Superconducting Axial Bearing – Description and Mechanical Properties

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Abstract. *Making use of high temperature superconducting material $Y_1Ba_2Cu_3O_7$ (YBCO) and permanent magnets of Ne-Fe-B an axial magnetic bearing has been constructed for a levitating rotor. A description of the evolved physical phenomenon and the construction details are presented as well as the experimental measurement procedure used for the determination of the equivalent stiffness and damping coefficients necessary for dynamic model of the complete rotor system.*

Keywords*: Superconductivity, Magnetic bearings*

1. INTRODUCTION

On the Superconductivity Laboratory (LASUP) installed in COPPE-UFRJ operates a research device able to accelerate a 5kg bearingless rotor up to 6,000 rpm (David, 2000). Understand the bearingless characterization as a rotor balanced without any mechanical contact, i.e. making use only of forces caused by magnetic effects. Such rotor which is aligned with the vertical, is supported, in this direction, by an axial superconducting bearing developed to use the repulsive force that arises (Meissner Effect) between superconducting blocks constituted of the material $Y_1Ba_2Cu_3O_7$ (YBCO) and permanent magnets sintered from Ne-Fe-B bound to its bottom. This superconducting bearing presents the feature of auto-stability, i.e. generates forces as opposed to relative movements between the permanent magnets that revolve attached to the axis and the blocks in the superconducting state. For transverse stability, a pair of self-bearings motors is used which, in addition to axial torque in the direction of the rotor, generate radial forces. In contrast to the superconducting axial bearing such radial forces are unstable and demand the actuation of a control system taking into account the feedback of the radial displacements and velocities observed in the rotor. The principal purpose of the text is the presentation of the experimental systematic developed to measure the stiffness and damping coefficients ratios associated to the superconducting bearing. These coefficients are required for system modeling and are dynamically determined through processing of oscillatory damped signals generated by accelerometers stuck to a cylindrical bearingless block, equivalent to the concerned rotor, as a response from impulsive forces applied to it. In the article are described the architecture of the research device and the phenomenology of interplay between the superconducting blocks and permanent magnets that are inclusive dependent on the mode how the superconducting blocks are refrigerated below their critical temperature making use of liquid nitrogen. The experimental results measured are presented. Finishing the article, are mentioned possibilities now viewed by the author of future applications of the technology.

2. PHYSICAL PHENOMENON

2.1. Superconductivy

The superconductivity was discovered in 1911, shortly after the development of refrigerating machines capable of reaching temperatures in which helium was in the liquid phase (4.2*K*=-268, 9*C*). The first element to demonstrate the new effect was the mercury, which featured null electrical resistivity when cooled to that temperature. Later other elements proved superconductive at temperatures lower than 9.2 *K*. In the 1960s, niobium alloys made superconductivity between 10*K* and 23*K*. It was believed then, based on theoretical considerations, that the upper limit for the occurrence of superconductivity would be 30*K*. In 1986, George Karl Bednorz and Alex Muller (Bednorz and Muller, 1986), of IBM's research labs in Zurich, observed superconductivity in the lanthanum cuprous oxide doped with barium at a temperature of 36*K*. This fact has become a landmark, having been overcome the barrier of 30*K*. As a consequence, a large number of researchers studied different compositions, until, in 1987, appeared the material $Y_1Ba_2Cu_3O_{7-\delta}$ (YBCO) that passed the superconducting state at a temperature of 92*K*. The discovery sparked a revolution in interest for superconductivity since it, instead of helium liquid (4.2*K*), the phenomenon would depend on the liquid nitrogen (77*K*), much easier to obtain (nearly 100 times cheaper) and with greater thermal capacity.

The superconducting materials are classified as type I and type II. Mercury is an example of the type I and the YBCO of the type II. The materials that present the superconducting effect above 30K are known as the high temperature ones. The YBCO is then a high temperature type II superconducting material.

Other superconducting materials are presently under research but YBCO is considered to be the one with the best performance associated to the use of liquid nitrogen (Labalestier, et al., 2001).

2.2. The Meissner effect.

Effect of less known, but which arises for the same reasons of the microscopic loss of electrical resistance in superconducting materials, it's called the Meissner effect (Meissner and Ochsenfeld, 1933), discovered experimentally in 1933. This effect is the exclusion of a magnetic field by a superconducting material, as shown in Fig. 1. As a result of this exclusion the force F arises which is used for the axial bearing.

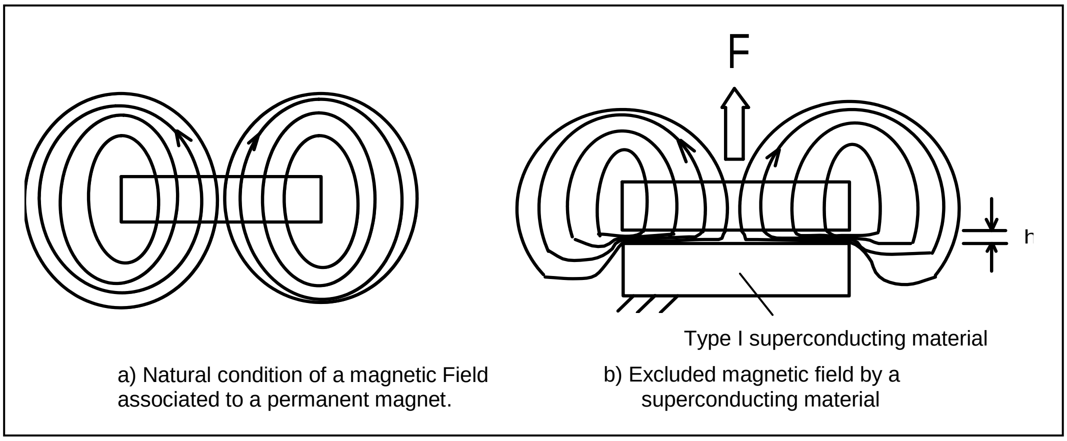

Figure 1. The Meissner Effect

The total exclusion of the magnetic field is a characteristic of type I superconducting materials. The type II materials allow a partial penetration, above a certain magnetic field level, characterizing a mixed state, as shown in Fig. 2 (David, 2000). A very interesting consequence of this mixed state is the so called auto-stability of magnetic bearings making use of type II superconducting materials (David, 2000), (Dias, 2009). Restoration forces react to displacements between the superconductors and the permanent magnets. It is shown in Fig. 2 a horizontal stabilizing force F reacting to a horizontal displacement X of a permanent magnet levitating with a gap h above a type II superconducting material.

A very important feature of the axial superconducting bearing is its minimum resistance to torsion along the vertical axis, much lower than any conventional solution and even electromagnetic bearings (Sotelo, 2007).

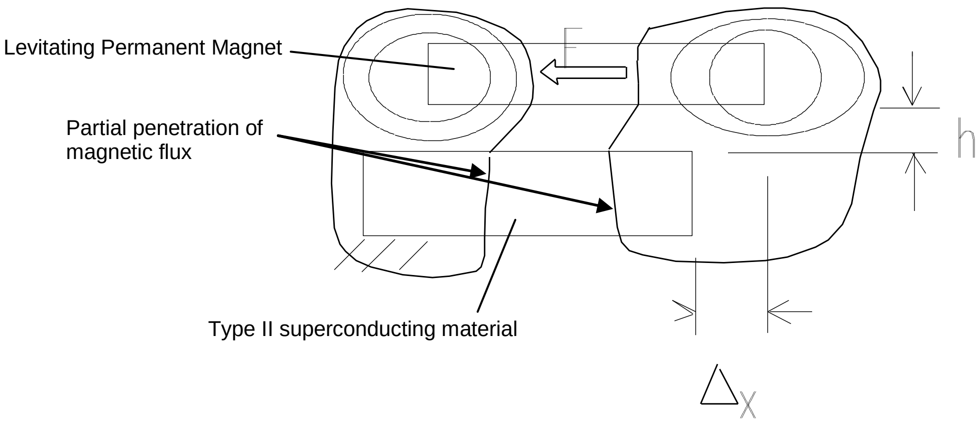

Figure 2. Partial Penetration of the Magnetic Flux and Auto-Stability

3. CONSTRUTIVE DETAILS

For the construction of the superconducting axial bearing seven blocks of the ceramic YBCO where used. These blocks have been manufactured in the IPHT (Institut fuer Physikalische Hochtechnologie) situated at the city of Jena, Germany (Gawalek et al., 1991). The blocks have a cylindrical geometry (30 mm diameter and 16 mm height). A typical curve relating the repulsion force F_z between the type II YBCO blocks and a permanent magnet is shown in Fig. 3. It can be seen that for a 3 mm gap h a force F of 30N appears.

The used arrangement was done by positioning one of the seven blocks at the center and the remaining ones at the vertices of a regular hexagon with 32 mm side. Two axisimetric NeFeB permanent magnets were used as shown in Fig. 4. Making use of an adequate support, and of a posterior yoke, the permanent magnets are connected to the bottom of the levitating rotor. The superconducting blocks were positioned inside of another copper support which is refrigerated by liquid nitrogen at a cryogenic recipient, as shown in Fig. 5. Additional details can be seen in (David, 2000).

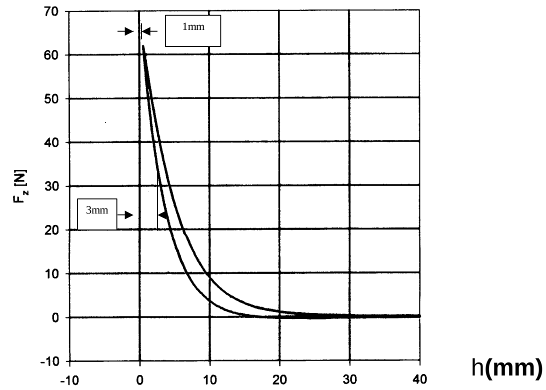

Figure 3. Levitation force between type II superconducting YBCO blocks and permanent magnets.

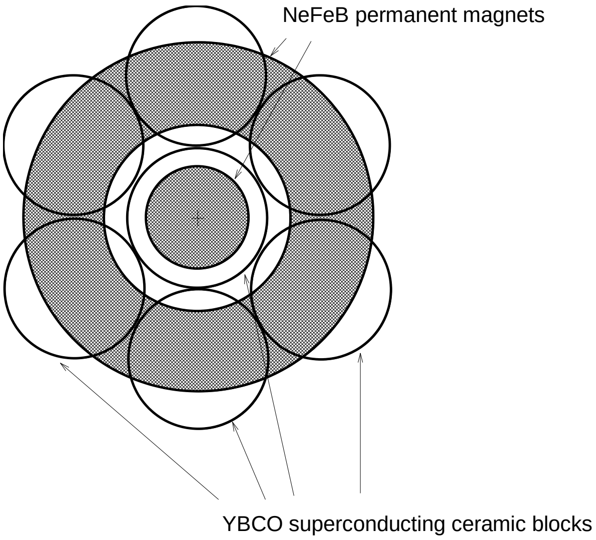

Figure 4. Axial superconducting bearing arrangement.

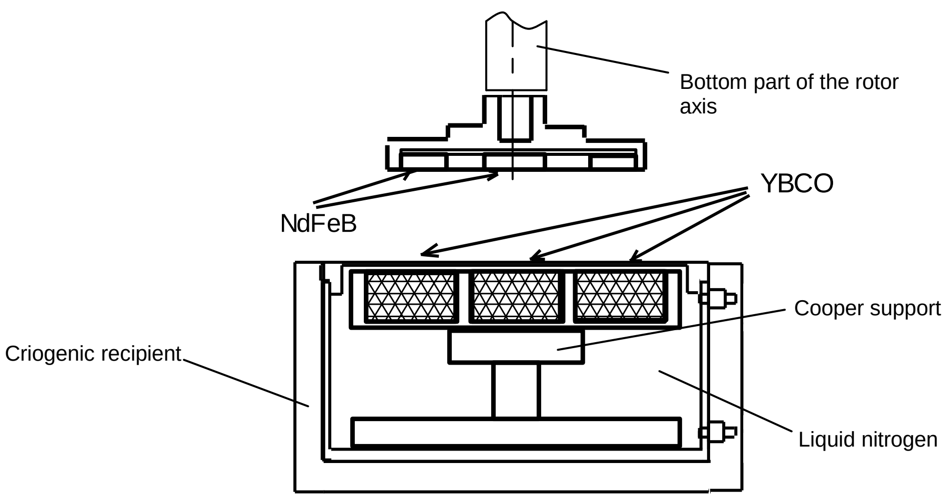

Figure 5. Mechanical details of the superconducting bearing arrangement.

4. MEASUREMENT DEVICE

Besides the levitation force, the axial superconducting bearing, as a self-stable one, presents stiffness and damping coefficients both in the horizontal and vertical directions. These values are necessary for the rotor dynamics model of the system (David, 2000). In order to determine these values, a measurement device has been constructed as shown in Fig. 6. The rotor was substituted by a brass block. The geometry of this block was adjusted to simulate the mass of the levitating rotor and to decouple the horizontal and vertical vibrations modes.

One characteristic of the superconducting axial bearing is that its behavior is dependent on the intensity of magnetic flux through the ceramics during the refrigeration process (David, 2000), (Sotelo, 2007). In the present concept, this intensity was adjusted by modifying the distance between the permanent magnets and the ceramics before the cooling process of the superconducting material by the liquid nitrogen. Simple removable cylindrical aluminum supports with different heights (5, 10, 20, 30 and 40 mm) were used to vary this distance and consequently the magnetic field intensity through the YBCO ceramics blocks in ambient temperature, before they acquired the superconducting state (Fig. 6). When the YBCO blocks critical temperature was achieved and the superconducting state established, the cylindrical supports were removed and the self-stable levitation phenomenon was observed.

Accelerometers were connected to the brass block positioned both in horizontal and vertical directions. Voltage signals proportional to the instantaneous separately excited vertical and horizontal accelerations were acquired by the instrumentation schema shown in Fig. 7.

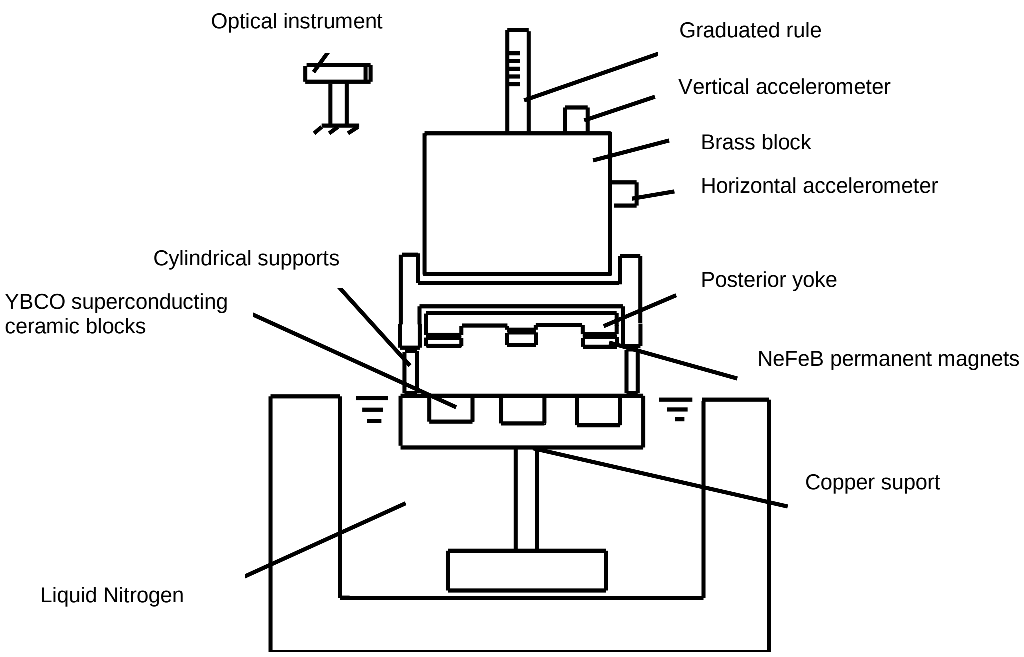

Figure 6. Measurement device

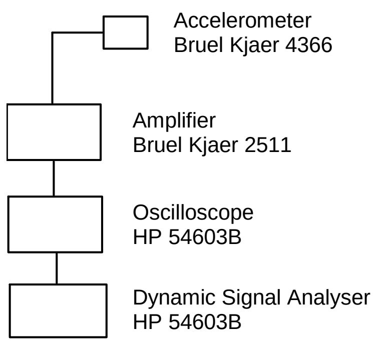

Figure 7. Data acquisition system

The experimental routine consisted in measuring the levitating height after the superconducting state was achieved and the cylindrical supports were removed for each cooling height (5, 10, 20, 30 and 40 mm) determined by the correspondent used set of cylindrical supports. This measurement was done making use of the graduated rule attached to the brass block with the aid of the optical instrument.

After that and making use of an instrumented hammer, vibrations were carefully and separately excited in the levitating body both in the horizontal and in the vertical direction. The chosen geometry of the brass block was successful in the avoidance of significant coupling between vertical and horizontal movements.

A typical curve showing the oscillatory evolution of the acquired voltage signal proportional to the instantaneous accelerations observed in the levitating brass block is shown in Fig. 8.

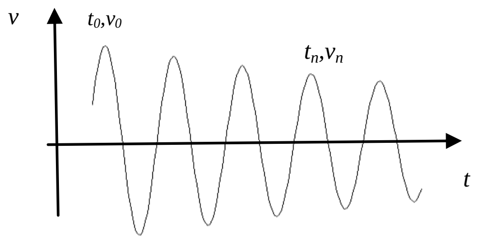

Figure 8. Time function of the voltage proportional to acceleration.

With the action of the dynamic signal analyzer, as shown in Figure 7, a table with the relevant first "i" localized maximum values of the above typical curve could be determined, as shown in Table 1.

i	*t(ms)*	*v_i(mV)*
0	347,65	716,17
1	738,28	670,67
2	1113,3	564,42
3	1492,2	498,86
4	2234,4	405,13
5	2976,6	340,51
6	3347,7	304,44
7	3714,8	262,05

Table 1. Numerical values of localized maxima of the response of the superconducting bearing to a horizontal impulsive load (height of cooling – 10mm). (David, 2000)

Due to the low damping of the superconducting bearing, characterized by the low decay of the free vibration typically shown in Fig. 8, it can be considered that the damping factor ζ is much lower than the unity. In such a case, the free vibration damped frequency f_a is practically the same as the not damped free vibration frequency f_n:

$$f_a \cong f_n \tag{1}$$

$$f_a = f_n\sqrt{1-\zeta^2} \tag{2}$$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{M}} \tag{3}$$

Where f_n as well as f_a are measured in *cycles/s*, k is the equivalent stiffness of the levitating body, measured in SI units *(N/m)*, and M the mass of the levitating body in kg .

These frequencies can be determined from the measured experimental values as shown in Fig. 8 and Table 1 counting the measured number of cycles and the associated time difference:

$$f_n = \frac{i_{final} - i_{initial}}{t_{final} - t_{initial}}, \text{ where:} \tag{4}$$

$i_{initial}$ - i_{final} : Number of cycles determined by the numerical difference between the natural numbers associated to the considered initial and final localized maxima.

$t_{initial}$ - t_{final} : Variation of time, measured in *s*, between the occurrence of the considered localized maxima.

From (3) and (4), the following equation can be then used for the determination of the equivalent stiffness:

$$k = M\left(2\pi \frac{i_{final} - i_{initial}}{t_{final} - t_{initial}}\right)^2 . \qquad (5)$$

Due to the low damping effect in the superconducting axial bearing, the localized maxima decay of the curve shown in Fig. 8 obey to the following equation, that can be seen in good vibration analysis texts, as (Ripper Neto, 2007):

$$\frac{v_{initial}}{v_{final}} = e^{\frac{c}{2M}(t_{final} - t_{initial})} . \qquad (6)$$

In equation (6), c is the equivalent damping factor of the superconducting bearing measured in SI units, Ns/m. This value is then determined by the following expression:

$$c = \frac{2M}{t_{final} - t_{initial}} \ln \frac{v_{initial}}{v_{final}} \qquad (7)$$

Taking into account the described experimental procedure, results that have been measured are shown in Fig. 9 and Fig. 10.

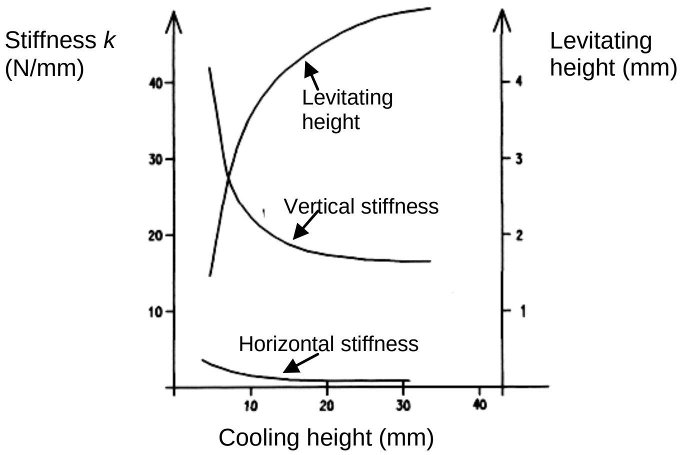

Figure 9. Levitating height, horizontal and vertical stiffnesses in dependence of the cooling height.

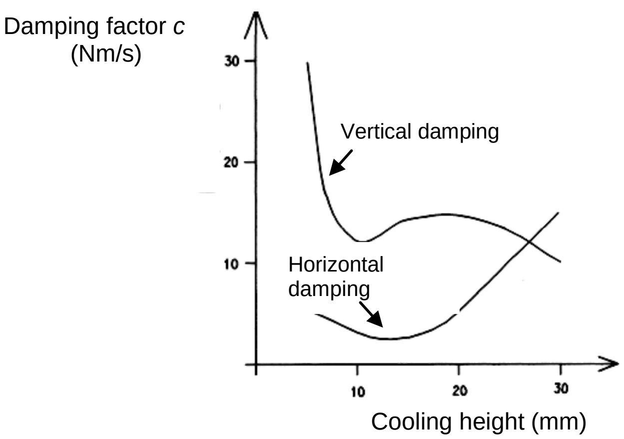

Figure 10. Horizontal and vertical damping factors in dependence of the cooling height.

5. CONCLUSIONS.

The results shown fin Fig. 9 and Fig. 10 were considered in the dynamical model used to control a levitating rotor that has achieved 6000 rpm. The observed dynamic behavior of the rotor presented good agreement with the foreseen results with this model. More details can be seen in (David, 2000)

Presently a levitating train is under development at the Superconductivity Laboratory (LASUP) installed in COPPE-UFRJ with uses some of the concepts of the presented axial bearing

Because of the low losses observed with the technology, as mentioned in item 2 above, it is probably the most adequate one to support axial flywheels for electric energy storage.

The author hopes that other researchers identify additional applications for this new materials technology.

6. REFERENCES

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