Experimental Tests and Simulations to the Design of an Electrodynamic Bearing

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***Abstract*—This paper describes an electrodynamic suspension system built with permanent magnets and aluminum plates. Initially, a simple case was studied to demonstrate the behavior of the levitation and drag forces for different conditions, such as air gap, angular velocity and thickness of the aluminum target. In the second part, numerical and experimental tests were performed to design an homopolar electrodynamic bearing (EDB). Forces obtained with eccentric operation as well as different rotor radial velocities are presented.**

I. Introduction

A. Overview

Active magnetic bearings, based on electromagnetic attraction forces to establish the conditions for dynamic positioning, occupy much of the technical literature and industrial applications [1]. However, they require sensors, power electronics and controllers that are not necessary for the operation of electrodynamic bearings (EDBs). This magnetic levitation technology, based on repulsive forces, uses the same principle applied in the Yamanashi JR-MagLev test line [2]. A disadvantage of EDB is the force dependence with the operational speed, which must be carefully considered [3-6].

B. Basic Principle of the Electrodynamic System

When a constant magnetic field crosses a moving surface made of conductive material, induced currents are produced and flow in the conductor. The current amplitude is a function of the velocity, eccentricity, air gap, electric conductivity as well as the magnetic field distribution.

The interaction of the magnetic induction (B) and the current density (J) is described by the Lorentz force law, which is written as:

$$\vec{f} = \vec{J} \times \vec{B} \qquad (1)$$

The force density, f, has two components that are known as drag and lift forces. The first one acts against the rotational movement while the second one collaborates for suspension of the system. The force components should be optimized according to the objective. For example, drag force must be maximized in a brake system, while lift force is improved for a suspension system.

A levitation system can be designed by analytical calculus [7] or numerical modeling followed by experimental tests. The second method is chosen in this paper due to the facility given by finite elements simulation (FEM) to achieve an optimized system.

II. Disk-PM Case

A. Bench Characteristcs

A simple experimental system was constructed to illustrate the characteristics of the electrodynamic levitation as shown in Figure 1. The experiment has provided results for different conditions. Most of them are related to forces as function of the air gap, thickness, and speed.

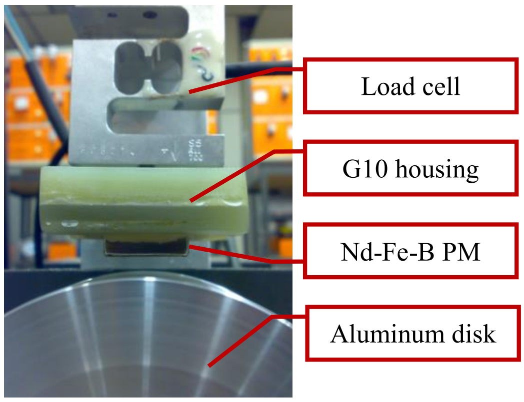

Figure 1. Experimental rig used for levitation and drag force measurements.

Table I presents the main parameters of the disk-PM bench, in which PM's magnetic flux was in the vertical direction. These values were also used to make numerical models, specifically, bi- and tri-dimensional models.

TABLE I. Disk-PM Parameters

Parameter	Value
PM Dimensions (mm)	25.4 x 25.4 x 12.7
Disk Dimensions (mm)	Φ150 x 40
PM Material	Nd-Fe-B N35
Disk Material	Aluminum

All simulations and experiments have considered different values for air gap, angular velocity and disk thickness (5 mm, 10 mm, and bulky disk).

B. Results

Experimental results have been used to validate bi- and tri-dimensional simulations. Figure 2 shows simulations as well as experimental results considering a 2 mm air gap, bulky disk and 30°C of temperature.

The curves in Figure 2 demonstrate that both numerical results tend to converge for high velocities, showing that bi-dimensional models are satisfactory in this case. Although tri-dimensional models seems to be more accurate, bi-dimensional represents less computer processing time. In the case of low velocities, tri-dimensional models seem to be mandatory.

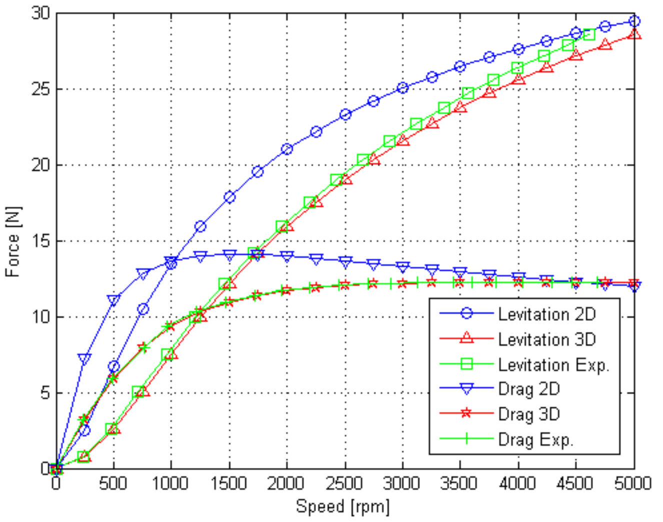

Figure 2. Levitation and drag forces for a 2mm air gap and bulky disk.

The system design must consider heat transfer, since temperature variations can reduce the system performance, and, in the worst case, damage the PMs.

In Figure 3 the drag and levitation forces are compared for temperature variation. The conclusion for this specific simulated case is that the levitation force is more sensible than the drag one. The levitation force decreases 78%, when compared initial (0 °C) and final (150 °C) temperatures, while drag force decays 40%. Therefore, the design of electrodynamic system must consider cooling factors. High temperatures affect the aluminum resistivity as well as the demagnetization of the permanent magnets.

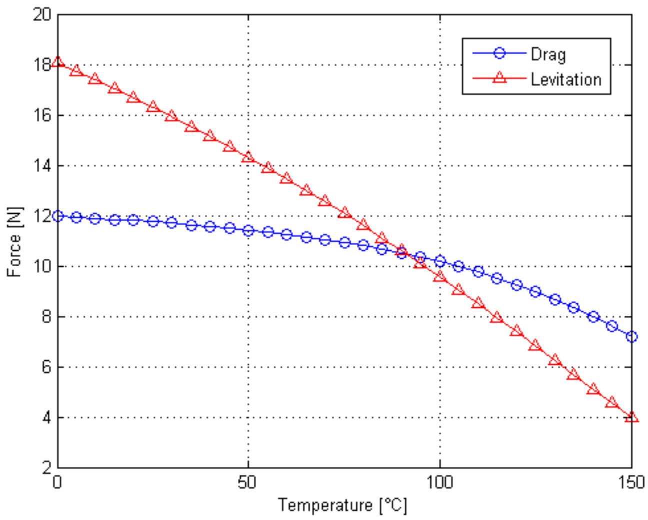

Figure 3. Simulated forces behavior with temperature for 2 mm air gap, 2,000 rpm and bulky disk.

The electrodynamic system is subjected to induced currents, and its amplitude is a function of the conductor parameters. When thickness is under analysis, it is possible to see a saturation value. In other words, the forces in a levitation system vary as a function of thickness while the skin depth (ζ) is not reached. If the thickness is higher than ζ, the force saturates and assumes a practically constant value.

The behavior of the electrodynamic forces with thickness shows that there is a specific thickness value, which can be chosen to optimize levitation force as well as conductor mass. Figure 4 shows simulated results of levitation force as function of thickness for different rotational velocities. In all four curves the saturation value can be seen, and it differs because the skin depth is dependent of the frequency. Therefore, the conductor thickness must be chosen for the required operation condition in order to guarantee a saturated operation. In the other hand, when the design is based on a brake system, drag force should be maximized, and then, thickness could be less than the skin depth.

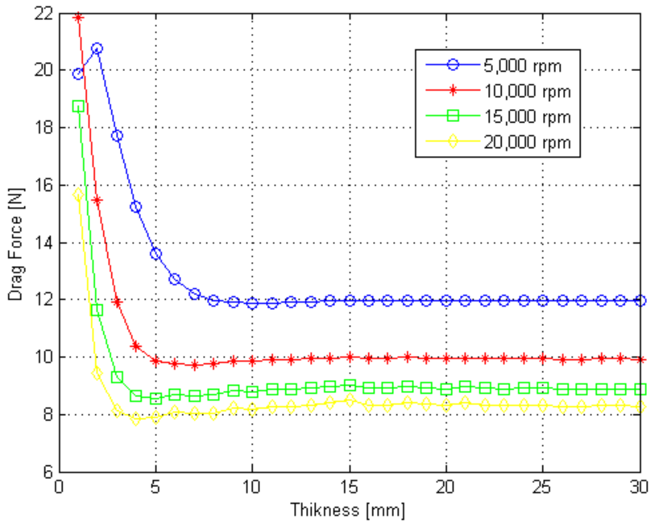

Figure 4. Simulated drag forces for a 2 mm air gap as function of thickness.

Figure 5 shows simulations of the levitation force curves for different disk thickness, from 1 to 30 mm. In contrary to drag force, levitation force increases for high thickness. Thus, an electrodynamic levitation system must have at least the skin depth thickness. In Figure 5, for example, the levitation force for a 20,000 rpm operation can be optimized with a 2.5 mm of thickness.

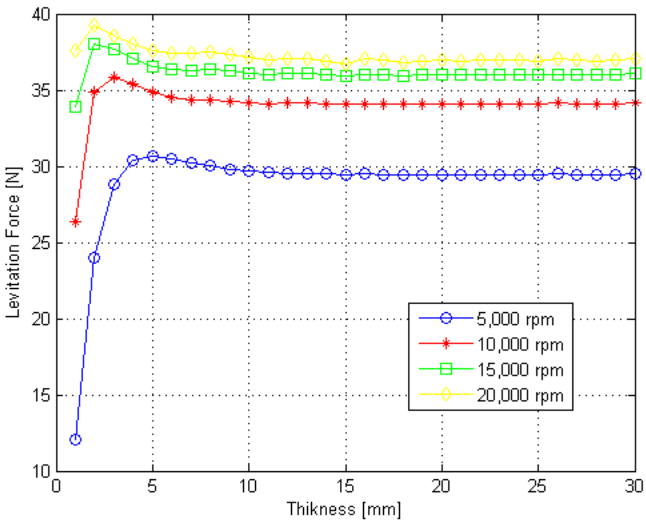

Figure 5. Simulated levitation forces for a 2 mm air gap as function of thickness.

III. HOMOPOLAR EDB

A. General Issues

The greatest advantage of radial homopolar EDB [4] is the low eddy current losses for centralized operation, since ideally no currents are induced in the rotor. In practice, permanent magnets (PM) are not perfectly magnetized and small eccentricities exist, departing from this ideal condition. Moreover, radially magnetized Nd-Fe-B rings are more expensive and difficult to produce than axially magnetized ones. Iron flux shapers can minimize these problems and are employed in this experiment, as shown in Figure 6. The PMs are axially magnetized and the flux shaper acts directing a radial magnetic flux. These flux shapers can be designed in order to optimize the radial magnitude of the magnetic field and maximize the stiffness and damping. Nevertheless, PMs with similar characteristics must be suitably selected.

The second challenge is to choose the ideal air gap that maximizes the levitation force and offers a secure operational condition.

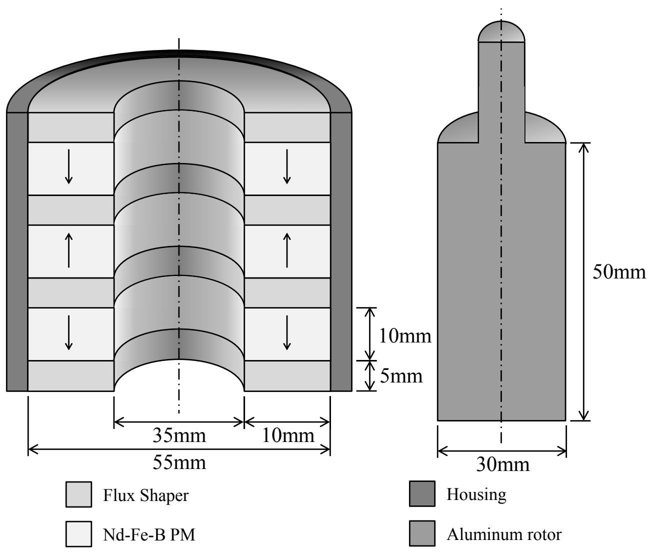

Figure 6. EDB stator and rotor section.

B. Experimental Bench

A second experimental bench composed by a CNC lathe, a force/torque sensor, and a data acquisition system was designed to measure the bearing forces as show Figure 7. The motor used is limited to 18,000 rpm. The positioning of the EDB rotor could be performed by the CNC lathe, which has tridimensional movement. Results have been obtained by sample average for each eccentricity and rotational velocity. By this way, it was possible to filter the noise.

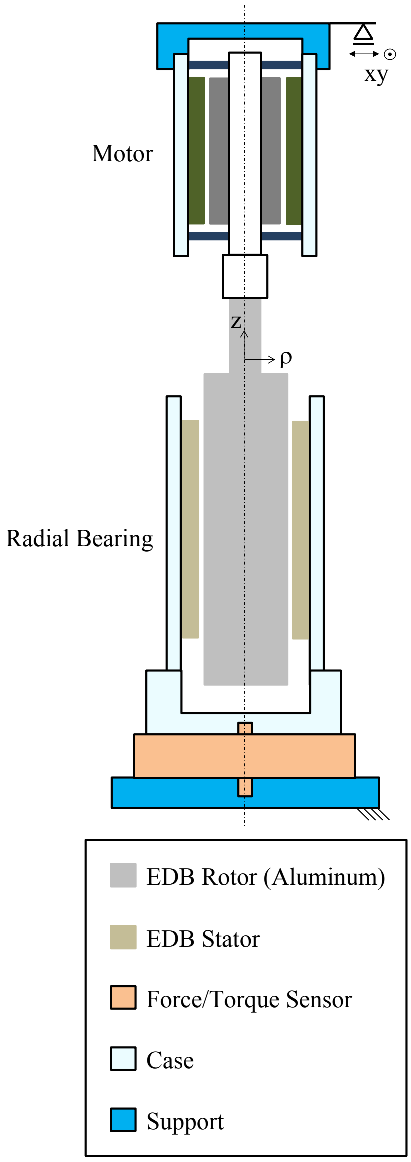

Figure 7. Representation of the experimental bench of the EDB.

Figure 8 shows the experimental bench during the tests. The EDB was built according to the parameters of Figure 6. An important characteristic of the homopolar bearing is low loss for centralized operation. This advantage can be noted in the linear force curves obtained for different eccentricities. The small deviations could be associated to losses. As shown in Figure 3, the forces decrease as temperature gets higher. Thus, as the system induces more current, greater is the loss and smaller are the forces.

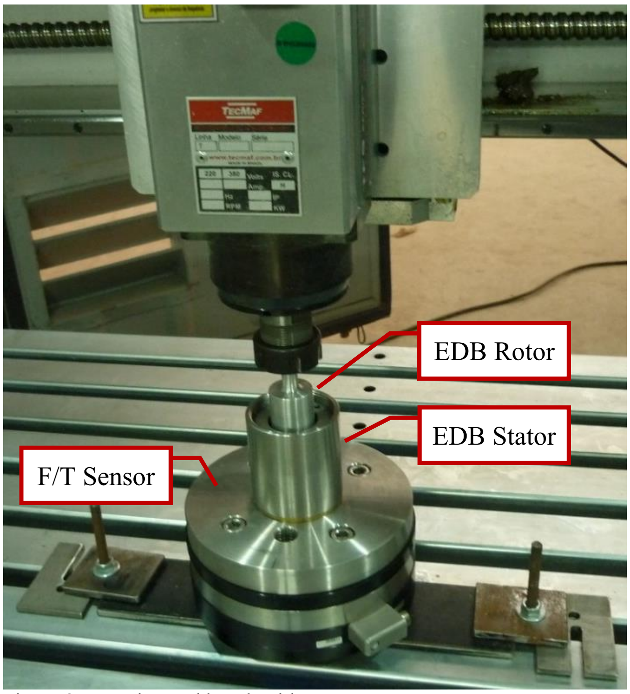

Figure 8. Experimental bench with EDB.

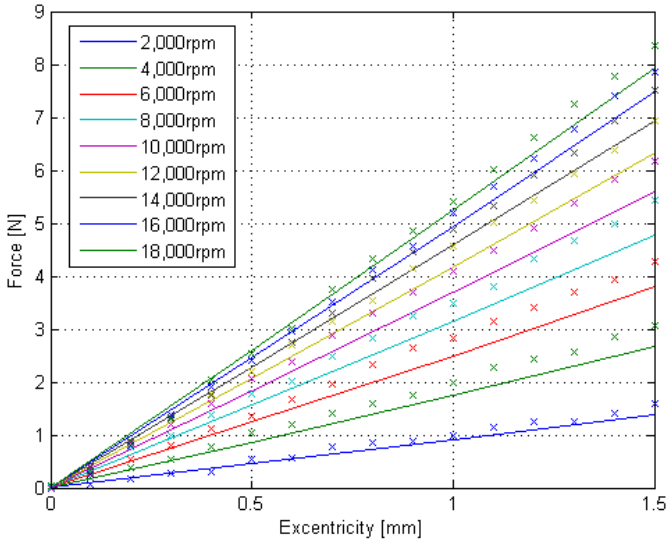

Figure 10. Drag force in the EDB rotor due to excentricity
(- numerical | x experimental).

Linear force behavior is also achieved when radial velocity occurs. Therefore, the mechanical parameters of the bearing are related to both conditions: eccentricity as well as radial movement, being stiffness a function of the first and damping to the second. Figure 11 shows lift force dependence with radial velocity.

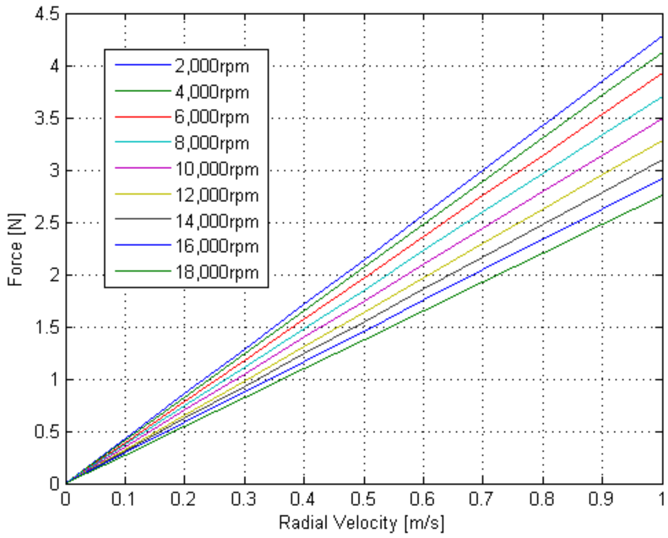

Figure 11. Simulated levitation force in the EDB rotor due to radial velocity.

Comparing levitation and drag forces associated with radial velocity (Figure 11 and Figure 12), it is noted that the last one increases with velocity while the first decreases. Therefore, the levitation damping of the EDB proposed decreases as speed gets high. In other way, drag damping increases with speed.

C. Results

The force values have been obtained varying eccentricity and angular velocity. The first by 0.1 mm steps, and the second by 2,000 rpm steps.

Figure 9 presents numerical and experimental results. In addition, the graphic shows the linear relationship with radial displacement revealing a constant stiffness for each rotation.

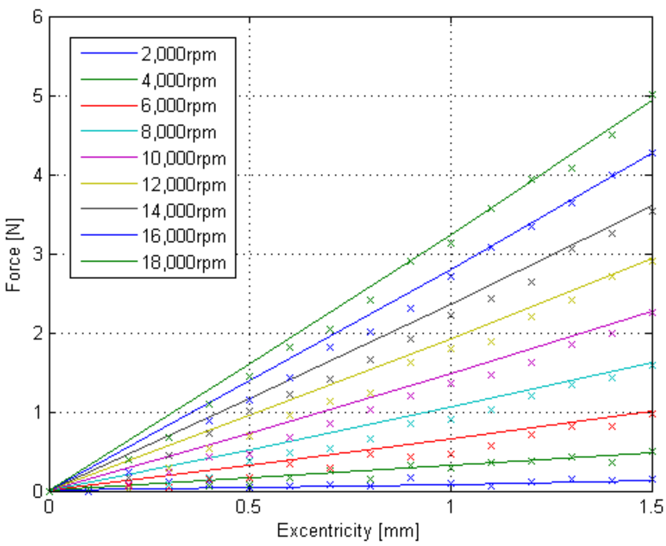

Figure 9. Levitation force in the EDB rotor due to excentricity
(- numerical | x experimental).

Unfortunately, the force does not act only in opposition to the displacement. There is another component, which is perpendicular to it. This one attributed to inductance of the system that delays the induced current, changing the resultant force angle. Therefore, the EDB has a singular characteristic. It has a levitation and a drag stiffness.

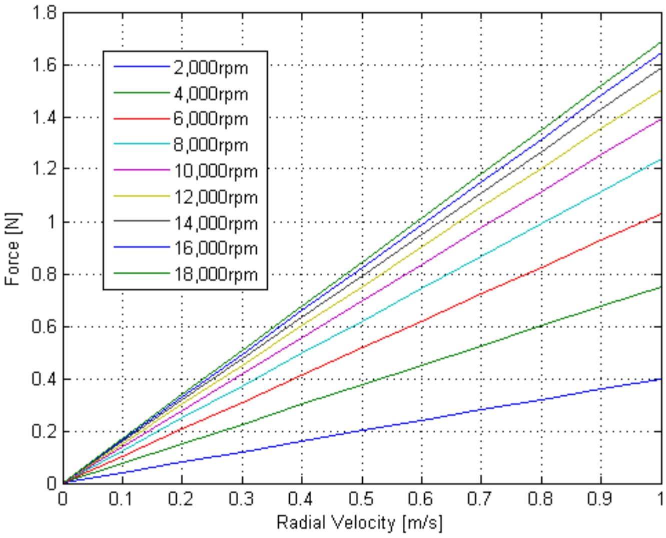

Figure 12. Simulated drag force in the EDB rotor due to radial velocity.

D. *Optimization*

Figure 13 shows numerical results for two EDB´s. One of them is based on the Figure 6 values and is called "Non-Optimized" system. The other one is called "Optimized" system. In this case, flux concentrators were dimensioned in order to maximize radial flux.

The flux concentrators for the optimized system have 6 mm width, and the rotor thickness adopted was 9 mm. This value could minimize rotor mass and has not affected forces amplitude.

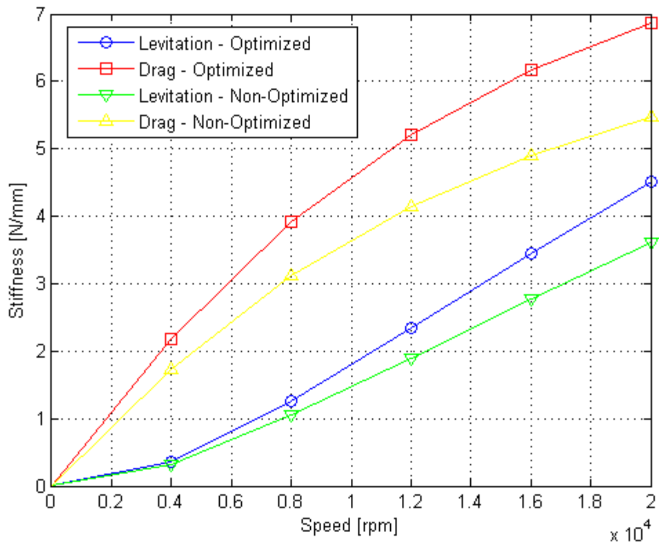

Figure 13. EDB stiffness for optimized and non-optimized system.

IV. Conclusions

The first part of this paper showed the possibilities and limitations offered by finite elements simulations to predict levitation and drag forces presented in electrodynamic magnetic bearings. Based on this knowledge, an electrodynamic bearing has been designed, constructed and tested. The advantages of an homopolar configuration were pointed out. Further investigation must be carried out to improve the forces magnitude.

V. Acknowledgments

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