical contact. Linear HTS bearings have also been proposed for micro actuators.

7. CONCLUSION

With the improvements in the field of superconductivity, the discovery of new materials with better properties, commercialization of these materials, and regarding the importance of rotary equipment in major industry, trends in research and development of superconducting magnetic bearings is broadened day by day. High efficiency compared to the cost of manufacturing and maintenance of these bearings as well as the increasing need to economic save in key industry, could reinforce the tendency to use these bearings instead of conventional bearings.

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