Stiffness Enhancement of a Superconducting Magnetic Bearing Using Shaped YBCO Bulks

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Abstract—High-speed superconducting motors and generators stand to benefit from superconductor magnetic levitation bearings if their stiffness characteristics can be improved. Here we investigate a novel thrust bearing geometry, comprising a conical frustum shaped permanent magnet and matching superconducting toroid and puck assembly, aimed at producing high stiffness coupled with high levitation force. To this end, we have constructed a bearing test rig enabling measurements of the levitation force and stiffness of the assembly of YBa$_2$Cu$_3$O$_{7-\delta}$ melt-textured bulks and Nd$_2$Fe$_{14}$B permanent magnet at temperatures down to 47 K. The experimental results are supported by finite element modeling that is validated against the experiment, and used to quantify the advantages of this configuration over a conventional cylindrical magnet and HTS puck arrangement. For axial displacements, the assembly produces higher and more consistent stiffness together with stronger restoring forces. For lateral displacements, the assembly produces up to double the lateral force and up to four times the stiffness. Our study also shows that the force contribution to the assembly from the small inner puck is negligible and it can therefore be eliminated from the bearing design.

Index Terms—Superconducting magnetic bearing, levitation force, toroid, conical frustum, HTS bulks.

I. INTRODUCTION

The aviation industry is looking increasingly towards hybrid-electric aircraft propulsion as a means of reducing carbon-dioxide emissions, and the demanding power, weight and efficiency requirements have renewed interest in multi-megawatt high-speed superconducting motors and generators[1], [2], [3], [4]. High-stiffness low-loss bearings are a key enabling subsystem for such machines. Since cooling is already available in a superconducting machine it makes sense to consider incorporating high-temperature superconductor (HTS) levitation bearings[5], [6], featuring passive stability and extremely low rotational losses. However, compared to mechanical and active magnetic bearings, HTS bearings are limited in applications by their low stiffness[6], [7].

The levitation force from truncated cone (or conical frustum) shaped permanent magnets (PM’s) of varying thickness was investigated recently[8], and it was found that the force could be optimized at a particular thickness. Here, we go a step further by introducing an HTS bulk with a matching recess, into which a frustum shaped PM can settle. Our hypothesis is that this geometry provides enhanced levitation and stiffness compared to a cylindrical PM and HTS puck. In this paper we report the measured force-displacement characteristics and their analysis using H-formulation finite-element models.

II. EXPERIMENTAL DETAILS

A test rig was constructed at Robinson Research Institute to measure the vertical (z) and lateral (x and y) levitation forces between a conical frustum-shaped PM and an HTS assembly, composed of a trapezoidal toroid and a small puck semi-recessed inside the toroid. The arrangement and dimensions of the PM and HTS are shown in Figs. 1 and 4(a). Both HTS parts are melt-textured YBa$_2$Cu$_3$O$_{7-\delta}$ bulks supplied by Can Superconductors[9] and the N50-grade NdFeB PM was supplied by SuperMagnetMan[10].

The large face of the PM is glued to an aluminium plate which is mounted on a 3-axis load cell sensor with a range of ± 500 N in each direction. This sensor is mounted on a linear displacement system capable of lateral (x) and vertical (z) movements. The displacement speed is set to 0.5 mm/s. Two linear variable differential transformer sensors provide the position of the PM. The servo motor is controlled using a TrioMotion MC464 with National Instruments CompactDAQ hardware and Labview making measurements of the analogue signals. The HTS puck is semi-recessed into an aluminium plate and secured with an aluminium filled epoxy. The HTS toroid is clamped onto the same plate with thermal contact aided by a thin layer of vacuum grease. This plate is mounted to a second aluminium plate which is attached from below to the top of the cold head of a Cryomech AL63 cryocooler. The apparatus is housed in a turbo-pumped vacuum chamber operating at a typical pressure of $10^{-5}$ hPa. The experimental arrangement is shown in Fig. 2.

Fig. 1. Cross-sectional view of the mounting assembly of the HTS bulks to the cryocooler cold head, and of the frustum PM to the force sensor.
Temperature is measured on the toroid with a PT100 resistance temperature detector attached to a flat region shaved onto the outer curved side. A diode sensor measures the temperature of the aluminium plate on which the HTS parts are mounted. The toroid temperature is maintained with a temperature controller and four heater resistors, with temperature feedback provided by the PT100. The toroid temperature can be stabilized over the range 42 K to 90 K. No temperature feedback provided by the PT100. The toroid temperature can be stabilized over the range 42 K to 90 K. No temperature measurement is carried out on the PM.

After moving the PM to its initial position for a field cooling (FC) or zero field cooling (ZFC) experiment the HTS assembly is cooled to the desired temperature. Next a zeroing of the load cell sensor (green), displacement sensors (blue) and translational stage and motors (red). The HTS assembly and mounting plates have been sectioned for clarity.

Results were compared with simulations from H-formulation finite element models implemented in COMSOL Multiphysics[11]. We employed the method detailed by Quéval et al.[12] wherein the field from the moving permanent magnet is applied as a time-dependent Dirichlet boundary condition on a thin air region enclosing the HTS. For a given remanent flux density \( B_r \), the PM field \( H_{ext}(x, y, z) \) only needs to be calculated once (using an A-formulation finite element model) and stored in a lookup table. The N50-grade value of \( B_r = 1.4 \) T was confirmed by comparing calculations of \( B_z \) versus \( z \) above the centre of the small face of the PM with values measured with a P15A Hall sensor from Advanced Hall Sensors Ltd.[13], see Fig. 3.

The material-dependent inputs to the model come via the nonlinear resistivity. For the HTS we take a bounded power law[14], [15]

\[
\rho(J) = \frac{\rho_{NS} \cdot \rho_{SC}(J)}{\rho_{NS} + \rho_{SC}(J)} \tag{1}
\]

where \( \rho_{NS} = 3.5 \times 10^{-6} \) Ω m is the assumed normal-state resistivity[16], and \( \rho_{SC} \) is the resistivity in the superconducting state given by

\[
\rho_{SC}(J) = \frac{E_c}{J_c} \left| \frac{J}{J_c} \right|^{n-1} \tag{2}
\]

\( J \) is the current density, and the \( n \)-value is set to 21 [17]. \( J_c \) is the critical current density at the electric field criterion \( E_c = 10^{-4} \) V/m and, in the absence of measured values, is our only adjustable parameter. For simplicity we take \( J_c \) to be field-independent and spatially homogeneous. \( J_c \) is assumed to be the same for both the toroid and puck. A finite resistivity of \( 1 \) Ω m is applied to the air region[18]. Vertical displacements of the magnet along \( z \) were simulated in a 2D-axisymmetric geometry (Fig. 4) with relative tolerance set to \( 10^{-4} \) and absolute tolerance set to \( 10^{-3} \). Mapped meshes created with an arithmetic sequence distribution method were applied to the HTS domains. A free triangular mesh was applied to the air domain. Lateral displacements along \( z \) required a 3D model and the relative and absolute tolerances were relaxed to \( 10^{-3} \) and \( 10^{-2} \) respectively, as in [12]. The 3D mesh was created by sweeping the 2D-axisymmetric mesh around the \( z \)-axis. The speed of the magnet displacement was set to 1 mm/s. The force is given by the integral of \( \mathbf{J} \times \mathbf{B} \) over the HTS volumes.
Spikes in force near the minimum displacement indicate unintentional contact between the PM and toroid. Finite forces were measured in the $x$ and $y$ directions, which should both be zero under ideal conditions. Possible explanations include an off-centre misalignment of the PM, and inhomogeneities in the HTS and/or PM[20]. The presence of spikes in $F_y$, together with $F_y$ being greater than $F_x$, is consistent with misalignment. But a ten percent decrease in $B_r$ along $y$ can also cause similar $F_y$ values.

Figure 5(b) shows the simulated levitation force for two values of $J_c$, 21.6 x 10^8 and 9.6 x 10^8 A/m², chosen to provide a reasonable comparison with the data. Note we have not tried to perform a precise fit to the experimental data, and the same $J_c$ values are used in all subsequent simulations. The maximum levitation force, dictated primarily by $B_r$, agrees well with experiment, and the qualitative shape of the curves is reproduced. A decrease in $J_c$ accounts for the observed increased hysteresis and reduced force with temperature.

Contributions to the force were investigated by repeating the measurements and simulations on the puck and toroid separately. The puck produced a maximum force of 19 N at 67 K and the slope of the force curve increases monotonically as the PM approaches, see Fig. 6(a). The simulated force curve, with the same $J_c$, agrees very closely see Fig. 6(b). The toroid was measured at 70 K and the data lies between the 61 and 77 K data from the puck-plus-toroid assembly. If the force contributions from puck and toroid were additive we would expect the maximum of the toroid-only data to occur around 130 N, putting it below the 77 K puck-plus-toroid curve. Simulation confirms that the force from the toroid is virtually the same as the assembly, suggesting that the puck is screened from the PM field by the opposing field induced in the toroid.

2) Field-cooled: Field-cooled sequences with $z$ going from 7.2 to 2.4 to 12.1 and back to 7.2 mm were performed at 47 and 70 K, see Fig. 7. Maximum force at $z = 2.4$ mm is 120 N, which is still appreciable and good from an applications perspective. The restoring force at $z = 12.1$ mm is -52 N. Note that the maximum force depends upon the field-cooled height of the PM, and field cooling at lower heights produces lower maximum levitation force but higher vertical stiffness. The 70 K data has larger hysteresis and a slight decrease in force compared to the 47 K data. Again, there is good qualitative and quantitative agreement between the measurements and simulations shown in panel (b). As in the ZFC case, we measured a non-zero $F_x$ and $F_y$, probably due to a slight misalignment of the PM in the $y$-direction.

B. Lateral displacement

Lateral force displacement loops, with $x$ traversing the sequence [0, 1, -1, 1, -1, 0] mm, were measured at 54 K
after field cooling with the PM at $z = 5.2$, 4.2 and 3.2 mm, see Fig. 8. The conical geometry accommodates wider lateral motion at higher $z$. Stiffness values determined from a linear fit are -14.7, -16.6 and -19.3 N/mm respectively. There is a very slight cubic term to the elastic contribution. The loops are very narrow, indicating weak damping. The maximum $z$-force is about ten percent of the maximum $x$-force, and the maximum $y$-force is of the order of a few percent.

The simulated force curves, also in Fig. 8, do not exhibit hysteresis. $F_x$ is almost linear, with a small cubic component, and the stiffness increases with decreasing $z$. $F_y$ consists of discretization noise and should ideally be zero. $F_z$ is slightly noisy but exposes an offset in the experimental data of approximately 0.5 mm.

V. DISCUSSION AND CONCLUSIONS

The agreement between measurements and simulations shows that our assumptions regarding $J_c$ are sound. According to the diode sensor, the recessed puck and base of the toroid could be up to 28 K colder than the PT100 temperature near the top of the toroid. The toroid presents a largely unshielded dark surface to thermal radiation. But below about 60 K the levitation force becomes limited by the field profile of the magnet[21], [22]. So even if $J_c$ increases, colder temperatures do not significantly affect the results. The field-independent $J_c$ reproduces the observations well, indicating that the actual field-dependence is weak in this field range.

The high stiffness and low hysteresis points to the bulks having a high $J_c$.[23] Damping could be increased, at the cost of reduced levitation force, by reducing $J_c$. This could be achieved, for example, by operating closer to $T_c$, thereby relaxing cooling requirements. Passive damping could also be improved by adding a thin copper eddy current damper[24].

An unexpected finding is that the forces from the puck and toroid are nonadditive. As an assembly, the centre puck plays no role and can be eliminated, reducing the amount of HTS used. Though not shown here, we have confirmed through simulations that this also holds under field-cooling conditions. Further simulations could be carried out to identify the optimal slope of the PM and toroid aperture.

So what advantages, if any, does the assembly and frustum PM configuration have over the traditional arrangement of a puck and cylindrical PM? Performing an equivalent comparison isn’t as simple as replacing the assembly with a puck of equal outer diameter (50 mm). Firstly, we employ simulation which not subject to material variations between bulks. Secondly, we consider a much narrower minimum puck-PM separation of 0.3 mm, similar to the gap between the sides of the frustum PM and the inside face of the toroid when $z = 2$ mm (see Fig. 4(a)). Thirdly, we take a PM with radius 12.7 mm, equal to the large radius of the frustum PM, and a matching thickness of 12.7 mm. These dimensions produce a similar FC force (125 N) at minimum separation as the frustum-assembly combination. Comparing the results in Fig. 9(a) reveals that the assembly has higher and more consistent vertical stiffness over most of the displacement.
range. Moreover, it generates superior restoring force for displacements above the field-cooling height of 7 mm. Comparing lateral force performance is complicated by the fact that the minimum separation between the toroid and frustum PM is not constant. So we take the average separation, equal to the initial separation of 1.3 mm (when \( x, y, z = [0,0,5] \) mm) as the field-cooling height for the cylindrical PM. Figure 9(b) shows that for displacements less than 0.4 mm the assembly provides an improvement in stiffness of about 33 percent. But because the assembly has a more linear response, the performance advantage increases at higher displacements. At \( z = \pm 1 \) mm the assembly produces just over double the lateral restoring force and around four times the stiffness. To provide similar performance, the cylindrical PM would need to be field-cooled at a much lower height of about \( z = 0.3 \) mm. The obvious disadvantage of the assembly geometry is that the range of permissible lateral movement is restricted and depends on the vertical position of the PM.

In summary, we have shown that a conical frustum shaped permanent magnet levitated above a matched trapezoidal HTS toroid experiences superior stiffness and restoring forces compared to a conventional cylindrical PM and HTS puck arrangement. Our ongoing studies will evaluate the dynamic performance of the frustum-toroid configuration under high-speed rotation of the PM to further assess its suitability for high-speed bearing applications.

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REFERENCES


