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Simulation of a Fuzzy Control of a Planar Magnetic Bearing

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***Abstract*—This work presents a simulation of a fuzzy control of a planar magnetic bearing used to levitate a planar magnetic object. To maintain the object in a desired position the acting magnetic force must be controlled. Such control is based on the correction of the supplying current as a function of the object displacement. To permit the changing of the current, a four quadrants chopper has been used to energize the bearing. The bearing parameters required for the simulation have been experimentally and analytically defined. The implementation of the proposed fuzzy control has led to good results.**

***Index Terms*—Actuators, displacement control, feedback circuits, fuzzy control, magnetic levitation.**

I. INTRODUCTION

Magnetic bearings are widely used for the levitation in the domain of transportation (Maglev) [1-5]. Their disadvantage resides in the instability of the levitated object. To achieve a stable levitation, a control circuit must be associated to the system. The control process is based on the control of the applied magnetic force by the action on the bearing exciting current according to the object displacement. In [6-8] the force control has been treated for the case of an alternative supplying current. For such control an approach based on the use of a PID regulator has been applied. In the case of radial magnetic bearings control LQ and $H\infty$ approaches have been applied [9-12].

In this work, a problem of magnetic levitation has been treated. Such a treatment has been focused on the design of a fuzzy control of a planar ferromagnetic object (see Fig. 1).

To permit the changing of the exciting current that generates the applied magnetic force, a four quadrants chopper has been considered [13], [14]. The bearing parameters required for the simulation have been experimentally and analytically defined. To obtain the transfer function of the levitation system the magnetic force expression has been linearized. In such linearization the winding inductance of the bearing has been assumed constant. The control process consists of the correction of the exciting current as a function of the object displacement x. If the object displaces to the bottom by a distance $-\Delta x$, the coil current i_0 must be increased by a quantity Δi. Otherwise, if the object moves upwards by a distance Δx, the current quantity Δi must be subtracted from the biased current i_0. To permit the sensing of the object displacement, a position sensor has been considered.

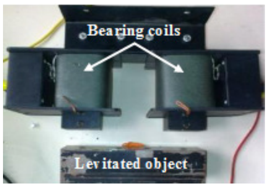


Fig.1. General view of the studied device. A U shape core has been used.

To permit the changing of the exciting current according to the evolution of the object displacement an adjustable voltage has been used. This later is produced by a fourth quadrants chopper. To achieve the correction of the current, a control loop has been used where a fuzzy regulator has been integrated. Such regulator permits the regulation of the position in the discrete domain. The operating rules have been chosen in the manner to ensure the stability of the levitated object after an accepting time [17-22].

II. MODELING OF THE LEVITATION PROBLEM

To obtain the expression of the magnetic force applied to the levitated object, an analytical modeling has been applied to the magnetic circuit related to the levitation system. For the considered one degree of freedom problem, the force is given by [15], [16].

$$F_m = c({}^{i}/_{x})^2 \tag{1}$$

Here x is the air gap between the core and the levitated object, i is the exciting current and c is a constant depending on the magnetic circuit properties. As a function of the winding geometrical parameters, the constant c is given by

$$c = \frac{1}{2}N^2\mu_0 S \tag{2}$$

Here N is the number of turns of the coils, S is the cross section of the air gap and μ_0 is the magnetic permeability of vacuum.

Really, the levitated object oscillates around the equilibrium position with very small displacement. So the applying of the Taylor series expansion on (1) has led to the force expression

$$F_m = K_x x - K_i i + F_0 \tag{3}$$

The coefficients K_x and K_i are respectively the displacement and current gains. They are analytically evaluated and given by

$$\begin{cases} K_x = 2\,ci_0^2/x_0^3 \\ K_i = 2\,ci_0/x_0^2 \end{cases} \tag{4}$$

x_0 and i_0 are respectively the displacement of the levitated object and the exciting current at the equilibrium position.

The evolution of the voltage in the coil is governed by the equation given by

$$V = R.i + L.\frac{di}{dt} \tag{5}$$

Here R and L are the resistor and the inductance of the coils. The voltage generated by the position sensor expressed as a function of the detected object displacement is given by

$$V_s = \alpha.x \tag{6}$$

The constant α is the displacing sensor gain.

The introduction of the magnetic and the gravitational forces in the Newton principle law applied to the levitated object has led to the dynamic equation below [6]

$$F_g - F_m = m\ddot{x} \tag{7}$$

Here m is the object mass, $\ddot{x}$ is the object moving acceleration and F_g is the gravitational force ($F_g = mg$, where g is the acceleration of the gravity).

The substitution of (3) in (7) has led to the object dynamic governing equation

$$F_r = -K_x x + K_i i = m\ddot{x} \tag{8}$$

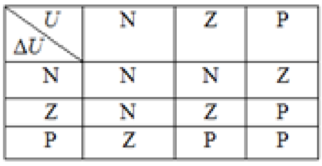
Here F_r denotes the resulting equation.

In (8) the gravitational force F_g has been cancelled by the constant component of the magnetic force F_0 related to the equilibrium position ($F_g = -F_0$).

III. SIMULATION OF THE CONTROL AND OBTAINED RESULTS

The association of the proposed supply circuit, the control loop and the magnetic bearing is clarified in Fig. 2. The four quadrants chopper is constituted by four switches (IGBT, diodes). This chopper permits the changing of the exciting current according the two directions in the two axes $(x, -x)$. The magnetic bearing is represented by an inductance in series with a resistor. These electrical parameters have been experimentally defined.

For the proposed fuzzy regulator, the chosen operating rules are illustrated in Fig. 4.



U / ΔU	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

Fig. 3. Rules of the used fuzzy regulator.

Here U and ΔU are the input voltage of the regulator and its evolution. N, Z and P are respectively the negative, the zero and the positive levels.

As we have previously mentioned the bearing resistor and inductance are experimentally defined. The resistor is R=0.22Ω, the inductance is L=29.64mH and the levitated object mass is m=1.8kg.

The equilibrium position x_0 randomly chosen is 5×10^{-3}m. The exciting current i_0 that ensures the levitation of the object at this equilibrium position is experimentally measured i_0=1.15A. The computation of the constant c has given a value c= 2.51×10^{-6}. The gains added to regulator are respectively K_1=8, K_2=5, K_3=13. To control the chopper, a pulse (0, 1) has been chosen for the switches 1 and 4. For the switches 2 and 3, pulses (1, 0) has been used.

The four quadrants chopper has been excited by a dc voltage V_c=100V in the discrete time.

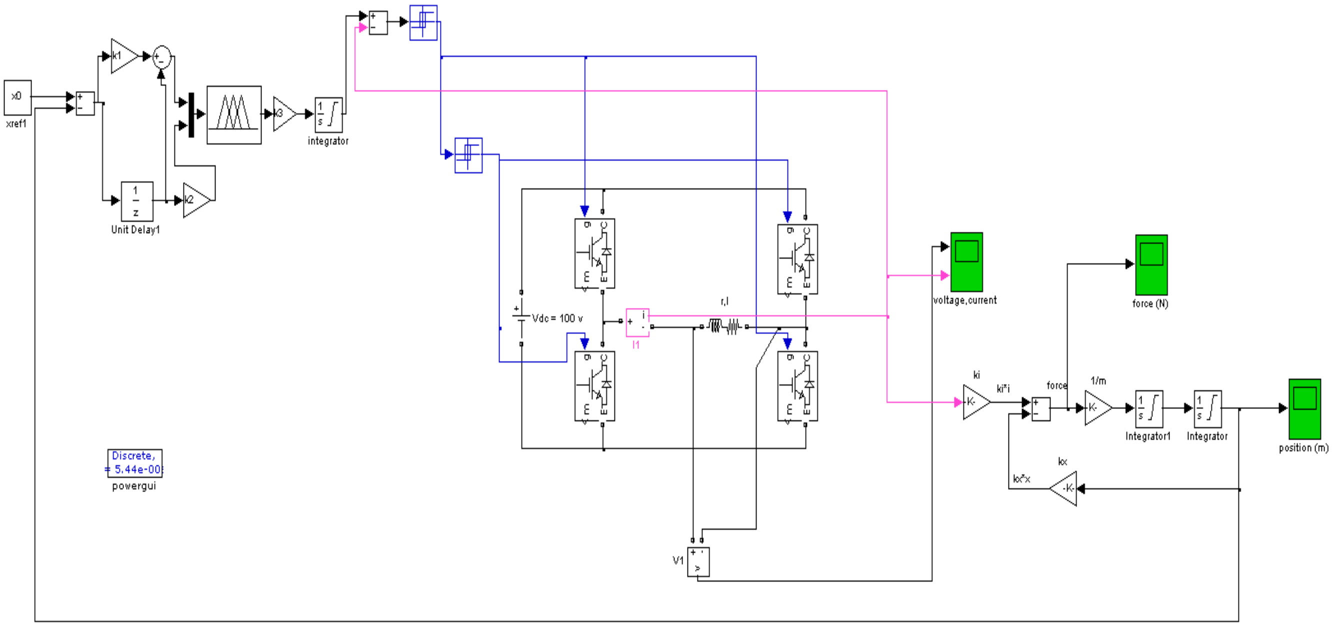
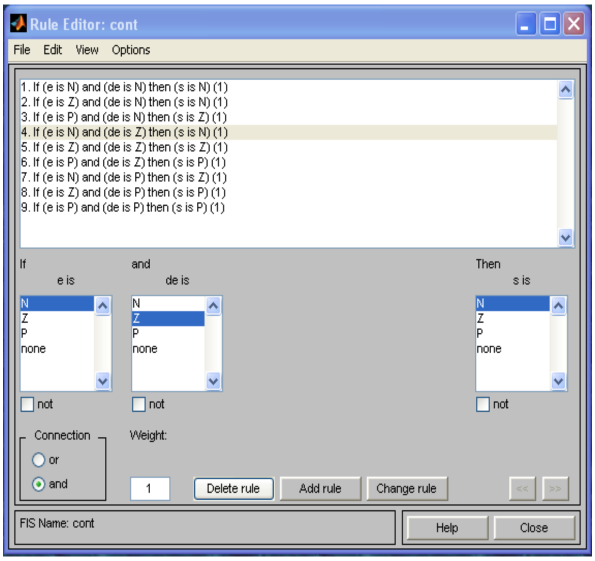


Fig. 2. Simulation bloc of the control of the studied planar magnetic bearing.

In the simulation process, the initial position related to t= 0s, the airgap has been chosen $x=3\times10^{-3}$m. To show the manner of introduction of the regulator parameters we present the figure below.



1. If (e is N) and (de is N) then (s is N) (1)
2. If (e is Z) and (de is N) then (s is N) (1)
3. If (e is P) and (de is N) then (s is Z) (1)
4. If (e is N) and (de is Z) then (s is N) (1)
5. If (e is Z) and (de is Z) then (s is Z) (1)
6. If (e is P) and (de is Z) then (s is P) (1)
7. If (e is N) and (de is P) then (s is Z) (1)
8. If (e is Z) and (de is P) then (s is P) (1)
9. If (e is P) and (de is P) then (s is P) (1)

If e is N and de is Z Then s is N

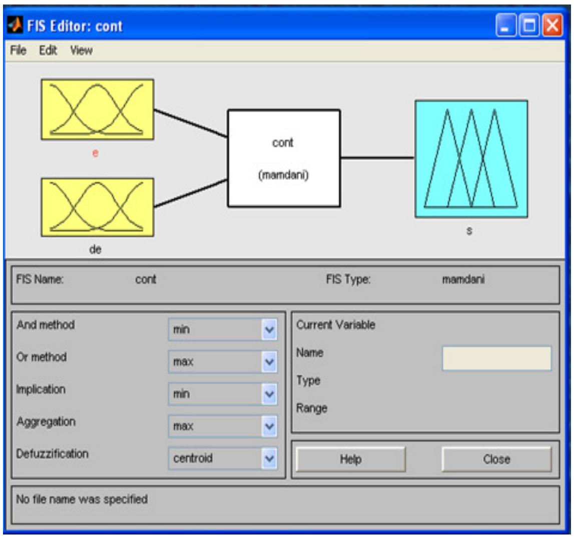
Connection: ● and

Weight: 1

FIS Name: cont

Fig. 4. Introduction of the rules of the used fuzzy regulator.

In Figure 4, **e**, **de** and **s** are respectively the input of the regulator, the evolution of the input and the output of the regulator. To understand the evolution of the input and the output of the regulator we present the figure below.



FIS Name: cont

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

No file name was specified

Fig. 5. The configuration of the fuzzy regulator.

In figure 5, the signals of the inputs **e** and **de** that give the output **s** has been chosen in the manner to obtain a stability of the system after an accepting time in the discrete domain. To obtain a good stability, the input and output signals have been improved by introducing gains.

The implementation of the proposed control method for the considered levitation system and the previously cited parameters has led to the results of Fig. 6. This figure that traduced the evolution of the levitated object position at a function of time shows clearly that the stability of the object position has been reached after 0.6s.

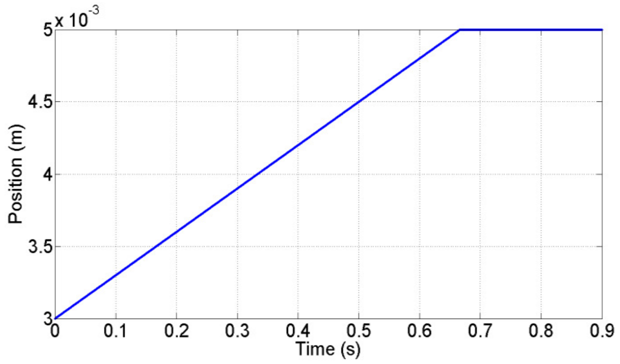


Fig. 6. Evolution of the position of the levitated object as function time.

During the control, the exciting current changes with the changing of the object position until the obtaining of the desired position. The evolution of the controlled current as a function of time is shown in Fig. 6.

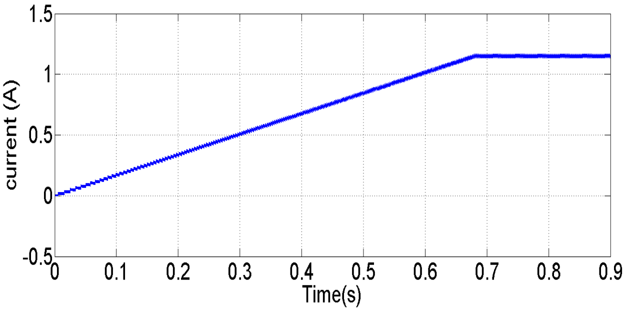


Fig.7. Evolution of the controlled current as function the time.

This figure shows that the current stabilizes after a time t=0.6s which is the same time obtained for the levitated object position. The reached value of the current related to the stabilization time i_0=1.15A. The capability of this value to permit the levitation of the considered object has been experimentally verified.

As we have seen previously, the principle component of the magnetic force F_0 is cancelled by the gravitational force F_g. The resulting force (see Eq. 8) that depends on both the position and the controlled current is used to correct the position of the object. The evolution of this force as a function of time is shown in Fig. 7.

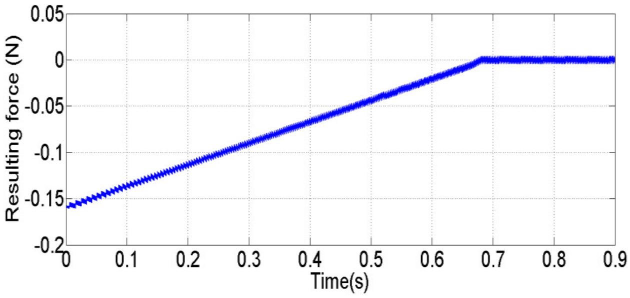


Fig.8. Evolution of the resulting force.

Figure 7 shows that the force oscillates around an average value that increases with the time. This average value stabilizes at zero after a time of 0.6s. The zero value of the force verifies that at this moment, the object position is for $x = x_0$ and the current $i = i_0$. At the obtained equilibrium position the first term of the magnetic force F_0 has been eliminated by the gravitational force term F_g, so the remaining force which is the resulting force is oscillating around the value zero. To verify the stability of our system, we have estimated the position error between the reference and the obtained values. The evolution in time of the position error is presented in Fig. 8.

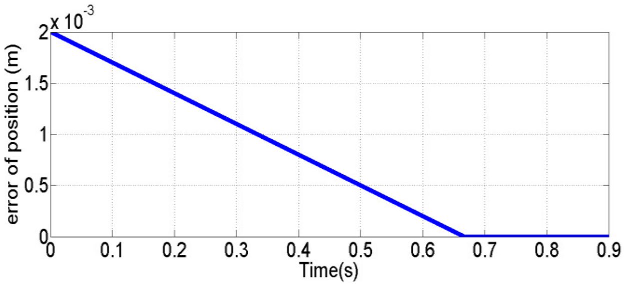


Fig. 8. Evolution of the position error as a function the time.

As we see in Fig. 8, the error becomes equal to zero after a time of 0.6s which is the same time of the stability of all the estimated control values.

IV. CONCLUSION

In this work, a study of planar magnetic levitation system has been achieved. The aim of such study was the conception of a control of the levitation of a planar ferromagnetic object. The use of a four quadrants chopper has been justified by the need of a controlled dc supplying voltage. To permit a control in the discrete domain, a Fuzzy controller has used. This last presents some advantages in comparison with analogical regulators (PD, PID). It permits the reduction of the stability time and the association of the DSP card. In our study, we have chosen a gain of the position sensor equal to 1which has led to a good stability of the system. Practically, a real value for the gain of the position sensor must be considered. This can lead to changes in the estimated value of the system.

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