

Tests with a self-stable superconducting magnetic bearing

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Abstract

This study presents the development and experimental validation of a Passive Superconducting Magnetic Bearing (PSMB) designed to achieve Technological Readiness Level 5 (TRL 5). Unlike traditional Active Magnetic Bearings (AMB) that rely on sensors, electronics, and a continuous power supply, the proposed PSMB system exploits the stable levitation forces produced by field-cooled (FC) high-temperature superconductors in combination with permanent magnets (Halbach-configured NdFeB array), thereby offering a simpler, fail-safe alternative. Finite Element Analysis (FEA) was conducted to simulate the system's magnetic field distribution and to optimize key design parameters, including the vertical cooling offset of YBCO superconductors and the levitation and guiding force values. These simulations demonstrated that stable rotor support can be achieved without the need for auxiliary components. Experimental validation involved integrating two PSMBs into a high-speed electric motor, which successfully operated up to 7000 rpm under both no-load and load conditions, thereby eliminating the need for traditional touchdown and thrust bearings. Results confirmed excellent lateral stiffness and effective levitation, although precise rotor centralization remains a challenge. Additionally, implementing a compact cryogenic system is necessary for future industrial applications. Overall, the findings highlight PSMBs as a viable and promising alternative to PSMBs, with the potential to simplify system architecture and improve reliability in high-speed rotating machinery.

Keywords: Superconducting Magnetic Bearing, Passive Levitation System, Field-Cooled Superconductors, YBCO Superconductor, Contactless Rotor Support, Electromagnet-Free Bearing

1. Introduction

Active Magnetic Bearings (AMB) based on the controlled attraction force on a ferromagnetic material given by currents flowing through electromagnets are commercially available and offered by many manufacturers [e.g., SKF, Waukesha, Mecos, Calnetix, Hitachi, Mitsubishi, Nanjing CIGU, Wuhan Jingcheng]. The operation relies on sensors, well-adjusted controllers, power electronic components, power sources with backup to ensure a continuous energy supply, and, additionally, mechanical touchdown bearings (Schweitzer and Maslen, 2010) for safety. The positioning is accurate, but the operation is complex, and the reliability requires a high investment.

The stable magnetic forces offered by Field Colling (FC) high-temperature superconductors in the proximity of permanent magnets open new perspectives (Supreeth et al., 2022; Sasaki et al., 2025) which, until now, have not been commercially explored for magnetic bearings (Moon, 2008; Baloochi et al., 2024) or even for MagLev trains (Stephan and Costa, 2024). However, if the limits of the stable characteristic are well understood and the construction layout is properly arranged, the future of Passive Superconducting Magnetic Bearings (PSMBs) is promising.

2. Theoretical background

Many of the so-called Magnetic Bearings available in industry are based on the controlled attraction forces between

electromagnets and ferromagnetic materials (EML method). Magnetic Bearings also utilize repulsion forces between magnetic fields of the same polarity (EDL method) and, finally, those based on the stable interaction between type II superconductors and permanent magnets (SML method). Fig. 1 summarizes these methods.

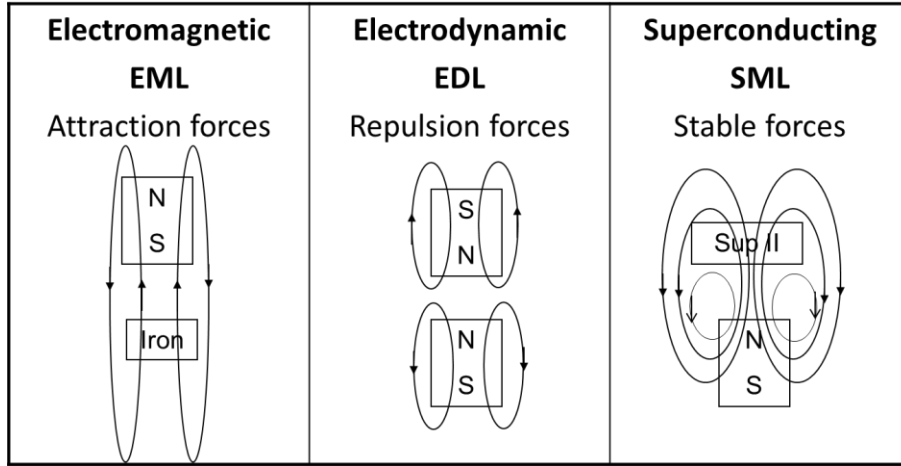


Fig. 1 The main types of Magnetic Forces.

Due to airgap constraints, the EDL and SML methods have not yet reached the same Technological Readiness Level (TRL) (EARTO, 2014) as the EML method for Magnetic Bearings. This paper describes efforts to achieve TRL 5 for a Passive Superconducting Magnetic Bearing (PSMB), emphasizing the advantages of stable forces while addressing the challenges of refrigeration required for superconductors.

3. Simulation

3.1 Computation of the magnetic field

Figure 2a illustrates the geometric configuration used in the finite element analysis within the longitudinal bisection plane along the symmetry axis. It defines the material domains of the PSMB computational model, with arrows indicating the magnetization vectors of the rotor's permanent magnets, arranged in a Halbach topology (Sotelo *et al.*, 2005).

For the YBCO superconducting blocks, the relationship between the current density J and the electric field E , Eq. (1), was considered (Carvalho *et al.*, 2023), where J_c , according to the Kim-Anderson model (Arsenault *et al.*, 2021), depends on the penetrating field density B , as shown in Eq. (2). The study considered the YBCO material with key parameters such as $n = 21$, $E_0 = 1 \times 10^{-4} \text{ Vm}^{-1}$ and $B_0 = 0.1 \text{ T}$ (Carvalho *et al.*, 2023). Simulations incorporated NdFeB permanent magnets with remanent flux densities of 1.25 T (N40) and 1.32 T (N45). Figure 2b presents the magnetization curve for Fe in the rotor's radial flux concentrators.

The 2D FE analysis determines the current distribution (Fig. 3a) and magnetic field (Fig. 3b) in the longitudinal bisection plane along the symmetry axis. The magnetization of superconducting YBCO rings via field cooling (FC) follows two steps: (1) cooling the rings away from the magnets at height (h_a) (Fig. 4a); (2) moving them to the final levitation height (Fig. 4b).

In the studied bearing, FC cooling involves vertical displacement of the rotor. If cooling occurs above the center ($h_a > 0$), stronger field penetration occurs in the upper bearing region. Upon central repositioning, levitation forces push the rotor upward, requiring a counteracting force to balance gravity.

$$E = E_0 \left(\frac{J}{J_c} \right)^n \quad (1)$$

$$J_c = J_{c0} \frac{B_0}{B_0 + |B|} \quad (2)$$

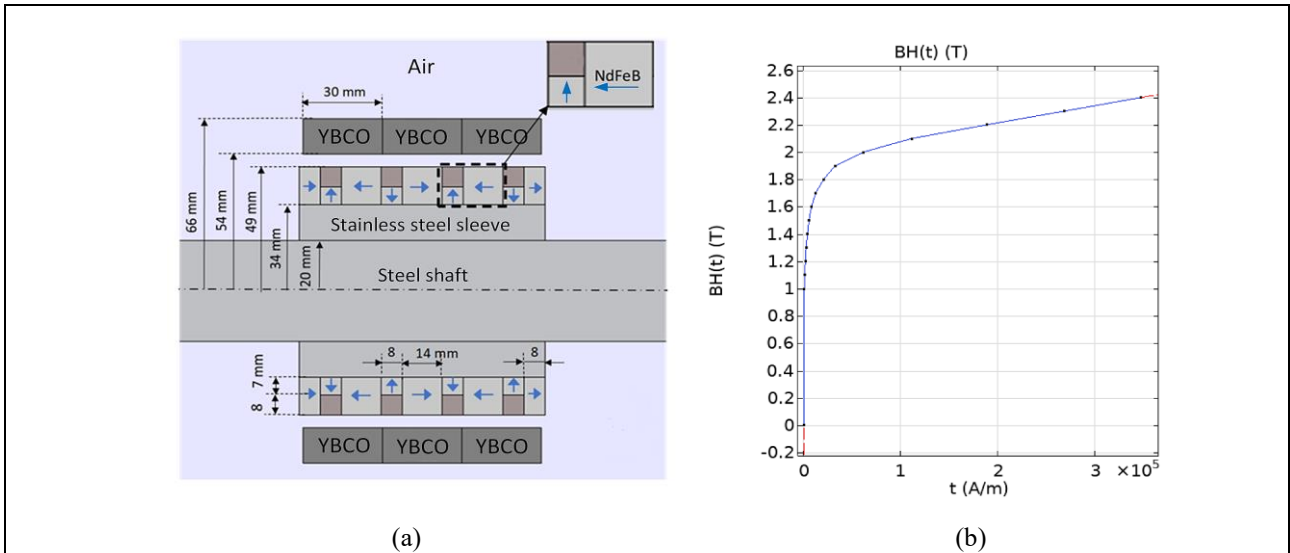


Fig. 2 (a) Geometry and materials considered in the finite element (FE) analysis, in the longitudinal bisection plane along the symmetry axis. (b) Magnetization curve for Fe in the rotor's radial flux concentrators.

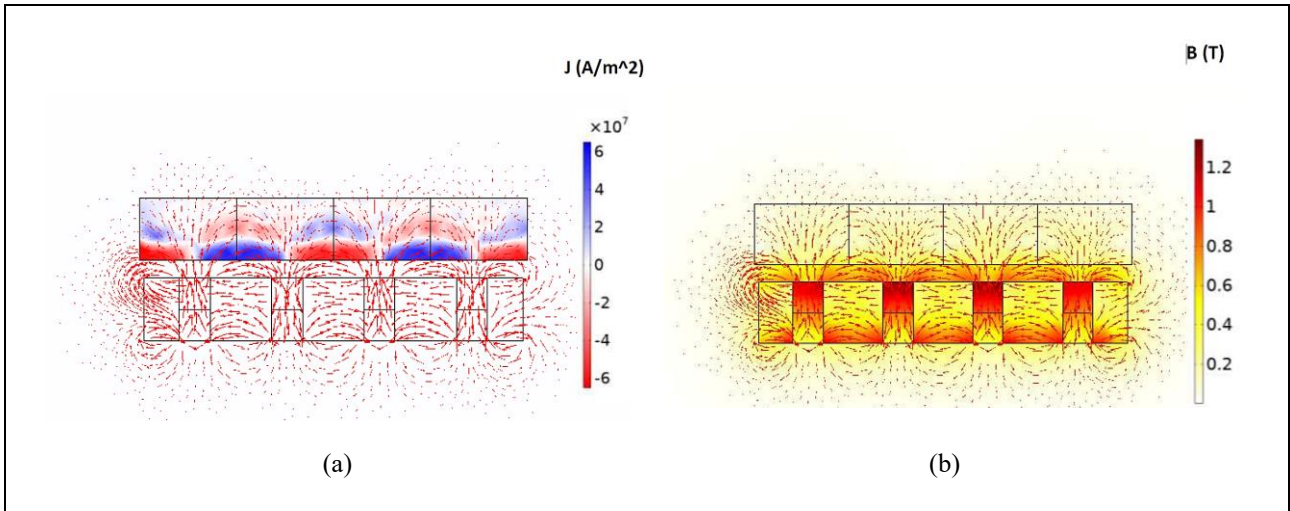


Fig. 3 Current density distribution (a) and field B distribution (b) in the 4 YBCO rings (2D upper symmetric cross section).

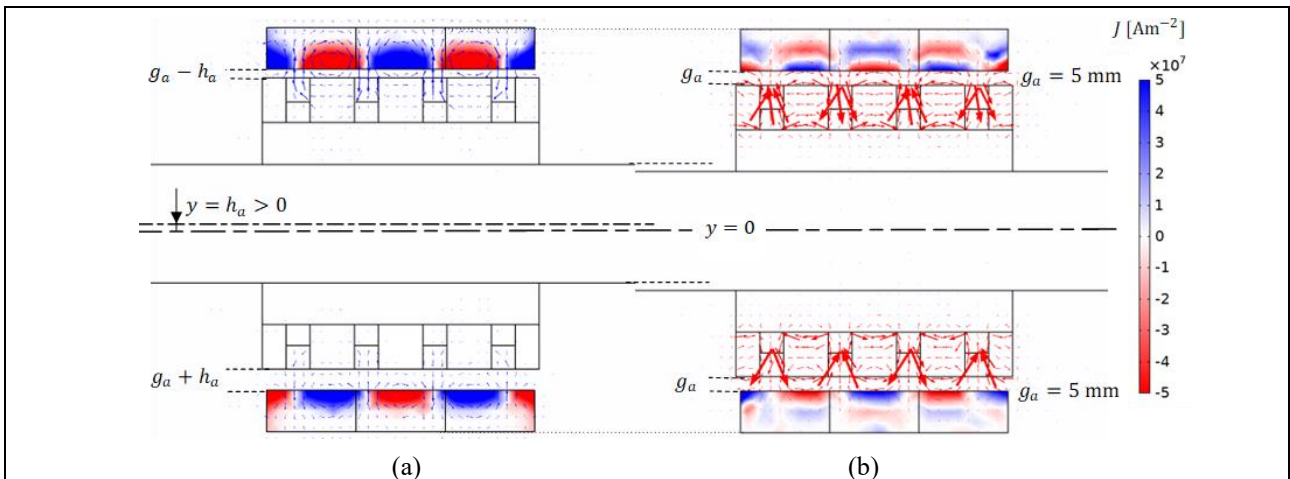


Fig. 4 Simulation of the field cooling process. Current and B distribution after: (a) the first and (b) the second YBCO magnetization step in the presence of an external field (FC).

3.2 Computation of the levitation force and the field cooling height for rotor weight compensation

The 2D FE simulations determined the levitation force per unit length (N/m) for a planar geometry with a depth of one meter along the z -axis. To calculate the levitation force per quadrant, the radial force projections in the y -direction, as shown by blue vectors in Fig. 5a, are integrated. Figure 5b shows how the magnetic levitation force F_{yc} depends on the rotor's vertical displacement or cooling height h_a set during the first magnetization phase under field cooling. Notice that when the rotor is positioned centrally, the air gap between the magnets and superconductors is 5 mm. Given that the cryostat wall has a thickness of approximately 2 mm, the practical maximum height for field cooling will be $h_a = 3$ mm. It can be verified from Fig. 5b that to ensure a magnetic levitation force of $F_{yc} = 130$ N, counteracting the rotor's weight, including the sleeve and magnet rings (≈ 13 kg), cooling must be performed with a vertical displacement of $h_a \approx 1.5$ mm.

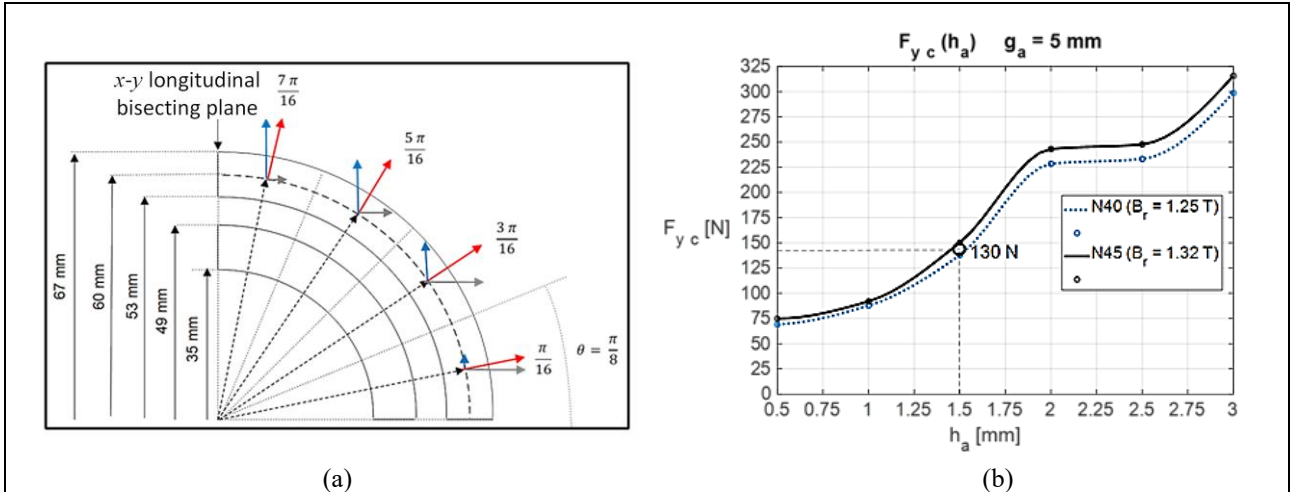


Fig. 5 (a) Computation of the levitation force $p/$ quadrant by integrating the radial force projections in the y -direction. (b) Levitation force F_{yc} with the rotor centered as a function of the cooling height h_a .

3.3 Computation of the guiding forces

The dependence of the PSMB guiding forces on its lateral rotor displacement (Δx) was also determined while maintaining its axis aligned with the stator axis, after cooling at a height of $h_a = 1.5$ mm. This dependence is illustrated in the graph in Figure 6 for two types of NdFeB magnets. The lateral magnetic forces for the cylindrical bearing geometry F_{xc} were obtained from the specific lateral. Results indicate that lateral guiding forces are significantly higher than the levitation forces, confirming the characteristic lateral stability associated with this type of superconductors' cooling.

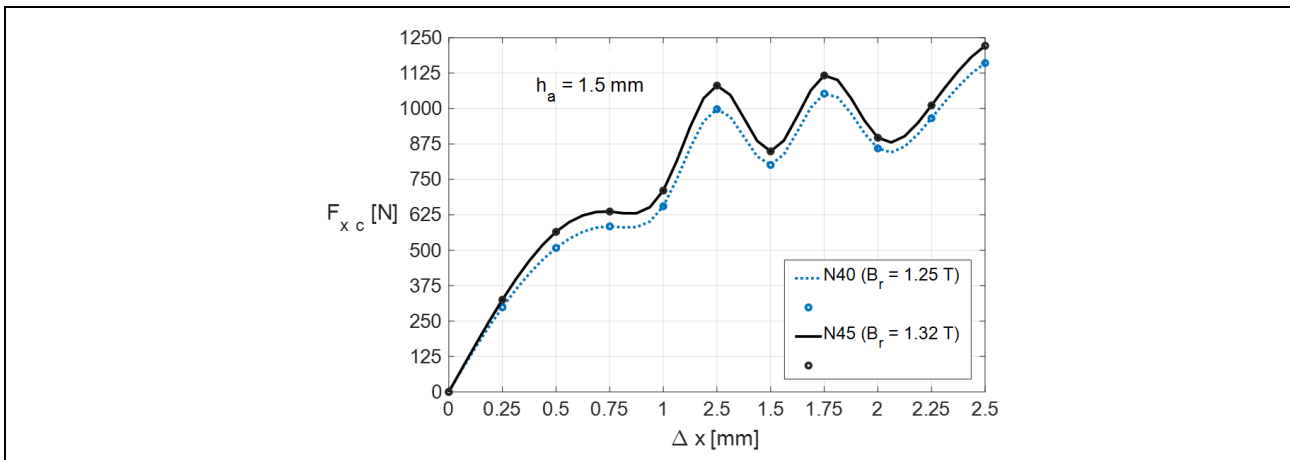


Fig. 6 Guiding force F_{xc} on the lateral displacement Δx .

4. Experimental results

4.1 Tests without load

Figure 7 shows a photo of the test bench. The Induction Motor (IM1) is located on the left side, alongside the Passive Superconducting Magnetic Bearings (PSMB1 and PSMB2). A WEG power electronic inverter, the CFW11, supplies this IM1. On the right-hand side, the Induction Motor (IM2) is connected to the grid through a tap-changing transformer (VARIAC), which will work as a load. Therefore, SMB2 is connected to the Drive End (DE), and SMB1 to the No Drive End (NDE) of IM1. The axes of the two motors are connected with a magnetic coupling to compensate for misalignments. Figure 8 presents the schematic connections, and Figure 9 presents the successful experimental result at 7.000 rpm without load (i.e., without grid connection).



Fig. 7 Test bench showing the left electric machine supported by two PSMBs (PSMB 1 and PSMB 2), and the right machine (load machine) using a magnetic coupling.

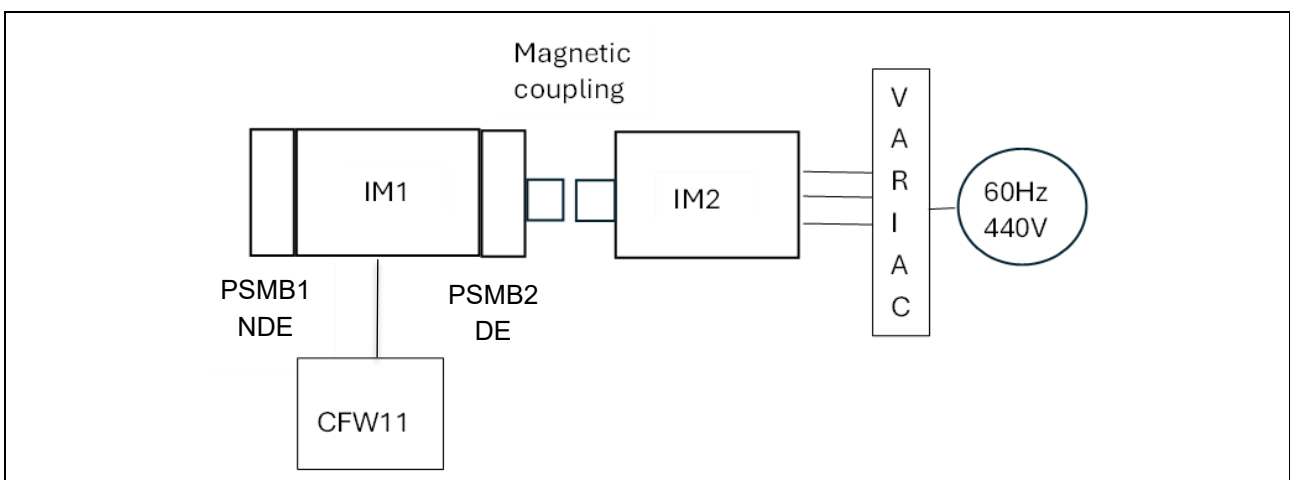


Fig. 8 Schematic drawing of the no-load test bench.

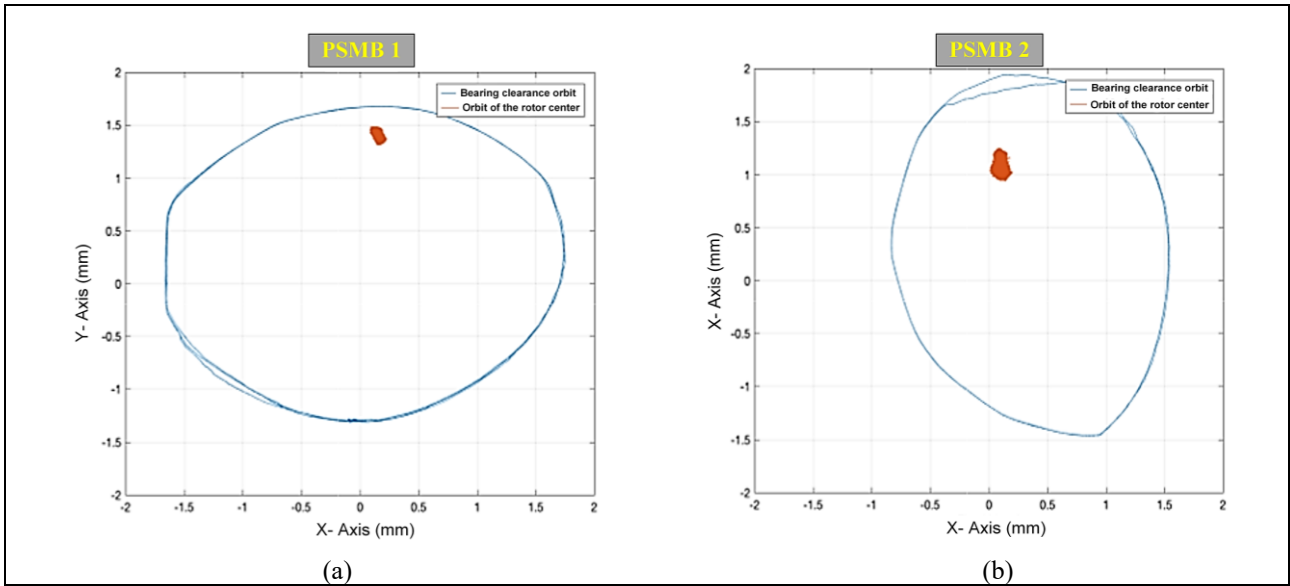


Fig. 9 XY plot of the rotor position of (a) PSMB 1 and (b) PSMB 2 at a velocity of 7000 rpm without load. The blue line gives the touch boundary condition.

4.2 Tests without load

Since the magnetic coupling proved not to be strong enough to support tests underload, i.e., the coupling was lost as soon as the grid connection was increased (Storti et al., 2025), it was replaced by a universal joint, as shown in Figure 10, which also compensates for misalignments. Moreover, to avoid harmonic disturbances on the Magnetic Bearing, IM1 was connected to the grid, and IM2 was supplied with a WEG electronic inverter CFW11, changing the experimental arrangement as seen in the schematic of Figure 11.



Fig. 10 Motors connected by a universal joint.

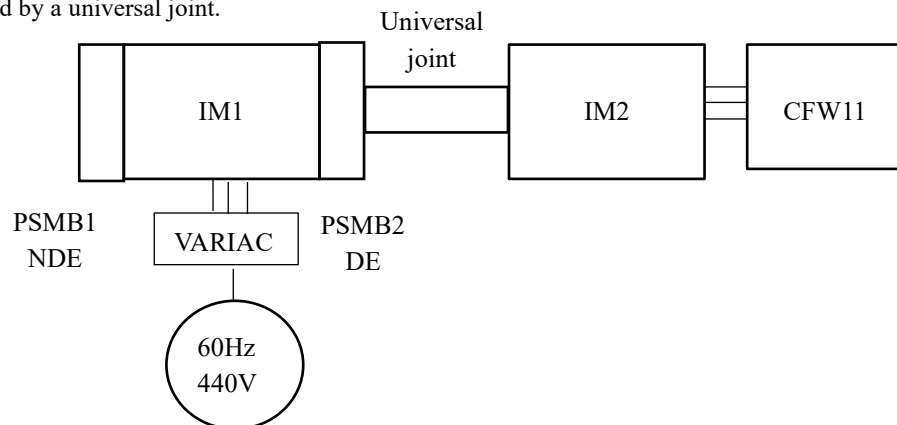


Fig. 11 Schematic drawing of the load test bench

The experimental results are shown in Figures 12, 13, 14, 15 and 16.

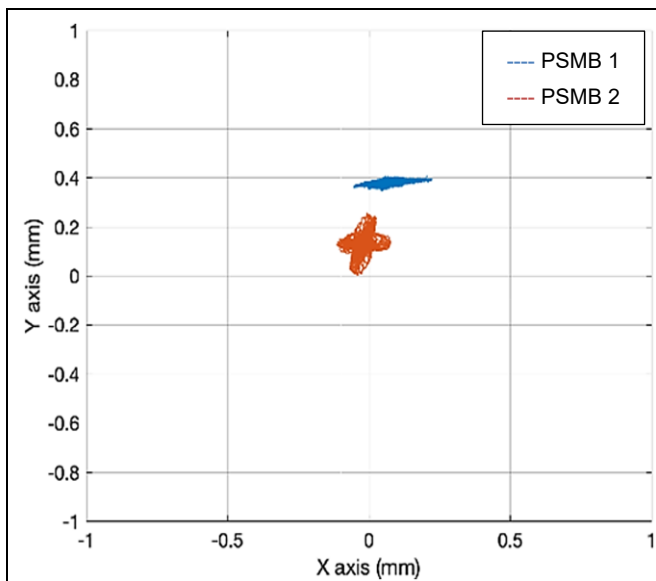


Fig. 12 XY plot of rotor position of PSMB 1 and PSMB 2 during acceleration without load to 3600 rpm.

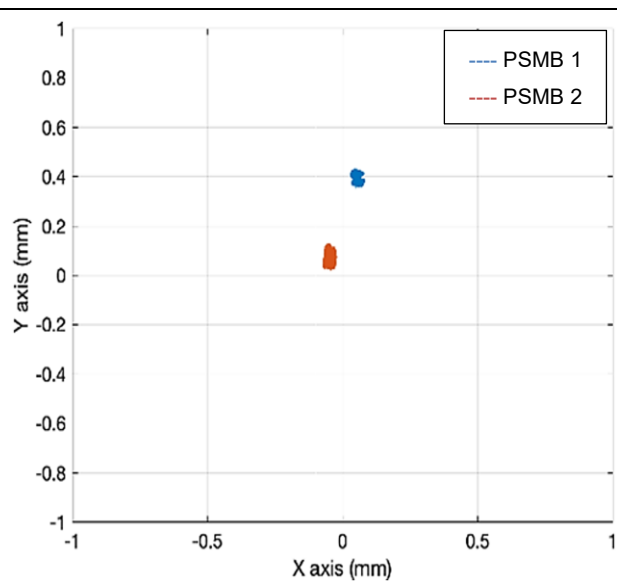


Fig. 13 Bearings position at 3600 rpm.

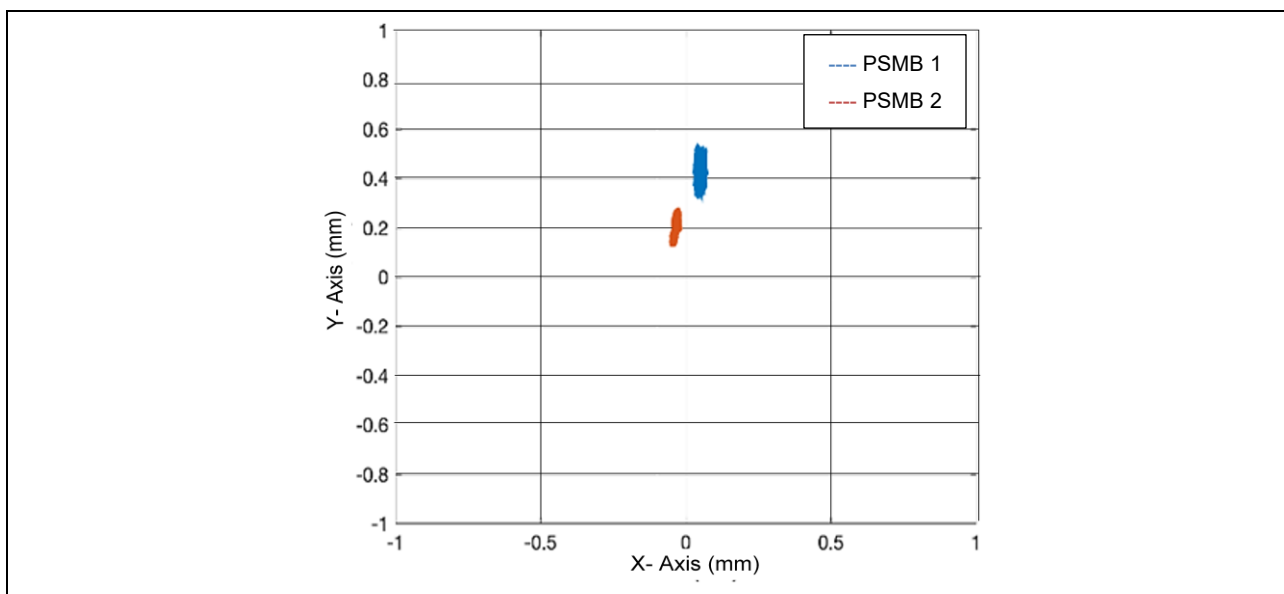


Fig. 14 XY plot of the rotor position of PSMB 1 and PSMB 2 during acceleration from 3600 rpm to 3640 rpm, corresponding to a load increase of 25% of the nominal torque.

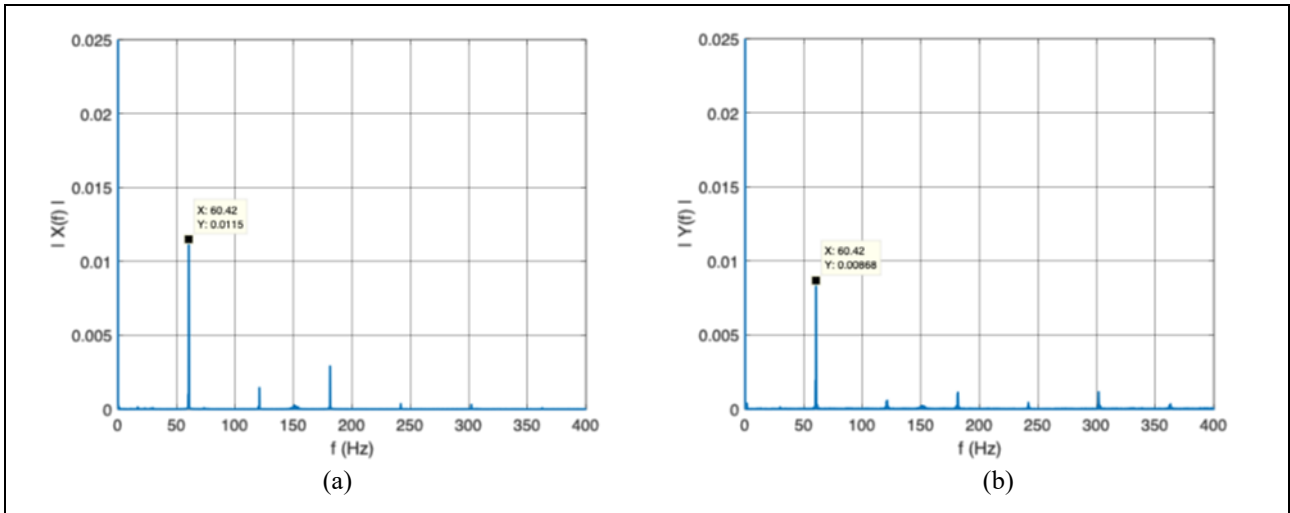


Fig. 15 Spectral analyses of PSMBs at 3640 rpm: (a) PSMB 1 on the X-axis, (b) PSMB 1 on the Y-axis.

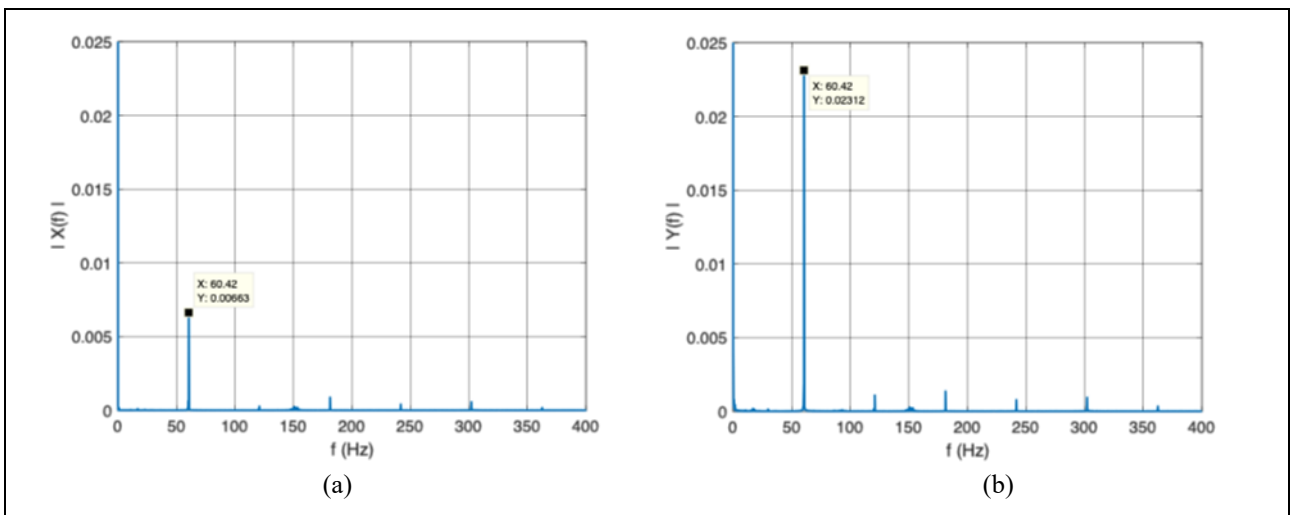


Fig. 16 Spectral analysis of PSMBs at 3640 rpm: (a) PSMB 2 on the X-axis, and (b) PSMB 2 on the Y-axis.

5. Conclusion

This paper describes the successful operation of an electrical machine with PSMB's. Even touchdown bearings and trust bearings are not necessary, simplifying the design and helping to offset the high costs of superconductors. The PSMB structure and tests, both with and without load, have been presented. The level TRL05 was reached. The primary challenge of PSMB is to ensure centralization to prevent radial forces under load. Investment is still needed in the development of a closed-circuit cryostat to make the bearing industrially applicable. The development will continue to reach higher TRL grades.

9. Acknowledgments

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