

DIGITAL CONTROL LABORATORY APPLIED TO TEACHING PURPOSES

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Abstract. *Dedicated equipment for control education as the ones produced by Feedback Instruments and Quanser, assists the education of the control theory, to make possible the implementation of several experiments, however these systems have high cost. To mount a control laboratory using the systems of such manufacturers implies in some investments. This barrier was the main motivation for this work, that the goal is a low cost equipment implementation to be part of a digital control laboratory using Digital Signal Processors (DSPs). These equipments will allow the elaboration and implementation of complex experiments applying discrete control theory, helping instructors elaborate complex experiments during the control courses, it will help students became familiar to digital signal processing and the Digital Signal Processor (DSP), allowing several implementation applying classical and modern control theory.*
A magnetic levitation system is developed as first experiment, it is called MAGLEV ("Magnetic Levitator") where a metallic element will be in controlled levitation. This type of experiment was explored as tool for educational purpose for some decades, as described by William G. Hurley in his article "PWM Control of the Magnetic Suspension System", therefore it serves to explore the concepts of electromagnetism theory, control theory and circuits project.

Keywords: *MAGLEV, Digital Signal Processor, Neodymium permanent magnet, Simulink, F2812 eZdsp*

1. Introduction

The magnetic levitation is based on the attractive and repulsion forces between two magnetized bodies, being used to support a metallic element in a stabilized position. For this system, however, as the theorem of Earnshaw, that says: The attractive or repulsion force between two magnetized bodies is inversely proportional to the distance that separates them (Earnshaw, 1842). In accordance to this theorem, there's no equilibrium point between the two magnetized bodies. The solution, after study forces behavior, is the incorporation of an active controller that will adapt instantaneously and automatically to the occurred variations between the involved forces, compensating them, and bringing stability to the system. The type of MAGLEV chosen in this work was a permanent magnet that offers a simple implementation. This type of system is studied at Massachusetts Institute of Technology (MIT) in Feedback Systems disciplines. The system used at MIT adopts a controller developed by Guy Marsden (Marsden, G, 2003), Marsden's implementation is the base for this maglev experiment proposed, this behavior is evaluated and a discrete controller developed to be implemented in a digital signal processor (DSP). The magnetic levitation experiment is composed of the following stages: Plant system survey, controller development, system simulation (MAGLEV), control software codification applying graphical tools (Simulink - Mathworks), DSP controller physical implementation and test. TMS320F2812 DSP from Texas Instruments is dedicated to control applications and is applied for the lab purpose in this work as the DSP through its F2812 eZdsp tool. This processor offers all the necessary resources for stand alone control system implementation, being the main element of low cost equipment, which is implemented in this work for the control laboratory purpose. Figure 1 illustrates the implemented system.

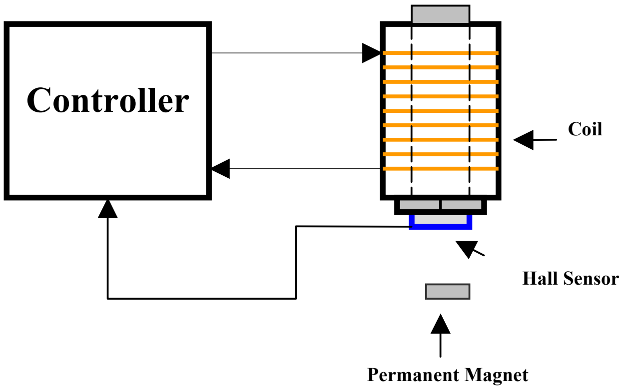

Figure1 MAGLEV - Permanent Magnet System

2. System Description

- Coil: It is composed of ferromagnetic nucleus, carries through attraction or repulsion of the element to be suspended, being energized for circuits of power commanded by the controller.
- Hall Sensor: Informs to the controller the element in suspension position.
- Element to be suspended: permanent magnet (Neodymium) interacts with the magnetic field generated by the coil, producing the levitation.
- Controller: Receives electrical information from the position Hall sensor, that represents suspended element position, process the control algorithm of control to take the necessary control action, setting the coil driver power.

3. Operation Proposal

The proposal of permanent magnet levitation is keep the permanent magnet in steady suspension by the addition of a controller that will handle the magnetic forces interaction that act in the system. The attractive power between permanent magnet and the magnetic coil nucleus are conducted by the inverse of distance law: $f(x) = \frac{1}{x}$, as illustrated for the graph of figure 2.

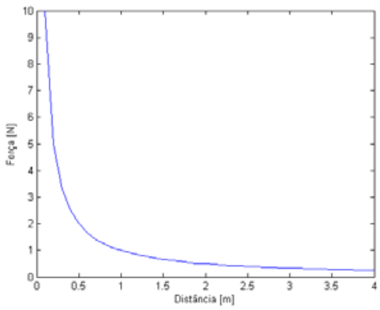

Figure 2 Force *versus* distance

The forces that are involved in the levitation system can be observed in the figure 3. Force of permanent magnet attraction (f_i) in opposition to the force of its proper weight(f_p). The magnetized bodies (permanent magnet and the bottom of coil nucleus) are separated for a distance "x", as illustrated.

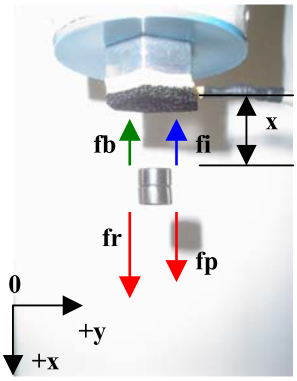

Figure 3 Maglev force distribution

Earnshaw (1842) defined static levitation as the steady suspension of an object against gravity attraction force. For a permanent magnet stable levitation in the system, permanent magnet should be in a distance *x*, in which the permanent magnet force weight and attraction force are approximately equal. This distance *x* is called point of operation or break-even point. In the operation point the dynamic behavior of the system is studied to carry through the project of the controller that will become a steady system. According to Earnshaw's (1842) theorem is not possible to reach static levitation using any combination of magnetic elements.

4. Modeling the System

f_p = m.g → f_p = 0.0542 [N] (1)

m = Weight of permanent magnet → m= 5,52 [g]

g = Gravity acceleration → g = 9,81 [m/s²]

$f_i(x)$= 1038,9x^2 - 32,734x + 0,3106 (2)

$f_i(x)$ → Permanent magnet attraction force with no power in the coil.

Appling Taylor series to eq.(2), assuming that equilibrium point is x= 0.0135[m], linearized equation of $f_i(x)$ will be represented to eq.(3).

$f_i(x)$= -4,6837 x + 0,1213 (3)

$f_b(v)$ → Permanent magnet attraction force in the equilibrium point with power in the coil.

$f_b(v)$= 0.0491 v + 0,0579 (4)

$|f_b(0)| \approx |f_p|$ → at equilibrium point x_0 = 0.0135[m] (5)

Equilibrium point x_0 = 0.0135[m] is now considered the origin of the system, forces orientation will be normalized according with x axis orientation, eq.(4) is rewritten bellow.

$f_b(v)$= -0.0491 v (6)

At equilibrium condition, eq.(7) represents the system static behavior.

$$f_p - f_i - f_b \cong f_r \cong 0 \quad (7)$$

Considering x_d as position disturbance and x_0 as equilibrium position, eq.(7) is rewrite as bellow:

$$f_p(x_0) - f_p(x_d) - f_i(x_0) - f_i(x_d) - f_b(v) = 0 \tag{8}$$

When disturbance x_d = 0 system is at static equilibrium, so eq.(8) is equal to eq.(7), where $f_p = f_i$ as expressed by eq. (9).

$$f_p(x_0) = f_i(x_0) \tag{9}$$

Considering disturbance $x_d \neq 0$ and the system at static equilibrium, dynamics system behavior will be evaluated. Eq.(9) will be introduced at eq.(8) considering $x_d \neq 0$, that result in eq.(10)

$$f_p(x_d) - f_i(x_d) - f_b(v) = 0 \tag{10}$$

The force $f_p(x_d)$ is dependent of system dynamics and is represented by eq.(11)

$$f_p(x_d) = \text{m}.\frac{d^2x}{dt^2} \rightarrow \text{m} = 5.52.10^{-3} \text{ [Kg]} \rightarrow f_p(x_d) = 0.00552 \, . \frac{d^2x}{dt^2} \text{ [N]} \tag{11}$$

As the origin of system is the point x_0 = 0.0135[m] eq.(3) is modified to simplify the system, eq.(12) will represent fi(x)

$$f_x^{`}(x) = -4.6837x \tag{12}$$

Applying eq.(6), eq.(11) and eq.(12) into eq.(10) we will have eq.(13)

$$0.00552 \cdot \frac{d^2x}{dt^2} - (-0.0491 \cdot v) - (-4.6837 \cdot x) = 0 \rightarrow \frac{d^2x}{dt^2} + 848.5 \cdot x = -8.895 \cdot v \tag{13}$$

Considering system initial conditions null, applying Laplace transformation to eq.(13) the open loop transfer function is obtained and represented by eq.(14)

$$\frac{X(s)}{V(s)} = \frac{-8.895}{s^2 + 848.5} \tag{14}$$

The transfer function represented by eq.(14) has an oscillatory behavior, a compensator is developed to stabilize the system, figure 4 represent the system plant.

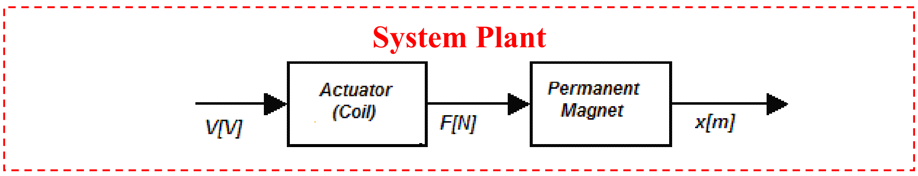

Figure 4 Maglev Plant Systems

Hall Sensor behavior was evaluated to determine its transfer function; two considerations were made to evaluate that.

a) Got the voltage response of Hall sensor varying permanent magnet position, coil was not energized.

b) Hall sensor output voltage was related with coil voltage variation, that was made between +12.0[V] to -12.0[V], permanent magnet was kept at equilibrium position x_0.

After several tests, the conclusion was that the position sensor behavior was almost linear near the equilibrium position and its transfer function represented by eq.(15), were Vs is sensor response.

$$Vs(x) = 302.x - 3.493 \ \ [V] \tag{15}$$

5. Developing and implementing the Controller

The block diagram in the figure 5 represents the implemented system, a calibration block was considered, this technique allow a graphical system implementation, by using Matlab Simulink capability.

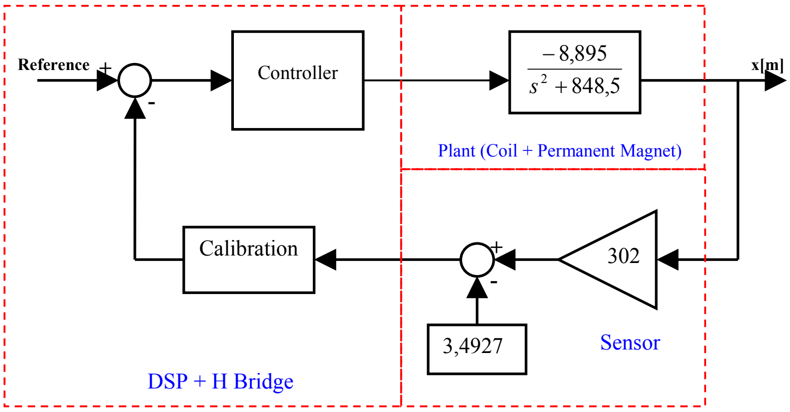

Figure 5 Maglev Block Diagram

To develop the controller is applied Matlab SISO Design Tool. Plant transfer function and sensor transfer function are ported to the tool, were, graphically is developed an appropriated controller. SISO design toll allow the designer to reach controller parameter like overshoot, rise time and so on. Tool illustration is presented in figure 6, were the lead lag controller for the maglev application was developed.

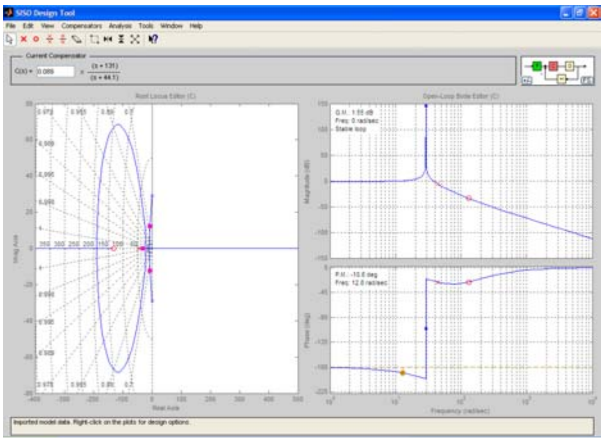

Figure 6 SISO Design Tool

The controller developed is represented by eq.(16)

$$C(s) = 0.089 \cdot \frac{(s+131)}{(s+44.1)} \tag{16}$$

Simulation block diagram is built using Simulink, as illustrated by figure 7, and its response for a unit step is illustrated by figure 8.

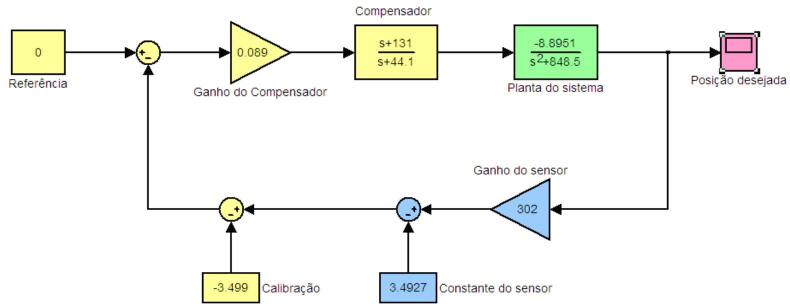

Figure 7 Simulation Block Diagram

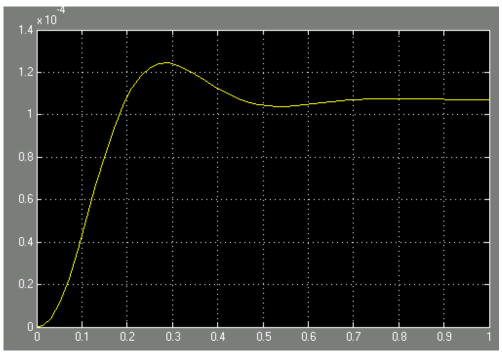

Figure 8 Response to unit step

A stable system was reached, and it is ported graphically to DSP. A tool called F2812 eZdsp board from Spectrum Digital is the DSP base for the experiment implementation, this tool allow a friendly interface with Matlab Simulink and Code Composer Studio, that is the Texas Instruments DSP software (SW) environment, these tool combined together allow designers perform graphical implementation. The stable system at discrete form is achieved using SISO design toll, Tustin approximation method and sampling frequency fs = 10 [KHz] are applied. Figure 9 show the discrete block diagram built into Simulink that has specific F2812 eZdsp blocks, as PWM module and A/D converter.

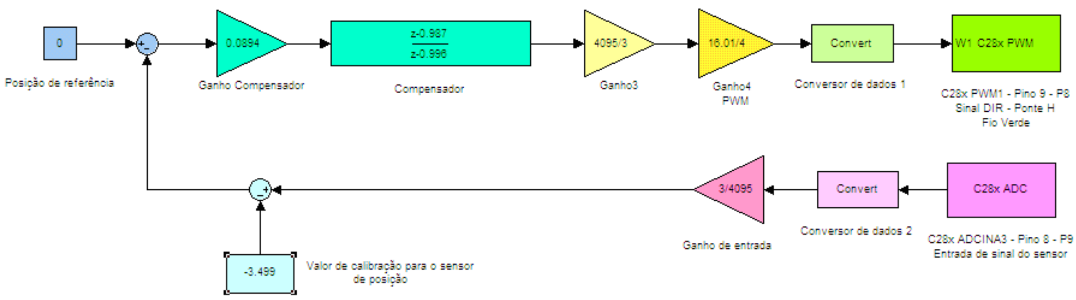

Figure 9 Discrete System Block Diagram

Discrete controller is represented by eq. (17) and its implementation is illustrated in figure 9.

$$C(z) = 0.08934 \cdot \frac{(z-0.987)}{(z-0.996)} \quad (17)$$

The DSP tool F2812 eZdsp needs simple external hardware (HW), it is composed of a board using a full H Bridge and a Hall sensor, as illustrated by electrical diagram in figure 10.

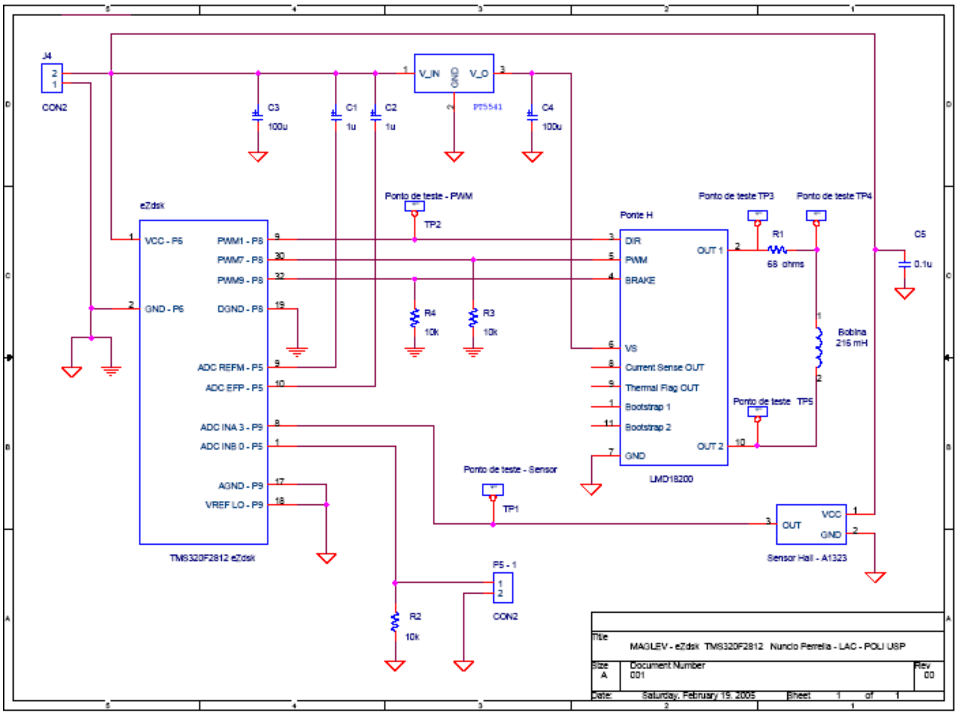

Figure 10 Hardware Implementation

F2812 eZdsp additional HW has considered a 2nd A/D input to provide input signal source to test performance like: unit step input, impulsive response and so on.
Stable levitation is reached as shown in figure 11, the controller and adjustment was developed graphically.

Figure 11 MAGLEV hardware

6. Conclusion

The controller implementation was easy, and a deep DSP theory knowledge was not required, the work was mainly dedicated to system modeling and controller design applying Matlab tool intensively.

Stable levitation was achieved; and the adjustments were made graphically using Simulink tool, this implementation proof that a low cost tool can be implemented to teaching purpose, the same hardware can be applied to many kinds of control implementation like: Motor control, temperature control and others. This implementation brings to students and research engineers a low cost tool option, allowing engineers and students learn and implement their needs applying DSP technology.

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