Controlling of Magnetic Levitation System using a Fuzzy system for tuning the PID Parameters

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Abstract: Magnetic levitation is an unstable and non-linear system. The main problem for these types of systems is how to develop a control system to obtain the desired output response. For years several techniques and methods have been followed to get a control system that meets requirements of stable performance. In this paper, a classical PID controller is implemented, to control a magnetic levitation system. A fuzzy system is used to modify the parameters of PID controller according to body position. The impact of system's non-linearity has been reduced with the suggested controller. The simulation results explain that the supervisory fuzzy-PID controller has a good robustness and a quality controller. The model of the system is simulated using Matlab R (2015) a Simulink.

Keywords: Magnetic levitation system, PID controller, Fuzzy control, and Matlab Simulink.

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1. Introduction

For many years Electromagnetic levitation has attracted many researchers, who interested in studying the nonlinearities behavior for systems in order to implement an effective control scheme [1][2]. Therefore, it needs to know what it the magnetic levitation. “Magnetic Levitation is described as a system which holds an object in the air without any physical contact between the object and the system” [3]. And to do this, it must cancel the force of gravity by an equal and opposite force using a strong electromagnet [4]. The difficulty is how to control the current flowing through the coil, which produces an appropriate magnetic field to lift the ball. A lot of control strategies have been suggested to get an effective and fast response. And These strategies are like linear, nonlinear, fuzzy logic controllers and etc [5].

In past years the fuzzy controller was used to solve difficult engineering problems that did not have accurate mathematical plant pattern [5], and for the flexibility with all systems. All these reasons make the fuzzy logic to be a good choice to control nonlinear systems like electromagnetic levitation systems[6][7]. And in addition, PID controller has a good performance to reduce the error in the response of the system. Therefore, a combination of fuzzy and PID controllers was designed to extract the advantages of both controllers. The experiments show that the self-tuning-parameter fuzzy PID controller has a better performance in compared to a classical PID controller in control the magnetic levitation system [8][9].

The purpose of this paper is to highlight the use of intelligent techniques with classical techniques in order to lead the system to a state of stability.

This paper is structured as: Section 2 introduces the literature review. Magnetic Levitation System modeling is presented in section 3. The design of the fuzzy Self-Tuning PID controller is given in section 4. Section 5 shows the simulation and experimental results. Finally, section 6 gives the conclusions.

2. Related Works

There are many kinds of research in the literature that involves design and implementation the magnetic levitation system. N. Naz, et al., (2013) [1] presented feedback linearizing controller to reduce the error and settling time for the magnetic levitation system, and to get good performance. For comparison, a sliding mode and PID controllers are implemented. T. Tariq, et al., (2013) [2] explained how to use the Fuzzy logic controller to make the magnetic levitation system more stable by keeping the ball in the air. And showed that Fuzzy logic controller is better than the LQR control. A. Awelewa, et al., (2013) [3] introduced the magnetic levitation system's behavior, by using the root locus technique to reach to the stability of the system. And to prove that the system can be effective, stable and useful only by modifying the parameters of the controllers. R. Precup, et al., (2017) [5] presented developing Takagi-Sugeno (T-S) Fuzzy logic in order to control the nonlinear behavior of magnetic levitation system, and to improve the performance of the plant that used T-S Fuzzy controller in terms of the output's response. N. Naz, et al., (2013) [10] introduced the real-time implementation of magnetic levitation system by using a sliding mode control and Kalman filter to estimate the unknown plant, and the system tested under external disturbance to prove its robustness. J. Iqbal, et al., (2016) [6] explained the design of magnetic levitation system by using H robust controller, and by taking into consideration the uncertainties in current and the output. M. Hypiusova, et al., (2017) [7] presented the design of a robust PID controller for a magnetic levitation system in the field of a frequency domain, to guarantee the desired performance.

3. The Mathematical Model of the Magnetic levitation System

This section explains the mathematical modeling of the system. The model is obtained by applying the basic equations of physics and mechanics to the system that can be represented by differential equations. The simplified diagram of magnetic levitation system is given in figure 1.

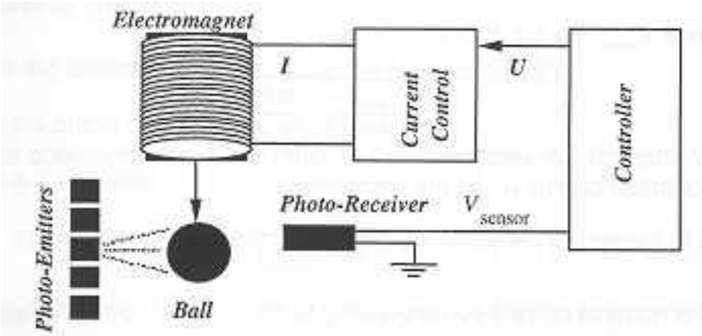


Figure (1): Simplified Magnetic levitation System Diagram

The system dynamics explaining the behavior of the moving ball are derived from Newton's laws, as expressed in (1) [3]:

$$F_a + F_e = F_g \tag{1}$$

And can be rewritten as:

$$F_a = F_g - F_e \tag{2}$$

Where

- F_a denotes the accelerating force because of the ball mass.
- F_e denotes the Magnetic force ("F_e defined as the rate of change of work done with distance as the ball is moved from one position to the other by the force").
- F_g represents gravity force.

$$F_a = m\ddot{X} \quad , \quad F_g = mg \quad , \quad F_e = k\frac{I^2}{x^2}$$

So, It can be rewrite (2) as follow [1]:

$$m\ddot{X} = mg - k\frac{I^2}{x^2} \tag{3}$$

- m is the mass of the levitated object.
- g represents gravity.
- X denotes the distance between the ball and the electromagnet.
- I is the amount of current that passes through the electromagnet.
- k is a coefficient.

A photo-sensor (infrared-based) may be used to give a measurement of the distance of the ball’s position from the electromagnet to ensure that the ball at the desired position by providing a voltage, when X_0 is the primary operating point and γ >0.

$$\boldsymbol{V_{sensor}} = -\boldsymbol{\gamma}(\boldsymbol{X} - \boldsymbol{X_0}) \tag{4}$$

And when $X=X_0$, the output of the sensor will be zero, and the variation in Vsensor is given as:

$$\Delta\, \boldsymbol{V_{sensor}} = -\boldsymbol{\gamma X} \tag{5}$$

The amount of current that passes through the electromagnet is provided by the relation:

$$\boldsymbol{I} = \mathbf{0.15}\boldsymbol{U} + \boldsymbol{I_0} \tag{6}$$

Where, I_0 is the primary operating current at primary ball position X_0. And the variation in current is:

$$\Delta\, \boldsymbol{I} = \mathbf{0.15}\ \Delta\boldsymbol{U} \tag{7}$$

From equation (5), it can be seen that the electromagnetic force is always a negative term as the inductance parameter decreases while the ball moves away (x increases). Hence the magnetic ball is always pulled over to the electromagnet whatever the sign of the coil current is. The output of the sensor changes according to the appropriate amount of effort in order to make the ball stable and keep it in that mode.

The non-linear model from equation (3) can be linearzed around the nominal operating point (X_0, I_0) as:

$$\boldsymbol{m}\Delta\ddot{\boldsymbol{X}} = \boldsymbol{\lambda}\Delta\boldsymbol{X} - \boldsymbol{\alpha}\Delta\boldsymbol{U} \tag{8}$$

Where, ΔI has substituted by 0.15ΔU.

$$\boldsymbol{X}(\boldsymbol{s}) = \Delta\boldsymbol{X}(\boldsymbol{s}), \quad \boldsymbol{U}(\boldsymbol{s}) = \Delta\boldsymbol{U}(\boldsymbol{s}) \tag{9}$$

The constant k can be determined from the equilibrium conditions around (X0, I0) which are given by making the derivatives of the non-linear model equal to zero-yielding:

$$\boldsymbol{mg} = \boldsymbol{k}\frac{\boldsymbol{I_0^2}}{\boldsymbol{X_0^2}} \tag{10}$$

This gives:

$$\boldsymbol{k} = \frac{\boldsymbol{mgX_0^2}}{\boldsymbol{I_0^2}} \tag{11}$$

Finally, the transfer function G(s) of the considered system is approximated to second order:

$$\boldsymbol{G(s)} = \frac{\boldsymbol{y(s)}}{\boldsymbol{U(s)}} = \frac{\boldsymbol{\eta}}{\boldsymbol{S^2 - W_0^2}} \tag{12}$$

$$\boldsymbol{\eta} = -\frac{\boldsymbol{\gamma F_1}}{\boldsymbol{m}} = \frac{\boldsymbol{0.3kI_0}}{\boldsymbol{X^2}} \frac{\boldsymbol{\gamma}}{\boldsymbol{m}} \frac{\boldsymbol{mgX_0^2}}{\boldsymbol{I_0^2}} = \boldsymbol{0.3} \frac{\boldsymbol{\gamma g}}{\boldsymbol{I_0}} \cong \frac{\boldsymbol{3\gamma}}{\boldsymbol{I_0}} \tag{13}$$

$$\boldsymbol{w_0} = \sqrt{-\frac{\boldsymbol{F_x}}{\boldsymbol{m}}} = \sqrt{\frac{\boldsymbol{2I_0^2}}{\boldsymbol{mX_0^3}} \frac{\boldsymbol{mgX_0^2}}{\boldsymbol{I_0^2}}} = \sqrt{\frac{\boldsymbol{2g}}{\boldsymbol{X_0}}} \cong \sqrt{\frac{\boldsymbol{20}}{\boldsymbol{X_0}}} \tag{14}$$

Note that this linear system is independent of the levitation-ball mass. Under state space form, this linearized system can be described by the straightforward companion form:

$$\dot{x} = Ax + Bu = \begin{bmatrix} 0 & 1 \\ w_0^2 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ \eta \end{bmatrix} u \tag{15}$$

$$y = Cx = [1 \quad 0]x \tag{16}$$

Where,

$$y(s) = \Delta V_{sensor}(s) = X_1\,,\ \ and\ \ \dot{X}_1 = X_2 \tag{17}$$

In this state equation, the state variables are as follows:

$$X_1 = \Delta V_{sensor},\quad X_2 = \Delta \dot{V}_{sensor} \tag{18}$$

Here, the output “X1 and X2” represent the position of the ball and the velocity (represent the ideal system without a noise) [1][10][11]. And to keep the balance of the ball against the effect of gravity, it requires modification of the magnetic force.

4. Design of the Fuzzy Self-Tuning PID Controller

In this section two controllers for the magnetic levitation system to be stable will be presented; the Proportional Integral Derivative (PID) controller, and a fuzzy system that tunes the PID gains, to regulate the output by control the current through the coil, the coil current is used as input to control the ball position, to produce magnetic field when DC current is applied.

A. PID Controller

The proportional-integral-derivative controller is commonly used due to the simple structure and robust performances. The PID controller has the following form as illustrated in (19), here u(t) represents the output of the classical controller [12][13]:

$$u(t) = K_p e(t) + K_i \int_0^t e(t) d\tau + K_d \frac{d}{dt} e(t) \qquad (19)$$

The “magnetic levitation system” is a nonlinear system, so it is difficult to try to use classical control method to achieve ideal control effect [8]. For this reason, it uses here Fuzzy PID controller.

B. Fuzzy System for Tuning the PID Parameters

The Appropriate PID controller depends on the choice of the parameters. For this reason, it can be used the Fuzzy system for Self-Tuning PID parameters, and gets the advantages of both Fuzzy and PID controllers, to arrive at optimal control strategies. Figure 2 illustrated the general structure of the "self-tuning parameter fuzzy PID controller" [12][8]. Where r(t) is the desired position and y(t) is the actual position of the ball. The error (e) and its change (Δe) are the inputs of the fuzzy control, and the outputs will be the changes of the parameters (K_p, K_i, K_d).

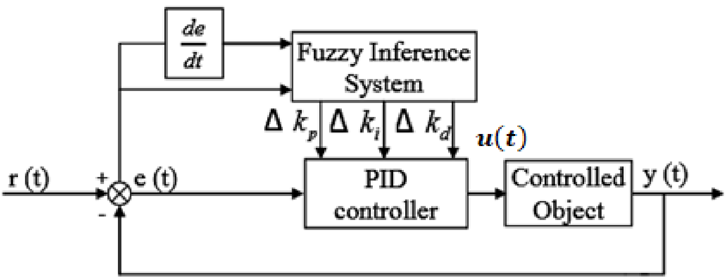


Figure (2): Basic structure for “Self-Tuning parameter Fuzzy PID Controller”

Fuzzy logic rules are used for self-tuned the PID parameters to get suitable values of the parameters to control the output as illustrates in (20) and (21) [8]:

$$\left.\begin{aligned} e(t) &= r(t) - y(t) \\ \Delta e(t) &= e(t) - e(t-1) \end{aligned}\right\} \quad (20)$$

$$\left.\begin{aligned} K_{p(t)} &= K_{p(t-1)} + \Delta K_{p(t)} \\ K_{i(t)} &= K_{i(t-1)} + \Delta K_{i(t)} \\ K_{d(t)} &= K_{d(t-1)} + \Delta K_{d(t)} \end{aligned}\right\} \quad (21)$$

Where $K_{p(t)}$, $K_{i(t)}$, and $K_{d(t)}$ are the tuning parameters of the PID controller, and $K_{p(t-1)}$, $K_{i(t-1)}$, and $K_{d(t-1)}$ are the PID parameters before tuning. To control the position of the ball which is the purpose of the controller, it makes the output of the controller as the input (voltage) to the Electromagnet, in order to control the current through the coil of the Electromagnet. And from finding the relationship between the PID parameters and e and Δe, by using the Fuzzy PID controller, it leads to produce a good dynamic performance. To do this, it must select the variables of the error (e) and the its change (Δe) of the system as inputs for the fuzzy control, it has been chosen seven linguistic values of the fuzzy sets as {MH, MM, ML, ZE, AL, AM, AH}, that is {Minus High, Minus Middle, Minus Low, Zero, Affirmative Low, Affirmative Middle, Affirmative High} [12][13][14]. Table 1, Table 2 and Table 3 shows the Fuzzy rules for tuning the PID parameters. Figure 3 shows the membership function for the inputs (e and Δe).

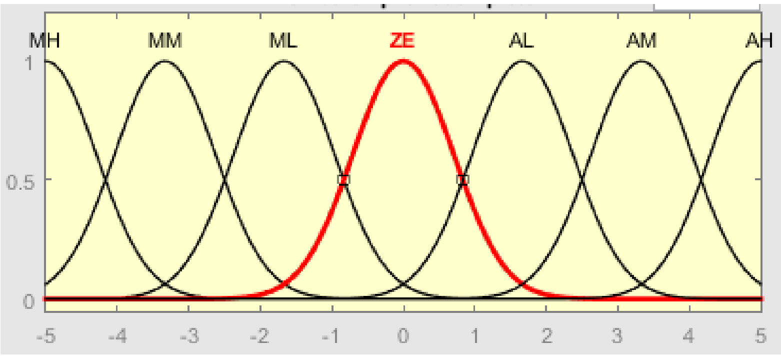


Figure (3): e and Δe membership functions

Table 1: Fuzzy rules for K_p

e	Δe						
	MH	MM	ML	ZE	AL	AM	AH
MH	AH	AH	AM	AM	AL	AM	ZE
MM	AH	AH	AM	AL	AL	ZE	ML
ML	AM	AM	AM	AL	ZE	ML	ML
ZE	AM	AM	AL	ZE	ML	MM	MM
AL	AL	AL	ZE	ML	ML	MM	MM
AM	AL	ZE	ML	MM	MM	MM	MH
AH	ZE	ZE	MM	MM	MM	MH	MH

Table 2: Fuzzy rules for K_i

e	Δe						
	MH	MM	ML	ZE	AL	AM	AH
MH	MH	MH	MM	MM	ML	ZE	ZE
MM	MH	MH	MM	ML	ML	ZE	ZE
MS	MH	MH	ML	ML	ZE	AL	AL
ZE	MM	MM	ML	ZE	AL	AM	AM
AL	MM	MM	ZE	AL	AL	AM	AH
AM	ZE	ZE	AL	AL	AM	AH	AH
AH	ZE	ZE	AL	AM	AM	AH	AH

Table 3: Fuzzy rules for K_d

e	Δe						
	MH	MM	ML	ZE	AL	AM	AH
MH	AL	ML	MH	MH	MH	MM	ZE
MM	AL	ML	MH	MM	MM	ML	ZE
ML	ZE	ML	MM	MM	ML	ML	ZE
ZE	ZE	ML	ML	ML	ML	ML	ZE
AL	ZE	ZE	ZE	ZE	ZE	ZE	ZE
AM	AH	ML	AL	AL	AL	AL	AH
AH	AH	AM	AM	AM	AL	AL	AH

5. Simulation and Experimental Results

The design of a controller for any system depends on the good knowledge of the plant, and by knowing the magnetic levitation system; it is possible to say that the classical control unit doesn't meet the system's requirements to make it stable. In this section, comparison of the Fuzzy

PID and PID controllers is given. The mathematical model of the system with controllers has been implemented in Matlab Simulink, as illustrated in figure 4.

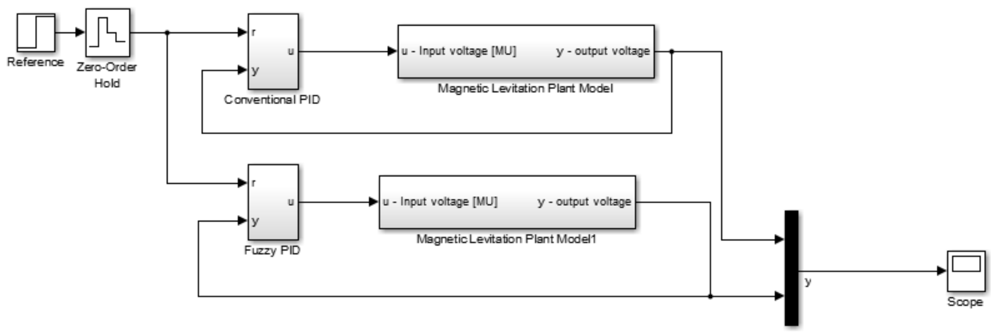
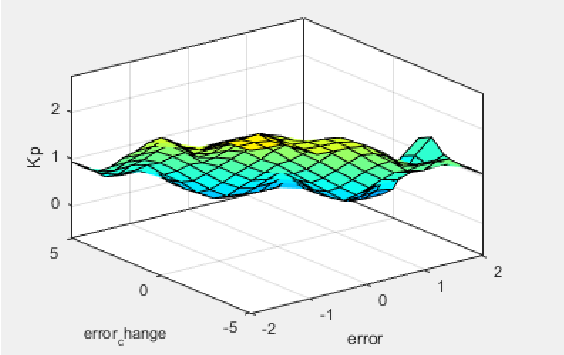


Figure (4): The Matlab Simulink of the System

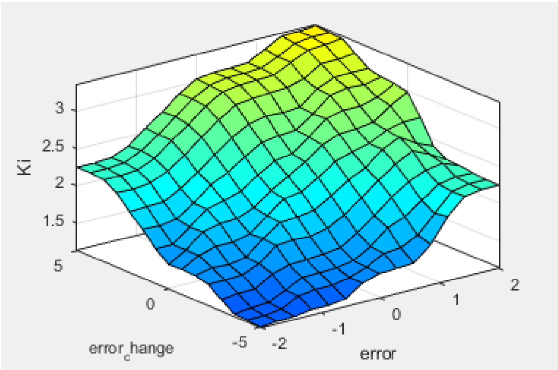
The width of the fuzzy sets for output K_p has been chosen [-1 3], K_i, has been chosen [1 3.5] and for K_d, [0 1]. And for inputs, the range of the error and error rate have been chosen [-5 5]. These values were chosen according to the values that obtained from the Ziegler-Nichols method (closed loop P-control test), that use for tuning the PID controller to obtain the perfect values of its parameters. By applies the unit step reference to the input of the system and get the response, and from the response, it can be finding the values of L and T (L=1.3, and T=1.1) and Compensate the values in table 4. Thus, the following values can be obtained (K_p=1.01538, K_i=2.6, and K_d=0.39). Figure 5 shows the change of the three parameters of PID with Fuzzy logic.

Table 4: The Ziegler-Nichols' Formulas for the controller parameters.

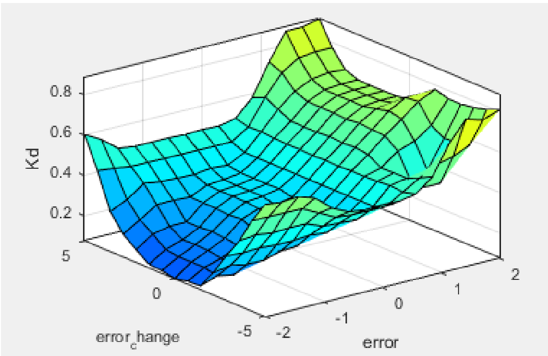
	K_p	K_i	K_d
P	T/L	∞	0
PI	0.9T/L	L/0.3	0
PID	1.2T/L	2L	MM



ΔK_p Response curve



ΔK_i Response curve



ΔK_d Response curve

Figure (5): PID parameters change curve.

From the simulation performance of the system with PID and Fuzzy PID self-Tuning parameters is shown in figure 6, it can see that the Fuzzy PID controller reaches faster to the equilibrium point with small overshoot than the PID controller.

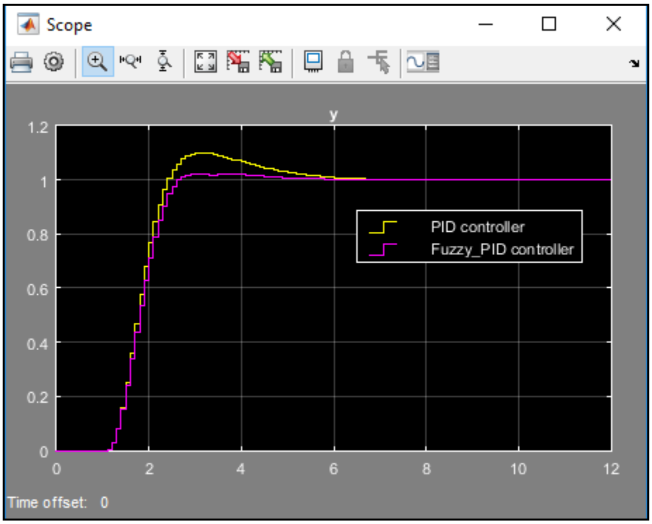


Figure (6): Comparisons of PID and Fuzzy PID control.

6. Conclusion

In this paper, a Fuzzy-PID and classical PID controllers are designed for a magnetic levitation system, in order to see the comparison in response between the two controllers using Matlab Simulink. A Ziegler-Nichols method has been used to find the perfect values of the PID parameters. These values are used to choose the membership functions and the rules of the Fuzzy logic controller for tuning PID parameters, and apply it to the plant. As we can see in the simulation and experimental result section, the performances of the fuzzy PID controller was better than the classical PID controller. The suggested controller reduce the settling time and maximume overshoot of the system's response.

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التحكم بنظام الرفع المغناطيسي بأستخدام النظام الغامض لتدريب معلمات المسيطر PID

م.م. رؤى حميد احمد*

المستخلص : نظام الرفع المغناطيسي هو نظام غير مستقرو,غير خطي. المشكلة الرئيسة لهذه الانواع من الانظمة هي كيفية تطوير نظام التحكم للحصول على استجابة الاخراج المطلوبة ، لسنوات تم اتباع العديد من التقنيات والاساليب للحصول على نظام التحكم التي تلبي متطلبات ألاداء المستقر. في هذه الورقة، يتم تنفيذ وحدة تحكم PID الكلاسيكية، للسيطرة على النظام الرفع المغناطيسي واستخدام النظام الغامض لتعديل معلمات المتحكم PID وفقاً لموقع الجسم، وبالتالي تقليل تأثير اللاخطية للنظام من خلال المتحكم المقترح. وتوضح المحاكاة أن وحدة تحكم المنطق الغامض لضبط معلمات ال PID لديها متانة جيدة وجودة تحكم. يتم محاكاة نموذج النظام باستخدام الماتلاب.

الكلمات المفتاحية: نظام الرفع المغناطيسي، المتحكم PID، والنظام الغامض.

*وزارة التعليم العالي والبحث العلمي