A FUZZY CONTROLLED ELECTROMAGNETIC AXIAL BEARING

José Andrés Santisteban[1]
Daniel S. Sacramento[1]
[1]UFF-TEE, Av. Passo da Pátria 156, São Domingos, Sala D509, CEP 24210-240, Niterói, RJ, Brazil.
Phone: 55.21.2620-7070 br. 337, Fax: 55.21.27174446; e-mail: jasl@mec.uff.br

Sérgio R. Alves Mendes[2]
[2]UFRJ-PEE, Cidade Universitária, CT, Sala H305, CEP 21945-970, Rio de Janeiro, RJ, Brazil.
Phone: 55.21.2260-5010 br. 239, e-mail: mendes@coe.ufrj.br

Abstract. *The use of magnetic bearings is a promising technology; the absence of mechanical friction and any type of contamination are some characteristics that justify their application in different industrial activities. To domain this technology is necessary the study of diverse fields of electric engineering such as: electromagnetism, control, electrical machines, analog and digital systems and power electronics.*
Sophisticated techniques are necessary for the control of a magnetic bearing, because there are an electrical non-linear relationship between the airgap and the current. In this work the Fuzzy logic approach was used to design the controller. This technique allows constructing a control system based in a group of rules in a similar way as the human thought does. The use of this logic is justified in systems whose dynamic behavior is not well known. These rules were based on experimental results of a derivative proportional controller (PD) previously implemented and then tested through computer simulations.
In order to compare theoretical results with experimental values, a test workbench was constructed. These results will be presented in this work.

Keywords: *electromagnetic levitation, axial magnetic bearing, fuzzy control.*

1. Introduction:

Nowadays, magnetic bearings for electric machines are becoming an important issue to be considered in industrial activity due to their advantages (Schweitzer, 1994). Engines that use this type of technology possess characteristics such as very high speed, greater useful life and free of oil, contributing to solve the problem about pollution and the preservation of the natural resources. Some examples where the absence of any type of contamination is important, and the use of magnetic bearings is justified, are the food industries and medical equipments.

The magnetic forces can be obtained in a passive way (using permanent magnets, diamagnetic materials or even superconductors) or in an active way (where electromagnets currents are controlled using a position feedback). In this paper, we deal with the last approach.

An axial magnetic bearing differs from a radial one for acting along the axis of the rotor. Different to a conventional axial magnetic bearing that use two windings, in this work only a winding is used, this is because it was initially designed for a real application where a rotor should operate in the vertical position. Nevertheless, the fuzzy controller design can be extended to conventional approaches with two windings (Santisteban, Salazar and Stephan, 2000). With minor changes this approach can be also applied to Maglev Systems (Sinha, 1987).

Figure (1) shows the electromagnetic structure. In order to control this system were used: an inductive displacement sensor, a power supply with IGBT's and their drives. The controller was implemented with a personal computer that accommodates an A/D and a D/A cards.

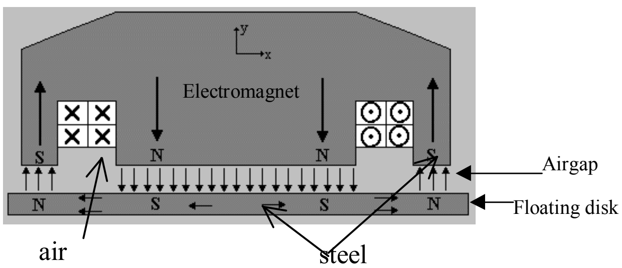

Figure 1. Magnetic poles created by the magnetic flux crossing the airgap.

In Fig. (1), the upper part (fixed electromagnet) is responsible for the generation of the magnetic field. The N coils, when supplied by an electric current of intensity I, produce a magnetic field of intensity H along a closed trajectory according to the Ampere's Law. The trajectory covers the fixed region, the airgap and the floating disk.
Deriving the expression of the magnetic energy (*Wg*) with respect to the airgap *y* (Santisteban and Mendes, 2000), the expression for the total force of attraction exercised by the upper part over the floating disk is:

$$\mathbf{F}_{total} = \frac{\mathrm{d}W_g}{\mathrm{d}y} = \mu_0 \cdot \frac{(N \cdot I)^2}{2 \cdot y^2} \cdot S_g \cdot (+\mathbf{a}_y), \tag{1}$$

where S_g is the effective surface where attraction happens and μ_o the magnetic permeability of the air. Alternatively Eq. (1) can be shown as in Eq. (2):

$$\mathbf{F}_{total} = K_{força} \cdot \frac{I^2}{y^2} \cdot (+\mathbf{a}_y), \tag{2}$$

where:

$$K_{força} = \frac{N^2 \cdot \mu_0 \cdot S_{externa} \cdot S_{central}}{2 \cdot (S_{externa} + S_{central})}, \tag{3}$$

and: I - electromagnet current; $S_{central}$ and $S_{externa}$ - areas of the central circular surfaces and the external of the util airgap.

From the constructive characteristics, the numerical values are:

$$K_{força} = 2.14\ 10^{-4}\,(\mathrm{H \cdot m \cdot esp^2}),$$

$$\mathrm{F}_{total} = 2.14 \cdot 10^{-4} \cdot \frac{I^2}{y^2} \cdot (+\mathrm{a}_y)\,\mathrm{N}. \tag{4}$$

Through a simulation program based on finite elements, this equation was shown valid for the region of operation [(Ferreira, Santisteban and Mendes, 2000), (Ansys®, 1994)]. This force depends of just two variables: current and airgap but in a non-linear way, which makes fuzzy logic appropriated to control the axial magnetic bearing.

2. The fuzzy Logic Controller:

Fuzzy logic incorporates the natural human way of thinking in a control system, making possible the implementation of a controller with a performance like a human operator (Shaw and Simões, 1999). This method possesses one great advantage: the capacity to express in systematic way inexact and/or badly defined amounts. A fuzzy model is characterized by a group of rules that relates the variables of the system, being each rule composed by an antecedent and a consequent. The fuzzy logic manages uncertainties representing them as terms with a level of certainty that varies in the numeric interval [0 1]. The total certainty is represented by the value 1. The fuzzy logic has been used as an alternative control technique for different applications like the automatic control of focus in video cameras, the adjust of the intensity and duration of the cooking in microwave ovens, the control of the cycles of the washing machines, the temperature control in air conditioning equipments and so on.

In all those examples, the rules of control are based in the previous experimental knowledge of the operators. When the dynamic response of the process is under control, several techniques continue being proposed. Some of them include the substitution of conventional adaptive control for combination of classical controllers (P, PD, PID) and fuzzy logic in order to change the control parameters. Others authors use the fuzzy logic approach to simulate the classical controllers but at the same time add the particular characteristics of fuzzy logic. The combination of neural network, genetic algorithms and fuzzy logic are other approaches currently in development.

In this work a proportional derivative fuzzy controller (PD) was developed. The transference function for the mechanical system is given by:

$$G(s) = \frac{1}{ms^2}, \tag{5}$$

where m is the mass of the floating disk.

To get a stable controlled system, it would be sufficient to design a Proportional Derivative controller (Ogata, 1970). However, the non-linear relationship between force, displacement and current as shown in Eq. (4) implies to use some linearization technique. Moreover, the position reference alters the linearized function and, the weight of the mobile disk modifies the dynamic response of the controlled system. In this work, the deduction of the parameters of the simulated PD fuzzy controller was based in a previous implementation that used analog circuits (Santisteban, Mendes and Stephan, 1998). The parameters chosen for this work were good to levitate an almost 22.5N disk.

The use of other mobile disks and different position references resulted in different PD parameters. With this experience, the Fuzzy Logic Controller (FLC) was appropriately designed. Three inputs were considered: position error, position error variation and position reference. In Fig. (2) is shown the complete diagram of the fuzzy logic controlled system. The inputs are multiplied by gains to normalize them before to reach the (FLC). Figures (3a), (3b), (3c) and (3d) show the membership functions of the inputs and the output current.

The mechanical model includes the non-linear Eq. (4) and the Eq. (5). The electrical model includes the resistance and the inductance of the electromagnet. It should be noted that in this case was considered the dependence between inductance and airgap. It is also shown the source current implemented by a comparator, a D type flip-flop, a 10 kHz clock and a voltage source of 100V DC. Finally, in order to compensate the influence of different disks over the performance of the system, the FLC output is multiplied by a factor that depends on the disk weight.

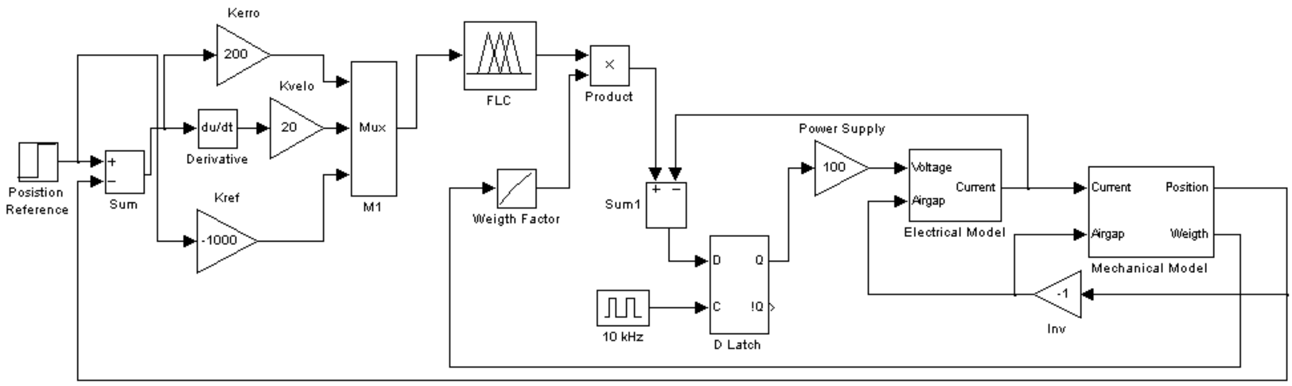

Figure 2. Block diagram of the fuzzy logic controlled system.

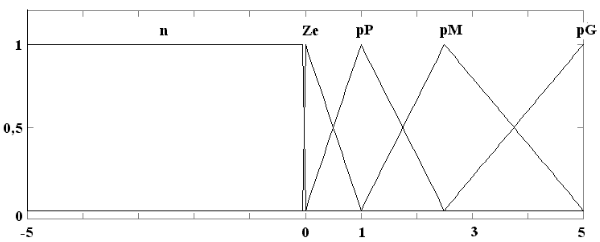

Figure 3a. Membership function for position error (mm).

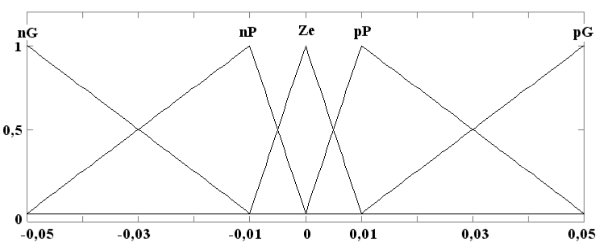

Figure 3b. Membership function for position error variation (m/sec).

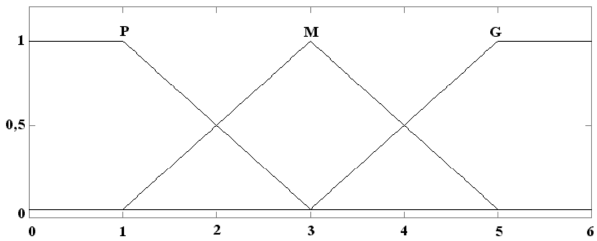

Figure 3c : Membership function for position reference (mm).

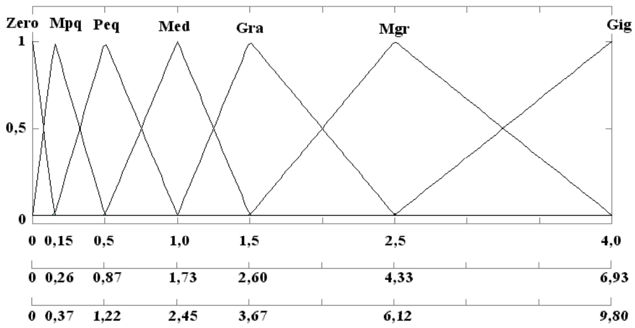

Figure 3d : Membership function for the output current (A).

In Fig. (3d) are shown three horizontal scales for current, which are related to the different weight of floating disks (15N, 30N and 45N). The weight of the mobile disk utilized in this work, almost 22.5 N, don't belong to the membership function above, so was necessary multiplied this output current by a factor 1.51.

The simplified fuzzy control rules can be summarized as shown in Tab. I and are valid for the position reference (M=3mm). Other two tables were defined for (P=1mm) and (G=5mm) position references. It should be noted in this Table that the true number of rules could be simplified to 29 because for any negative position error (**N**), the reference current will be zero. This is possible, because the magnetic axial bearing is using only a winding instead of two as happen in the conventional ones (Hung, 1995). Finally, the defuzzification was done through the centroid method.

Table 1. Fuzzy control rules.

		Change of position error (*Speed*)						
		nG	**nM**	**nP**	**ZE**	**pP**	**pM**	**pG**
Position error	**N**	Zero	Zero	Zero	Zero	Zero	Zero	Zero
	ZE	Zero	Zero	Zero	Zero	Mpq	Peq	Med
	pP	Zero	Zero	Zero	Mpq	Peq	Med	Gra
	pM	Zero	Zero	Zero	Peq	Med	Gra	Mgr
	pG	Zero	Zero	Peq	Med	Gra	Mgr	Gig

3. Experimental Results:

In Fig. (4) is shown the experimental electromagnetic bench. It can be seen the displacement sensor.

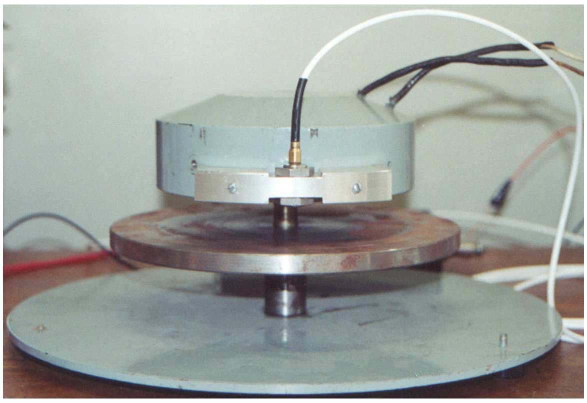

Figure 4. Experimental axial bearing.

The control algorithm was translated for a program using the computer language "C". Sampling rate was fixed in 500 µs (interruption routine). At first, the certainty degrees of control variables are identified and then a correspondent value for the current is founded from a table. This table was mounted using the fuzzy tools of SIMULINK® and MATLAB® programs. Debugging was tested through simulations using the following methods: singleton fuzzyfication and centroid defuzzyfication. In Figures (5) and (6) the experimental step responses are respectively shown from: 1.5mm to 1.0mm and 0.5mm to 1.0mm. The scale for both figures is: horizontal: 20ms / div; vertical: 1V / div. The maximum error was 5% approximately. Zero volts (0V) is indicated by a dash on the left side of each figure.

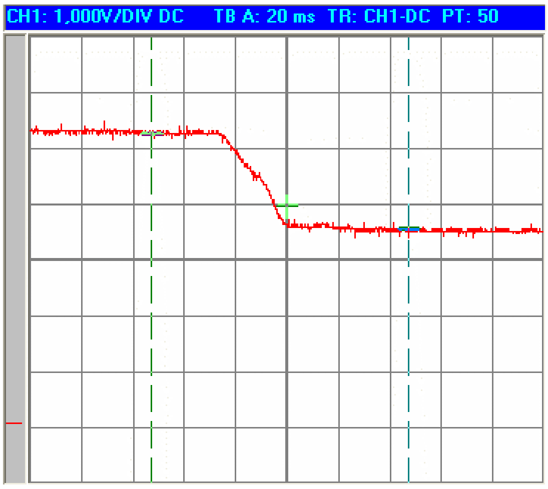

Figure 5. Step response (1.5mm to 1.0mm)

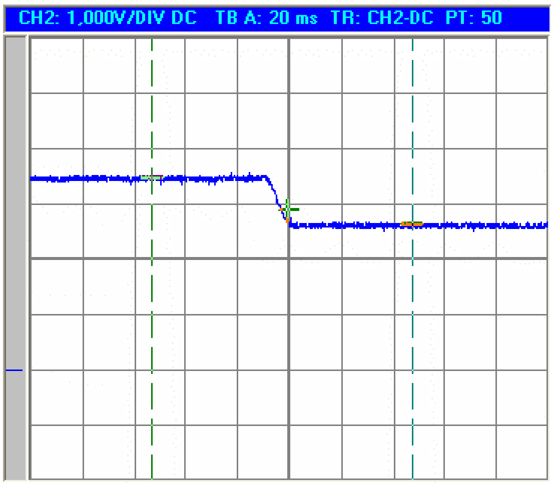

Figure 6. Step response (1.0mm to 0.5mm)

4. Conclusions:

- A fuzzy logic controller for an axial magnetic bearing was simulated and successfully tested.
- The control algorithm can be easily changed in order to control different electromagnetic structures such as the radial magnetic bearings.
- As a next step, a PID fuzzy control implementation is under development based on this work.

5. Acknowledgement

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