# A New Passive Maglev System Based on Eddy Current Stabilization

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**In this paper, a new passive Maglev system is presented that is capable to levitate at a short distance from a dedicated guide. The magnetic suspension is assured by the repulsion of proper shaped permanent magnets that are present both on the fixed guide and on the moving suspended part. The presence of a conductive (aluminum) sheet that surrounds the magnets on the guide allows to overcome the intrinsic instability of the system when the suspended part is in relative motion with respect to the guide. The motional induced electric currents on the sheet interact with the magnets of the mover producing a stabilizing force. The detailed structure of the proposed system is described and the main results of the simulations by means of a hybrid electromagnetic FEM-MOM code coupled with the equation of motion of the rigid body are shown and commented.**

***Index Terms*—Finite element method (FEM), force computation, magnetic levitation, method of moments (MOM), moving conductors.**

## I. Introduction

Magnetic LEVITATION (maglev) systems are transportation systems that use vehicles which are levitated at short distance from a dedicated guideway by magnetic forces. These vehicles also use magnetic forces for noncontacting guidance and propulsion, and are able to reach speeds greater than 150 m/s (540 km/h).

Two main types of maglev transportation systems have been developed [1]. The first is based on a system of electromagnets that produce an attraction force between the vehicle and the guideway. In order to maintain a constant clearance between the vehicle and the rails, the system uses a servo-control mechanism which adjusts the electromagnets currents. The main limitation of this system is the potential unreliability of the servo-control system whose malfunctions would be extremely dangerous for the whole system. Furthermore, the electromagnets are very heavy and result in a more expensive structural design of the guideway.

The second type of maglev system is based on superconducting magnets and operates in repulsive mode with forces obtained by the interaction between the high magnetic field of a set of primary superconducting magnets and currents induced by the movement of the whole system on secondary coils properly positioned on the guideway. The main problem of such systems is the complexity of the cooling system required to maintain the correct cryogenic temperature of the superconducting coils, and the very high magnetic field in the passengers' compartment.

As an alternative to the previous methods, many authors tried to develop maglev systems based on the natural repulsive force of two oppositely magnetized permanent magnets. However, these attempts have been set aside due to problems with the intrinsic instability of passive magnetic systems as stated by the Earnshaw's theorem (1842) [2].

In a maglev system, the presence of conductors in relative motions suggests that the steady conditions on which Earnshaw's theorem is based can be overcome. It is then worth to investigate arrangements of permanent magnets and conductive bodies which, under the correct dynamical conditions, are characterized by a compensation of the unstable forces due to the permanent magnets with those related to the eddy currents.

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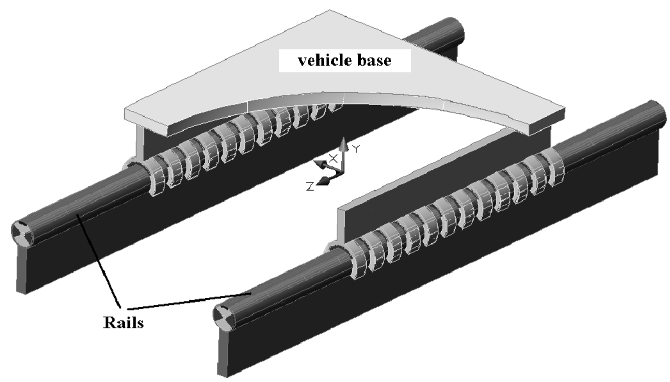


Fig. 1. Schematic representation of the proposed maglev system.

The coupled electromechanical analysis necessary to assess the dynamical stability of the system is a challenging task. In [3], the authors have investigated the effectiveness of a hybrid FEM/MOM formulation for eddy current problems with moving conductors and in [4] they have discussed a method for the determination of forces and torques that can be advantageously used in conjunction with the formulation in [3].

The equation of the motion of the rigid body expressed in terms of the coordinate of the center of gravity and of the Euler angles are coupled with the electromagnetic equation in order to evaluate the dynamical behavior of the system.

## II. The Proposed System

The proposed system is schematically represented in Fig. 1. A system of permanent magnets properly positioned on to the guideway forms the rails; each rail is surrounded by a conductive sheet. Another system of permanent magnets complementarily shaped with respect with those on the rail is placed on the vehicle.

Fig. 2(a) shows the magnetic structure of the rail and of a single unit of the vehicle. The rail is composed of a five Neodymium Ferro Boron (Nd-Fe-B) permanent magnets whose

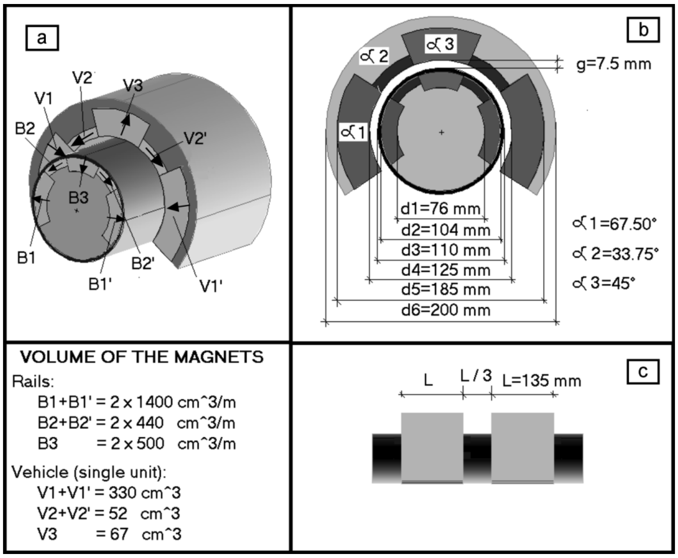


Fig. 2. Schematic representation of the proposed maglev system.

magnetization directions are shown by the black arrows. The magnets are mounted on a nonconductive nonmagnetic support and are surrounded by an aluminum sheet. The structure does not vary along the $z$-axis (i.e. the motion) direction.

The vehicle unit contains only permanent magnets whose magnetizations are opposite with respect to the direction of the correspondent magnet of the rail. The whole vehicle system is obtained by assembling together a number of single units calculated to counterbalance the nominal weight of the loaded truck levitating at a distance of about 7.5 mm over the rails.

Fig. 2(b) shows the dimensions of the system. Since the distance between two consecutive units influences the force along the $z$ and $x$ directions, these units need the correct separation from each other. The arrangement of the vehicle units along the $z$-axis direction is shown in Fig. 2(c).

The operation of the proposed system can be easily explained by the following considerations. Let us assume a configuration characterized by symmetry of the system with respect to the $y$–$z$ plane and with a uniform distance of the vehicle from the rail along the $z$-axis direction. This is an unstable equilibrium configuration when no relative movement exists between the rails and the vehicle.

If the vehicle moves with respect to the rail, an eddy current system takes place on the aluminum sheet in a region that is approximately located under the vehicle. These currents interact with the permanent magnet of the vehicle and the Lorentz forces act in order to reduce the cause that produces the eddy currents themselves. This is achieved by a velocity reduction but also by moving the source of the inducing fields (the permanent magnets) away from the conductive region. In correspondence of the assumed symmetry configuration the resultant of the forces is a braking force only. The force resultant in the $x$-axis direction is zero because of the symmetry and that in the $y$-axis combines with the levitation force.

If the symmetry condition does not hold, a net force appears along the $x$-axis. It is easy to recognize that this force is in the opposite direction with respect to the destabilizing force in the $x$-axis direction due to the permanent magnets. If we consider a displacement of the vehicle in the $x$-axis direction the vehicle would move in that direction and collapse on the rails. The eddy currents induced on the aluminum sheet are stronger on the side characterized by a reducing distance between the rails and the mover and are weaker on the other side where the distance is greater. The net resulting force is then directed along the negative $x$-axis direction.

The described stabilizing effect works as well as in the case of rotations. Let us consider a small rotation of the vehicle around the $y$-axis with the origin on the center of gravity. The head of the vehicle moves in the $x$-axis direction while the tail in the opposite direction. Points at intermediate positions are characterized by displacements that are proportional to their distances from the center of gravity. By repeating the same considerations we easily identify the torque of the forces between the induced currents and the permanent magnets as a stabilizing torque since it would produce a rotation in the opposite direction with respect to the one above assumed.

For the stabilization to be effective, the forces and torques due to the eddy current must be greater than the destabilizing forces and torques. This is the motivation for the choice of segmentation of the vehicle into a number of units. If the vehicle were an arrangement of permanent magnets with uniform constitution along the $z$-axis direction, the eddy currents would exist in correspondence of the edges of the vehicle only and their effect would not be sufficient to produce strong enough stabilizing forces and torques. The segmentation increases the active region of the rails involved in the production of these forces and torques. As a drawback, an increase in drag force in the $z$-axis direction results.

The results obtained by a commercial FEM code [5] able to take into account the motion with one degree of freedom have confirmed this qualitative analysis. In order to perform a deeper insight into the behavior of the system a dedicated numerical code has been adopted.

## III. Numerical Formulation

The formulation in [3] and [4] has been used to perform the electromagnetic analysis of the system and to evaluate the forces and the torques. The vehicle is considered as a rigid body whose motion is described in terms of the coordinates of the center of gravity and of the Euler angles.

Fig. 3 shows the simulated magnetic structure. The length of the rails is 25 m and their distance is 60 cm. The payload, not shown in figure, is a cube with edge of 1 m. The total mass of the moving part (including the magnets) is 500 kg.

Each rail is enclosed in a fictitious surface that coincides with the surface of the aluminum sheet. The magnets of the vehicle are enclosed in two further surfaces that are at rest one with respect to the other (as they are part of the same rigid body) but moving with respect to the rails. The velocity component of the center of gravity in the direction of the rails is assigned; the other two components, as well as the derivatives of the Euler angles are free and are governed by the rigid body dynamical equations.

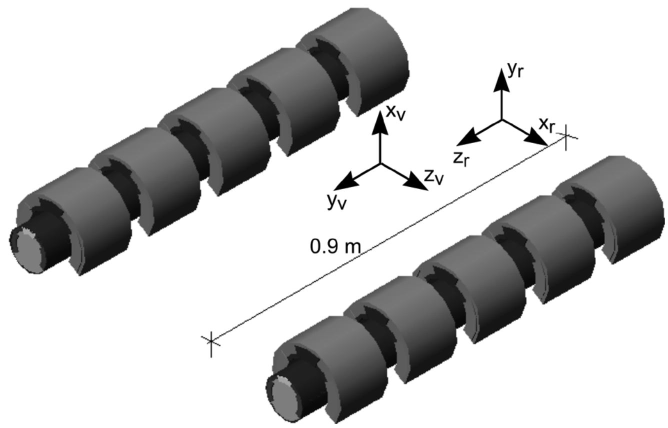


Fig. 3. The simulated magnetic structure.

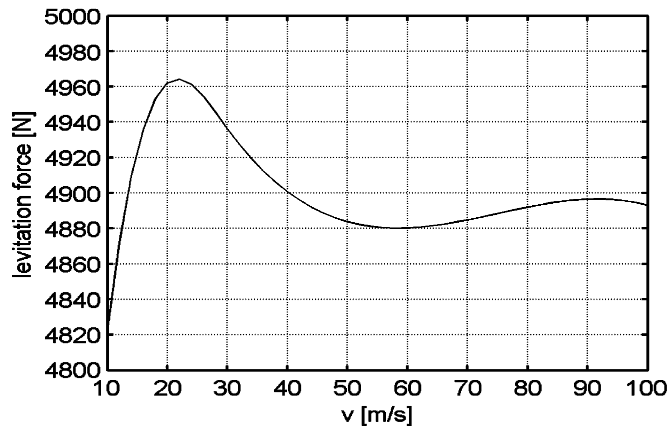


Fig. 4. Levitation force as a function of speed.

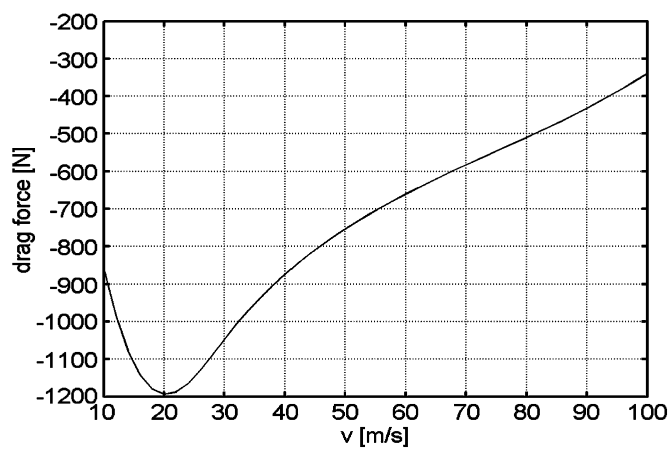


Fig. 5. Drag force as a function of speed.

By using the same notation as in [3], the governing equations can be written in the form

$$
\begin{aligned}
A_1\underline{H}_t + A_2\underline{I} &= K_1\underline{H}^{S,\mathrm{ext}} \\
C_1\frac{\partial}{\partial t}\underline{I} + C_2\underline{I} + C_3\underline{E}_t &= K_2\underline{B}^{S,\mathrm{ext}} + K_3\underline{E}^{S,\mathrm{ext}} \\
D_1(H)\frac{\partial}{\partial t}\underline{H} + D_2\underline{H} &= K_4\underline{E}_t^* + K_5\underline{H}^{S,\mathrm{int}}.
\end{aligned} \tag{1}
$$

The first two equations represent the continuity condition of the tangential component of the magnetic and of the electric fields on the four surfaces introduced above. The last is the Galerkin form of weighted residual relative to a FEM formulation in terms of edge elements for the magnetic fields $H$ inside the same surfaces.

In the present context, we observe that the terms $\underline{H}^{S,\mathrm{ext}}$, $\underline{B}^{S,\mathrm{ext}}$, and $\underline{E}^{S,\mathrm{ext}}$ that are due to independent current sources are zeros and the only source term is $\underline{H}^{S,\mathrm{int}}$ that depends on the magnetization of the permanent magnets. The elements of the matrix $C_2$ are functions of the relative velocity between the triangles belonging to the fictitious surfaces. In the case under study, the rails are fixed and the velocities of a point $Q$ on a surface attached to the vehicle can be expressed as

$$\boldsymbol{v}_Q(t) = \boldsymbol{v}_C(t) + \boldsymbol{\omega}(t) \times \boldsymbol{r}_{QC}$$

where $\boldsymbol{v}_C$ is the velocity of the center of gravity, $\boldsymbol{\omega} = (\omega_x, \omega_y, \omega_z)$ is the vector of the angular velocity, and $\boldsymbol{r}_{QC}$ is the vector from the center of gravity $C$ to the point $Q$.

Fig. 3 also shows the reference frames. Axes $x_r, y_r, z_r$ are attached to the rails and $x_v, y_v, z_v$ coincide with the principal axes of inertia with the origin on the center of gravity. The orientation of $x_v, y_v, z_v$ with respect to $x_r, y_r, z_r$ is expressed by Euler's angles. The angles corresponding to the (unstable) equilibrium position are $\vartheta = \pi/2$, $\psi = 0$, and $\varphi = \pi/2$. The governing equations of the motion of the rigid body around its center of gravity are

$$
\begin{aligned}
\mathcal{A}\frac{d\omega_x}{dt} - (\mathcal{B} - \mathcal{C})\omega_y\omega_z &= T_x \\
\mathcal{B}\frac{d\omega_y}{dt} - (\mathcal{C} - \mathcal{A})\omega_x\omega_z &= T_y \\
\mathcal{C}\frac{d\omega_z}{dt} - (\mathcal{A} - \mathcal{B})\omega_x\omega_y &= T_z.
\end{aligned} \tag{2}
$$

They are coupled with the equation of the center of gravity

$$M\frac{d\boldsymbol{v}_C}{dt} = \boldsymbol{F} \tag{3}$$

In these equations $\mathcal{A}$, $\mathcal{B}$, and $\mathcal{C}$ are the principal moments of inertia with respect to the principal axes $x_v, y_v, z_v$; $M$ is the total mass of the mover; $\boldsymbol{F} = (F_x, F_y, F_z)$ and $\boldsymbol{T} = (T_x, T_y, T_z)$ are, respectively, the total force and the total torque on the mover with respect to the $x_r, y_r, z_r$ axes.

The angular velocities expressed in terms of the Euler's angles are

$$
\begin{aligned}
\omega_x &= \frac{d\vartheta}{dt}\cos\varphi + \frac{d\psi}{dt}\sin\varphi\sin\vartheta \\
\omega_y &= -\frac{d\vartheta}{dt}\sin\varphi + \frac{d\psi}{dt}\cos\varphi\sin\vartheta \\
\omega_z &= \frac{d\psi}{dt}\cos\vartheta + \frac{d\varphi}{dt}.
\end{aligned}
$$

Initial conditions corresponding to the static magnetic configuration with all the velocities set to zero have been assumed. The component along the rails direction of the velocity is assigned and is kept constant during the motion. The vehicle starts moving with $v_x = v_y = 0$ and $\omega_x = \omega_y = \omega_z = 0$ from a perturbed position with respect to the (unstable) equilibrium configuration characterized by displacement in the $x$-axis direction $\Delta x = 3.5$ mm.

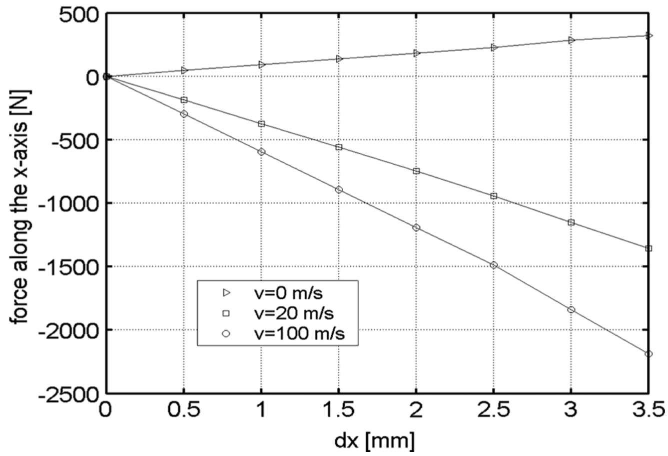


Fig. 6. Force in the $x$-axis direction as a function of the displacement of the mover in the same direction.

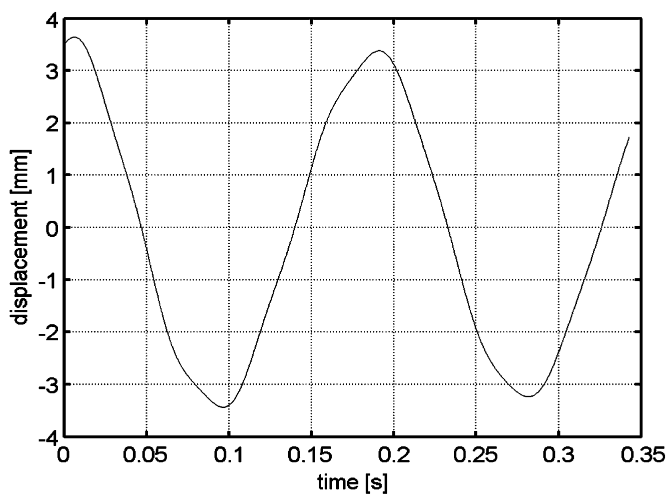


Fig. 7. Displacement of the center of gravity along the $x$-axis.

We integrate (1) between $t_k$ and $t_{k+1}$ assuming a constant velocity distribution in the interval. The newly evaluated currents are utilized for the force and torque calculation that will be employed in the integration of (2) and (3) to obtain the velocity at $t_{k+1}$. By (1), we can evaluate the current at $t_{k+2}$, and so on.

## IV. Results

We performed a number of simulations of the system at velocities in the range from $v_z = 10$ m/s to $v_z = 100$ m/s using time steps from 1 to 0.1 ms. Fig. 4 shows the resultant levitating force $F_y$ on the mover as a function of the speed when it translates maintaining a centered position. The force corresponding to a given speed has been obtained by averaging the $F_y(t)$ in correspondence to the time interval needed to cover 10 m. Fig. 5 reports drag force $(F_z)$ as a function of the speed obtained as before.

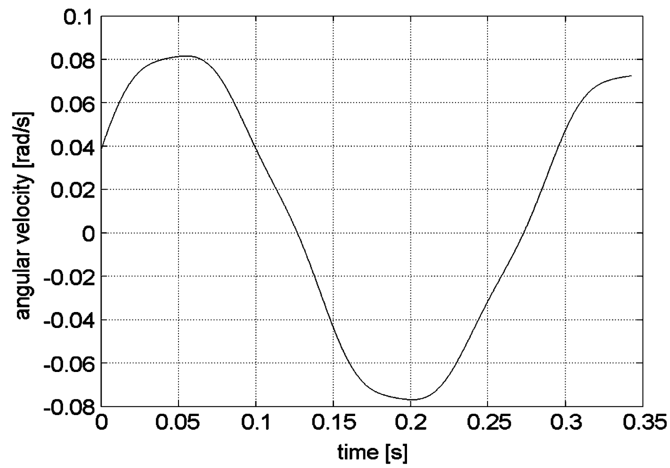


Fig. 8. Angular speed around the axis $y_r$.

Fig. 6 shows the component of the force on the mover as a function of the displacement in the positive $x$-axis direction. When the mover is at rest or the aluminum sheet is removed, the force has a destabilizing effect. On the contrary, also at relatively low speed the force has a stabilizing effect.

Fig. 7 shows the component along the $x$-axis direction of the displacement of the center of gravity of the vehicle evaluated at the speed of 70 m/s while Fig. 8 shows $\omega_y$, the angular velocity of the oscillations around the $y$-axis.

## V. Conclusion

A maglev system based on the repulsive forces between permanent magnets has been analyzed. The eddy currents induced on an aluminum sheet positioned around the permanent magnets on the guideway have been exploited to overcome the intrinsic instability of the system. The main drawback of the proposed system, consisting of a strong drag force, can be reduced by substituting the aluminum sheet with null flux coils.

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