Prototype of a disc-type HTS bearing

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Abstract

A prototype of a rotational machine with two HTS bearings supporting a rotor without a mechanical contact has been designed, manufactured and tested. An arrangement of HTS elements with 180-g total mass provide stable suspension of a 3.6-kg rotor with 1.0-mm operating gap. The maximal load capability of the bearing was measured to be 220 N in the radial direction and 150 N in the axial. The ratio of the radial load capability to the mass of superconductors exceeded 120. The maximum rotation frequency was 14500 rpm.

1. Introduction

A progress in the trapped field of the High-Temperature Superconductivity made possible development of practical non-contact passive magnetic bearings operating at the temperature of liquid nitrogen. Superconducting magnetic bearings have been developed for flywheel energy storage systems, electric motors and centrifuges [1,2,3]. The state-of-the-art radial and axial load capacities of such bearings reach 10000 N with operating gaps of 1 to 3mm.

This paper describes a design of a superconducting magnetic bearing - a disk-type superconducting bearing - which allows for a modular design in which the load capacity can be easily changed by adding or removing identical modules forming the bearing. Such a system may find application, for example, in flywheels used for spacecraft orientation as well as on-board energy storage, for rotary centering of gyrodynes and in different rotating machinery.
2. Magnetic Bearing system

Fig. 1 shows a schematic diagram of a magnetic bearing system, comprising two disk-type magnetic bearing supporting a common rotor without a mechanical contact. The magnetic bearing system consists of housing, rotor with permanent magnets and steel disks, stator with HTS elements and a thermo-insulating jacket. The overall dimensions of the system (including the thermo-insulating jacket) are $230 \times 230$ mm. The rotor mass is 3.6 kg.

The rotor consists of a shaft and two rotating portions of the magnetic bearings, each including two subassemblies of ring-shaped permanent magnets attached to steel disks. The rotating portions of the magnetic bearings are firmly mounted on the shaft.

The stationary portions of the magnetic bearings consist of the aluminum-alloy disks with embedded HTS elements. The outer diameter of a stationary portion is 125 mm. The disks are sandwiched between the bearing magnetic subassemblies mounted on the rotor with 1.0-mm separation from each of the subassembly.

The entire system is assembled within stainless steel housing with 135 mm in diameter and 127 mm in length. The housing has two end caps with pass-thru openings for the shaft. The output shaft diameter is 13 mm. The housing is placed inside a cooling jacket made of a high-density styrofoam with an opening for pouring liquid nitrogen. Prior to cooling, the rotor was set in the central position using initial-alignment bushings. After the cooling, these bushing could be removed and the rotor could be levitated without a mechanical contact.

The main components of any HTS magnetic bearing are permanent magnets and high-temperature superconductors. The design presented in this paper uses NdFeB magnets and bulk disk-shaped YBaCuO superconductors. It comprises two magnetic subsystems, each including disk-shaped axially-magnetized...
outer and inner magnets concentric with the bearing axis, separated radially by aluminum-alloy rings and attached to an axial face of a disk made of magnetic steel (Fig. 1). The magnetization directions of the outer in inner magnets in each subassembly are opposite to each other as well as to the magnetization directions of the identical magnets in the other subassembly. Two subassemblies are located axially against each other with the magnets in two subassemblies facing each other and separated by a 7-mm gap. The outer and inner diameters of the outer magnets are 92 mm and 68 mm respectively. The outer and inner diameters of the inner magnets are 64 mm and 44 mm. All the magnets are 8-mm thick. The magnetic-steel disks are also 8-mm thick - a sufficient thickness to carry magnetic flux between the outer and the inner magnets without saturating the disk material.

Fig. 2a shows a schematic diagram of the magnetic system of the bearing prototype. Fig. 2b shows a radial distribution of the axial magnetic field in the middle plane of the gap between two magnetic subassemblies. It can be seen that the field has two extremes of the opposite polarities, where the absolute value of the field reaches approximately 0.69 T, and a high-gradient area in between these extremes. In this design the superconductors operate in the "Field-Cooled" (FC) mode.

Fig. 3 shows photographs of the assembled prototype of magnetic bearing (a) and its components (b). Fig. 4 shows the assembled rotor (a) and a setup used to measure bearing characteristics (b).

![Fig. 2. (a) schematic cross-section of the bearing magnetic system; (b) distribution of the magnetic field in the magnetic gap](image)

3. HTS element manufacturing

HTS elements used in the bearing prototype were cut out of single-domain samples of $Y_1Ba_2Cu_3O_x$ + 25 mol. % $Y_2O_3$ + 0.07 wt. % ZnO + 1wt. % CeO$_2$ ceramic produced by means of a directional crystallization using elongated seeds [4]. These samples were 48 mm in diameter and 15 mm in height and were capable of trapping 1-1.2 T fields at 77K (Fig. 5). Single-domain $Gd_1Ba_2Cu_3O_x$ + 30 mol. % $Gd_2BaCuO_3$ with dimensions 38x1.8x5 mm$^3$ (LxWxH) was used as a seed.

An advantage of elongated seeds is that a large primary crystal is formed at the early stages of the crystallization process, resulting in a more stable and more oriented subsequent crystal growth throughout the rest of the sample. This ensures a large final crystal size and reduces the crystallization time.

In total, the magnetic bearing system included 14 superconducting disks 28mm in diameter and 5mm
in height. These disks were cut out of single-domain ceramic samples produced as described above. The total surface area of the disks was 86 cm$^2$, total mass - 180 g.

4. Experimental results and consideration

Axial and radial force-displacement characteristics of the bearings were measured, see Fig. 6. When loaded radially up to 100 N, the rotor was displaced by 0.21 mm. Therefore, the suspension stiffness was approximately 476 N/mm. After cyclic loadings with amplitudes up to 49 N the rotor returned to the original position. However, a residual displacement was observed when the load amplitude exceeded 49N, for example a cyclic load with 200 N amplitude resulted in 0.089 mm of the residual rotor displacement. The suspension stiffness in this case dropped to 270 N/mm. Therefore, 49 N should be considered as a load limit when the rotor residual displacement is of primary concern. When loaded in the
axial direction, the bearing at first exhibited significantly lower suspension stiffness than in the radial direction - on average 224 N/mm when loaded up to 150 N. The residual rotor displacement was 0.25 mm. However, when the bearing was loaded second time, the suspension stiffness was found to be significantly higher: 345 N/mm. This could be explained by pinning vortices during bearing loading.

The rotor was spun up to 14500 RPM when levitated in HTS magnetic bearings at 77 K using an external 60 W motor coupled to one of the shaft ends. A drag torque exerted on the rotor was measured as a function of the rotational speed. The drag torque was found to increase nearly linearly with the speed. When the rotor spun in the air, the drag torque was 0.067 N·m at 10000 RPM (11.2 W of rotational losses). The main contribution was likely from aerodynamic losses, enhanced by the condensation and subsequent icing on the rotor. When the machine cavity containing the rotor was filled with Helium instead of the air, the drag torque dropped to 0.0297 N·m (4.95 W). The polar moment of inertia of the rotor (including the bearing magnets) was 0.0043 N·m·s², which resulted in a kinetic moment of 4.53 N·m·s at 1047 rad/s (10000 RPM). These values are comparable with those of conventional gyrodyne.

![Fig. 5. Photos of a 48 mm-diameter sample: (a) as-obtained, (b) polished and (c) distribution of a field trapped in the sample](image)

![Fig. 6. (a) radial and (b) axial force-displacement characteristics of the bearing prototype. T=77K.](image)
5. Conclusion

A design of a disk-type passive magnetic bearing using bulk single-domain High-Temperature Superconductors has been proposed. The "disk-type" construction allows to realize a "modular" approach to the design in which the load capacity can be easily changed by adding identical modules forming the bearing. A prototype of a magnetic bearing system utilizing two proposed bearings to suspend a common rotor has been designed, built and tested. The superconductors operate in the "Field-Cooled" (FC) mode. Such a system may find application, for example, in flywheels used for spacecraft orientation as well as for rotary centering of gyrodyynes. The kinetic moment of the rotor (including the bearing magnets) was 4.53 N·m·s. at 1047 rad/s (10000 RPM). These values are comparable with those of conventional gyrodyynes.

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