“Scale-up” of the Portuguese Superconductor type-ZFC Magnetic Levitation System Fulfilling the Functional Criteria of the Maglev-Cobra

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Abstract— Magnetic levitation train systems are being developed as part of a new generation of mass transportation systems. This thesis will deal with the latest trend of these type systems, the superconductor magnetic levitation system using zero-field cooling, with a track made of permanent magnets, the ZFC-Maglev. This thesis will try to propose a competitive solution, using data retrieve from a similar system, the Maglev-Cobra train, which uses field cooling. To this end, a study of the levitation and guidance forces is made for the ZFC-Maglev system so that fulfills the functional criteria of the Maglev-Cobra.

Index Terms— Maglev; Superconductor; Zero Field Cooling; ZFC; Permanent Magnets

I. INTRODUCTION

The industrial revolution of the XVIII and XIX centuries, led to an exponential growth in population in the XX century within urban centres. Mass transport became a problem, as the population had the need to commute between home and work places. Motorized transports became imperative, due to the unstoppable increase in city size. Thus began the collective mass transport system: bus, train and metro.

The necessity of an efficient and non-polluting public transportation system, with competitive implementation and maintenance costs, is nowadays a vital part of a society evermore focused in living in big city centres.

However, these means of transportation are characterized by a high implementation and operational cost. Furthermore they may have their own specifications, which may not be compatible with the environment where they need to be placed. Examples are the curvature ray need for a train to turn, the inclination of the tracks [1], maximum train speed and also how power is supplied to it.

In recent years a new type of transportation is being researched: the superconducting levitation train, also known as Maglev. This system uses magnetic fields to make the carriage of the train levitate, usually leaving propulsion to linear motors.

The scientific area of energy (DEEC) from Instituto Superior Técnico (IST), has been developing this type of technology since 2006, in conjunction with the Superconductivity Laboratory from the federal university of Rio de Janeiro (UFRJ).

The Maglev offers a set of advantages in comparison to the traditional train system. As it does not rely in attrition in order to move, the Maglev systems requires less power, while at the same time producing less sound pollution. It can also be inserted in overpasses for easier city integration.

This paper is inserted in the theme “Superconducting levitation vehicles in zero-field cooling”. It aims at developing a new system that fulfils the functional criteria of the Maglev-Cobra developed by the UFRJ, which uses field-cooling for its superconducting levitation system. Thus, this paper will consist in a study of the levitation and guidance force required for a functional prototype.

II. THE VEHICLE MAGLEV-COBRA

The Maglev-Cobra is a vehicle which uses a levitation system based on field cooled superconductors, and tracks that are made of permanent magnets and ferromagnetic pieces as shown in Figure 1.

Figure 1 - Maglev-Cobra track: (a) Magnetic field distribution; (b) Photo of the rail topology used by Maglev-Cobra track [1]

A way of viewing the field cooling process of the superconductors, is by considering them as blocks connected by springs to four walls, in such a way that all springs are in their lowest level of potential energy. Any movement that the blocks may suffer will lead to the actuation of the springs, in order to restore them to their original position.

Figure 2 - Illustration of the spring like restitution force of a HTS block in field cooling

This work was developed in Instituto Superior Técnico, University of Lisbon, Lisbon, Portugal.

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A photo of the Maglev-Cobra vehicle can be seen in Figure 3. On the photo of the module it is possible to see the cryostats, in which the superconductors are lodged, along its borders. There are six cryostats per each module, having each 24 superconductors. Each segment can hold up to ten passengers, thus leading to a normalized total weight of 1500(Kg).

Figure 3 - One module of the Maglev-Cobra vehicle [2]

It is also possible to see the linear motor in its central part for its propulsion system. In Figure 4 it is shown a picture of the primary and secondary of the linear motor. The Maglev-Cobra vehicle was designed to operate at low speed, usually around 8(m/s) [3] [4].

Figure 4 - Linear motor used by the Maglev-Cobra train [3]

All data relative to the Maglev-Cobra vehicle was obtained from thesis that dealt with its conceptual design [1] [3]. The superconducting levitation system has the following characteristics:

1 - There are six cryostats per module of the vehicle as shown in Figure 5(a), each containing 24 YBa2Cu3Ox superconductors, whose dimensions are of 63x63x13(mm);

2 - The bottom wall of the cryostat has a thickness of 2(mm);

3 - Each module has a mass of 300(kg), and it is capable of sustaining up to ten passengers of 100(kg);

4 - The field cooling position is made at a distance of 25(mm) from the tracks;

5 - The guidance force must be such that it should allow the train to do curves at a speed of 3.6(m/s), having a maximum displacement from its movement centre of 10(mm)

III. FEM MODEL AND ITS VALIDATION

A. FEM model and its equations

The levitation system is composed by two crucial elements: the permanent magnets and the type II superconductors. With this section, it is intended to determine, from a FEM simulation, the influence of the presence of superconductors in zero field cooling (ZFC) over a magnetic field, produced by a set of permanent magnets forming a certain array geometry. In particular it is intended to determine the strength of the force generated by the superconductors for levitation proposes (force over the z axis).

The approximation of a type II superconductor in ZFC condition to a magnet, leads to the circulation of currents in its interior, which are most significant in its surfaces, so that the external field is repelled. From these currents it is possible to determine the electrical and magnetic field distributions, both for the superconductors as for their surroundings.

Figure 6 - Steps for the electromagnetic force computation

There can be considered three distinct model regions: the air, the superconductors and the permanent magnets. In the air and superconductors regions the density current (\(\mathbf{J}\)) and the magnetic field (\(\mathbf{H}\)) can be determined by the same set of equations (equations (1) and (2)), being that the only difference between the two regions is the function by which the electrical field (\(\mathbf{E}\)) is defined, equations (3) or (4), respectively. The region defined by the magnets is considered only as a source of field, and is modelled so that it has a remnant magnetic flux density.

The computation of density current (\(\mathbf{J} = [J_x, J_y, J_z]\)) and the magnetic field (\(\mathbf{H} = [H_x, H_y, H_z]\)) are common to all regions, being taken directly from Maxwell’s equations for slow varying phenomena in time (quasi-stationary regime).
The air is considered a linear region [5], where Ohm’s Law can be applied. Thus the electrical field is given by relation (3), where \( \rho \) is the air electrical resistivity.

\[
E_{\text{air}} = \rho \frac{\partial \mathbf{B}}{\partial t}
\]  

(3)

This thesis uses a macroscopic modelling approach of type II superconductors. The key departure comes in the form of a non-linear E-J relationship. For the simulated model, it was considered the model presented in the papers [5] [6], where the electrical field and current are given by an E-J characteristic law, that takes the form of equation (4). The electrical field \( E_{\text{SC}} \) within the superconductor is given by a function of the superconductor parameters: \( E_0 \), \( J_c(B) \), \( n \) and \( B_0 \). The critical electric current density is field dependent and given by relation (5).

\[
E_{\text{SC}} = E_0 \left( \frac{J_c(B)}{J_c(B)} \right)^n
\]  

(4)

\[
J_c(B) = \frac{J_{c0}}{B_0 + ||B||} \left( \frac{B_0}{J_{c0}} \right)
\]  

(5)

The \( n \) parameter represents the possible states of conductivity by the superconductor [7], being that when it has the value of 1, it is in its resistive state, and when it tends to infinite it is in its ideal superconductive state, that is, \( E_{\text{SC}} = 0 \) in all superconductor volume. As for \( E_0 \) parameter it is the value of the critical electrical field.

For the computation of the critical current of the superconductor it is considered \( J_{c0} \) and \( B_0 \) which are parameters that depend on the type of superconductor. These parameters essentially regulate the density current in function of the norm of the magnetic flux density applied to the superconductor. Table 1 presents the generic values of a YBCO superconductor, which were used in the FEM program.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_0(T) )</td>
<td>0.1</td>
</tr>
<tr>
<td>( J_{c0}(A/m^2) )</td>
<td>( 2 \times 10^7 )</td>
</tr>
<tr>
<td>( E_0 (V/m) )</td>
<td>( 1 \times 10^{-4} )</td>
</tr>
<tr>
<td>( n )</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 1 - Generic YBCO superconductor parameters used in the FEM program

To determine the strength of the electromagnetic forces generated in the superconductor’s surface by a magnetic field, it will be used the Maxwell Stress Tensor. This technique allows the computation of forces, knowing only the distribution of the magnetic field over a closed surface. The application of this technique to a cubic figure yields the following force equations.

\[
F_x = \frac{\mu_0}{2} \left( (H_x^2 - H_y^2 - H_z^2)_f - (H_x^2 - H_y^2 - H_z^2)_s \right) + \mu_0 S_{\text{inf}} \left( (H_x H_y)_f - (H_x H_y)_s \right)
\]  

(4)

\[
F_y = \frac{\mu_0}{2} \left( (H_x^2 - H_y^2 - H_z^2)_f - (H_x^2 - H_y^2 - H_z^2)_s \right) + \mu_0 S_{\text{inf}} \left( (H_x H_y)_f - (H_x H_y)_s \right)
\]  

(5)

\[
F_z = \frac{\mu_0}{2} \left( (H_x^2 - H_y^2 - H_z^2)_s - (H_x^2 - H_y^2 - H_z^2)_f \right) + \mu_0 S_{\text{inf}} \left( (H_x H_y)_s - (H_x H_y)_f \right)
\]  

(6)

B. Model validation

In order to do a successful scale-up for a ZFC based levitation system, there is the need to compute the differential model formed by equations (1) to (5) that can determine, with enough accuracy, the magnetic field distribution resulted from the interaction of the superconductor with a permanent magnet. Knowing the field distribution, one can compute all electromagnetic force components using Maxwell’s Stress Tensor as described previously.

To validate the model two steps are made. In the first step, it will be simulated the superconductor and magnet geometry whose experimental results were presented in Painho’s thesis [7]. The experiment presented in this thesis is ideal for a 2D simulation, so it is a good starting point for model validation. After the 2D simulation holds up, a 3D version is developed. At this point, a new experimental activity will be made, now using the ZFC-Maglev track topology considered for the future scale up model. The 3D model results will be confronted with the results obtained from the experiment effectuated at the laboratory.

As stated before, the first attempt at verifying the proposed model for the computation of forces is made based on the results of the thesis [7]. The geometry is presented in Figure 7. It consists of eight permanent magnets with a remnant field of \( 1.25(T) \) and six \( YBa_{2.5}Cu_{3}O_{7-\delta} \) superconductors. This geometry is ideal for a 2D cut in the \( xy \) plane, as it is quite symmetrical considering any plane, mainly in the \( z \) direction.
to determine the levitation force at each superconductor. The simulated and experimental results are shown in Figure 9.

![2D field distribution for an air gap of 1(cm)](image)

Figure 8 - 2D field distribution for an air gap of 1(cm)

![Graph comparing the experimental force with the simulated ones](image)

Figure 9 - Graph comparing the experimental force with the simulated ones

Though the error for an air gap inferior to 1(cm) is quite high, both the 2D and 3D simulated values do tend to stick to the experimental values. The high error may be caused by the FEM program, or might be an experimental error. Since there is not a way to be certain, a final experimental validation will be made by doing an experiment now with the topology required for the ZFC-Maglev levitation system, comparing it after with the values given by the FEM model.

The proposed configuration for the ZFC-Maglev consists of four YBCO superconductors of type 2, overlapped over twelve permanent magnets, whose remnant magnetic flux density is of 1,25(T). The dimension of the components is shown in Figure 10. There is an air gap of 1(cm) between the superconductors, and the magnets have a spacing of 1,5(cm) over x direction and of 2(cm) over the y direction.

![ZFC track and superconductor placement, a mesh of 0.5(cm) was used](image)

Figure 10 - ZFC track and superconductor placement, a mesh of 0.5(cm) was used

The magnets are oriented differently in each row of magnets as shown in Figure 11. The lateral magnets have their polarization according to the positive direction of the z axis, while the central row magnets are in the opposite direction.

![Permanent magnet orientation in the ZFC-Maglev track](image)

Figure 11 - Permanent magnet orientation in the ZFC-Maglev track

In order to determine the experimental levitation force, the sensor Scaimे K12+LMVu shown in Figure 12(a) was used. It is a compression force piezoelectric sensor with an error of 0.1%, capable of registering forces up to 150(N).

Figure 12(b) shows a photo of a track module for the ZFC-Maglev is composed by twelve $N_d F_p B$ permanent magnets with a remnant field of 1,25(T), following the disposition proposed for the Maglev vehicle with levitation based in zero field cooling (ZFC).

Over the magnets, there are four superconductors of $YBa_2Cu_3O_{7-x}$ within a foam box with the same dimensions used for the simulation, as shown in Figure 12(c). The superconductors are arranged in columns of two. The box is sealed by a foam top for better thermal isolation of the YBCO blocks. The foam includes a hole used for filling the box with liquid nitrogen.

The total assembly is presented in Figure 12(d). This assembly allows the for an air gap between 0,75(cm) and 2,5(cm).

![Experimental activity components](image)

Figure 12 - Experimental activity components; (a) Photo of the piezoelectric force sensor Scaimе K12+LMVu; (b) Triple magnet trail disposition for the ZFC-Maglev; (c) Disposition of the superconductors inside the foam box following the same geometry used in the simulation; (d) Total assembly for the experiment

There is a consistent error between the experimental and simulated values on average of 21%. This comes from the numerical precision associated with the mesh used. This could be removed using a finer mesh in FEM model. However, the
computational effort was too much for our current hardware. Since, the order of the error values is almost the same, independent of the air gap, the FEM model can be considered validated. Hence, Figure 13 shows the simulated values increased by the average error and the experimental values.

Figure 13 - Graphic comparing the simulated force increased by the average error with the experimental force for the ZFC-Maglev track

IV. ZFC-MAGLEV SCALE-UP TO THE MAGLEV-COBRA

In order to develop a Scale-up version of the ZFC-Maglev that fulfills the functional criteria of the Maglev-Cobra, a trial and error search method is employed.

A. Functional criteria specifications

Considering the characteristics of the Maglev-Cobra presented in section II, the development of a ZFC-Maglev system must have the following characteristics:
- Each module has to support a maximum weight of 15000(N) distributed by six cryostats, which corresponds to 2500(N) per cryostat;
- The module should levitate between 5(mm) and 25(mm), therefore the levitation system must generate enough force within this set of height values;
- Since the cryostat’s bottom wall has a thickness of 2(mm), the minimum height assumed was of 10(mm);
- The maximum guidance force is of 5400(N) distributed by the six cryostats, which corresponds to 900(N) per cryostat.

B. Search method

The levitation height dictates how much force the levitation system can produce. Despite this fact, when planning a new potential solution it should not be considered the most relevant parameter, and priority should be given to increasing the size of the elements of system: permanent magnet track and superconductor blocks.

All simulations were made using the finite element model developed and validated in section III, by using six superconductors (two columns of three) and enough magnets to cover the space occupied by the superconductors. The usage of so few elements, both magnets and superconductors, is due to the computational demands of a larger model 3D model. The model uses a mesh of 5 (mm) on all superconductor surfaces.

From the Maglev-Cobra specifications shown before, it is established that each cryostat must support at least 2500(N) of levitation force. In order to get a competitive solution, regarding the number of superconductors used in the Maglev-Cobra, each superconductor must develop a minimum of 104(N) of levitation strength. This means that the proposed solution must develop a levitation force of around 600(N), with a minimum air gap of 1(cm), as the simulated model uses six superconductors.

For each iteration of a potential solution, in a first instance it is verified if the minimum levitation force is guaranteed. If this criterion is met, it can proceed to guidance force verification, where the force must be of restitution, which means it must be opposed to the lateral displacement direction. If this point fails, it can be opted to improve the solution, or discard it and search for a new one.

C. ZFC-Maglev final solution

Only the final geometry of the Scale-up is presented in this paper. Table 2 lists the dimensions of each element and Figure 14, shows the dimensions indicated for the geometry.

<table>
<thead>
<tr>
<th>Dimensions(mm)</th>
<th>Permanent Magnets</th>
<th>Superconductors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Width</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Height</td>
<td>30</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 2 - Dimensions of the elements of the final geometry

Figure 14- Final geometry achieved for a ZFC-Maglev module

The force results per superconductor for this geometry are listed in Table 3. For an air gap of 12.5(mm), the levitation force criterion is almost met. Considering that each superconductor has a cross section of 60x60(mm²), the ZFC-Maglev would need 26 superconductors per cryostat, instead of the 24 superconductors used in the Maglev-Cobra, which brings the total levitation force of one cryostat up to 2500(N).
<table>
<thead>
<tr>
<th>Air gap (mm)</th>
<th>Levitation force (N)</th>
<th>Guidance force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1277</td>
<td>107</td>
</tr>
<tr>
<td>7.5</td>
<td>928</td>
<td>95</td>
</tr>
<tr>
<td>10</td>
<td>705</td>
<td>77</td>
</tr>
<tr>
<td>12.5</td>
<td>577</td>
<td>62</td>
</tr>
<tr>
<td>15</td>
<td>447</td>
<td>53</td>
</tr>
<tr>
<td>17.5</td>
<td>353</td>
<td>43</td>
</tr>
<tr>
<td>20</td>
<td>278</td>
<td>36</td>
</tr>
</tbody>
</table>

Table 3 - Levitation and guidance force per superconductor in function of the air gap, with the guidance force computed for a displacement of -5(mm) from its central position, for the final geometry

Using the FEM program, the total guidance force generated by the superconductors is computed for a set of lateral displacements within the interval [-4.4](cm). The result for 26 superconductors, that is 13 superconductors in two columns in parallel, is shown in Figure 15.

![Figure 15](image)

Figure 15 - Graph of the guidance force in function of the lateral displacement for the final geometry

The maximum guidance force in Figure 15 is of 680(N) for a displacement of 2(cm), which is still below the required 900(N) for a maximum displacement of 1(cm) established by the criteria of the Maglev-Cobra. However, one has to limit the allowed interval for lateral displacement into a stable and nearly linear region situated between [-1,1](cm), as indicated in the same figure. In this case, the maximum guidance forces stayed at 500(N).

Having attained the required levitation force, it can be established at this time that the guidance force is a weakness of the ZFC-Maglev system topology.

V. TECHNICAL AND ECONOMIC ANALYSIS COMPARISON BETWEEN THE ZFC-MAGLEV AND THE MAGLEV-COBRA

A. Levitation and guidance force comparison

The forces developed by the Maglev-Cobra, both levitation and guidance, was retrieve from the thesis [1]. This thesis concerns the optimization of the permanent magnet track, and as such includes information about the original geometry. The forces presented here are in force per meter, since the total force will be higher, the longer the vehicle. With proper spacing, each cryostat fits in one meter, and there are two parallel cryostats per meter. As such, the force data is considered to be the developed force by two cryostats, and thus it is divided by two, for comparison with the force values of the final ZFC-Maglev geometry.

![Figure 16](image)

Figure 16 - Levitation force comparison between the Maglev-Cobra and the ZFC-Maglev scale-up

The developed solution for the ZFC-Maglev is capable of generating more force than the one used by the Maglev-Cobra, as shown in Figure 16. This means that for levitation proposes the Portuguese track layout is better, as it allows for a higher developed levitation force.

The main drawback however, as stated in section V, is the guidance force. The main problem with zero-field cooling is system stability in terms of keeping the vehicle on the tracks. Figure 17 compares the guidance force developed by each Maglev. The Portuguese layout does implement a solution which has a natural stability point in the middle of the track. However, Figure 17(b) shows that the “Scale-up” solution is not capable of reaching the minimum guidance force value off 900(N) for a displacement of 1(cm). By contrast the restitution force of the Maglev-Cobra is much higher at 1(cm), having the value of 4000(N), thus having a good safety margin for the required displacement.

![Figure 17](image)

Figure 17 - Total guidance force comparison: (a) Maglev-Cobra guidance force, and (b) ZFC-Maglev guidance force; Red line indicates the minimum guidance force of 900(N)
B. Implementation cost analysis

Maglev-Cobra’s thesis [1] has estimated the cost of the Maglev-Cobra implementation for a 100(km) track. Table 4 lists the cost per 100(km) in the unit of millions of US dollars for steel, permanent magnets, aluminium and superconductors.

<table>
<thead>
<tr>
<th>Steel cost</th>
<th>Permanent Magnet cost</th>
<th>Aluminium cost</th>
<th>Superconductor cost</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.07</td>
<td>1320</td>
<td>0.87</td>
<td>1.87</td>
<td>1335</td>
</tr>
</tbody>
</table>

Table 4 - Implementation cost per 100(km) for the Maglev-Cobra track, in millions of US dollars, in November of 2011

For the cost analysis, each element type has been considered individually, being that the total cost was shown at the end of the analysis. About 96% of the implementation cost comes from the permanent magnets found in the tracks. The Maglev-Cobra track is composed of two rails whose cross section dimensions are indicated in Figure 18. A special reference is given to the steel core between the magnets and on their sides.

The track used by the ZFC-Maglev solution would consist in two rails like the one presented in Figure 19. The dimensions of the permanent magnets are the same as the ones previously indicated in Table 2 of section IV.

This type of track consists only of permanent magnets and aluminium as a fitting to keep the magnets fixed in place. This way, the rail has a direct economic advantage over the one used by the Maglev-Cobra, as it does not need a steel core. A second point in its favour the total volume of permanent magnets used. In Figure 20 a visual comparison is made, concerning the volume of magnets used per meter. In it, one meter of the ZFC-Maglev rail is sorted in parallel with the two permanent magnets that form one rail of the Maglev-Cobra.

<table>
<thead>
<tr>
<th>Steel cost</th>
<th>Permanent Magnet cost</th>
<th>Aluminium cost</th>
<th>Superconductor cost</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>618</td>
<td>0.87</td>
<td>2.02</td>
<td>621</td>
</tr>
</tbody>
</table>

Table 5 - Implementation cost per 100(km) for the ZFC-Maglev track layout, in millions of US dollars, using the values of November of 2011

C. Operational cost analysis

As the superconducting levitation system is composed of passive elements, the only operational cost will be the cooling system for the superconductors, in order for them to be in their superconductive state at temperatures below the 90(K). This makes the required quantity of liquid nitrogen to cool the superconductors, the only operational cost. To obtain a quantitative value of the needed liquid nitrogen, results from the master thesis [8], were used to evaluate the superconductor power losses in function of the magnitude of a periodic applied magnetic field over a superconductor and for a frequency value that will depend of the vehicle speed and track dimensions as explained next.
Figure 21 - Graph of the power losses in function of the magnitude of the applied magnetic field over the superconductor for 5(Hz) [16]

Figure 22 is a schematic representation of the magnetic field distribution on the ZFC-Maglev track. The illustration indicates the distance $\Delta x$ for which a time period is defined according to the Maglev speed. From it, it becomes possible to define a frequency for the magnetic field on the superconductors, as the field between the centres of two consecutive lateral permanent magnets. This distance is of 6.5(cm).

From distance $\Delta x$, it was possible to determine the magnetic field frequency using equations (7) and (8), by imposing the velocity at which the vehicle moves.

$$v = \frac{\Delta x}{\Delta t} \rightarrow \Delta t = \frac{\Delta x}{v}$$  \hspace{2cm} (7)

$$f = \frac{1}{\Delta t} \rightarrow f = \frac{v}{\Delta x}$$ \hspace{2cm} (8)

Using the results from the simulation the final geometry for an air gap of 12.5(mm), it was possible to determine the average of the magnetic field which crosses the inferior surface of the superconductor blocks ($B_z$), which is equal to 1(mT). This field was chosen as it is the one that will induce currents within the superconductors, in the first few millimetres. Using data from the graph from Figure 21, for a frequency of 5(Hz) the power loss density can be estimated to be about $5.5 \times 10^{-5} \ (W/cm^2)$. As the power losses are proportional to the frequency, the losses can be computed for other frequencies proportionally. Therefore, the power losses density as function of the Maglev speed is given in Figure 23.

The current density is concentrated near the surfaces of the superconductor blocks. Thus, the considered volume to compute the total power losses is restricted to a 1(mm) shell near the superconductor surface.

Knowing the total power losses, it is possible to estimate the duration of the liquid nitrogen deposit. Since it has a pressure valve, the heating process of the cooled superconductors is made at a constant pressure, allowing the use of Heat Law equation (8).

$$Q = mC_p \Delta T$$ \hspace{2cm} (8)

In (8), the term $m$ is the mass of liquid nitrogen (whose mass density is of 800(Kg/m$^3$)) [8], and $C_p$ its specific heat at constant pressure ($2.042 \times 10^3$JKg$^{-1}$K$^{-1}$) [8]. The liquid nitrogen is at a temperature of 77(K), and evaporates at a temperature of 78(K). Thus, it was possible to determine the duration of the deposit using equation (8) with $\Delta T = 1$ and $Q = P_{loss} \times t$.

$$t = \frac{mc_p}{P_{loss}}$$ \hspace{2cm} (8)

The required liquid nitrogen for the Maglev-Cobra is assumed to be 5(l) per day [9], having each cryostat a storage capacity of 2.5(l) [10]. Assuming that one Maglev-Cobra vehicle operates for 12 hours, the power losses density can be computed using the proposed simplified thermal model, knowing that at the time the superconductors had the dimensions of 64x32x12(mm), though also using 24 superconductors. The results are shown in Table 6.

Table 6 - Consumption of liquid nitrogen by the Maglev-Cobra in a 24 hour window

<table>
<thead>
<tr>
<th>Volume of liquid nitrogen (l)</th>
<th>Power losses of the 24 superconductors (W)</th>
<th>Power losses density (W/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0,19</td>
<td>$3,1 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

In order to compare the efficiency of the Maglev-Cobra and ZFC-Maglev in terms of liquid nitrogen consumption, the volume of liquid nitrogen is computed for the same 12 hour operation time, using the information gathered from Figure 21, the simplified thermal model is applied to generate Table 7.
Comparing the results for an operation time of 12 hours, shows that ZFC-Maglev consumes about 27% less liquid nitrogen than the Maglev-Cobra. This means that the ZFC-Maglev will have a much lower operational cost.

### Table 7 - Consumption of liquid nitrogen by the ZFC-Maglev in a 12 hour window

<table>
<thead>
<tr>
<th>Volume of liquid nitrogen (l)</th>
<th>Power losses of the 26 superconductors (W)</th>
<th>Power losses density (W/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,68</td>
<td>0,14</td>
<td>$5,5 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

The work developed in this thesis was focused on developing a competitive solution for a Maglev system, using the Portuguese solution proposed by professors António Dente and Paulo Branco, so that it would fulfill the functional criteria of the Maglev-Cobra.

The studies concerning the track and superconductor placement, found that an increase in number of permanent magnets per unit of area in the track, will lead to stronger levitation forces. As for the guidance force, it was postulated that its major portion comes from the facets present in the gap between the superconductors. The size of this gap should be dimensioned taking into account the layout of the track’s permanent magnets, though, in some cases, a bigger gap should lead to higher guidance forces.

The final geometry developed during the “scale-up” process has superconductors whose size is almost identical to those used by the Maglev-Cobra’s levitation system. This allows the train to switch between track types, as only the cooling method must be changed.

The proposed solution offers an outstanding economical advantage. With a near identical investment cost in superconductors, the track cost was almost halved, allowing the saving of 702 million US dollars, as it does not employ a steel core to increase the magnetic field density. It also fairs better for the generation of a levitation force, due to clever magnet placement.

The operational costs were computed using a rather simplistic thermal model, which was not validated. However, if it holds true, the ZFC-Maglev consumes 27% less liquid nitrogen than the Maglev-Cobra. This adds to the economical advantage of the ZFC-Maglev, as it is expected that it will consume less liquid nitrogen.

The main disadvantage of the Portuguese solution is not being able to generate enough guidance force to reach the minimum value. Though it does reach two thirds of the minimum value, it does so at double the maximum lateral displacement distance.

Further studies need to be done concerning the consumption of liquid nitrogen by the levitation system, in order to obtain a better understanding of the operation costs involved in this type of magnetic levitation system. Using the data collected in this thesis and the thesis [8] a new FEM program may be developed to analyse the power losses of the system.

In regards to the guidance force, a possible solution might be the introduction of more or bigger permanent magnets in curves. Lateral permanent magnets will establish a new field over the lateral facets of the superconductors, allowing for better guidance force values. Alternatively, increasing the height of superconductors may also be done, as an increase in lateral area will also bring higher force values.

A second possible solution to the guidance force, is including a second type of cryostat whose superconductors are used only for guidance force generation, similarly to the T-shaped guideway presented in the State of the Art.

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REFERENCES
