Magnetic Bearings set for a flywheel system

Guilherme Goncalves Sotelo, Rubens de Andrade Jr., and Antonio Carlos Ferreira

***Abstract*— A flywheel energy storage system (FESS) has been developed at the Laboratory for Applied Superconductivity of the Federal University of Rio de Janeiro, Brazil. In order to improve the performance of the FESS, a passive magnetic bearing system was designed. The system provides radial and axial stability to the flywheel. The whole passive bearing system is composed of a Permanent Magnetic Bearing (PMB) and a Superconducting Magnetic Bearing (SMB). This PMB presents an attractive force that is responsible for providing radial stiffness and also reducing the total load above the SMB. The use of a PMB allows cost reduction with superconductors and refrigeration, but has as a drawback a limited stability region. In this work a new configuration of PMB having Nd-Fe-B magnets rings and a back yoke is investigated to optimize the magnetic circuit (reducing the reluctance). As a result, the levitation force and stiffness are increased for the same permanent magnets volume. Finite Element Method (FEM) simulations using the critical state model, validated by previous work, were applied to design the different SMB configurations constructed. Testes for force measurements of axial and radial force were carried out in Zero Field Cooling (ZFC) and Field Cooling (FC) processes. The ZFC simulations results presented good agreement with the measured axial forces, having a levitation force of up to 400N in ZFC for a 130mm diameter bearing. Finally, the cost-benefit analysis was carried out for all tested topologies.**

***Index Terms*— Permanent Magnetic Bearing, Superconductor Magnetic Bearing, Flywheel.**

I. INTRODUCTION

THIS paper presents a magnetic bearings set developed to work in a flywheel energy storage system [1][2] [3]. The bearing set are composed of a Permanent Magnetic Bearing (PMB) and a Superconducting Magnetic Bearing (SMB), Fig. 1. SMBs are useful to high-speed rotational devices because they can operate at high speed with very small energy losses and self-stability [4], but they have high cost and need refrigeration. In the other hand, PMBs have low cost, but are not able to produce completely stable levitation, as predicted by Earnshaw's theorem [5]. One possibility to optimize the bearing system benefit-cost is the use of a PMB working as an auxiliar bearing of a SMB. By this way, the whole system are able to produce stable levitation, reducing the cost with refrigeration and superconductors blocks. In the attempt to optimize the PMB, a new configuration is introduced here and it is compared with a conventional PMB [6] [7](both having the same permanent magnet volume). The new PMB presents higher levitation force and stiffness than the older configuration.

The thrust SMBs studied here are composed basically of rare earth permanent magnets rotors and $YBa_2Cu_3O_{7-\delta}$ (YBCO) superconducting stators refrigerated by liquid nitrogen (LN2). They are able to reach self stability due the flux pinned inside the superconductors in a Field Cooling (FC) process. When the superconductors are cooled without the field of permanent magnets, Zero Field Cooling (ZFC) process, a maximum levitation force is reached, but the bearing stiffness is too small [4]. For this work two SMBs prototypes were built and the analysis is developed considering the following parameters: the mapped magnetic flux density, the levitation force for ZFC and FC processes and the bearing's stiffness in different cooling gaps. The SMB prototypes tested are: a Flux Shaper (FS) topology [1] [8] [9] and an Axially Magnetized Ring (AMR)[10] [11], both having the same dimensions and permanent magnet volume too. The main difference between these SMB prototypes are the direction of magnetization of Nd-Fe-B. A previous work [12] presented an preliminary comparative analises of these SMB topologies, and more concluding results will be presented here. The measurements show that the FS configuration presents a larger levitation force for ZFC. However, in FC process both configurations present very simular levitation force (while increasing the gap), even for various initials gaps tested. After FC process, when the gap is decreased, AMR presents a little higher levitation.

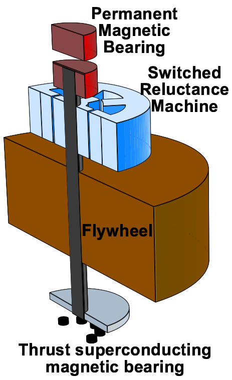

Fig. 1. New flywheel prototype having both PMB and SMB.

II. PERMANENT MAGNETIC BEARING

Due to high magnetic flux density reached by Nd-Fe-B magnets and theirs low cost, applications with permanent magnetic bearings have become attractive, in spite of been very instable. And so, PMB can be used as a auxiliar bearing for a SMB to reduce the load weight of the rotor and the flywheel and to increase the stiffness of the whole bearing system. It makes possible to reduce significantly the quantity of superconductor blocks in the SMB, bringing down the overall cost. Previous work [7] [8] showed a PMB topology using 2 rings configuration presenting satisfactory results. In the

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G.G. Sotelo, R. de Andrade Jr. and A.C. Ferreira are with the Federal University of Rio de Janeiro.

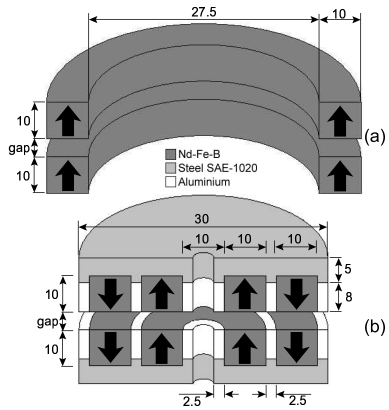

Fig. 2. Cut view of 2 PMB topologies using Nd-Fe-B magnetic rings:(a) 2 PM rings configuration, (b) 4 PM rings and back yoke configuration.

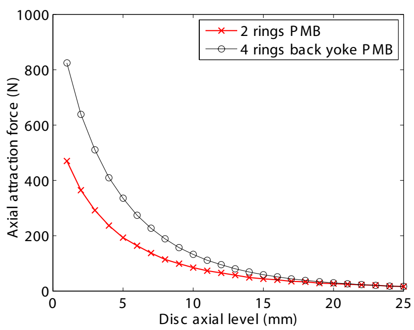

Fig. 3. 2D FEM simulated axial attraction force as a function of PMB disc axial level.

present paper a new PMB configuration is proposed using the same permanent magnet volume, but with 4 rings and a bake yoke that has the function of reducing stray magnetic flux. Fig. 2 shows the two topologies of PMB that will be compared here. The Nd-Fe-B rings are made with N35 material, whose coercivity force and remanent field are -918kA/m and 1.198T, respectively. In order to provide a damping mechanism due to induced current by inhomogeneity field, 3 small aluminium rings are introduced between the rings magnets in 4 rings topology, as shown by Fig. 2(b).

To develop the analysis comparing these 2 PMB configurations, 2D and 3D Finite Element Method (FEM) simulations were made. In these simulations the magnetic forces are calculated during the postprocessing stage applying the virtual work method. Attractive force results for different disc axial levels are presented in Fig. 3, and it shows that the new configuration (4 rings and a back yoke) presents an increase of over 73% in the force for a gap of 5mm. This result can be attributed to the reluctance reduction in this PMB magnetic circuit.

Other function of these PMB is positioning radially the system. The restoring force is important to help to bring back the operational position of the flywheel when the shaft is displaced radially. The maximum radial displacement is limited by the air gap length of the electrical machine used in the flywheel system. A switched reluctance machine is used in this work, and it has an air gap of 2.5 mm. The restoring radial

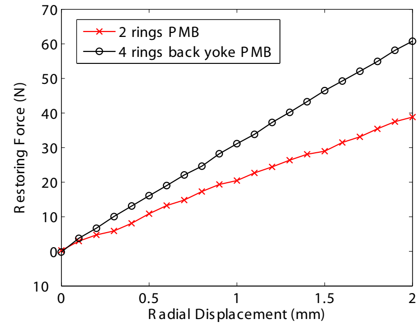

Fig. 4. 3D FEM simulated restoring force for a radial displacement in PMB.

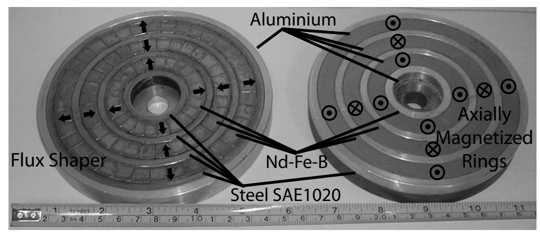

Fig. 5. Compared SMB topologies having approximated the Nd-Fe-B volume.

force for a lateral displacement is presented in Fig. 4. The 2 rings PMB topology has a stiffness of 19.4N/mm, whilst the 4 rings and back yoke present stiffness of 30.4N/mm, for a 5mm gap. Axial and radial forces results indicate that 4 rings and back yoke topology must be considered as good option to work together with others stable bearings.

III. SUPERCONDUCTOR MAGNETIC BEARING

In this section two kind of thrust superconductor magnetic bearings will be compared: FS [1] [8] [9] and AMR [10] [11] configurations. The FS and AMR topologies were build having the same Nd-Fe-B (N35) volume, but the main difference between them are the magnetization orientation. Both configuration are made with steel SAE-1020, aluminium and Nd-Fe-B, as shown in Fig. 5. In FS topology, the magnetic flux density is concentrated in an intermediary ring steel by two opposites polarities radially magnetized Nd-Fe-B discs. To obtain the rings magnetized radially, it was necessary to use small rings segment. As shown in Fig. 5, FS uses an aluminium cover that has a function of supporting the system. In the AMR topology the Nd-Fe-B rings are magnetized axially, and a back yoke is introduced to reduce the reluctance. Advantages of FS are: it is lighter (FS and AMR mass are, respectively 1.84kg and 2.43kg) and it has steel between consecutive magnets (eliminating irregularity in B). AMR advantages are: it can be constructed much more easily (it does not need glue) and auto stability among their rings magnets in the base because of the back yoke (while in FS bearing theirs permanent magnets have a potential energy stored). The AMR configuration has a diameter of 130mm, while the FS one has 140mm (because it's aluminum encapsulation). The height of permanent magnets rings for both topologies is 10mm.

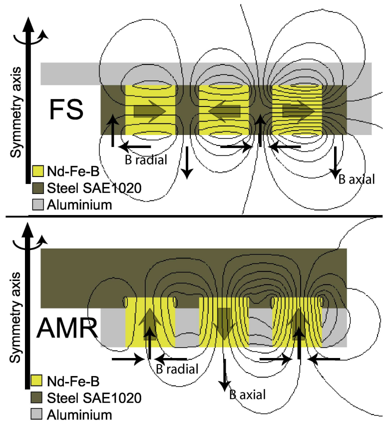

Fig. 6. Flux lines and some magnetic induction vectors for FS and AMR stators discs.

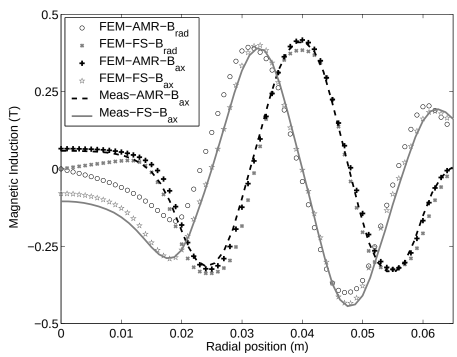

Fig. 7. Measured and FEM simulated magnetic induction for radial and axial components for FS and AMR stators discs.

A. Magnetic Induction

This section discuss the magnetic arrangement of FS and AMR topologies, induction configuration of both topologies. Some FEM simulations were performed by 2D Axisymmetric static magnetic analysis. The first simulation results, presented in Fig.6, show the flux lines for both SMB stators discs magnets. In this figure the magnetic induction in some specific positions are represented by vectors in radial and axial direction.

From the comments introduced above, it is possible to see that magnetic induction for FS and AMR have a dual configuration. It means that the profile of axial B component of FS rotor is approximately the radial component of AMR rotor and vice-versa. The expectative described above was confirmed by Fig. 7, that shows the FEM B results simulations (for radial and axial components), and magnetic induction measurements for both stators discs in the axial direction. Another important result shown by Fig. 7 is a good agreement among axial component of magnetic induction measurements and calculations made by FEM. These results are still important to find maximum B gradient and determine where the YBCO cylinders must be placed.

B. Levitation Force for Zero Field Cooling

This section presents the measured force in ZFC refrigeration process for FS and AMR topologies. Both topologies

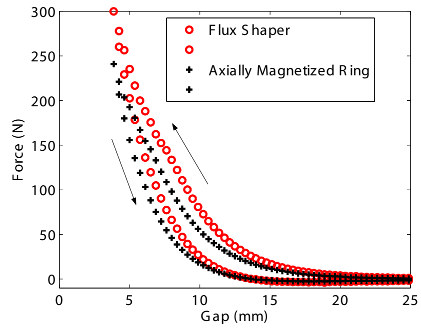

Fig. 8. Levitation force for 2 SMB topologies in zero field cooling refrigeration process.

uses the same stator base that is composed of 9 YBCO discs, with 28 mm diameter and 10 mm height. Each YBCO disc are equally distributed and centered in radius of 450mm. This distance were chosen taking in consideration the size of the YBCO discs, the number of available superconductor and the maximum B gradient region present in figure 7. In ZFC measurements the YBCO was cooled by a distance of 45mm from the permanent magnet rotor (where its magnetic field is negligible), and the permanent magnetic disk was approximated to the YBCO stator by a speed of 0.75mm/s. When a minimal gap of 3.5mm was reached the moving direction was inverted, and it was returned immediately with the same speed. During all this process the levitation force is measured and synchronized with the position data. The result for the ZFC process described above is presented on Fig. 8. As may be seen on this figure, the FS configuration presents a larger levitation force than AMR one. This result should be attributed to the fact that FS configuration has a greater peak-to-peak value of magnetic induction in the axial direction (see Fig. 7) than AMR one, associated with very low penetration flux into the YBCO superconductor.

C. Levitation Force for Field Cooling

For FC refrigeration process the YBCO was cooled when the magnets disc was in an initial distance from it. The measurements were made for the followings initials gaps: 3mm, 5mm, 7mm and 9mm. Then the disk was vertically elevated 450mm at 0.75mm/s. Finally, the disk was brought back to a vertical distance of 1mm above the superconductor. The first FC presented results compare various initials gaps for FS topology, and they are shown in figure 9. As expected, it can be observed that for lower initials gap the attraction force is higher, and the capability to support loads is decreased. It is obviously attributed to the greater trapped flux for lower initials gaps.

The next results for FC are presented in Fig. 10, and it compares FS and AMR topologies for 3mm, 5mm and 7mm initials gaps (without considering their weight forces). It is possible to observe that the attraction and compression forces are very similar for both bearings configurations. These results suggest that the trapped magnetic field in both bearing configurations should be of the same intensity and profile.

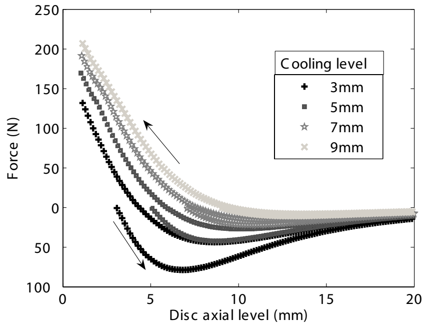

Fig. 9. Levitation force for 2 SMB topologies in field cooling refrigeration process.

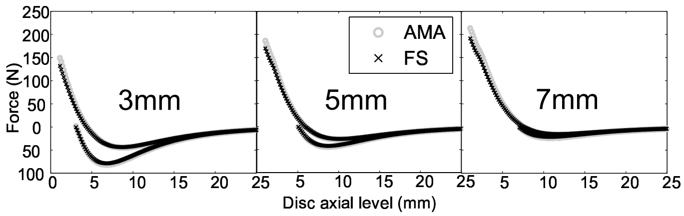

Fig. 10. Levitation force for 2 SMB topologies in field cooling refrigeration process.

D. Radial restoring Force for Field Cooling

Radial restoring force is important to bring back the shaft to its working position when a disturbance occur in the system. AS MEDIDAS SERO FEITAS ESSA SEMANA E OS RESULTADOS SERO INCLUDOS EM BREVE.

IV. CONCLUSION

This paper presented a magnetic bering set to work in a flywheel system. Initially, two PMB topologies were compared and the new magnetic arrangement proposed allowed significant increase in levitation and radial forces by reduction in the circuit reluctance. Two topologies of thrust SMB were analyzed: a FS and an AMR, having dual magnetic induction topologies. For ZFC tests the AMR have lower levitation force than FS, but these vertical levitation forces are similar when FC process are adopted, even for various tested initials gaps. COMPLETAR A CONCLUSAO.

ACKNOWLEDGMENT

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