Levitating Bearings using Superconductor Technology

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Abstract — This work focuses on the viability, conception and experimental evaluation of using the zero field cooling technique to build a superconductor magnetic bearing based on NdFeB permanent magnets and YBCO superconductor bulks, also referred to as high temperature superconductors.

Among many others, advanced works have been carried out where similar prototypes were developed, either for the construction of large-scale flywheels as for the application in the textile industries. However, the approaches made in these works use the field cooling technique, whereas the approach in this thesis uses zero field cooling, which in fact have proved to be more efficient, presenting less Joule losses. In this work, the geometric placement of the permanent magnets and high temperature superconductors is carefully performed to keep symmetry along the main axis and to minimize the air gap of the prototype between the rotating part (rotor) and the static part (stator). Moreover, studies made during the development of this work involve changes in these geometric placements, either in the rotor as in the stator. Additionally, a finite element model is designed for simulation and viability study of the bearing, calculating the estimated levitation and guidance forces involved. Experimental validation is achieved by building a structure in conformity with the previously simulated geometry and comparing the simulation results with the ones obtained by measuring the existing forces in the real prototype. The results allow the conclusion that it is possible to build a superconductor magnetic bearing using the zero field cooling technique, providing an important insight on how the system behaves.

Keywords—Superconductor magnetic bearing; High temperature superconductors; Permanent magnets; Magnetic levitation; Zero field cooling.

I. INTRODUCTION

Superconductivity is the phenomenon of certain materials exhibiting zero electrical resistance and repelling the magnetic fields when their temperature is lowered below the critical temperature. After cooled, superconductors perform as Permanent Magnets (PMs), generating a magnetic field. Each superconducting material has an absolute critical temperature above which it loses its superconducting properties [1].

In 1911, superconductivity was first observed by the Physicist Heike Kamerlingh Onnes [2]. It was found during this observation that when mercury (Hg) is cooled to the boiling point of helium (He), which is 4.2 K, the electrical resistivity of mercury is almost zero. In 1913, it was discovered that lead (Pb) has almost zero resistivity at absolute temperatures below 7 K. Later, in 1933, the researchers Walther Meissner and Robert Ochsenfeld noticed that superconductors expelled applied magnetic fields, a phenomenon that is now known as the Meissner effect [3]. In 1935, the brothers Fritz London and Heinz London showed that the Meissner effect was a consequence of minimization of the electromagnetic free energy carried by superconducting current.

In 1950, Lev Landau and Vitaly Ginzburg postulated the Ginzburg-Landau theory of superconductivity basing on which it was possible to first explain the behavior of type II superconductors [3]. The complete microscopic theory of superconductivity, also known as the BCS theory, was finally proposed in 1957 by John Bardeen, Leon N. Cooper, and Robert Schrieffer. This theory explains the superconducting current as a superfluid of Cooper pairs, pairs of electrons interacting through the exchange of phonons. The main peak of discoveries took place between 1986 and 1987, when High Temperature Superconductors (HTSs) with critical absolute temperatures above 30 K started to be discovered. In 1987, the Chu’s group and Kitazawa’s group jointly announced and published the discovery of Yttrium-Barium-Copper-Oxide, i.e., YBa2Cu3O7 (YBCO) with critical temperature 92 K, as type II superconductor. The discovery of the YBCO was an important achievement because liquid nitrogen could now be used for cooling instead of the expensive liquid helium.

The transition of type I superconductors from normal state to superconducting state occurs instantly at the critical temperature and they repel magnetic field lines fully, therefore lines cannot penetrate this superconductor. This transition is shown in Fig. 1.

![Figure 1 - type I superconductors transition](image)

In type II superconductors, the transition from a normal state to a superconducting state occurs in a continuous way. The YBCO superconductor is the most common example of type II superconductor. This transition is shown in Fig. 2.

![Figure 2 - Type II superconductors transition](image)
Some magnetic field lines can penetrate through this type of superconductor allowing flux pinning, which is also known as Quantum Locking. This property allows the Field Cooling technique (FC) to be used with the Type II superconductors, in which they are cooled in the presence of a magnetic field, fixing their position and orientation once the state of superconductor is achieved.

When type II superconductor bulks are cooled in the absence of any magnetic fields, known as the Zero Field Cooling (ZFC) technique, flux pinning does not occur and the trapped flux density is almost null. In this case, the superconductor is repelled to a position where the magnetic flux is nearly zero [4,5]. Hence, levitation systems can be FC [6] or ZFC [7].

In [8-11] recent studies confirm that some of the existing levitation systems use permanent magnets on one part and type II superconductor bulks on the other part and can be used as frictionless rotating bearings. These can be sub-divided onto horizontal axis rotating systems, in which the levitation forces are radial and vertical axis rotating systems in which the levitation forces are axial to a vertical axis [12-15]. The technical characteristics of some of these systems are shown in Table 1 [19].

### TABLE I. ROTATING SYSTEMS BASED ON LEVITATION FORCES [19]

<table>
<thead>
<tr>
<th>Axis</th>
<th>Use</th>
<th>Angular speed (rpm)</th>
<th>Stator</th>
<th>Rotor</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>Flywheel</td>
<td>40000</td>
<td>NdFeB PM</td>
<td>YBCO bulks</td>
<td>[8]</td>
</tr>
<tr>
<td>Vertical</td>
<td>Flywheel</td>
<td>4000</td>
<td>YBCO bulks</td>
<td>NdFeB PM</td>
<td>[9]</td>
</tr>
<tr>
<td>Horizontal</td>
<td>HTS motor</td>
<td>1500</td>
<td>YBCO</td>
<td>NdFeB PM</td>
<td>[10]</td>
</tr>
<tr>
<td>Horizontal</td>
<td>Flywheel</td>
<td>15860</td>
<td>YBCO</td>
<td>PM rings</td>
<td>[11]</td>
</tr>
</tbody>
</table>

In [12,13] some other frictionless rotating bearing systems have been already designed to levitate using the FC technique. This technique implies significant hysteresis losses due to magnetic flux trapping.

In [7,14], further works have proposed a linear HTS magnetic levitation system based on the ZFC technique with guidance, where this guidance is obtained by an adequate distribution of existing magnetic fields, generated by a specific array configuration of multi-pole PMs. In [7], it is proposed that when the cooling process takes place in the absence of a magnetic field, maximum screening is generated in the superconductors. Such behavior causes only a small portion of flux lines to enter the superconductor, resulting in the presence of more tangential field lines in the horizontal surface of the HTS, hereafter responsible for the production of higher levitation forces. Concerning the guidance forces in an FC vehicle, they depend on the height value where superconductors were cooled. The same does not occur for the ZFC vehicle where guidance force values are preserved. In [18], the Joule losses in this kind of systems were studied, proposing that in the ZFC-Maglev they are more significant for higher speeds of the vehicle.

These proposals proved to be viable and feasible, showing that the ZFC technique presents higher levitation power due to the Joule effect losses in the FC technique. For this reason it is possible to say that the ZFC technique over performs the commonly used FC technique.

In [15], another study proposed a linear electromagnetic launcher with propulsion forces using Meissner effect based on the ZFC technique. In this work, it was proved that the values of levitation forces measured experimentally using ZFC are similar to simulations considering a relative magnetic permeability of $\mu_r = 0.22$ for the YBCO bulk. Moreover, this approximation allows, at this level, to test the proposed SMB design not only without excessive computational effort due the 3D representation, but also with enough reliable quantitative results in the modeling and performed simulations. Therefore, the viabilty study in the present work relies in this study, as it takes into account the same value for the magnetic permeability coefficient.

The main contribution of the present work development of a SMB using Permanent Magnets (PMs) and High Temperature Superconductors (HTSs) with the ZFC technique, to analyze its features, advantages and drawbacks. The final experimental results are compared to the simulations and validated.

This work is organized as follows: Section II presents the modelling of the SMB prototype. Section III presents the simulations performed. Section IV refers to the prototype design and section V to the prototype construction. Moreover, section VI presents the experimental methods and its results. Finally in Section VII some conclusions are drawn.

## II. MODELING

The cylindrical geometry of the frictionless rotating bearing model studied is based on the linear HTS magnetic levitation system using a ZFC technique as presented in [7,14]. Repulsion of magnetic fields can be modeled by a relative permeability lower than the unit $\mu_r < 1$ for the HTS bulks. The NdFeB PMs used have a permanent magnetization $M$ given by:

$$ M = B_r / \mu_0 $$  \hfill (1)

where $B_r$ is the permanent magnet remainder magnetic flux density, $\mu_0$ is the vacuum magnetic permeability [16].

The type II superconductors, in the case of ZFC technique, create diamagnetic fields such that, the normal component of the resultant magnetic field on the boundary of the superconductor surfaces becomes almost zero [7]. The diamagnetic field is created by a superficial peripheral current density on the superconductor that contributes for the levitation forces [7]. Hence, a specific volume crossed by a specific current density under the influence of a magnetic field suffers a volume force density $f$ [17] is given by:

$$ \vec{f} = \vec{J} \times B $$  \hfill (2)

$$ \vec{f} = \mu (\nabla \times \vec{H}) \times \vec{H} = \mu (\nabla \cdot \vec{H}) \vec{H} - \frac{\mu}{2} \nabla \left( \frac{\nabla \times \vec{H}}{\left| \nabla \times \vec{H} \right|} \right) $$  \hfill (3)

where $\vec{J}$ is the current density in the superconductor, $\vec{B}$ is the magnetic flux density, $\mu$ is the medium magnetic permeability and $\vec{H}$ is the magnetic field.

The volume force density can be decomposed in Cartesian coordinates system [17] given by:

$$ f_m = \frac{\partial}{\partial n} \left( \mu H_n H_m - \frac{\mu}{2} \sigma_{mn} |H|^2 \right) ; \sigma_{mn} = \begin{cases} 0 & m \neq n \\ 1 & m = n \end{cases} $$  \hfill (4)
where \( f_m \) is the volume strength density component, \( m, n = (x, y, z) \) depending on the considered component, \( H_n \) and \( H_m \) are the magnetic field components and \( \delta_{mn} \) is a Kronecker delta.

The component \( f_m \) of the volume force density is the gradient in \( n \) direction of the Maxwell stress tensor component \( T_{mn} \) depending on the magnetic field components \( H_n \) and \( H_m \) [17]. \( T_{mn} \) is given by:

\[
T_{mn} = \mu H_n H_m - \frac{\mu}{2} \delta_{mn} |H|^2
\]  

Consider a cube or rectangular block with one of the six surfaces parallel to the \( xy \) plan. Using ZFC technique, the value of the magnetic field normal component to this surface should be zero \( H_z = 0 \). The normal component of the Maxwell stress tensor to this surface \( T_{zz} \) [17] is given by:

\[
T_{zz} = -\frac{\mu}{2} (H_x^2 + H_y^2)
\]  

Consider \( n \) and \( t \) as normal and tangential components of the Maxwell stress tensor. (6) can be rewritten, as given by:

\[
T_n = -\frac{\mu}{2} |H| t
\]

where \( T_n \) is the Maxwell stress tensor normal component and \( H_t \) is the magnetic field tangential component to the surface parallel to the \( xy \) plane.

The levitation and guidance forces can be calculated by integrating the Maxwell stress tensor along the superconductor surfaces.

The levitation forces \( F_{Lev} \) along \( z \) axis [17] are given by:

\[
|F_{Lev}| = \frac{A}{\mu} \frac{|B_t|^2}{2}
\]

where \( A \) is the surface parallel to the \( xy \) plane and \( B_t \) is the magnetic flux density tangential component.

### III. SIMULATION

The cylindrical geometry of the frictionless rotating bearing model studied is based on the linear HTS magnetic levitation system using a ZFC technique presented in [7,14]. Considering that the ZFC SMB is composed by a static part (stator) and a rotating part (rotor), the part that should levitate is the rotor. Hence, the proposed design of the frictionless rotating SMB model [19] has an inner rotor part including the trails of PMs and an outer stator part including the discontinuous lines of HTS bulks. The outer stator part contains two discontinuous rings of equally spaced NdFeB HTS bulks. An alternative approach using PMs and HTS rings instead of bulks was discarded for economic reasons. Actual rings have to be made with specific geometry and dimensions, whereas generic bulks are much cheaper and easier to obtain.

The inner rotor part contains three discontinuous rings with five equally spaced NdFeB permanent magnets.

All PMs belonging to the same discontinuous ring, are magnetized with concordant poles towards the axis. The three inner discontinuous rings of PMs are magnetized in an alternate North-South-North way, such as the two border rings of magnets have concordant polarizations and the middle ring of magnets opposite polarization. The rings of magnets in this geometry present a distance of 20 mm between each other. The discontinuous rings of PMs and HTS bulks are interposed in such a way to provide guidance forces [4]. The perspective view of the frictionless SMB with spatial distribution of PMs and of HTS bulks is shown in Fig. 3.

![Figure 3 - Perspective view: distribution of PMs and HTSs](image)

The projection views of the frictionless SMB geometry and its dimensions are shown in Fig. 4.

![Figure 4 - Projection view: spatial distribution of PMs and of HTSs bulks](image)

Several case studies were analyzed. For all the case studies, calculations were performed by simulations using a finite element modeling (FEM) approach. The PMs considered in the simulations are neodymium magnets, i.e. \( \text{Nd}_2\text{Fe}_{14}\text{B} \). Each one has a rectangular form with dimensions 25x25x14 mm and a mass of 0.06 kg. The HTS bulks considered in the simulations are made of YBCO (Yttrium Barium Copper Oxide) material. Each one has a rectangular form with dimensions 32x32x14 mm and a mass of 0.09 kg.

For the simulations that were carried out, both FC and ZFC techniques are analyzed. The assumed value of the permanent magnet remainder magnetic flux density is \( B_r = 1.2\ T \) [10]. For the ZFC technique, the assumed relative magnetic permeability for the HTS bulks is \( \mu_r = 0.2 \) [4, 5, 16].
A. Case 1 - levitation forces between one PM and one HTS

This case study simulates and evaluates the levitation forces, namely the repulsion forces between one PM and one HTS. For the simulation, it is assumed that both the PM and the HTS are horizontally disposed with both centers aligned at a given vertical distance. An example of the simulation showing the ZFC distribution of magnetic flux between the PM and the HTS at 12 mm vertical distance is shown in Fig. 5.

Both ZFC and FC techniques were simulated and compared. Several distances between the upper surface of the PM and the lower surface of the HTS were considered. For FC, the magnetization distances are also taken into account. The ZFC and FC techniques: repulsion forces between a PM and a HTS at several distances is shown in Fig. 6.

![ZFC distribution of magnetic flux at 12 mm vertical distance](image)

**Figure 5 - ZFC distribution of magnetic flux at 12 mm vertical distance**

![ZFC and FC techniques: repulsion forces between a PM and a HTS at several distances](image)

**Figure 6 - ZFC and FC techniques: repulsion forces between a PM and a HTS at several distances.**

*Fig. 6 clearly shows that the ZFC repulsion forces between the PM and the HTS at several vertical distances are always higher than FC repulsion forces. Moreover, it shows that when the FC magnetization distances increase, the repulsion forces get closer to ZFC, as expected.*

The results obtained for the repulsion forces between the PM and the HTS (Fig. 6) are similar to the ones presented in [4,18].

B. Case 2 - SMB levitation and guidance forces

This case study evaluates the levitation forces and the guidance forces between the PMs and the HTSs for the proposed design of the frictionless rotating SMB. Several air gap distances were considered.

The perspective view of the magnetization directions and contours for the frictionless rotating SMB is represented in Fig. 7.

![SMB: perspective view of magnetization directions and contours](image)

**Figure 7 - SMB: perspective view of magnetization directions and contours**

The transversal view of the magnetization directions and contours for the frictionless rotating SMB is shown in Fig. 8.

![SMB: transversal view of magnetization directions and contours](image)

**Figure 8 - SMB: transversal view of magnetization directions and contours**

The longitudinal view of the magnetic flux density lines for the frictionless rotating SMB is shown in Fig. 9.

![SMB: transversal view of magnetic flux contours](image)

**Figure 9 - SMB: transversal view of magnetic flux contours.**

The arrows (Fig. 7 to Fig. 9) represent the magnetic polarization direction of the PMs.
The levitation forces and the guidance forces versus the air gap size for the frictionless rotating SMB in both ZFC and FC modes are shown in Fig. 10 and Fig. 11. Results for FC are shown for 150% and 200% relation between the cooling distance and operational distance [6]. In this case, the operational distance is equal to the air gap. These figures show that levitation forces and guidance forces decrease when the air gap increases, as expected. Moreover, these figures clearly show that the forces obtained using ZFC technique outperform those obtained by the FC technique.

Figure 10 - Frictionless SMB: levitation forces.

Using this new prototype design, 3D FEM simulations were carried out, where the balanced and unbalanced rotor conditions shown in Fig. 12 are considered to obtain the sustaining rotor forces [21].

The plot of the levitation forces vs. the air-gap for the final model is shown in Fig. 13. Results were obtained using the previous 3D FEM model, while changing the rotor/stator air gap value from a realistic minimum value of 4 mm to the maximum value of 12 mm.

Figure 13 - Levitation forces vs. air gap [21]

The guidance forces can be measured imposing a specific translation displacement in the y axis direction from the equilibrium position. The graph of the guidance forces is shown in Fig. 14, where the same air gap values from the levitation forces simulations were used.

Figure 14 - Guidance forces vs. air gap [21]

For the current geometric dimensions, the interval between ±10 mm is the stable range, from where the rotor can return to its equilibrium position.

As expected, both levitation and guidance forces are higher for a smaller air gap of 4 mm. The total weight of the 15 PM in the rotor is about 8.83 N. The total weight of the 16 bulks in the stator is about 14.12 N. Fig. 8 and Fig. 9 show that for ZFC the levitation and guidance forces are higher than the rotor weight. Hence the SMB seems viable and self-sustainable in both horizontal and vertical positions.

Figure 11 - Frictionless SMB: guidance forces.

Due to some budget limitations, it was not possible to cover the cost of the 16 YBCO bulks. Therefore, a different prototype version was implemented to validate the simulations, as shown in Fig. 12.

In a later phase of the work, the necessity of building a SMB presenting higher levitation forces while being built with the same parts became important. Moreover, an alternative was studied in order to maximize the levitation forces in the SMB without changing the air gap, modifying the distance between the each PM ring in the rotor to 5 mm.

The simulations with the new geometry were carried out and the values obtained confirm that this method provides an increase in the levitation forces as the PM rings come closer to each other. The counterpart is that in this case, the stable range for the guidance forces will be smaller and subsequently the guidance forces will decrease relatively to the first geometry results, seen in Fig. 14.
The result of the simulations made with the new rotor model for the levitation forces is shown in Fig. 15.

Figure 15 - Levitation forces vs. air gap for the new geometry

The result of the simulations made with the new rotor model for the guidance forces is shown in Fig. 16.

Figure 16 - Guidance forces vs. lateral displacement for the new geometry

As it can be observed, when comparing this graph with Fig. 14, the change in the geometry with the approximation of the PM rings caused a decline in the guidance forces. It is also possible to see that the stable range from where the rotor can return to its equilibrium position has diminished to ±8 mm.

IV. PROTOTYPE DESIGN

The choice of materials plays an important role in this work. The main characteristics of the SMB model result from this choice. It will affect the structure resistance and stiffness, as well as the ability to conceal the liquid nitrogen inside the stator part while providing a good thermal insulation. An important aspect when choosing the materials for this prototype is that none of these interferes with the magnetic forces produced by the HTSs and PMs. This means that all the materials in the SMB should have a relative magnetic permeability of approximately $\mu_r = 1$.

Since the stator is directly in contact with the liquid nitrogen, it has to be made of a material that can resist to temperatures in the order of 77 K without breaking while being also impermeable. It is very important that it possesses a low thermal conductivity coefficient in order to retain the cold temperature inside the structure. Therefore, rigid polyurethane was the material chosen for the stator.

Because of the necessity of having several rotors for the experiments, Polylactic acid plastic (PLA) was the material chosen because it proved to be a relatively good material when compared to high density polyurethane, since it can also be easily built using additive manufacturing with the already used 3D printers, also presenting relatively low weight.

Several other types of parts were designed to assemble the SMB parts together, namely rods, nuts, corners and washers. There are no other special requirements besides being transparent to the magnetic field and resisting the clamping stress at low temperatures. For this reason, the rods were made of ertacetal and the other parts in Acrylonitrile Butadiene Styrene (ABS) so they could be printed.

In [20], the SMB prototype was modeled in 3D CAD design software to meet the following requirements: i) provide a structure to keep the distances, relative positions and the air gap of the HTSs and PMs [19]; ii) provide a sealed body (stator) to cool and maintain the HTSs immersed in liquid nitrogen; iii) develop a modular prototype; iv) design a prototype with easy assembly and disassembly features for practical PMs and HTSs accessibility, maintenance and/or replacement.

The outer part of the SMB is the stator. This part does not move and supports 16 HTSs distributed in two rings. This part design proposes two types of pieces to be built: two exterior slices and two interior slices. The complete rotor, i.e., the rotor exploded view is shown in Fig. 18.

The inner part of the SMB is the rotor. It is the rotating part of the SMB and supports 15 PMs distributed in three rings. This part design proposes two types of pieces to be built: two exterior slices and two interior slices. The complete rotor, i.e., the rotor exploded view is shown in Fig. 18.
Subsequently, when the rotor is at rest in the bottom part of the stator, the air gap between the bottom HTSs and PMs is 6 mm, while the air gap between the upper HTSs and PMs is 11 mm.

Other parts were projected, namely rods, nuts, corners and washers to assemble the SMB parts together. Special care was taken in the modeling of these parts. As the polyurethane from the stator part has limited mechanical resistance, the miscellaneous parts were modeled to carefully keep the parts assembled without hurting the delicate material.

With all the components modeled, the SMB was assembled. The full assembly exploded view is shown in Fig. 19.

The rotor parts were made of Polylactic acid plastic (PLA) and were manufactured using a 3D printer. For an easier understanding and identification of each rotor model, names were given to the rotors based on the distance between each PM ring. Therefore, the rotor constructed with the original geometry shown in section 3.2 – distance of 20 mm between each PM rings – was named “rotor D20”. This rotor is shown in Fig. 22.

The stator was built using a 3 axes CNC milling machine with the technical drawings provided by the CAD software. The machine used was an Ouplan 2010 with a working area of 1900x900 mm. The final construction of the inner stator slice is shown in Fig. 20.

The final construction of the inner stator slice is shown in Fig. 21.

The rods previously mentioned were built in a material named ertacetal. Likewise, they were threaded using a lathe machine.
In order to avoid the dropping of liquid nitrogen between the slices of the stator, a thin film made of flexible rubber was used as an insulator. This film was applied in the parts where the stator slices make contact with each other. The film insulators used are shown in Fig. 24.

The final assembled construction of the SMB, without the rotors is shown in Fig. 25.

VI. EXPERIMENTAL METHODS

In this section, numerous tests regarding the fine robustness and sealing of the structure are presented, several features like nitrogen usage are addressed and finally, the experimental setup of each experience and the computed results are presented and examined.

A. Robustness and sealing tests

In order to study the behavior of the structure constructed at working conditions, several tests were performed. These conditions are characterized by working at low temperatures, in the order of 77 K (liquid nitrogen temperature) and under clamping forces that close the stator slices together. Hence, the stator part was totally submerged in liquid nitrogen, without any HTSs inside, until the system achieved a state of stability. In this first test, the used materials presented a good resistance within the working temperature range during the first experiences, without breaking or exhibiting any type of weakness.

To ensure the structure, namely the stator, would enclose the liquid nitrogen in an efficient way, some leak tests were firstly elaborated. These tests were made in a first phase with water, until the stator was successfully insulated. After several steps in order to try to seal the stator, the used of clamps and the rubber based insulation tape proved to be the best solution. In order to measure the volume of liquid that the stator holds, the water inside the stator was poured to a measuring jug. The volume measured was about 270 ml.

B. Nitrogen usage

In order to estimate the rate at which the liquid nitrogen would evaporate from inside the stator, a graph of time vs. weight was elaborated. This was achieved by pouring liquid nitrogen inside the stator until the structure was full. To read the weight values a weighting scale was used. With the structure standing on the weighing-scale, the time was measured until the weight stopped falling. The graph of weight vs. time is shown in Fig. 26.

It is easy to see that the rate at which the liquid nitrogen evaporates in the first 600 seconds can be considered linear, and therefore possible to calculate. The evaporation rate in mL/min of the liquid nitrogen in the stator was calculated and is given by:

\[
LN_{er} = \frac{814 - 727}{600 - 60} = 0.161 \text{ g/s} = 9.67 \text{ g/min} \quad (9)
\]

Before proceeding to any measurement of the results, an experiment was elaborated with the SMB at fully working conditions in order to verify the proposed model and the magnetic forces involved. This step was important and had a big contribution in deciding the experimental set-ups in order to extract the information needed with the best possible precision. The procedure started by assembling the stator and assembling the improved rotor D20. Then, the process of nitrogen pouring was carried out for about 10 minutes, until the HTSs were completely submerged in liquid nitrogen, therefore at 77 K. As the rotor was being introduced, it was possible to feel relatively strong guidance forces. This behavior shows that the HTSs were at the desired temperature. It was also observed that the rotor did not levitate, remaining at rest in the lower part of the stator. This fact created the necessity of building the previously mentioned rotor D5. Moreover, the rotor D5 was also inserted in the stator. As expected, the levitation forces were higher using this geometry.

Due to the previous stated reason, after inserted, the rotor levitated, reaching the higher part of the structure. It was also possible to feel that the guidance forces were much weaker with this rotor than with rotor D20.
C. Experimental set-ups

The set-up prepared in order to compute and compare the values of how the real SMB prototype behaves with the simulations previously elaborated was carefully planned. With the purpose of measuring the forces and the distances associated to the system, a dynamometer and a caliper were used, respectively.

In order to measure the levitation forces [21], a structure was built to support the SMB. With this structure, it was possible to connect the rotor to a string and pull it down by the two sides. This string was then connected to a dynamometer, which measured the levitation forces. For better precision, the dynamometer was hooked to a screw that was attached to the structure. Rotating the screw would vary the air gap distance between the rotor and the stator. The experimental set-up to read the levitation forces is shown in Fig. 27.

![Figure 27 - Experimental set-up used to read the levitation forces](image)

After the usual process of nitrogen pouring was carried out, the rotor D5 was inserted and the values were read from the dynamometer while the screw was used to vary the air gap. The caliper was used to read the air gap distances between the rotor and the stator.

In order to measure the guidance forces [21], a simple set-up was prepared. The structure consists in a fixed shaft to confine the rotor movement while measuring the guidance forces by pulling the stator. To avoid friction, the stator is fixed to a cart that allows movement through the rotor axis direction. The forces reacting to this movement are read with a dynamometer that is connected to the kart with a string, in order to estimate the guidance forces. After the usual process of nitrogen pouring was carried out, the rotor D5 was inserted into the stator. While reading the values from the dynamometer, an axial rotor misalignment was forced to measure the guidance forces that push or pull the rotor to its axial equilibrium position. The caliper was used to read the lateral displacement of the rotor in relation to the stator.

The process of measuring the guidance forces is shown in Fig. 28.

![Figure 28 - Guidance forces measurement](image)

D. Results

In this section, the results obtained from the experiences with the real SMB model are compared with the simulation results computed previously. The levitation forces vs. eccentricity graph was computed and is shown in Fig. 29.

![Figure 29 - Levitation forces vs. eccentricity graph](image)

It is possible to observe that the approximation is reasonably good. However, one minor issue causing the discrepancy between the results might be the simple linear approximation of the relative magnetic permeability $\mu_r = 0.2$ used in the simulations in order to characterize the model.

The guidance forces vs. lateral displacement graph was computed and it is shown in Fig. 30.

![Figure 30 - Guidance forces vs. lateral displacement graph](image)

After comparing the plotted values, it is possible to observe a slight discrepancy between the experimental results and the outcome of the simulation results. Such behavior can be justified again by the simple linear approximation of the relative magnetic permeability modeled.
E. **Free damping regime analysis**

Understanding the characteristics of the dynamic response of the ZFC SMB to an unbalanced rotor condition is critical. For this reason, using the SMB prototype, the PM rotor was initially pulled to a lateral displacement position of 17 mm away from its equilibrium. The rotor was then released from this initial position until it reached its stable equilibrium, where the resulting guidance force becomes null. The graphic with the computed real dynamics is shown in Fig. 31.

![Figure 31 - Real dynamics and the 2nd order model](image)

Analyzing the two curves, it is possible to observe that there is a change in the frequency over time in the “real dynamics” blue curve. Subsequently, it is viable to conclude that the damping factor changes over time and the system cannot be represented by a second order linear system.

VII. **CONCLUSIONS**

Despite of the minor issues stated above, both results can be considered rather similar, allowing the conclusion that the levitation and guidance forces previewed by our FEM model were successfully verified experimentally, yielding accurate results with good agreement. Therefore, this work permits the conclusion that it is technically viable to produce a frictionless SMB based on the studied geometry, using the ZFC technique.

Analyzing the overall outcome, it is possible to conclude that the methods chosen in the implementation of the real SMB prototype such as the design, the choice of materials, the manufacturing techniques as well as the carried out tests to the structure were successfully executed.

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