A MICROCONTROLLED MAGNETICALLY-LEVITATING PLATFORM

Daniel Alves Borges[1], Gustavo Alex Zanata[2], José Wilson Lima Nerys[3], Bernardo Pinheiro de Alvarenga[4] and Enes Gonçalves Marra[5]

Universidade Federal de Goiás
Escola de Engenharia Elétrica e de Computação
Praça Universitária, s/n, Setor Universitário
74605-220 – Goiânia – GO - Brazil
1 – danielalbor@gmail.com
2 – gzanata@gmail.com
3 – jwilson@eee.ufg.br
4 – bernardo@eee.ufg.br
5 – enes@eee.ufg.br

***Abstract* – This paper presents the first stage of a project of a platform with a magnetic levitation system for didactic purposes and for demonstrating to non-specialists some applications in control systems and electromagnetic concepts. The definitive control system is to be implemented with an inner loop for the current and an outer loop for the position and controlled through a microcontroller. The power system is to be implemented using a half-H bridge with a 300 V dc link voltage. The platform is projected to bear masses up to 300 kg.**

***Keywords* – Electromagnet, MagLev, magnetic levitation, microcontroler.**

I. INTRODUCTION

Magnetic levitation is a frequently found subject in technical literature. Although magnetic levitation is applied to small objects, significant improvement might be done regarding the positioning control accuracy [1, 2].

Magnetic levitation, which means no contact between the moving object and the fixed part, is suitable tool for micro machines because mechanical friction decreases significantly, improving resolution and accuracy of the positioning device. The main disadvantage of levitation is that the system is inherently unstable hence feedback control is usually required for stabilization [3].

There are three groups of magnetic levitation [4]. First there is the electrodynamics levitation system that consists in a magnetic material realizing relative movement from a flat conductor. Parasite currents will be induced on the conductor and these currents will generate a contrary magnetic field by the Lenz Law. The interaction between these bodies will generate a magnetic pressure and then a magnetic repulsive force on the magnetic material. Another kind of magnetic levitation system is the superconductor levitation that is based on superconductor materials and extra refrigeration systems.

Finally we have the electromagnetic levitation systems. The most common method for magnetic levitation is based on the utilization of electromagnets. An electromagnet is a device similar to a permanent magnet controlled by electric current in order to produce magnetic forces controlled by electric currents [5].

A magnetic levitation system largely known is the MagLev (***Mag**netic **Lev**itation*). The MagLev is a kind of transportation system for heavy masses where the friction with the ground is almost absent, implemented through repulsion or attraction electromagnetic-forces caused by devices with electromagnetic properties [6].

The main aim of the proposal herein presented is to implement a demonstrative didactic platform on electromagnetic levitation and feedback control systems.

II. MAIN SCHEME

The main structure of the system is composed of a platform containing 4 electromagnets on their edges, which are able to support up to 300 kg. The platform is to be levitated by electromagnetic attraction forces between the electromagnets and a FeSi trail located above the platform.

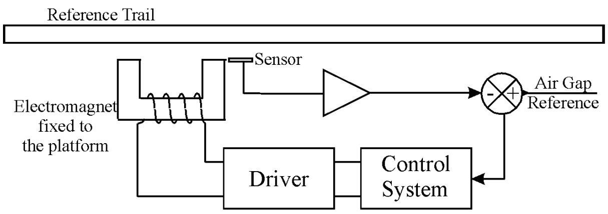

Fig. 1 – Main scheme of the control system.

The attraction force is produced by electromagnets supplied with direct current. The air gap between the platform and the trail is adjusted based on the positioning-sensor and Hall-Effect current-transducer signals. Fig. 1 shows the simplified scheme of the control system. Although it is not shown in the main scheme of fig. 1, there is an inner loop for the dc-current control.

III. MATHEMATICAL MODEL FORMULATION

The electromagnets are set up as FeSi “U-shape” cores, as presented in fig. 2.

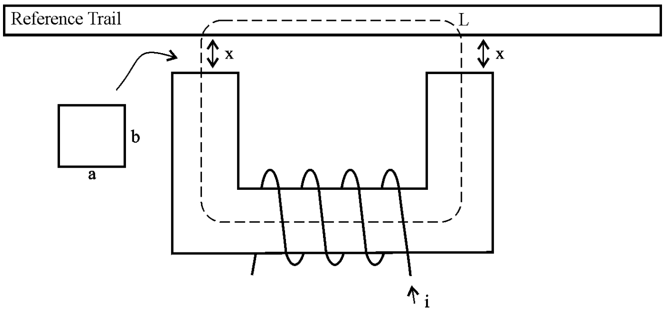

Fig. 2 – Electromagnet structure details.

The expression for the attraction force is a function of the number of turns of the coil. The direct current through the coil and the air gap between the platform and the reference trail are related according to Ampère's Law, as follows:

$$\oint H \cdot dL = N\,i\,. \tag{1}$$

H is the magnetic field intensity (A/m), dL is the differential element of length (m) through the magnetic-field path, N is the number of turns of the coil and i is the electric current through the coil (A).

Considering that the iron is not saturated and its magnetic permeability is much greater than that of the air, the flux paths through the iron can be neglected, yielding:

$$H \cdot 2x = N\,i \;\therefore\; H = \frac{N\,i}{2x}\,. \tag{2}$$

Where x is the length of the air gap. The magnetic flux density, B (T) is:

$$B = \mu_0\, H\,. \tag{3}$$

Where μ_0 (H/m) is the air magnetic permeability.

The magnetic flux, ϕ (Wb) through the cross section A (m^2) of the core is given by the following expression:

$$\phi = \oint_A B \cdot dA \;\therefore\; \phi = B\,A\,. \tag{4}$$

The flux linkage λ, which flows through the reference trail, is:

$$\lambda = N\,\phi\,. \tag{5}$$

The inductance L (H) is given as the ratio between the flux linkage and the electric current through the coil:

$$L = \frac{\lambda}{i}\,. \tag{6}$$

The electromagnetic energy stored in the electromagnet is:

$$\omega = \int_0^{\lambda} i \cdot d\lambda \;\therefore\; \omega = \frac{1}{2} i\,\lambda\,. \tag{7}$$

The attraction force F generated on the electromagnet is given by:

$$F = \frac{d\omega(x)}{dx}\,. \tag{8}$$

Thus, after the appropriate arrangements of expressions (2) to (8), the attraction force is written as:

$$F = \frac{\mu_0\, A}{8}\left(\frac{N\,i}{x}\right)^2. \tag{9}$$

In order to take into account the magnetic flux dispersion in the air gap [7], the cross-section area is modified to:

$$A_T = (a + x)(b + x)\,. \tag{10}$$

Where a and b are the lateral length of the core. Thus, the attraction force expression is derived replacing (10) into (9):

$$F = \frac{\mu_0\, A_T}{8}\left(\frac{N\,i}{x}\right)^2 \tag{11}$$

IV. PRELIMINARY TESTS

Table I points out the characteristics of the prototype used for the first experimental tests and fig. 3 shows a picture of the electromagnetic prototype.

Fig. 4 exhibits the force as a function of the current in the coil, for different number of turns, obtained by calculation from (11). The air gap (x) is kept in 5 mm and the gravity acceleration is considered to be 9.8 m/s^2. The higher is either the number of turns or the current through the coil, the higher is the produced magnetic force.

TABLE I
Electromagnet Physical Characteristics

Dimensions			
Length	**Height**	**Width**	**Interspace**
98 mm	94 mm	22 mm	54 mm
General Characteristics			
Number of Turns	**Air Gap**	**Core Material**	
Variable (250 – 3000)	Variable	FeSi laminated	

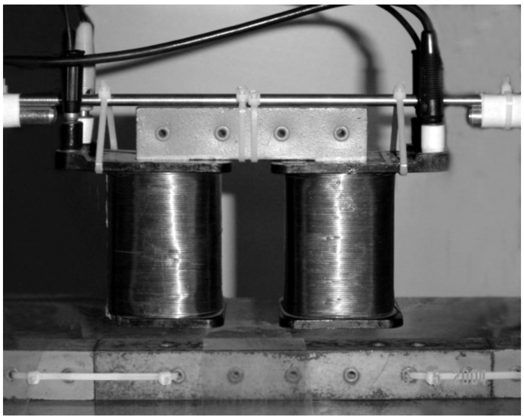
Fig. 3 – Electromagnet prototype used for experimental tests.

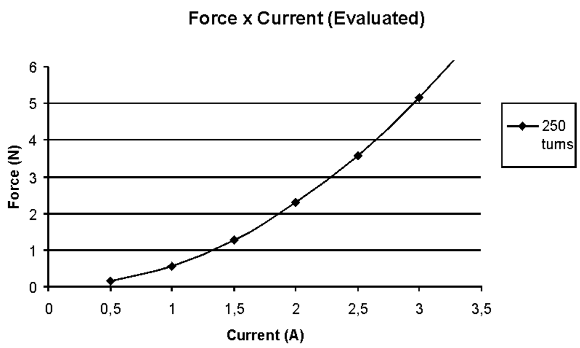

Fig. 4 – Evaluated force as a function of applied current

Table II and fig. 5 present preliminary experimental results obtained from the system shown in fig. 3. The air gap is 5 mm and it is used a 250 coils electromagnet.

TABLE II
First Test

Current (A)	0,5	1,0	1,5	2,0	2,5	3,0
Force (N)	0,147	0,559	1,254	2,254	3,616	5,410

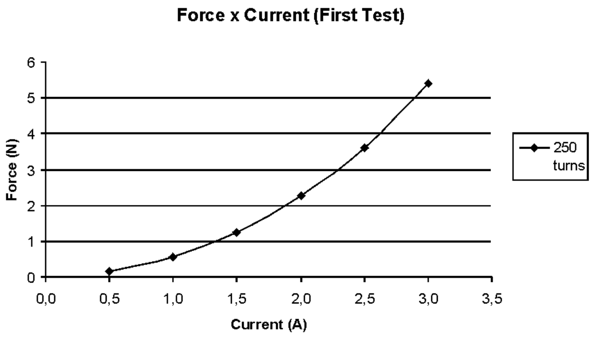

Fig. 5 – Force as a function of applied current experimentally obtained (250 turns and air gap of 5 mm).

The comparison between the results obtained from mathematical computations and experimental measurements for force resulted in a relative error of about 0.5%, which indicates a satisfactory model validation to project a larger scale electromagnet for the magnetic levitation system. From expression (11), it was verified that a current of 3.5 A, applied to an electromagnet of 3000 turns is able to levitate a mass of about 86 kg, for a 5 mm air gap.

V. THE LARGER SIZE ELECTROMAGNET

From the previous results, it was decided to implement an electromagnet with 3000 turns in order to allow the levitation of a relatively heavier mass with a suitably selected electric current. The dimensions of the designed electromagnet are shown in fig. 6. It has to embed 3000-turn coil of 14 AWG isolated wires fixed on the bottom of the platform.

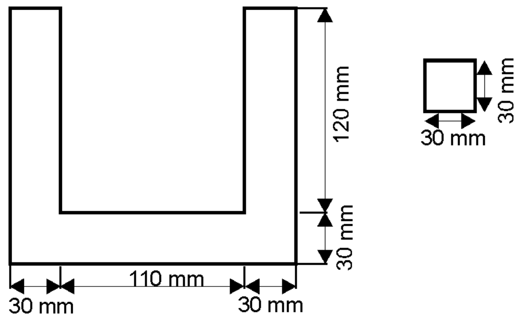

Fig. 6 – Lager size electromagnet design-characteristics.

As the electromagnet characteristics were defined, some calculations were carried out to estimate the mass the system is able to uphold under different values of air gap. The results are pointed out in table III and fig. 7. It can be noticed that it is possible to levitate a mass of about 86 kg with a current of 3.5 A and an air gap of 5 mm and a mass of 16 kg for the same current, but an air gap of 15 mm.

Table III
Calculus for the definitive Electromagnet

Air Gap of 15 mm			Air Gap of 10 mm		
Current (A)	**Force (N)**	**Mass (kg)**	**Current (A)**	**Force (N)**	**Mass (kg)**
0.5	3,18	0,32	**0.5**	5,65	0,58
1.0	12,72	1,30	**1.0**	22,62	2,31
1.5	28,63	2,92	**1.5**	50,89	5,19
2.0	50,89	5,19	**2.0**	90,48	9,23
2.5	79,52	8,11	**2.5**	141,37	14,43
3.0	114,51	11,68	**3.0**	203,58	20,77
3.5	155,86	15,90	**3.5**	277,09	28,27
4.0	203,58	20,77	**4.0**	361,91	36,93
4.5	257,65	26,29	**4.5**	458,04	46,74
Air Gap of 7.5 mm			**Air Gap of 5 mm**		
Current (A)	**Force (N)**	**Mass (kg)**	**Current (A)**	**Force (N)**	**Mass (kg)**
0.5	8,84	0,90	**0.5**	17,32	1,77
1.0	35,34	3,61	**1.0**	69,27	7,07
1.5	79,52	8,11	**1.5**	155,86	15,90
2.0	141,37	14,43	**2.0**	277,09	28,27
2.5	220,89	22,54	**2.5**	432,95	44,18
3.0	318,09	32,46	**3.0**	623,45	63,62
3.5	432,95	44,18	**3.5**	848,58	86,59
4.0	565,49	57,70	**4.0**	1108,35	113,10
4.5	715,69	73,03	**4.5**	1402,76	143,14

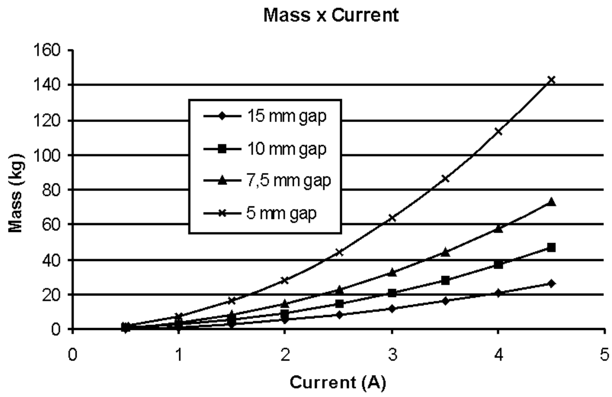

Fig. 7 – Mass as a function of applied current for the definitive electromagnet

Fig. 8 shows the implemented electromagnet and fig. 9 shows the mass × current characteristic for a 150 V dc link and an air gap or 5 mm.

Fig. 8 – The Electromagnet

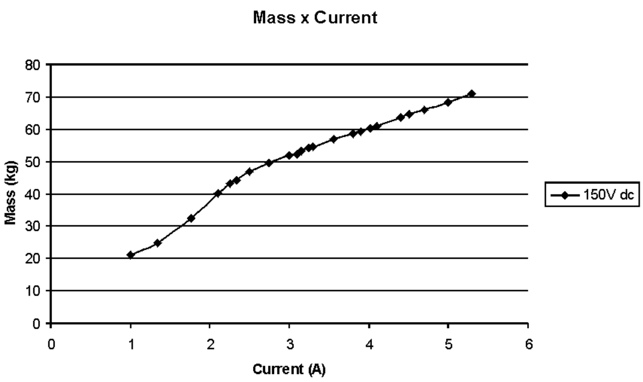

Fig. 9 – Mass × Current Characteristic for a 150V dc link

VI. THE CONTROL SYSTEM

The power system that has been under implementation uses a half-H bridge configuration, as shown if Fig. 10. This configuration has been chosen because it allows a fast change in current when both switches (A and B) are simultaneously closed and when they are simultaneously opened.

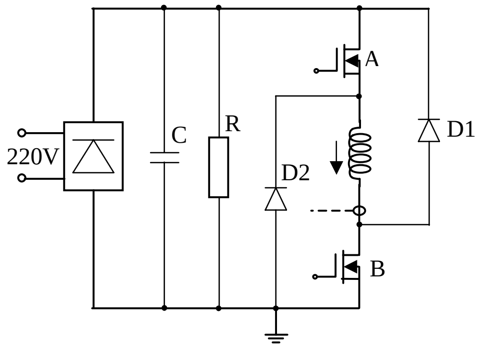

Fig. 10 – Half-H bridge for the power system

Fig. 11 shows the first part of the power system that was implemented. It contains the integrated circuit IR2110 that is used to drive the pair of switches, and that it is not present in Fig. 10.

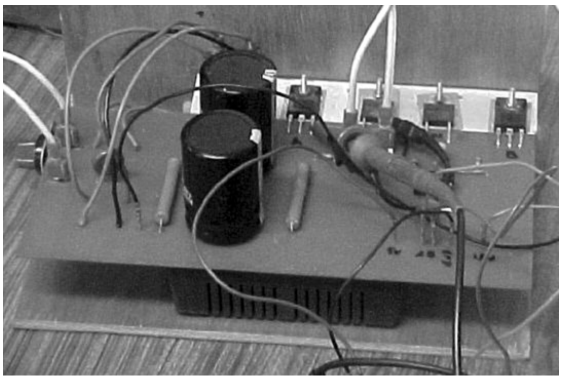

Fig. 11 – Implemented Half-H bridge

The mass × current characteristic depicted in Fig. 9 was obtained using the implemented half-H bridge of Fig. 11. The reference signal to drive switches A and B was generated by an 8051 microcontroller at a switching frequency of about 3.5 kHz. Fig. 12 is a sample of the voltage waveform applied to the electromagnet in order to obtain the mass × current characteristic shown if fig. 9.

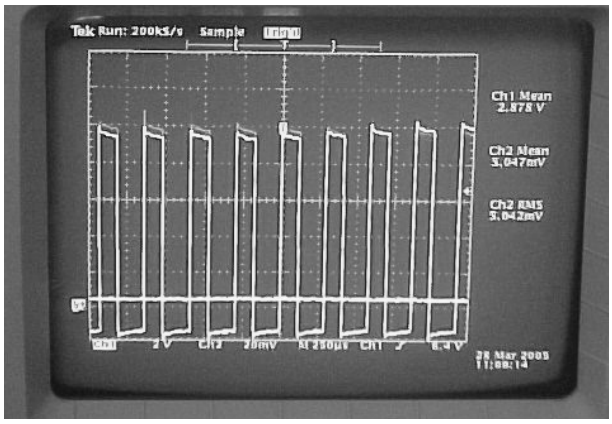

Fig. 12 – Voltage waveform applied to the electromagnet

The control system has been under study. The main concern in the present stage is about the positioning sensor, which was not chosen yet. The signal from this sensor is to be compared with the position reference signal to generate the reference for the current. The effective current is achieved through a Hall-effect current transducer. The current controller is to be implemented using a hysteresis control so as to allow the necessary fast adjust in current.

The control algorithm is under development and it is to be processed by a microcontroller. The future tests will indicate whether or not it will be necessary the use of a digital signal processor.

VII. CONCLUSION

In this first stage, the first experimental tests toward the implementation a larger-size electromagnet prototype to levitate a platform with approximately 300 kg were carried, in order to attest the technical feasibility of the scheme.

The final purpose of the project is to achieve a system able to bear a person whose weight reaches up to 100 kg under reliable and secure conditions, in order to accomplish a real scale demonstrative prototype where any non-specialist person will be able to experience the effects of magnetic levitation. Such a system is intended to be used as a show room in expositions, technical and scientific fairs as well as a didactic structure to teach control theory and electromagnetic fundamentals.

The final version of the work will bring additional experimental results and formulation details on the control system of the real scale set-up.

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