MAGNETIC LEVITATION CONTROL SYSTEM OF A STEEL BALL BASED IN A MICROCONTROLLER.

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Abstract. *Researches about magnetic levitation are being developed in several places of the world. This issue has a large scientific interest since their concepts are now utilized in diverse areas like magnetic bearings for electric motors and high speed transport systems - "MAGLEV". In both cases, one of the main advantages of the use of these concepts is the reduction of friction losses. Nevertheless, due to the instability of magnetic forces, the design of controllers becomes necessary to maintain in equilibrium point one levitated object. In this work, the design and implementation of an educational prototype of magnetic levitation will be shown. This consists of an electromagnet, a steel ball and a digital control system based in a microcontroller. Simulation and experimental results of this prototype are shown.*
Keywords: *Eletromagnet, Digital Controller,* Microcontroller

1. INTRODUCTION

The beginning of the magnetic levitation has been researched from middles of last century, contributing with the progress of several engineering areas, as in systems of high-speed transport MAGLEV(www.maglev.com); in the levitation of axes of motors through magnetic bearing (Schweitzer, 1994); in the construction of an artificial heart, as described by Schoeb and Dasse (2001), among other applications.

One of the first works proposed in this area was elaborated by Laithwait(1965), where repulsive magnetic force is used for the levitation, unlike Jayawant(1968), that uses attractive magnetic force to maintain the object floating.

In summary, to stay an object floating in the air, it is necessary to find a way to cancel by force of the gravity that acts on the same. If this object possesses in its iron-magnetic material composition, the application of a magnetic field, in such a way that produces in the object a force of same intensity and contrary direction by force of the gravity, will do with that the object floats in the air.

The magnetic suspension system used in this work was projected according Hurley(1997, 2004) and it is constituted basically by an electromagnet, a sensor of position, feeding sources and a controller to stabilize the position of a suspended sphere of steel in the air. The Fig.1 exhibition the outline of this system.

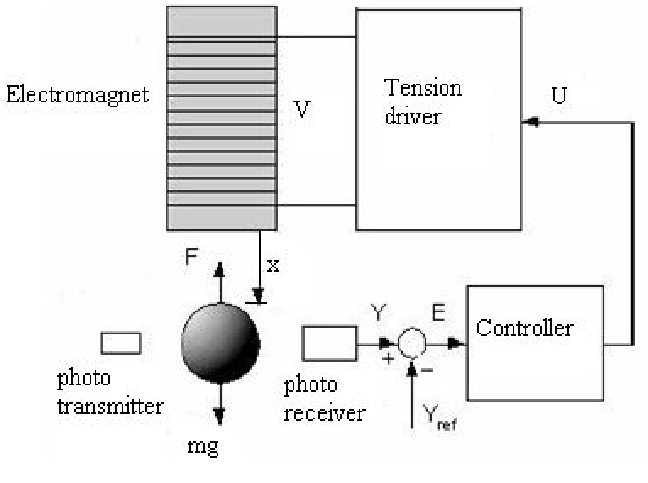

Figure 1. System of magnetic levitation

The operation is quite simple: a photo-transmitter is aligned with a photo-receiver so that the shade produced by the object, in the case a sphere of approximately 28,6mm of diameter and mass (m) equal 95,5g, will produce an electric sign that will indicate its position (Y). The mistake sign (E), that is the difference among the position of the sphere (Y) and the reference sign (Yref), it will be used by the controller so that, through a control sign "U " applied to the tension driver, can make to vary the tension " V " applied to the electromagnet, producing an alteration by force of attraction (F) of the electromagnet to annul the weight of the sphere (mg); make the sphere is floating at a distance (x) of the reel.

In this work it opts for using a control system for tension applied to the electromagnet, different from the traditional controls for current. This system type is characterized by the need of larger precision in the project of the plant. The main area of application of the control for tension is in systems of transport type MAGLEV.

2. DESCRIPTION AND PROJECT OF THE PROTOTYPE

2.1. Description of the prototype

A schematic drawing of the support of the reel meets in the Fig.2. In the nomenclature of the geometric parameters, presented to proceed, it is denominated of window to the straight section of the cylindrical space destined to the coil.

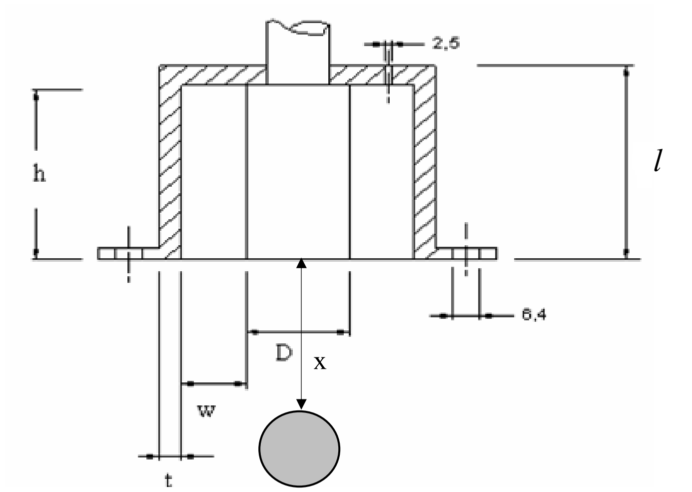

Figure 2. Draw schematic of the coil.

Where the parameters of the system sphere-coil are:

- Diameter of the sphere: *Desf = 28,6mm*
- Mass of the sphere: *m = 95,5 grams*
- Constant of length (*Desf* / 9): *the = 3,18 mm*
- Area of the traverse section of the copper thread: *Aw = 0,5 mm2*
- Diameter of the center: *D = 23,0 mm*
- Width of the window: *w = 14,5 mm*
- Height of the window: *h = 45,0 mm*
- Thickness of the coating: *t = 5,0 mm*
- Diameter of the thread of standard copper AWG: *dw = 0,72 mm*
- External diameter (2*t*+2*w*+*D*): *Dext = 62,0 mm*
- Larger height: *l = 60,0 mm*
- Turns number: *N = 832*

For the action of control of the sphere's position electronic circuits were developed to help the magnetic coil and a sensor of position of the optical type. Besides the reliability approach, the readiness was also contemplated, in the national market, of all the used components.

The characteristic equation of the system (Gp), according to Hurley(1997), it will be:

$$G(p) = \frac{X'(s)}{I'(s)} = \frac{-\frac{2}{I}}{\frac{s^2}{g} - \frac{1}{a}} \quad . \qquad (2.1)$$

Where g, $X'(s)$, $I'(s)$ and I represents, respectively, the acceleration of the gravity (9,8 m/s2), the instantaneous position of the sphere (*mm*), the instantaneous current in the coil (*A*) and the current in the equilibrium point *(A)*.

Considering w_n the natural frequency of the system:

$$w_n = \sqrt{g/a} \ ,$$

Obtaining:

$$\frac{X'(s)}{I'(s)} = \frac{-2g/I}{s^2 - w_n^2} \quad . \qquad (2.2)$$

As a = 3.178mm, the value of the natural frequency of the system will be w_n = 55,51 rad/s.

The equation (2.2) it is the transfer function of the plant which relates the relative position of the sphere with the control current applied in the electromagnet.

Substituting numeric values, the transfer function is:

$$\frac{X'(s)}{I'(s)} = \frac{-\frac{2g}{I}}{s^2 - 3081,4} \qquad (2.3)$$

The equilibrium position will be determined being analyzed the curve of the sensor, shown in the Fig.3, where Vs is the tension of exit of the sensor in Volts and x it is the distance of the sphere to the coil in mm.

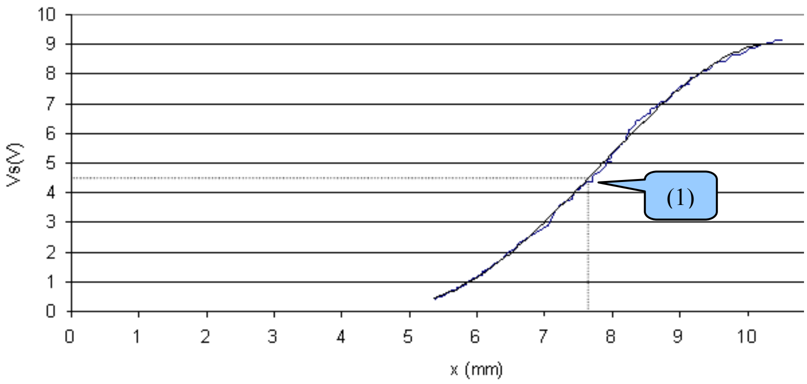

Figure 3. Curve of de sensor. Equilibrium point: x = 7,85 mm and Vs = 4,85 V (1)

Analyzing of the graph allows to establish that the area of high sensibility meets between the positions 5,4mm and 10,2mm and the values of the curve, out of this strip, they are in a constant landing of approximately 0V or 9V.

This sensibility area indicates that is convenient to establish the balance position as of 7,85 mm, the position corresponding to the medium tension, in the linear area of the curve.

2.2. Determination of the values of current and of tension of equilibrium

With the establishment of the balance position, it is also possible to determine experimentally the values of the current and of the electric tension in the equilibrium point.

For this a plate was made of acrylic with a thickness corresponding to 7,85 mm. Fastening this plate in the inferior part of the coil and with the aid of an electric source and a multimeter, was determined the value of the electric current and of the tension that maintains the sphere in the equilibrium position, as it is demonstrated in the Fig.4.

The procedure consists of applying an enough electric tension so that the sphere is "glued " in the plate of acrylic. Starting from there, it decreased the value of the tension applied to the coil slowly and with the aid of two multimeters (one to measure the electric tension and another to measure the current) the values were measured in the exact moment in that the sphere comes off of the plate. After several mensurations, the were following values were obtained for the current and balance tension:

Equilibrium current: $I = 1,17$ A (2.4)

Equilibrium tension: $V = 7,14$ V (2.5)

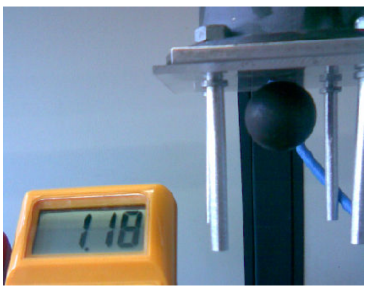

Figure 4.Experimentation to determine the current and the tension values in the equilibrium position.

As in this project it opted for implementing a control system with tension imposition, it should meet a transfer function that relates the displacement x with the tension of control v'.

The Fig.5 represents the equivalent circuit of the coil for small displacements and thus, the equation of the circuit is as:

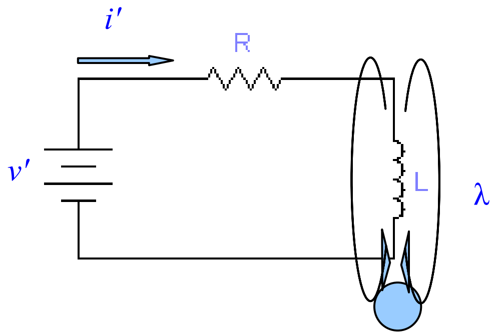

Figure 5. Equivalent circuit of the coil

$$V = Ri + d\lambda/dt. \tag{2.6}$$

Where R represent the resistance of the coil and λ does it represent the magnetic flow connected by the coil, being $\lambda=Li$, where do L and i represent the inductance and the current of the coil.

Expanding the equation (2.6) is had:

$$V = Ri + d(Li)/dt,$$
$$V = Ri + L\, di/dt + i\, dL/dt,$$
$$V = Ri + L\, di/dt + i\, (dL/dx)(dx/dt). \tag{2.7}$$

Admitting that around the operation point the controller is capable to maintain the object levitating in a fixed position, the third term of the equation (2.7) can be considered null. However, considering the transitory regime to arrive to the equilibrium point, this term can also be considered as a disturbance of applied tension to the resistance R and inductance L. With this in mind and, defining the tension of control v´ = V - Vo, with Vo being the equilibrium tension, equals I*R, will be considered, for effects of the position controller's project, the equation (2.8):

$$v' = R\, i' + L\, di'/dt. \tag{2.8}$$

Therefore, applying it transformed of Laplace it is had:

$$I'(s) = V'(s) / (sL + R) \tag{2.9}$$

How R= 5,6 Ω e L = 120 mH and considering the block diagram model of the levitation system with electric tension control is as shown in the Fig.6.

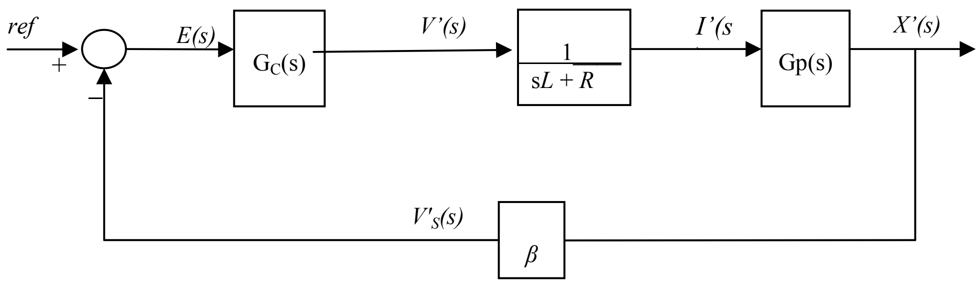

Figure 6. Block diagram model of the levitation system with electric tension control

Where Gc(s) and Gp(s) there are the transfer functions of the controller and of the plant to be controlled, respectively. Gp(s) it is given by the equation (2.2).

Considering a sensor of position gain β and a reference of position *ref* the same to zero, the transfer function of the system to be controlled, including the sensor, is given by:

$$V'_s(s)/V'(s) = \frac{-16,77.(\beta / L)]}{(s + R/L).(s+55,51).(s-55,51)} \quad . \tag{2.10}$$

Where $V_s(s)$ it represents the tension of exit of the sensor in the position x' and $V'(s)$ it represents the control tension in the entrance of the reel.

For the determination of the gain of the sensor, the curve of the sensor was re-done in such way that the maximum tension didn't surpass 5V, that is the tension limit in the entrance of the A/D converter of the used microcontroller (AVR Atmega16). This way, a new gain of the sensor was determined starting from the new curve, shown in the Fig.7, given by inclination of the curve.

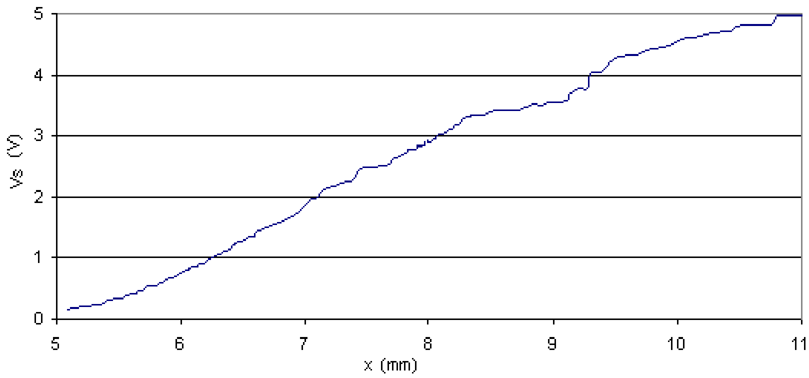

Figura 7. Gráfico expandido da área de alta sensibilidade.

As, in the equilibrium position $x=7,85mm$ and $Vs=2,24V$,

$$\dot{y}\,(7,85mm) = 0,785\ V/mm = 785\ V/m \tag{2.11}$$

These values can, eventually, suffer alterations because of influence of external luminous sources, since they were measured in a laboratory atmosphere, with closed window.

This gain of the sensor was considered valid for a variation of the order of 1 mm, for more or for minus, around the equilibrium point.

Therefore, substituting the values of β, L and R in the equation (2.10), the transfer function of the controlled system turns:

$$V'_s(s)/V'(s) = -109703.75 / [\ (s + 46,67).(s+55,51).(s-55,51)]. \tag{2.12}$$

2.3. Project of PID Controller

To have a better precision in the control of the process, that is to say, a null mistake of stationary regime, it opted for projecting a PID controller, that has the following transfer function(Ogata,2003):

$$Gc(s) = V'(s)/E(s) = K\ \frac{(\ K_d s^2 + K_p s + K_i\ )}{s}$$

In this stage, the tool "sisotool" of the program Matlab® was used where, after some simulations, were chosen the following values: Kd = 1; Kp = 20.0135; Ki = 10.0035 and K=0.18.

The transfer function of the continuous controller's is:

$$Gc(s) = \frac{0.18\ s^2 + 3.602\ s + 1.801)}{s} \quad . \tag{2.13}$$

2.3.1 Discretization of PID controller

For the discretization of the transfer function of the plant, a Zero Order Hold (Ibrahim,2006) was used, with a sampling frequency the same to 1000 Hz, being obtained the following result:

$$Gp(z) = \frac{V_s'(z)}{V'(z)} = \frac{1.808e\text{-}005\ z^2 + 7.148e\text{-}005\ z + 1.766e\text{-}005}{z^3 - 2.958\ z^2 + 2.912\ z - 0.9544} \ . \tag{2.14}$$

To proceed, PID digital controller it will be deduced through the classic PID analogical controller (eq. 2.13). This way, being applied Z transformed, the transfer function of the discreet controller is as:

$$G_c(z) = V'(z)/E(z) = \frac{183.6\ z^2 - 363.6\ z + 180}{z^2 - z} \qquad (2.15)$$

Resulting in the following equation of differences to be implemented in the microcontroller:

$$U(n) = U(n\text{-}1) + \ 183.6E(n) - 363.6\ E(n\text{-}1) + \ 180\ E(n\text{-}2)\} \ . \qquad (2.16)$$

Where $U(t)$ it is the sign of actuation in the tension driver of the coil and $E(t)$ it is the difference between the exit of photo-receiver and the reference value.

The step response of the feedback system with digital controller is shown in the Fig. 8, where it can be noticed a time of accommodation close to 3s.

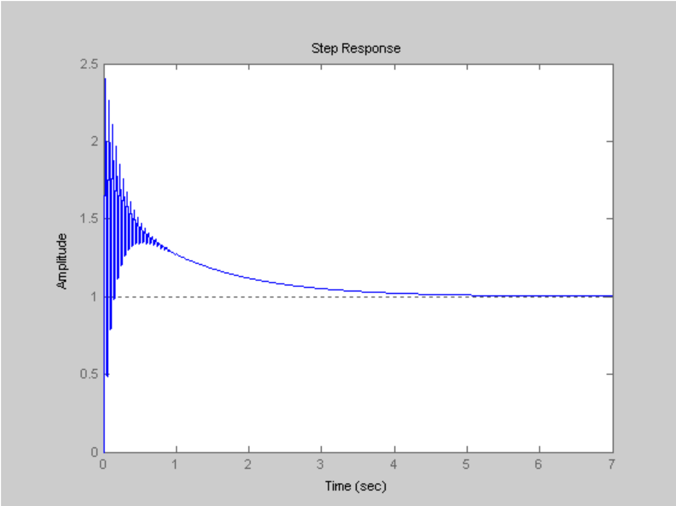

Figure 8. Step response of the feedback system with digital controller

2.4. Results

The final assembly can be seen in the Fig. 9.

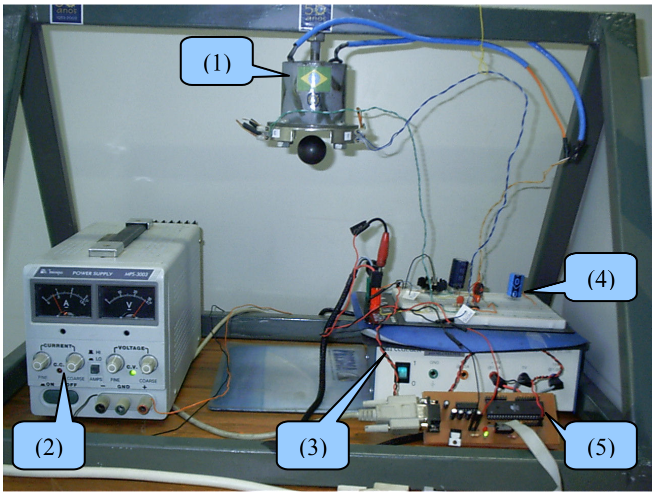

Figure 9. Final assembly of the project: Coil and sensor(1), Feeding source for the coil(2), Feeding source with +5, +15 and -15V(3), Circuits of optical conditioning of the sensor and of feeding of the coil (4) and Plate with AVR Atmega 16(5).

The Fig. 10 exhibition a "pront-o-board " where they were mounted the circuit of optical conditioning of the sensor(circuit 1) and the circuit of feeding of the coil (circuit 2).

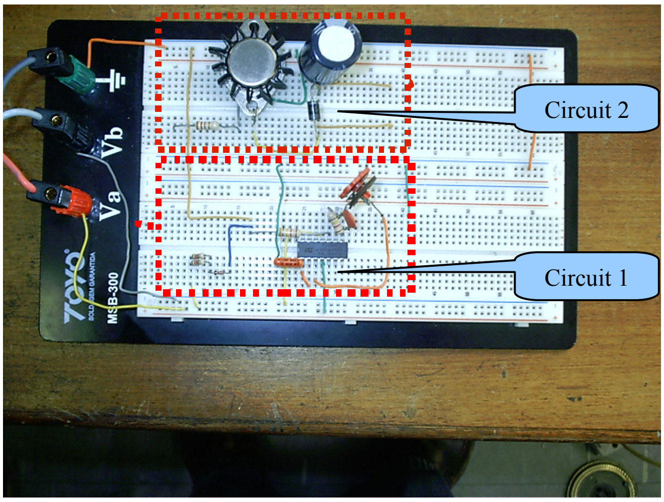

Figure 10. Assembly plate with the devices.Circuit of optical conditioning of the sensor (circuit 1). Circuit of feeding of the coil (circuit 2).

Details of the circuit 1 and circuit 2 can be seen in the Fig. 11 and Fig.12

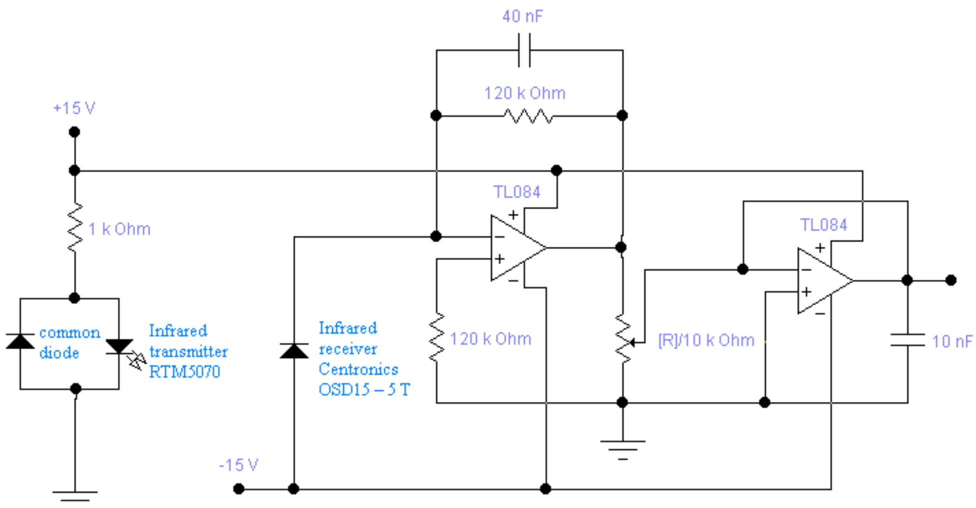

Figure 11. Circuit of optical conditioning of the sensor (circuit 1).

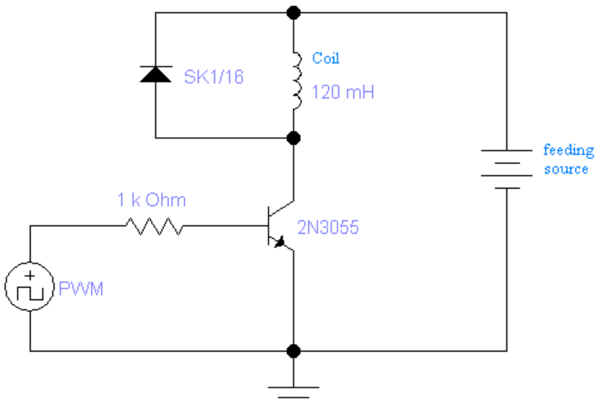

Figure 12. Circuit of feeding of the coil (circuit 2).

3.1. Obtained results: position of the sphere.

The Fig.13 exhibition the exit tension of the sensor of position along the time in permanent regime, that corresponds to 7.85 mm of distance of the coil to the top of the sphere.

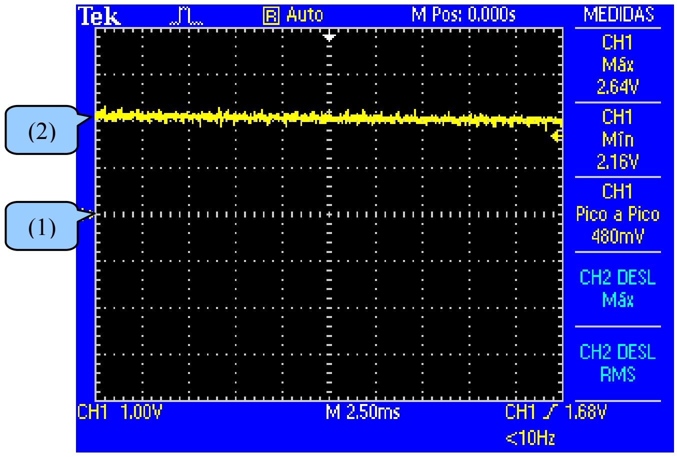

Figure 13. Exit tension of the sensor.
Reference level:Vs = 0 V and scale= 1 V/div (1); Tension of exit of the sensor Vs = 2.2 V (2)

Analyzing Fig. 13, it can be noticed a small oscillation around the equilibrium point, but that doesn't commit the stability of the system. The Fig. 9 exhibition the sphere levitating in the equilibrium point.

3.2. Obtained results: external disturbance.

In this procedure an external disturbance was inserted to the position of the sphere, through a small " beat " in the same, in order to visualize the system response in this condition.

The Fig. 14 exhibition the system response to this disturbance.

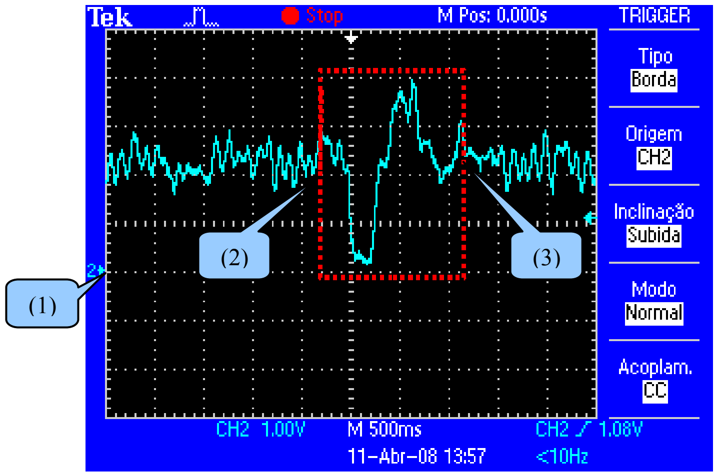

Figure 14. System response to this external disturbance. Reference level:Vs = 0 V and scale= 1 V/div (1); Beginning of the disturbance(2) and Come back to the previous condition(3)

In spite of this procedure not to have been simulated in Matlab® and, therefore, it not to compare with simulation response, the analysis of the Fig. 14 allows to conclude that the system response in a satisfactory way to the condition of imposition of an external disturbance, that is to say, the sphere returns approximately to the previous position 1,5 s after the beginning of the disturbance.

3.3. Obtained results: step response.

In this procedure a step of value equal to 0,2 V (that corresponds to a displacement of the sphere around 1,6mm) it was inserted in the reference entrance (*ref*), using the program implemented in the microcontroller.

The Fig. 15 exhibition the system response for this situation.

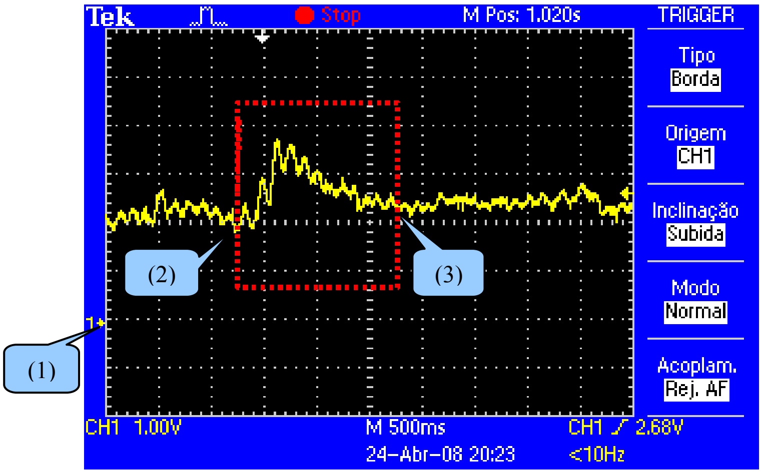

Figure 15. Step response. Reference level: Vs = 0 V and scale= 1 V/div (1); Tension of exit of the sensor before the application of the step: Vs = 2.2 V (2) and Tension of exit of the sensor after application of the step: Vs = 2.4 V(3)

We can see that the accomodation time is close to the one observed in the simulation from the figure 2.7, around 3s.

3.4. Obtained results: current in the coil in the equilibrium point.

For the mensuration of the current in the equilibrium point a sensor of hall effect (model NW-SC-50 of Newtronic) was used, properly gauged so that each measured ampere it is equal to a volt of tension in the exit of the sensor.
The Fig. 16 illustrates the form of wave of the current in the coil, with the sphere in the equilibrium point.

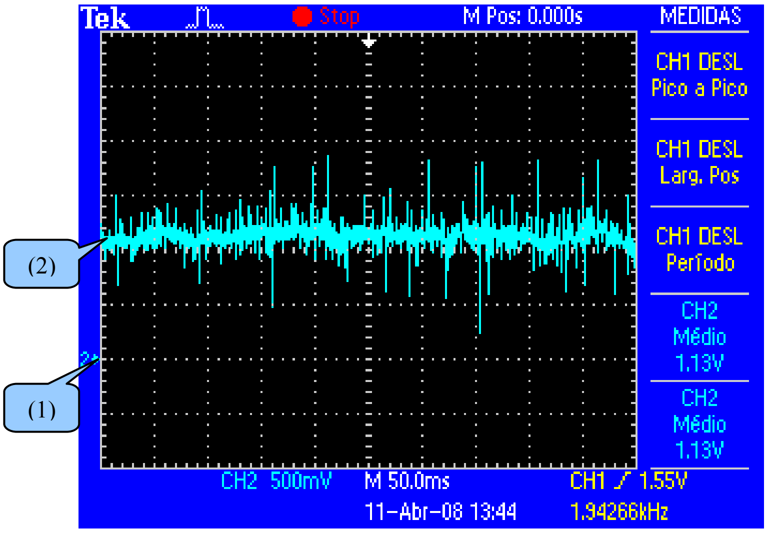

Figure 16. Form of wave of the current in the coil. Reference level: I= 0 A and scale= 0,5 A/div(1); Current in the coil: I=1,13 A (2)

Analyzing Fig. 16, it can be noticed that the medium value of the current is worth 1.13A, very close of the current foreseen for the equilibrium point, that is of 1.17 A (eq. 2.4).

4. CONCLUSIONS

In this work the project and the implementation of a system of control of a magnetic levitation of a sphere of steel were presented, using a control for tension, instead of a control for current. A PID discreet controller implemented with a microcontrolador was considered .

The control for tension demanded a detailed modeling of the system, mainly in relation to the resistance values and inductance of the coil, essential in this control type.
With the use of this strategy, it was possible to grant the use of a sensor of current.

The determination of the value of resistance of the coil didn't demand great efforts, unlike the determination of the inductance, where it was necessary the assembly of an experiment.

The presented results show that, in spite of the difficulties of its modeling and of the noises inserted by the environment, the proposed controller answered satisfactorily in relation to the foreseen, so much in relation to the equilibrium position, as in relation to the current value in the coil.

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