

Modeling and Control of Magnetic Levitation System via Fuzzy Logic Controller

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Abstract

Fuzzy logic controller (FLC) is an attractive alternative to existing classical or modern controllers for designing the challenging Non-linear control systems. It does not require any system modeling or complex mathematical equations governing the relationship between inputs and outputs. Fuzzy rules are very easy to learn and use, even by non-experts. It typically takes only a few rules to describe systems that may require several lines of conventional software code, which reduces the design complexity. By considering these advantages, this paper presents the design and analysis of a FLC controller for the magnetic levitation system. Additionally, a classical PID controller is also designed to compare the performance of both types of controllers. Results reveal that FLC found to give better transient and steady state results compare to the classical PID.

1. Introduction

Magnetic suspension systems, as a kind of contact-free and wear-free suspension, play an important role in precision motion control and have been studied and applied in many research fields, such as mechanical engineering, automatic control and biomedical engineering [1]–[5]. In order to achieve an overall better performance, trade-offs have to be taken among precision, rising time, overshoot and stable-state deviation in different magnetic suspension systems. Growing attention has been paid to its optimization and control in past several decades and the control algorithms have been developed from typical linear control strategies to intelligent control methods [6]–[14].

Although PID control is a proficient technique for the handling of non-linear systems but modeling these systems is often troublesome and sometimes impossible using the laws of physics. Therefore, using a classical controller is not suitable for nonlinear control application [15]. Alternatively, Fuzzy Logic Control are useful when the processes are too complex for analysis by

conventional quantitative techniques or when the available sources of information are interpreted qualitatively, inexactly, or uncertainly [16]. It does not require any system modeling or complex mathematical equations governing the relationship between inputs and outputs. Fuzzy rules are very easy to learn and use, even by non-experts. It typically takes only a few rules to describe systems that may require several lines of conventional software code, which reduces the design complexity [17]. PID control requires the model of the system for the determination of the parameters of PID controller using control theory and finally the development of an algorithm for the controller. Whereas in case of fuzzy logic the system behavior is characterized using human knowledge which directly leads to the design of control algorithm on the basis of fuzzy rules. These rules are in terms of the relationship of inputs to their corresponding outputs, and precisely determine the controller parameters. Any adjustment or debugging only requires modification in these fuzzy rules instead of the redesigning the controller. Hence control technique based on fuzzy logic not only simplifies the design, but also reduces the monotonous task of solving complex mathematical equations for nonlinear systems. As a result, fuzzy logic controller delivers a better performance in cases where the conventional controller does not cope well with the non-linearity of a process under control [18]. In fuzzy control we focus on gaining an intuitive understanding of how to best control the process, then we load this information directly into the fuzzy controller.

This paper describes an implementation of FLC. The design procedure utilizes MATLAB[®] Fuzzy Logic toolbox and is implemented using SIMULINK[®] version 7.1. One of the great advantages of the Fuzzy Logic toolbox is the ability to take fuzzy systems directly into SIMULINK[®] and test them out in a simulation environment [19]. Although the authors have no experience of controlling the ball and beam system before, a somewhat better controller is designed based on the simple fuzzy rules. The triangular membership functions are used, and the centroid method is used for

defuzzification. A classical PID controller has been also designed in MATLAB[®] for the system studied here, which will be used as a comparison to the FLC designed. The remainder of the paper is organized as follows. In Section 2, we have presented a mathematical modeling of the magnetic levitation system. Section 3 discusses a design scheme of FLC controller. In Section 4, results are discussed and a comparison has been made between PID and FLC based on simulation results. Finally in section 5, we have concluded all the discussion presented in our paper.

2. Modeling of Magnetic levitation system

The magnetic levitation system is a magnetic ball suspension system which is used to levitate a steel ball on air by the electromagnetic force generated by an electromagnet.



Fig. 1: Magnetic Levitation system

Figure 1 shows the magnetic ball suspension system consists of an electromagnet, a ball rest, a ball position sensor, and a steel ball. The magnetic ball suspension system can be categorized into two systems: a mechanical system and an electrical system. The ball position in the mechanical system can be controlled by adjusting the current through the electromagnet where the current through the electromagnet in the electrical system can be controlled by applying controlled voltage across the electromagnet terminals.

From Ampere's circuit law and faraday's inductive law, the magnitude of the force $f(x, i)$ exerted across an air gap h by an electromagnet through which current i flows can be described as:

$$f(h, i) = -\frac{i^2}{2} \frac{dL(h)}{dh} \quad (1)$$

The total inductance L is a function of the distance and given by

$$L(h) = L_1 + \frac{L_0 H_0}{h} \quad (2)$$

Where L_1 is the inductance of the electromagnetic (coil) in the absence of the levitated object, L_0 is the additional inductance contributed by its presence, and H_0 is the equilibrium position. The parameters are determined by the geometry and construction of the electromagnet, and can be determined experimentally. Substituting equation (2) into (1) yields

$$f = \frac{L_0 H_0}{2} \left(\frac{i}{h} \right)^2 = \beta \left(\frac{i}{h} \right)^2 \quad (3)$$

$$\beta = \frac{L_0 H_0}{2} \quad (4)$$

$$f = f_0 + \left(\frac{\partial f}{\partial L_0} \right) \Delta L_0 + \left(\frac{\partial f}{\partial H_0} \right) \Delta H_0 + \left(\frac{\partial f}{\partial i} \right) \Delta i + \left(\frac{\partial f}{\partial h} \right) \Delta h \quad (5)$$

Eliminating higher order terms give

$$f = f_0 + \left(\frac{\partial f}{\partial i} \right) \Delta i + \left(\frac{\partial f}{\partial h} \right) \Delta h \quad (6)$$

Evaluating equation (6) using (4) and (5) yields

$$f = \beta \left(\frac{I_0}{H_0} \right) + \left(\frac{2\beta I_0}{H_0^2} \right) \Delta i - \left(\frac{2\beta I_0^2}{H_0^3} \right) \Delta h \quad (7)$$

Where, I_0 is the equilibrium value. At equilibrium, the weight of the object is suspended by the electromagnetic force, f_0 . The force required to maintain equilibrium, f_1 is

$$f_1 = f - f_0 \quad (8)$$

Combining equations (7) and (8) gives

$$f_1 = \left(\frac{2\beta I_0}{H_0^2} \right) \Delta i - \left(\frac{2\beta I_0^2}{H_0^3} \right) \Delta h \quad (9)$$

The voltage equation of the electromagnetic coil is given in equation 1.

$$V = iR + L(h) \frac{di}{dt} \quad (10)$$

Assuming the suspended object remains close to its equilibrium position, $h \approx h_0$ and therefore

$$L(h) = L_1 + L_0 \quad (11)$$

Also assuming that $L_1 \gg L_0$ equation (10) can be simplified as

$$V = iR + L_1 \frac{di}{dt} \quad (12)$$

The principal equation for the suspended object comes by applying Newton's second law of motion. For

this one degree of freedom system, a force balance taken at the centre of gravity of the object yields

$$M \frac{d^2 h}{dt^2} = -f_1 \quad (13)$$

The sensor can be modeled as a gain element,

$$V_s = K_s h \quad (14)$$

Where V_s is the sensor output voltage and K_s is an experimental gain between the object's position and the output voltage.

$$-M \frac{d^2 h}{dt^2} = \left(\frac{2\beta I_0}{H_0^2} \right) i - \left(\frac{2\beta I_0^2}{H_0^3} \right) h \quad (15)$$

$$-M \frac{d^2 h}{dt^2} = K_1 i - K_2 h \quad (16)$$

Where, $K_1 = \frac{2\beta I_0}{H_0^2}$ and $K_2 = \frac{2\beta I_0^2}{H_0^3}$

The Laplace transform of above equation obtained as:

$$(Ms^2 - K_2)H(s) = -K_1 I(s) \quad (17)$$

The Laplace transform of equation (28) is

$$I(s) = \frac{V(s)}{L_1 s + R} \quad (18)$$

The overall transfer function of the Maglev system is obtained as:

$$G(s) = \frac{V_s(s)}{V(s)} = \frac{-\frac{K_s K_1}{ML_1}}{\left(s + \frac{R}{L_1}\right) \left(s^2 - \frac{K_2}{M}\right)} \quad (19)$$

Table 1 summarizes the variables and parameters use in this problem. Here the problem is to maintain the ball at its operating point (position) of 0.03 meters from the coil.

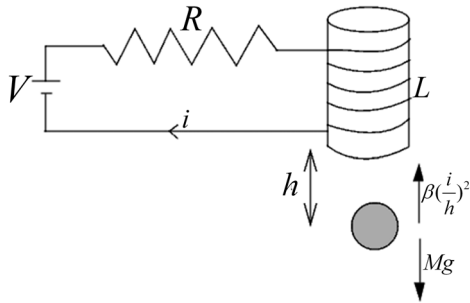


Fig. 2: A magnetic ball bearing system

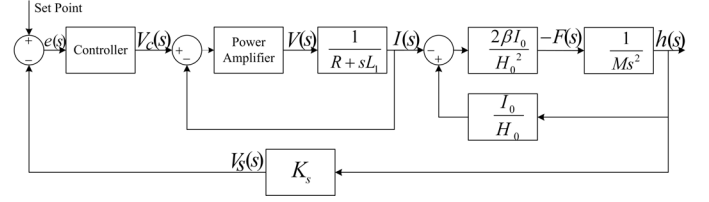


Fig. 3: Block diagram of Magnetic levitation system

Table1. Parameters of the magnetic Levitation system.

Parameters	Description	Values
H_0	equilibrium height of ball (m)	0.03
M	Mass of ball bearing (kg)	0.225
R	Resistance (Ω)	2.48
L_1	Inductor (H)	0.18
β	Constant related to magnetic force (Nm^2/A^2)	7.93×10^{-5}
I_0	Equilibrium current of the coil (A)	5
K_s	Sensor gain factor (V/m)	200
K_1	constant (N/A)	0.882
K_2	constant (N/m)	147

3. Design Methodology of FLC

For the fuzzification process, the triangular membership functions are used for both input and output with the universe of discourse as follows:

- $e = [-1, 1]$
- $\Delta e = [-1, 1]$
- $V = [-2, +2]$

These values were obtained by observing the corresponding values of e , Δe and control input u in the conventional system using the classical PID controller. Figures 3 and 4 show the membership functions used for the input and output variables.

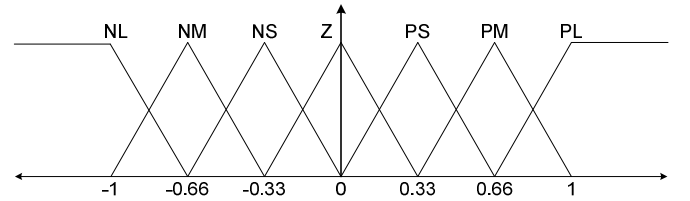


Figure 3. Input e and Δe Membership Function

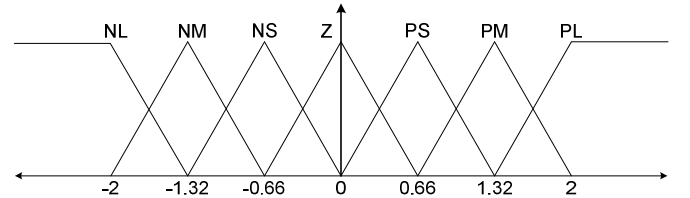


Fig. 4: Output Membership Function

Table 1 Fuzzy rule base

e \dot{e}	PL	PM	PS	Z	NS	NM	NL
NL	Z	NS	NM	NL	NL	NL	NL
NM	PS	Z	NS	NM	NL	NL	NL
NS	PM	PS	Z	NS	NM	NL	NL
Z	PL	PM	PS	Z	NS	NM	NL
PS	PL	PL	PM	PS	Z	NS	NM
PM	PL	PL	PL	PM	PS	Z	NS
PL	PL	PL	PL	PL	PM	PS	Z

3.1 Inference mechanism

The Inference Mechanism provides the mechanism for invoking or referring to the rule base such that the appropriate rules are fired. Using trial and error approach, the best inference mechanism to use in this case seems to be the *min-max* method.

3.2 Rule base

The rule base used in the design is given in Table 1. The rule base follows closely the rules that were suggested in [16].

3.3 Defuzzification

The defuzzification technique used was also found using trial and error. The defuzzification technique in this case that gave the least integral square error was the Centre of Gravity approach.

3.4 Scaling factor

Here the controller was tuned using input and output scaling factors to improve the performance of the system. The output scaling factor was needed to ensure that the control input u to the ball and beam is enough to move the beam accordingly in order to maintain its position. The scaling factors that were used are listed in Table 2.

Table 3 Scaling Factors

Scaling factors	Value used
e	1
Δe	0.05
u	2.5

4. Results and Discussion

Fig.5 and 6 show the coil current and control input (voltage) for both types of controllers. The result shows that the controlled electromagnet current can stabilize the

disturbances that otherwise, would cause the ball to either fall or attach itself to the electromagnet. In the steady state of Fig. 6, the electromagnet current with very few vibrations and the suspended position with very small errors coincide with the designed balance conditions: 5 A of electromagnet current producing a magnetic force which just counteracts the 0.225 kg weight of the ball suspended 0.03 m under the electromagnet. Fig. 7 shows the control surface of the FLC. It can be noted that, FLC has a linear control surface. This is due to the equal widths of membership function for input and output [20]–[21].

From the simulation results shown in Fig. 7, it can be observed that the fuzzy controller has better transient response than the classical controller. The overshoot of the FLC controller is 6% compared to 18% in the classical case. Furthermore, FLC has a faster transient response; it reaches to steady state in 0.3second to that of 1sec in PID. In comparison to the steady state value, both controllers satisfactorily attain the steady state value of 0.03 meter.

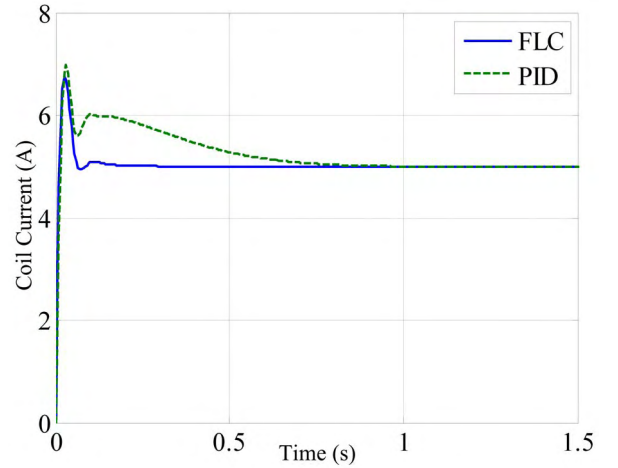


Fig. 5: Error Response for Both Controllers

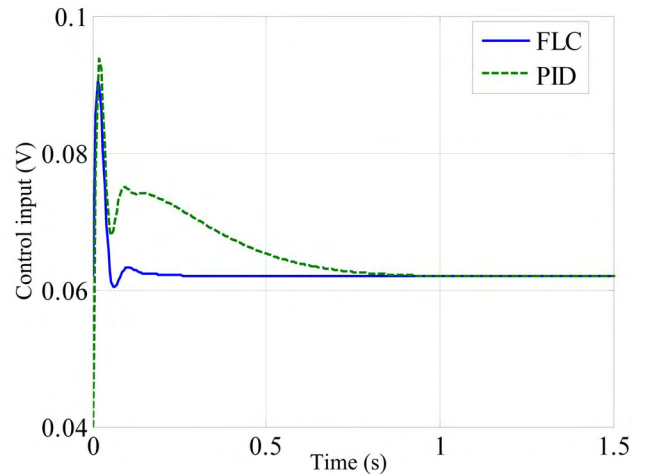


Fig. 6: Control Input Response for Both Controllers

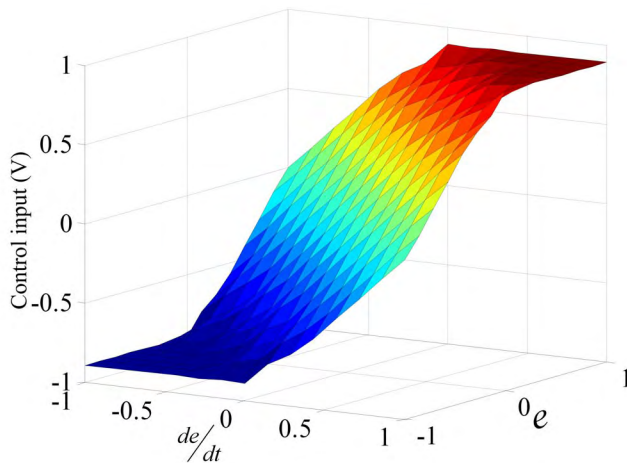


Fig. 7: Fuzzy control surface

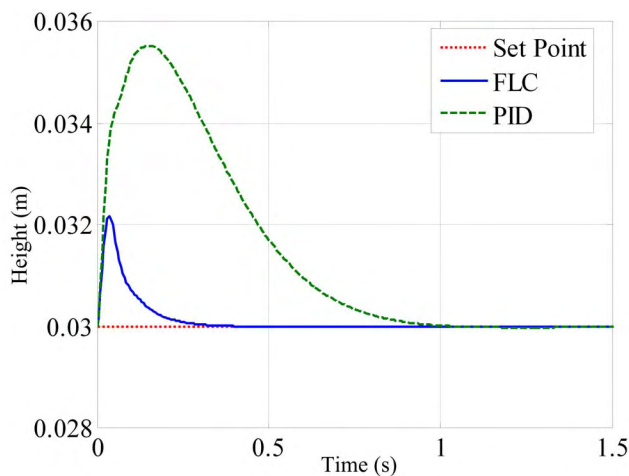


Fig. 8: Output Response of PID and FLC

5. Conclusion

An attempt to control the position of a steel ball in a magnetic levitation system using fuzzy logic has been proposed. From the simulation results, it has been shown that the fuzzy controller can stabilize the system efficiently. Also, the performance during the transient period of the fuzzy system is better in the sense that less overshoot was obtained. Moreover, the fuzzy controller provides a zero steady state error.

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