



Perspective

Towards the operational demonstration of a horizontal axis radial magnetic levitation bearing with zero-field cooled high temperature superconducting bulks

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ABSTRACT

This editorial provides views and guidelines on the development and operation of horizontal axis radial levitation passive magnetic bearings (PMB) with High-temperature Superconducting (HTS) bulks using Zero-Field cooling (ZFC) in the stator and permanent magnet (PM) rings in the rotor. These are based on results from a framework on the conception, study, optimization, implementation and experimental testing of proof-of-concept prototypes. Views and guidelines are given on: i) Methodologies to facilitate the initial Zero-field cooling ZFC magnetization process; ii) Topologies of HTS bulks for which levitation is verified with alignment of the rotor and stator axes; iii) PM rotor sizing to create guiding stability; iv) Addition of external limiting PM rings to significantly increase guidance forces and stiffness; and v) Scale-up principles to consider on the design of bearings to support higher weight rotors.

1. Introduction

The adoption of zero-field cooling (ZFC) promotes the creation of higher levitation and impulsion forces, less magnetic field penetration, and less associated electromagnetic losses than with field-cooling (FC), promoting an increase in the High-Temperature Superconducting (HTS) bulks lifetime. On the other hand, FC has been chosen for most magnetic levitation systems due to the provided guidance and stability created by magnetic flux pinning. Another reason for the choice of FC is that the HTS bulks in vessels or stators are kept close to the permanent magnet (PM) in rail tracks or rotors, during their cooling down close to the liquid nitrogen (LN₂) temperature, facilitating and reducing the work spent during the cooling process [1]. In ZFC, the HTS bulk parts are cooled down to the LN₂ temperature away from the influence of magnetic fields from PM parts, spending a significant portion of work to put those at the final operation position under the influence of PM magnetic fields.

A framework was developed in studying, optimizing, and imple-

menting experimental proof-of-concept prototypes of a fully horizontal axis radial levitation passive magnetic bearing (PMB) with zero-field cooled Yttrium Barium Copper Oxide (YBCO) HTS bulks in the stator and Neodymium Iron Boron (NdFeB) PM rings magnetized with radial polarization in the rotor. The stator included two rings with slots to house a maximum of eight bulks in each ring. The rotor included three PM rings radially magnetized, the polarization of the middle PM ring opposite from the two site PM rings. Fig. 1(a) shows a photo of the proof-of-concept prototype assembly with the rotor levitating at the center position with its axis aligned with the stator axis. Fig. 1(b) shows a photo with two half parts of one stator ring, made of milled polyurethan with a 40 kg m⁻³ density. Fig. 1(c) is a photo of one tested rotor with a distance of 20 mm between PM rings.

Finite element simulations to predict the magnetic field distribution and levitation and guidance forces for several topologies of HTS bulks in the stator and considering different distances between PM rings in the rotor were performed. The magnetic forces predicted by finite element

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analysis (FEA), were validated experimentally for a topology considering six HTS bulks in the bottom of the stator. The HTS bulks' zero-field critical current density and equivalent relative magnetic permeability for the testing temperature were also validated experimentally.

The following studies were performed: i) Prediction by finite element analysis (FEA) and measurement of levitation and guidance forces, and testing of dynamics and vibrations for an initial experimental proof-of-concept prototype with continuous PM rings [2]; ii) Optimization of the spacing between PM rings and between HTS bulk rings for given PM ring and HTS bulk dimensions to maximize guidance forces for given minimum levitation forces and experimental validation of optimization results [3]; iv) Prediction by FEA and experimental validation of the axial stiffness augmentation from the addition of external limiting PM rings [4].

This editorial gives views and guidelines towards the operational demonstration of such a horizontal-axis HTS radial levitation PMB, with HTS bulks using ZFC magnetization and PM rings, based on conclusions from numerical optimization studies and the testing of experimental prototypes that were built for proof-of-concept analysis.

2. Views and guidelines toward an operational demonstrator

The bearing, with the topological representation shown in Fig. 2, comprises a rotor with three equally spaced PM rings magnetized with radial polarizations, the middle one (m) with opposite polarization from the side ones (k). Also, a stator incorporating two discrete HTS bulk rings positioned in the zones between adjacent PM rings. The use of HTS bulks in the stator reduces the complexity of the cryostat and associated liquid nitrogen (LN₂) losses.

Simulation results have shown that with a uniform distribution of HTS bulks in the stator, using a total of sixteen bulks, it is not possible to keep the rotor levitating with its axis aligned with the stator axis [4]. This is because with a uniform distribution of HTS bulks in the stator, if after the HTS bulks ZFC, the rotor is placed at the center with its axis aligned with the stator axis, the resulting radial magnetic force is nearly zero, not compensating for the rotor weight. A non-uniform distribution of HTS bulks should be provided in the stator to generate a radial magnetic levitation force enough to compensate for the rotor weight, keeping it levitating at the center.

Results from FEA have shown that with a topology using eight bulks, six of which on the stator lower half (b), two in the bottom horizontal

row (g) and four distributed two by two in the right and left bottom forty five degree obliques rows, (f) and (h), and the other two in top horizontal row (c) of the stator upper half (a), the rotor and stator axes become aligned after the HTS bulks initial ZFC magnetization [4]. Simulation results have also shown that the four side vertical bulks, two in the right and two in the left sides, (e) and (i), do not contribute to levitation forces, contributing only to rotor alignment [4]. The absence of these four HTS bulks across the horizontal bisection plane will facilitate the construction of the cryostat with two independent parts, to be designated as upper and lower cryostat parts, (a) and (b). Also, with the removal of these four vertical HTS Bulks, the same levitation forces are guaranteed, and the investment costs are reduced significantly. The complexity of the upper cryostat part may be reduced with the existence of only two HTS bulks on the top horizontal row.

The split of the cryostat into two parts will facilitate the process of initial ZFC magnetization, by approximation to the PM rotor after the HTS bulks ZFC. In this process, the rotor is to be kept at the final operating position. The HTS bulks in upper and lower cryostat parts, (a) and (b), should be zero-field cooled separately and independently, far from the influence of the rotor magnetic fields. After the HTS bulks ZFC, the two cryostat parts could then be approximated to the rotor, fitting each other through guiding screwed rods that will fix the two cryostat parts together. For non-distortion of the intended HTS bulks ZFC magnetization, the two cryostat parts should be approximated gradually to the PM rotor, keeping always the same distance from both cryostat parts to the PM rotor. For the adopted topology shown in Fig. 2, with eight bulks, six in the lower part and two in the upper part, levitation will occur with the rotor and stator axes aligned [4]. After fixing together of stator upper and lower cryostat parts, (a) and (b), the distance between the two HTS bulks on the top horizontal row (c) and the rotor PM rings may be adjusted for fine matching of the rotor and stator axes alignment. Two independent LN₂ chambers, one in the upper and one in the lower cryostat parts, are to be filled and maintained independently, keeping the necessary LN₂ levels and cryogenic temperatures.

For the creation of rotor guiding stability, the relation $3w_m + 2d_m > 2w_{sc} + d_{sc}$ should be verified, where w_m and d_m are respectively the rotor PM ring widths and spacings, and w_{sc} and d_{sc} the stator HTS bulk ring widths and spacings. This is, whenever the distance between the rotor PM ring farther edges is higher than the distance between the stator HTS ring farther edges [3]. The guidance forces and stiffness

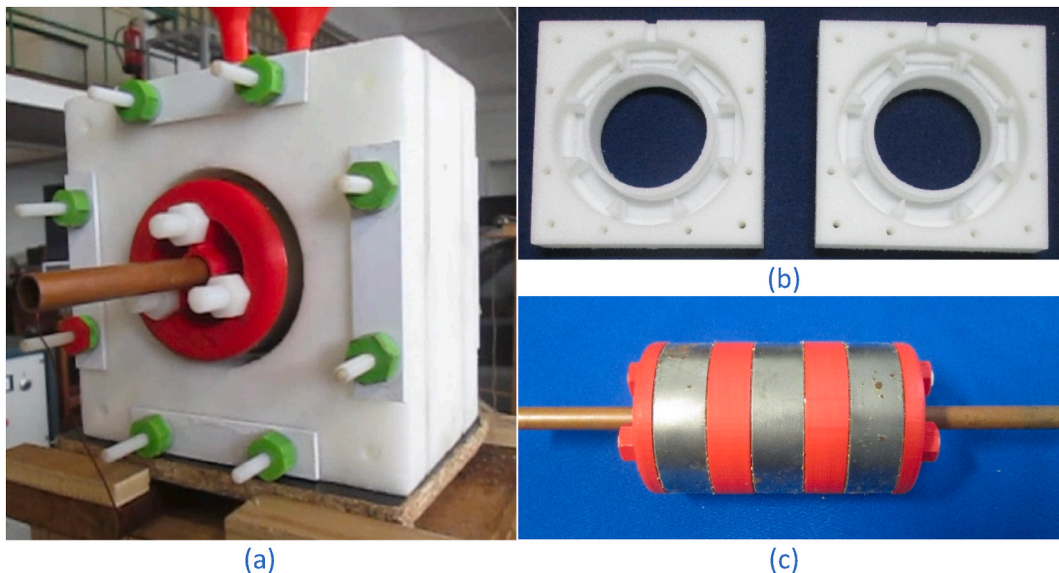


Fig. 1. Photos of: the of the proof-of-concept prototype assembly, with the rotor levitating at the center position (a); two half parts of one stator ring made of milled polyurethan with 40 kg m^{-3} density (b); tested rotor with a distance of 20 mm between PM rings (c).

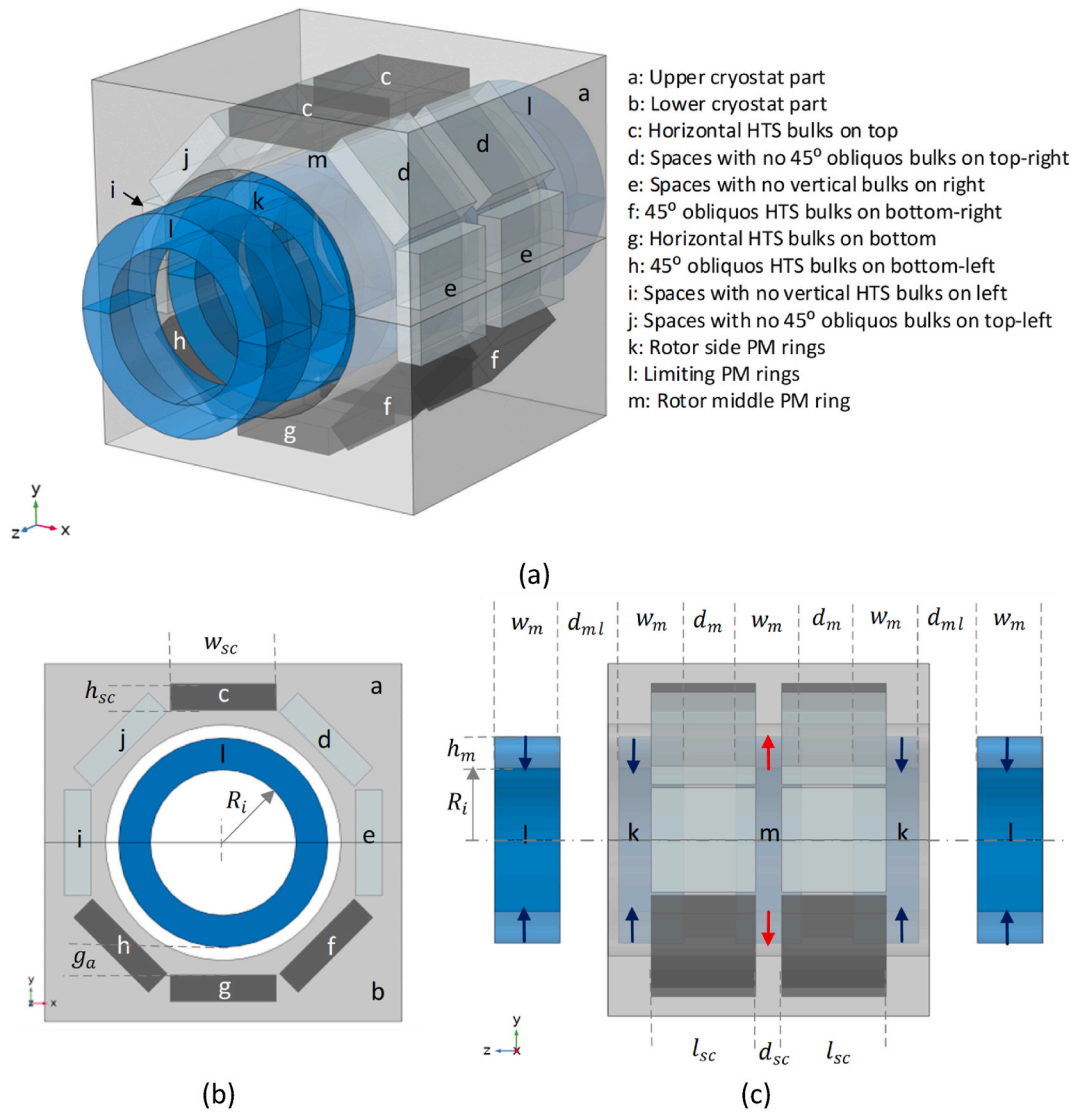


Fig. 2. Perspective (a), front (b) and side (c) view of the proposed passive HTS ZFC topology.

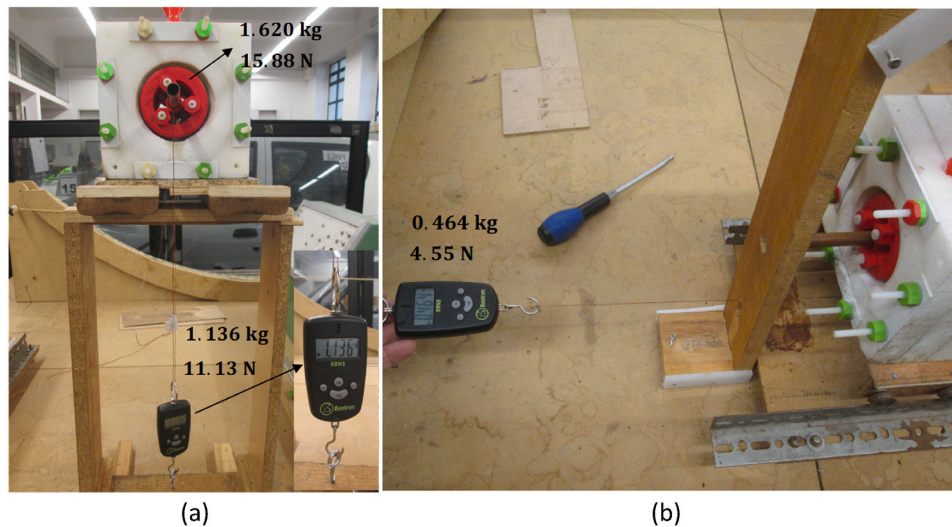


Fig. 3. Measurement of the levitation force (a) and maximum guidance force (b) with the proof-of-concept prototype, using a stator with six HTS bulks on the bottom and a rotor with $d_m = 20$ mm.

increase with the PM rotor width. On the other hand, the levitation force decreases with the PM rotor width. The objective should be to maximize the guidance force and stiffness so that the rotor is kept levitating with its axis aligned with the stator axis.

Fig. 3(a) and (b) show photos of experimental setups with the proof-of-concept prototype, during the measurement respectively of the levitation and guidance forces, using a stator with only six HTS bulks of dimensions $40 \times 10 \times 10 \text{ mm}^3$ at the bottom, and a rotor with a distance between PM rings $d_m = 20 \text{ mm}$, and a weight of 1.62 kg corresponding to a gravity force $F_g = 15.88 \text{ N}$. From Fig. 3(a), the measured levitation force was $F_{lev} = 27.01 \text{ N}$, because an impulsion force of 11.13 N was measured with the rotor and stator axes aligned, meaning that for this topology of six HTS bulks in the stator, the rotor levitates with its axis above the stator axis (with a positive vertical deviation). From Fig. 3(b) a maximum guidance force $F_{gui\max} = 4.55 \text{ N}$ was measured for an axial displacement $\Delta z = 10 \text{ mm}$ of the rotor.

Fig. 4(a) and (b) show graphs that overlay experimental measurement data against simulation results respectively for levitation and guidance forces, using the same rotor with $d_m = 20 \text{ mm}$ and gravity force $F_g = 15.88 \text{ N}$. Both graphs present simulation characteristics for the tested topology with only six HTS bulks at the bottom (dashed line with diamond marks), and for the topology with a total of eight HTS bulks, six at the bottom and two on the top of the stator (dotted line with cross marks). As expected, experimental measurements are closer to the simulation characteristics for the tested topology with no bulks on the top. The characteristic of the levitation force predicted by simulation for the topology with two bulks on the top, gives a levitation force equal to the rotor gravity force. Hence, for the topology with eight bulks in the stator (six at the bottom and two on the top), and a rotor with $d_m = 20 \text{ mm}$, levitation occurs with the rotor and stator axes aligned. A maximum guidance force of about 5 N was measured.

Table 1 summarizes the dimensions of the experimental proof-of-concept prototype with the results presented in the graphs of Fig. 4.

The guidance force for the presented ZFC geometry without external limiting PM rings (l) is still lower compared to horizontal axis HTS radial PMB using FC [5]. The addition of limiting external PM rings (l) with polarizations repealing the rotor side PM rings (k) to significantly increase the guidance force and stiffness was proposed and studied [4]. Results have shown that with the addition of external limiting PM rings (l), with a spacing $d_{ml} = 5 \text{ mm}$ from the rotor side PM rings (k), the guidance force will increase by about one hundred times. Simulation results have also shown that limiting PM rings (l) does not affect notably the HTS bulks ZFC magnetization.

After completing the assembly of the stator upper and lower cryostat parts and completing the HTS bulks initial ZFC magnetization, the two limiting PM rings (l) could then be gradually approximated to the rotor edges, keeping always the same distance from both limiting PM rings (l)

Table 1
Dimensions of the tested proof-of-concept prototype.

Dim.	Description	Size [mm]
g_a	Minimum gap distance between rotor PM rings and HTS bulks	10.5
h_{sc}	HTS bulks' height	10
l_{sc}	HTS bulks' length	40
w_{sc}	HTS bulks' width	40
d_{sc}	Spacing between the two HTS bulk discrete rings	10
h_m	PM ring height	12
w_m	PM ring width	25
R_i	PM ring inner radius	27.5
d_m	Spacing between adjacent PM rings of the rotor	20
d_{ml}	Spacing between rotor side PM rings (k) and limiting PM rings (l)	[5, 20]

to their closest rotor side PM ring (k) to avoid the rotor displacement. This modification will enable the use of such ZFC passive magnetic bearing on high-speed transmission applications that require high stiffness when subject to significant axial strains, such as axial flow turbines and suction or propulsion propellers.

Another issue concerns the scale-up of the magnetic levitation bearing to sustain higher-weight rotors. The increase in the rotor weight will imply a specific increase in the Maxwell stress tensor surface integration to generate magnetic forces that compensate for the rotor weight increase. This implies a specific linear scale expansion of the rotor PM ring and stator HTS bulk ring dimensions and their spacings. With the linear expansion of the PM ring height h_m , higher magnetomotive forces will be generated. The gap distance g_a should be sized according to the PM magnetization grade and the PM rings height h_m , and resulting magnetomotive forces.

3. Conclusion

Views and guidelines were given towards the implementation of an operational demonstrator of a horizontal axis radial levitation passive magnetic bearing with zero-field cooled high temperature superconducting (HTS) bulks, based on results from studies on experimental proof-of-concept prototypes. According to the obtained results, a topology with non-uniform distribution of HTS bulks in the stator, defined by six HTS bulks at the bottom and two HTS bulks on the top of the stator, is proposed to guarantee that levitation occurs with the rotor and stator axes aligned. The experience obtained during the zero-field cooling (ZFC) of the HTS bulks in the proof-of-concept prototype, has shown that it will be better to build a stator divided into upper and one lower cryostat parts, that during the initial ZFC magnetization approximate gradually with equal distances to the permanent magnet (PM) rotor, to avoid ZFC magnetization distortion. Experimental results have

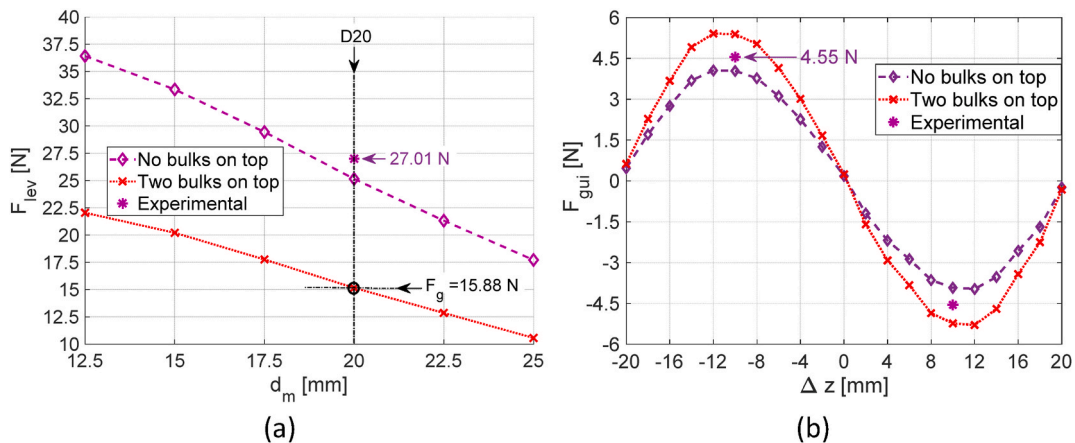


Fig. 4. Characteristics for the predicted levitation (a) and guidance (b) forces with the overlay of experimental measurements.

also shown that the addition of external limiting PM rings with the same polarization of the rotor side PM rings will significantly increase guidance forces and stiffness, enabling us to have a radial levitation ZFC passive magnetic bearing (PMB) configuration that will compete in terms of guidance force and stability with FC radial PMB configurations.

CRediT authorship contribution statement

António J. Arsénio Costa: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **João F.P. Fernandes:** Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Paulo J. Costa Branco:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jun Zheng:** Writing – review & editing, Writing – original draft, Visualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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