Experiments in a Real Scale MagLev Vehicle Prototype

G. G. Sotelo, D. H. N. Dias, O. J. Machado, E. D. David, R. de Andrade Jr., R. M. Stephan1
G. C. Costa2

Website: www.dee.ufrj.br/lasup
E-mail: sotelo@coe.ufrj.br

Abstract. A Brazilian real scale magnetically levitated transport system prototype is under development at the Federal University of Rio de Janeiro. To test this system a 180 m long line has been projected and it will be concluded by the end of 2010. A superconducting linear bearing (SLB) is used to replace the wheels of a conventional train. High temperature superconductor bulks placed inside cryostats attached to the vehicle and a magnetic rail compose the SLB. To choose the magnetic rail for the test line three different rails, selected in a previous simulation work, were built and tested. They are composed by Nd-Fe-B and steel, arranged in a flux concentrator topology. The magnetic flux density for those magnetic rails was mapped. Also, the levitation force between those rails and the superconductor cryostat, for several cooling gaps, were measured to select the best rail geometry to be used in the real scale line. The SLB allows building a light vehicle with distributed load, silent and high energy efficient. The proposed vehicle is composed of four modules with just 1.5 m of length each one and it can transport up to 24 passengers. The test line having two curves with 45 m radius and a 15% acclivity ramp is also presented.

1. Introduction

In big cities, like Rio de Janeiro, there is a need for an energy efficient and quiet public transportation with low environmental and urban impact. In this context, the Laboratory of Applied Superconductivity (LASUP) of Federal University of Rio de Janeiro (UFRJ) is developing a transport system named MagLev-Cobra [1-2]. The Maglev-Cobra technology is a Light Rail Vehicle (LRV) with Superconducting Linear Bearings (SLB) replacing the wheels. This approach improves the energy efficiency and reduces dramatically the vehicle weight and environmental noise at low speeds. In order to minimizing the urban impact, the Maglev-Cobra vehicle was proposed with multiple short units, allowing curves of 45 meters radius and ramps of 15% for velocities up to 70 km/h. Those properties allow the vehicle to be perfectly adjusted to the cities layout, making it possible to implement the MagLev-Cobra along roads and rivers profiles. When these short units are connected, the vehicle resembles a ‘snake’ or ‘cobra’ in Portuguese. The vehicle is propelled by an induction linear motor and has cryostats where the YBa2Cu3O7-y (YBCO) top seed melt textured blocks [3] are cooled by liquid nitrogen. The rails are made of Nd-Fe-B permanent magnets and they assemble with

1 Department of Electrical Engineering – Federal University of Rio de Janeiro. Address: CT, Bl. I-2000 Sala 148, Cidade Universitária, Rio de Janeiro, Brazil. PO-BOX: 68553, CEP.: 21941 - 972.
2 Universidade Estadual da Zona Oeste. www.uezo.rj.gov.br
the vehicle YBCO blocks the SLB. This SLB allows the Maglev-Cobra to run with low noise and almost no friction [4]. The same physical principle has also been used by IFW-Dresden [5] and Southwest Jiaotong University [6] in smaller scale transport system prototypes.

As a first step, a real scale module with one meter long was built, as shown in figure 1. This module is aluminium made and their whole weight is 160 kgf (with no load). This section is supported by 4 cryostats, with YBCO superconductors inside, that levitate with a gap between 25 mm (with no load) and 5 mm (with a full load).

![Figure 1. MagLev Cobra 1 meter section with human load. The picture in the right side shows a detail of one the cryostats over the rail.](image)

The main goal of this paper is to present the MagLev-Cobra system and the efforts to define the permanent magnets line design. As this magnetic line represents a significant cost percentage of the project, it must be chosen carefully.

The MagLev-Cobra line will interconnect two buildings (CT-I and CT-II) of the UFRJ Center of Technology that are 133 m apart. The conclusion of the project is estimated at the end of 2010.

The paper is organized in the following way: Section 2 will present the SLB conception and the tests made to choose the better design for the prototype. Section 3 shows the chosen vehicle design, which has four modules with 1.5 m long each. Section 4 shows the track layout that has been projected to interconnect CT-I and CT-II. Finally, section 5 presents the conclusion of this work.

2. Superconducting linear bearing

The SLB used for the real scale MagLev prototype is composed of 6 cryostats per module, and a Nd-Fe-B magnetic rail. The superconductors are accommodated inside the cryostats, specially designed for this application. The cryostats are attached to the vehicle and filled with Liquid Nitrogen (LN$_2$) to keep the High Temperature Superconductors (HTS) refrigerated at 77K. Twenty-four multi-seeded (3 seeds) YBCO bulks with size of 32 mm x 64 mm x 13 mm are located inside each cryostat. The HTS blocks were arranged to cover the whole cryostat bottom area. Several possible designs of SLB were simulated using the model presented in [7]. Using the YBCO arrangement described above, 3 permanent magnet (PM) rail prototypes were implemented for more detailed tests.
The 3 different geometries of magnetic rails that were built to test the magnetic levitation force are shown in figure 2. A commercial 35M Nd-Fe-B was used, having a coercive force of 903 kA/m and a remanent magnetic induction of 1.198T. The gray rectangles in figure 2 represent the iron material SAE-1020. The rail presented in figure 2(a) is composed by several Nd-Fe-B permanent magnets of 120 mm x 30 mm x 120 mm, magnetized in the y direction (geometry A). In terms of flux concentration, this rail is called Flux Shaper (FS) with two PM rows. The rail shown in figure 2(b) is composed by permanent magnets of 100 mm x 50 mm x 50 mm, with magnetization in the y direction in a FS configuration with also two PM rows (geometry B). Figure 2(c) shows a geometry composed by permanent magnets of 100 mm x 25 mm x 50 mm and 100 mm x 50 mm x 50 mm, with magnetization in the y direction and arranged also in a FS configuration (geometry C). However, the difference between this rail and the two other ones is the number of PM rows that now are three PM rows instead of two.

Several kilometers of PM rails will be built and its cost is mainly dependent of the area of the cross section of the PM material. The cross section area of the Nd-Fe-B materials for geometries A, B and C are, respectively, 7200 mm$^2$, 5000 mm$^2$ and 5000 mm$^2$. It can be concluded that the PM cost of geometry A is 44% higher than the Nd-Fe-B cost of geometries B and C.

![Figure 2](image)

**Figure 2.** Magnetic rail geometries tested. The dimensions are in mm.

The first analysis of the three different rails was done by mapping the z component of the magnetic flux density field ($B_z$) for different z levels from the rail surface. Once, the rail geometries have symmetry along the main moving direction (x direction), the measurements were done by taking into account the lateral section symmetry, along the y direction. The $B_z$ was mapped at the following z levels: 2 mm, 5 mm, 10 mm, 15 mm, 20 mm and 25 mm from the surface of the rail, and the results are shown at figure 3 for the geometries A, B and C, respectively. It can be seen that the absolute value of $B_z$ above the pole is higher for the A and B geometries compared with geometry C.

To measure the levitation force between the cryostats and the PM rail, an experimental rig was used [7]. This system was able to control the relative position of the cryostat in the z direction. To measure the levitation force, a load cell was connected above the cryostat. The tests were done starting the cryostat in an initial position from the magnetic rail. The cryostat was filled with LN$_2$ to cool the YBCO blocks in the desired z field cooling (FC) gap. After that, the cryostat was approached very slowly ($v=1$ mm/s) to the rail, in a quasi-static process, until a minimum gap of 5 mm was reached. Then, the cryostat was elevated until a maximum gap of 105 mm from the magnetic rail, where the influence of its magnetic field can be neglected. Finally, the cryostat changes its movement direction.
and it returns to the initial position. The measurements for the three rails geometry and four different z FC gaps are presented in figure 4.

![Figure 3. Magnetic field profile of the magnetic rails.](image)

If the FC gap is larger the value of the levitation force in z direction increases, but the lateral force and, consequently, the vehicle stability decreases. The upper limit for this initial FC gap is the zero field cooling (ZFC) process, when the magnetic field provided from the PM rail is negligible. In the present work, the gap used for the ZFC process was 105 mm. Therefore, it is important to find an optimum FC gap that gives a sufficient levitation force and a good stability. Thus, according to the measurements, the FC gap for this SLB was chosen 30 mm. In figure 4 (b) when a gap of 5 mm is reached for Geometry C, a vertical force of 2450 N (or 250kg) per cryostat is obtained.

Even though geometries A and B have the peak value of $B_z$ higher than geometric C, due to the cryostat design and the superconducting arrangement inside it, the magnetic levitation force for the C geometry is higher than that for the two others geometries. Another advantage of geometry C, in comparison with geometries A and B, is the higher value for the lateral force, when a displacement in the y direction is applied on the superconductor. This force is proportional to the maximum velocity that the vehicle can move during a curve (centrifugal force). Those lateral forces for a y displacement will be presented in a future work.
3. Vehicle design

The proposed vehicle is made of short modules, which are 1.5 meter long, 2.5 m high and 2.3 m large. When the modules are connected, the vehicle can follow curves with just 45 m of radius. Each module offers space for twelve passengers and maximal loaded weight of 1500 kgf.

A linear motor gives the traction. Since this propulsion method only needs electric energy, which is mainly generated by hydro power plants in Brazil, the Maglev-Cobra has low polluting effect. Since the noise level is low, the vehicle can run inside cities on elevated structures. The estimated construction costs are 1/3 of that necessary for subways. Moreover, the energy consumption and the maintenance costs are lower than that of a conventional LRV (Light Rail Vehicle) since no mechanical contacts and rotational parts are necessary.

The Maglev-Cobra demonstration system will have two passenger modules and two cabin modules, figure 5a. In figure 5b, the interior design conception can be seen. Each module is supported by 3 pairs of cryostats with a full-load capacity of 250kgf per cryostat. The linear motor (weighting 250kgf), an electronic frequency inverter (weighting 50kgf), an air-conditioning unit (weighting 50kgf), the mechanical structure (weighting 190kgf) and 12 passengers (80kgf x 12 = 960kgf) sum up the module load.

In figure 6, a transversal cut view of a Maglev-Cobra module is presented, it shows the linear induction motor, one pair of cryostats and the magnetic rails, protect by a covering structure.
Figure 5. Design of a MagLev-Cobra four sections vehicle.

Figure 6. Maglev-Cobra on a pedestrian bridge.

4. Track layout

The MagLev-Cobra track projected will be interconnecting two buildings (CT-I and CT-II) of UFRJ Center of Technology, figure 7, apart of 133 m. Due to the low vehicle load (1000 kgf/m), the vehicle can travel supported by light elevated structures of the same kind used for pedestrians bridges, as shown in figure 6. The vehicle starts its course at ground level in CT-I, making a left curve with 45 m radius and, in a sequence, a right curve with the same radius. After this right curve, the MagLev starts to ascend a 62 m ramp with an increasing aclivity. A maximum aclivity of 15% is reached after 33 m along the ramp. Finally, the vehicle goes on in a linear and horizontal track along 71 m, when it reaches the second floor of CT-II building. There is also a 47 m service line, figure 7, which will be used to take it from a closed parking place, where the vehicle will be assemble and fixed. The whole track, including the service track, will be 180 m long.
5. Conclusion

This paper presented some new results and considerations about the MagLev-Cobra project. The proposed vehicle gives a futuristic view along its way, matching high technology, modern design, environmental restrictions and social requirements. The vehicle was projected with four short modules, 1.5 meters long each, and can transport up to 24 passengers in every travel. Details about the 180 m long magnetic line layout that will integrate 2 builds inside the university are presented. This line has 2 curves with 45 m radius and a ramp with 15% of acclivity. Three geometries of magnetic rails were tested and the levitation force results were compared for several field cooling gaps, indicating the more promising configuration to be implemented in the future line.

6. Acknowledgment

This work is financially supported by the Brazilian agencies FAPERJ, CNPq and CAPES.

7. References

[1] Stephan R M, David E G, Andrade Jr. R, Sotelo G G, M O J, De Haas O and Werfel F 2008 XX International Conference On Magnetically Levitated Systems and Linear Drives, San Diego.
[2] Stephan R M, David E G and De Haas O 2008 XX International Conference On Magnetically Levitated Systems and Linear Drives, San Diego.
[3] Werfel F N, Flögel-Delor U, Rothfeld R, Wippich D and Riedel T 2001 Physica C: Superconductivity 357-360 (1) 843
[4] Moon F C, Superconducting Levitation: Applications to Bearing & Magnetic Transportation 1994, Ed. Wiley-Interscience
[5] Schultz L, De Haas O, Verges P, Beyer C, Röhlig S, Olsen H, Kühn L, Berger D, Noteboom U and Funk U 2005, IEEE Transactions on Applied Superconductivity 15 (2) 2301
[6] Wang J, Wang S and Zheng J 2009 IEEE Transactions on Applied Superconductivity 19 (3), 2142
[7] Dias D H N, et al 2009 IEEE Transactions on Applied Superconductivity 19 (3), 2120