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Design and performance analysis of fuzzy supervisory controller for a magnetic levitation system

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K E Y W O R D S

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Fuzzy Supervisory Control

Hybrid Control

Membership Functions

A B S T R A C T

This paper presents a fuzzy supervisory controller for a magnetic levitation system. The proposed method incorporates fuzzy logic over conventional controllers. This method combines advantages of fuzzy logic controller and conventional controllers to improve the performance of a magnetic levitation system. The conventional PID controllers have various limitations and are usually uncertain in terms load and air gap changes due to their constant parameters. To overcome aforementioned limitations, a Fuzzy-Supervisory controller has been designed which tunes the three gains i.e. K_p, K_i and K_d of the PID controller. Rules of the fuzzy controller have been defined to calculate the optimal range of gain values. Performance parameters of the proposed supervisory controller e.g. rise time, maximum peak overshoot and settling time have been evaluated using MATLAB/SIMULINK and compared with the conventional controllers. The simulation results verified the effectiveness of the proposed Fuzzy Supervisory controller under different operating conditions.

1. Introduction

A magnetic levitation or a maglev system fundamentally consists of an object which is levitated in air under influence of its magnetic field. This idea finds extensive applications in many systems like magnetic bearings, contactless melting and high-speed trains. Maglev trains have great advantage over conventional ones due to absence of metallic contact friction. This explains their high speed and low noise features. A brief technical description of Magnetic Levitated body is given below.

A simple magnetic levitation system is given in Figure 1, it has a ferromagnetic metallic ball (as used in bearings) with mass ‘m’. The ball is levitated under the influence of the magnetic pull of the electromagnet along its vertical axis at a distance ‘x’. The infrared detector will detect the position of the ball. The detector will generate a control signal. This signal is given at the input of the controller in the form of a voltage. The driver converts it into a current. The current passing through a coil generates an electromagnetic force which in turn attracts the ball. The sum of electromagnetic force and gravitational force induces an upright motion in the ball. If the distance x increases, the controller will increase the amount of current. If the distance x decreases the controller will decrease the amount of current and so the ball remains suspended.

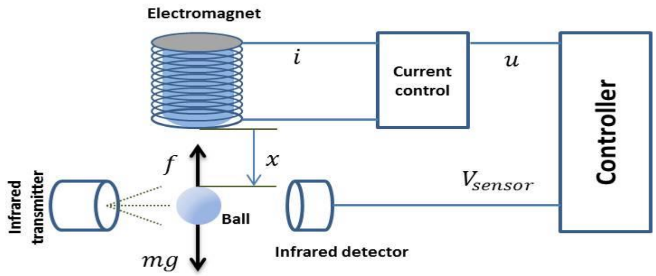

Fig. 1. Schematic of a simple magnetic levitation system [1]

An integral state feedback control method based on T-S fuzzy model for nonlinear and unstable magnetic levitation ball system is presented in [2]. They have designed a two controller system consisting of a local and a global controller. The local controller is designed by using the integral state feedback control whereas the global controller is constructed by a parallel distributed compensation (PDC) method. Furthermore, the feedback gain is obtained using a linear matrix inequality (LMI). A stable ball levitation with better control performance has been reported after simulations and experiments.

The stability control of a levitating object in a magnetic levitation plant is presented in [3] using a Fractional order PID (FOPID) controller. The Maglev plant and FOPID controller both have been designed in MATLAB-Simulink. The stability of the proposed system is determined via the Routh Hurwitz stability criterion. Ant Colony Optimization (ACO) algorithm and Ziegler Nichols method has been used to fine-tune the parameters of FOPID controller. The presented controller exhibits efficient results in comparison to the traditional IOPID controller.

Another study [4] presents a multi-loop Model Reference Adaptive Control (MRAC) scheme that leverages a nonlinear autoregressive neural network with external inputs (NARX) model in as the reference model. Authors observed that the performance of multi-loop MRAC-fractional-order proportional integral derivative (FOPID) control with MIT rule largely depends on the capability of the reference model to represent leading closed-loop dynamics of the experimental ML system. The obtained reference model is independent of the tuning of other control loops in the control system. This multi-loop control structure resulted in improvement of disturbance rejection performance of the system.

The design of an adaptive state feedback controller (ASFC) for a magnetic levitation system (MLS) is presented in [5]. A nonadaptive state feedback controller (SFC) is designed by linearization about a selected equilibrium point. The results indicate that the designed controller outperforms the state feedback controller.

In [6], Tran et al. suggested using a Fuzzy logic controller to further tune the PID controller. It tunes the gain parameters of PID controller by using fuzzy inference engine. The suggested system turned out to be very flexible as compared to conventional PID controller. In [7], Verma et al. proposed an Optimal Fractional Order Proportional Integral Derivative (OFPID) Controller for magnetic levitation system. They optimized system parameters using Nelder's-Mead algorithm. Then using Oustaloup's method, integer order approximation of the Fractional Order PID controller is done. They validated the performance of their proposed scheme with that of a PID controller. In [8], Baljinder Singh and Vijay Kumar proposed an Adaptive PID controller. This controller was implemented on real time control equipment designed for educational purposes i.e. GML1001. The results revealed that the adaptive PID controller is more efficient as compared to conventional feedback controller which failed to restrain the position of the levitated ball due to non-linearity and parameter ambiguity. In [9], Huang et al. presented a more efficient idea of controlling a magnetic levitation system i.e. using two electromagnets instead of one for a controlling a magnetic levitation system. The magnet placed above the ball attracts it while the one below repels it. A two degree of freedom PID controller is applied instead of one degree of freedom for hassle free levitation.

In [10], Silviu Folea et al. have designed a Fractional Order Controller for Magnetic Levitation system. Although Fractional order controller is used in stable processes, but the authors proved that the controller designed by them helped increasing the stability of the magnetic levitation system and also provided robustness to the system. The proposed fractional order controller was compared with conventional PID controller proving that the proposed system outperforms a simple conventional controller. In [11], Lalbahadur Majhi et al tested the performance of PID controller and Fractional order PID controller for magnetic levitation system, fabricated by Feedback Instruments (Model No 33-210). Both these controller as executed in MATLAB and SIMULINK domain and their parameters are tuned by firefly algorithm. Experiments show that Fractional order PID controller gave better results that conventional PID controller. Authors of above mentioned papers have adopted a simple model of levitating a metallic ball in air. However, in this paper a practical system has been adopted i.e. levitation of a

Maglev train above the track. Stefani et al. [12] has also described a mathematical model of a Maglev train.

In this paper, a PID controller supervised by a fuzzy controller has been proposed and implemented to improve the performance of the magnetic levitation system. This paper furthers the field by presenting a hierarchical control approach in designing a controller for magnetic levitation system. In this approach in addition to a PID controller, an additional fuzzy supervisory controller has been assigned on top the PID controller which helps in improved efficiency and prevention of failures in an automatic way. The designed Fuzzy Supervisory controller has the flexibility of suitably tuning the gains of conventional PID controller to get the desired response under various operating conditions. Gaussian membership functions have been used to fuzzify the gain parameters. Mamdani inference engine has been used to map inputs to corresponding outputs and centre of gravity defuzzifier has been employed to get crisp values which reflect the gain parameter of the designed PID Controller. The results show that the issues regarding varying load and parameters changes have been resolved quite satisfactorily. The Mathematical model of magnetic levitation is presented in section 2. The design of conventional PID controller and Fuzzy Supervisory controller is summarized in section 3. In section 4, Simulation results for the proposed controller are analysed and compared under different operating conditions. Section 6 concludes the paper.

2. Mathematical Model of Magnetic Levitation System

A cross sectional diagram of a simple Maglev train as shown in Fig. 2. The train is supported by 8 electromagnets. It can have 6 different motions but here only one motion is considered and that is to levitate the train above the track in upward direction. Here 'h' is the height of the train from the track, 'z' is the height of train from lower contact point with the track and so 'd' is the gap distance between train and the track is given by Eq. 1.

$$d = z - h \tag{1}$$

Time derivatives are taken through Eqs. 2 and 3.

$$\dot{d} = \dot{z} - \dot{h} \tag{2}$$

$$\ddot{d} = \ddot{z} - \ddot{h} \tag{3}$$

The Electromagnets produce a force which is dependent on magnetic flux due to current as shown in Fig. 2. For small variations in current and gap distance, this force is nearly represented by Eq. 4.

$$f_1 = -Pi + (Qd) \tag{4}$$

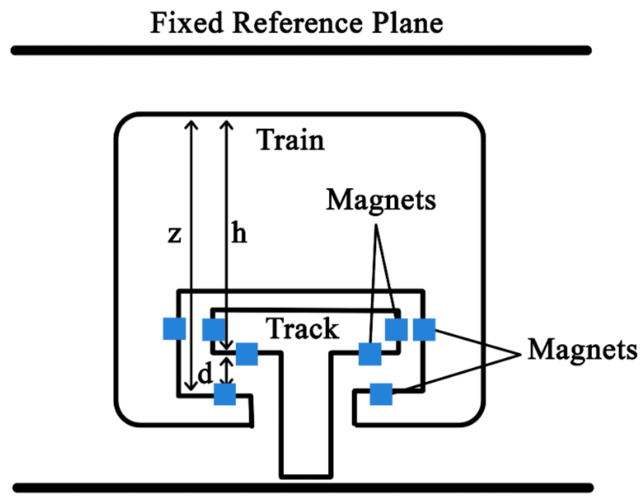

Fig. 2. Cross Section of Maglev Train [12]

The above equation shows the balance of forces. Here P and Q are positive constant. P represents magnetic force per ampere and Q is the reaction force per mm of distance 'd'. The force accelerates the train in vertical direction, so:

$$f_1 = M\ddot{z} = -Pi + Qd \tag{5}$$

As the current increases, the gap distance d reduces, so current i is given a negative sign. The network model is given in Fig. 3. The figure represents a generator driving a coil wound around a magnet on the vehicle. The voltage induced in the coil by the vehicle motion is represented by Eq. 6.

$$v_L = L\frac{di}{dt} \tag{6}$$

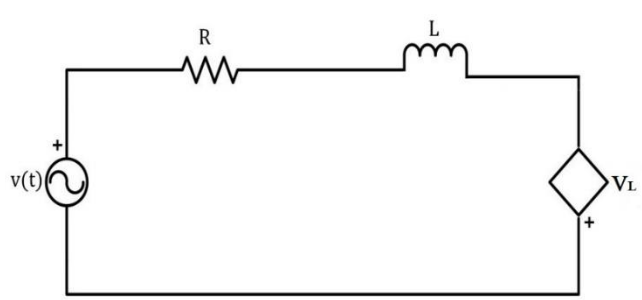

Fig. 3. Magnetizing Circuit Model

Units are considered in Eqs. 7, 8 and 9.

$$volt = henry.\frac{ampere}{time} \quad (7)$$

$$volt = henry.\frac{ampere}{time}.\frac{newton}{newton}.\frac{millimeter}{millimeter} \quad (8)$$

$$volt = henry.\frac{\frac{newton}{millimeter}.\frac{millimeter}{time}}{\frac{newton}{ampere}} \quad (9)$$

And so the voltage induced in the coil came out to be as given in Eq. 10.

$$v_L = \frac{LQ\dot{d}}{P} \quad (10)$$

It is assumed that the magnetic flux loss is negligible.

Applying KVL;

$$Ri + L\frac{di}{dt} - \frac{LQ\dot{d}}{P} = v \quad (11)$$

The three state variables are given by Eqs. 12, 13 and 14.

$$x_1 = d \quad (12)$$

$$x_2 = \dot{d} \quad (13)$$

$$x_3 = i \quad (14)$$

Consider Eqs. 5, 11, 12 and 13, our state equations are Eqs. 15, 16 and 17.

$$\dot{x}_1 = (0)x_1 + (1)x_2 + (0)x_3 + (0)v \quad (15)$$

$$\dot{x}_2 = \left(\frac{Q}{M}\right)x_1 + (0)x_2 + \left(\frac{-P}{M}\right)x_3 + (0)v \quad (16)$$

$$\dot{x}_3 = (0)x_1 + \left(\frac{Q}{P}\right)x_2 + \left(\frac{-R}{L}\right)x_3 + \left(\frac{1}{L}\right)v \quad (17)$$

Converting above equations into matrix form, we have;

$$\begin{bmatrix}\dot{x_1}\\ \dot{x_2}\\ \dot{x_3}\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ Q/M & 0 & -P/M\\ 0 & Q/P & -R/L\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 1/L\end{bmatrix}[v]$$

Therefore, the characteristic equation becomes as Eq. 18.

$$s^3 + \frac{R}{L}s^2 - \frac{QR}{ML} = 0 \quad (18)$$

Its roots give us the poles of transfer function. As the coefficients of characteristic polynomial have differing algebraic signs, that's why we can say that the system is unstable. This is an open loop system.

In order to stabilize this system, state feedback (with gains K_1, K_2, K_3) is employed. Also, a reference input $u_1(t)$ is introduced to observe its performance.

$$v = K_1x_1 + K_2x_2 + K_3x_3 + u_1(t) \quad (19)$$

So the resulting closed loop system is:

$$\begin{bmatrix}\dot{x_1}\\ \dot{x_2}\\ \dot{x_3}\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ \frac{Q}{M} & 0 & \frac{-P}{M}\\ \frac{K_1}{L} & \frac{H}{P} + \frac{K_2}{L} & \frac{-R}{L} + \frac{K_3}{L}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 1/L\end{bmatrix}[v]$$

Now we need to set the values of K_1, K_2 and K_3 to place the system poles at any desired location. To proceed with state variable design methods, the parameters *M*, *P*, *Q*, *L* and *R*, as previously defined, must be estimated. We assume that each car of the train weighs about 8000 kg. Since each car is supported by 4 magnets, so we can say that each magnet will support 2000 kg.

A static test is performed without control i.e. the air gap is clamped shut, causing '*d*' to be zero. A -120 V source is applied to the magnetizing circuit. With a time constant of 1/30s, -8 A eventually flows at steady state. A resultant force of 4000 N is measured (in addition to that of gravity). Voltage is carefully varied until the car levitates with *d* = 10 mm under the influence of 8 A of current. This represents the system being at equilibrium.

If the magnetizing circuit is at steady state, the static test can be used to get *R* and *L*.

$$R = \frac{v}{i} = \frac{-120}{-8} = 15\,\Omega \quad (20)$$

And from time constant during the static test, we have Eq. 21.

$$T = \frac{L}{R} \quad (21)$$

Therefore;

$$L = RT = \frac{15}{30} = 0.5\,H \quad (22)$$

We can compute P from the data when air gap was clamped shut (d = 0) as given in Eqs. 23-26.

$$f1 = -Pi + Qd \tag{23}$$

$$4000 = -P(-8) + Q(0) \tag{24}$$

$$P = \frac{-4000}{-8} \tag{25}$$

$$P = 500\ N/A \tag{26}$$

When the car levitates at equilibrium position, we can calculate H

$$f1 = -Pi + Qd \tag{27}$$

$$0 = -(500)(8) + (Q)(10) \tag{28}$$

$$Q = 400\ N/mm \tag{29}$$

Therefore, the parameter values are; $M = 2000$, $Q = 400$, $P = 500$, $L = 0.5$, and $R = 15$.

Now, after putting the above mentioned numeric values, the feedback system equations are given as Eq. 30.

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0.2 & 0 & -0.25 \\ 2K_1 & 0.8 + 2K_2 & -30 + 2K_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 2 \end{bmatrix} [u_1] \tag{30}$$

The characteristic equation for the feedback system is given by Eq. 31.

$$\begin{vmatrix} s & -1 & 0 \\ \frac{-Q}{M} & s & \frac{P}{M} \\ 0 & \frac{-Q}{P} & s + \frac{R}{L} \end{vmatrix} = s^3 + (30 - 2K_3)s^2 + (0.5K_2)s + 0.4K_3 + 0.5K_1 - 6 \tag{31}$$

Suppose it is desired that our system poles should be at as given in Eq. 32.

$$s = -4, -2 - 3j, -2 + 3j \tag{32}$$

Our characteristic polynomial would be as Eq. 33.

$$(s + 4)(s + 2 + 3j)(s + 2 - 3j) = s^3 + 8s^2 + 29s + 52 \tag{33}$$

By comparing we get Eqs. 34, 35 and 36.

$$30 - 2K_3 = 8 \qquad K_3 = 11 \tag{34}$$

$$0.5K_2 = 29 \qquad K_2 = 58 \tag{35}$$

$$(0.4)(11) + 0.5K_1 - 6 = 52 \qquad K_1 = 53.6 \tag{36}$$

For this choice of feedback gains, the feedback system model is represented by Eqs. 37 and 38.

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0.2 & 0 & -0.25 \\ 107.2 & 116.8 & -8 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 2 \end{bmatrix} [u_1] \tag{37}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \tag{38}$$

MATLAB software has been used to calculate transfer function from state space as Eq. 39.

$$T(s) = C[SI - A]^{-1}B \tag{39}$$

The transfer function of our system came out to be Eq. 40.

$$T(s) = \frac{-0.5}{s^3 + 8s^2 + 29s + 25.2} \tag{40}$$

Once the transfer function of the system has been computed, the performance of the system is then checked. To measure the performance, a step function is applied to a control system as the input signal and the response of the system is measured at the output. The performance parameters i.e. rise time, peak over shoots and settling time can be quantified from the produced waveform. A practical magnetic levitation system is a non-linear system; therefore, it is important to design a controller. We require a fast and stable system with minimum oscillations as well overshoot, so a PID controller has been selected which is explained below.

3. Supervisory Control of Magnetic Levitation

The single loop control system comprising of a plant and a controller or specifically a fuzzy controller is normally used for simple applications. But for much complicated systems, a multilevel control structure is useful in achieving control objectives. Multilevel control structure holds its importance due to the fact that different controllers can be designed in this structure to target different objectives. Usually, the lower level controller directly interacts with the process and the higher level controller exercises supervision of the lower level controller [13].

In this research work a conventional PID controller has been used as a primary controller and a fuzzy controller has been utilized in the supervisory role as shown in Fig. 4. If the PID controller fails to generate the appropriate control actions then a fuzzy controller adjusts the parameters of PID controller to rectify the situation.

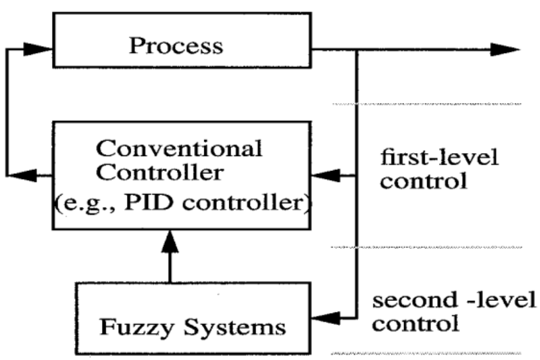

Fig. 4. Two level fuzzy supervisory control system

3.1 PID Controller

A classical PID controller is widely used in industrial applications due to its simplicity and robust performance and is shown in Fig. 5. The error between the desired and set point is used for generating the corrective actions in the form of three gain parameters i.e. K_p , K_i and K_d.

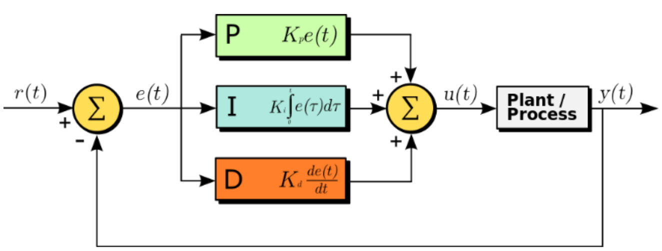

Fig. 5. A conventional PID control system

The transfer function of a PID controller is given as Eq. 41.

$$G(s) = K_p + \frac{K_i}{s} + K_d s \tag{41}$$

Another equivalent form of the same is Eq. 42.

$$u(t) = K_P e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{de(t)}{dt} \tag{42}$$

Where K_p, K_i and K_d are Proportional, Integral and Derivative gains respectively. It combines proportional, derivative and integral of the error signals which determine command signal 'u' for the system. A PID controller can also be written in terms of gain ratios, as $T_i = K_p/K_i$ and $T_d = K_d/K_p$. Table 1 shows the effect of gain coefficients on the system performance [14].

Table 1

The effects of gain coefficients on the performance of PID controller system

Type	Rise Time	Overshoot	Settling Time	Steady State Error
K_p	Decrease	Increase	Small Change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Small Change	Decrease	Decrease	Small Change

In order to optimize the performance, tuning of PID gains is required which is not a trivial task. Usually PID gains are tuned by human experts. After many simulations and changing K_P, K_i and K_d, the following values were practically estimated to get the desired performance, i.e. Rise time (s) = 0.503, Settling time (s) = 1.66 and Peak Overshoot = 0.432%; $K_P = -140$, $K_I = -136$, $K_D = -40$.

The system was simulated without and then with a PID controller and those responses appear in Table 3. Thus, we got our desired response. However, the PID controller has constant gain parameters. It is uncertain in case of parameters variation or load changes of induction motor. Therefore, it is desired to design a supervisory fuzzy controller which can suitably tune the parameters of PID controller.

3.2 Design Methodology of Fuzzy Supervisory Controller

A systematic way of designing supervisory controller is as follows; (a) Input and output variables of fuzzy control system are identified, (b) a universe of discourse is defined for these variables, (c) fuzzy sets are formulated and membership functions are selected, (d) a fuzzy rules table is built, (e) Define the gain values of conventional PID controller, (f) Simulate the system and iterate the gain values, rule table and fuzzy sets such that the desired performance is obtained. The block diagram of the fuzzy supervisory control system is given in Fig. 6.

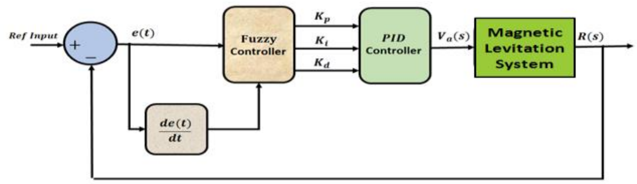

Fig. 6. Block Diagram of fuzzy supervisory control system

In order to design a fuzzy logic based control system, various input and output ranges were assumed. A universe of discourse from -100 to +100 has been defined for two inputs i.e. "Error" and "Rate of Change of error" for each of the corresponding outputs K_p, K_i and K_d. Fig. 7 and Fig. 8 depict the plots of membership functions for "error" and "rate of change of error" respectively.

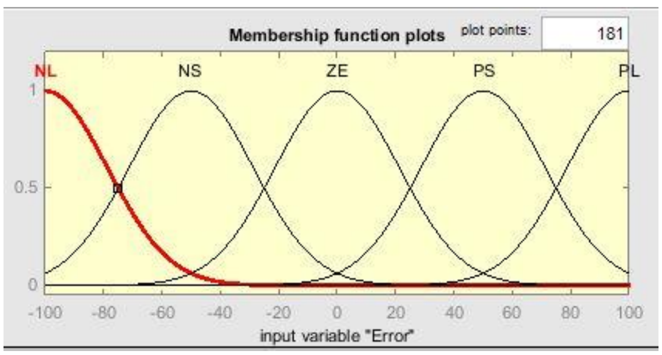

Fig. 7. Membership function plot for input variable i.e. error

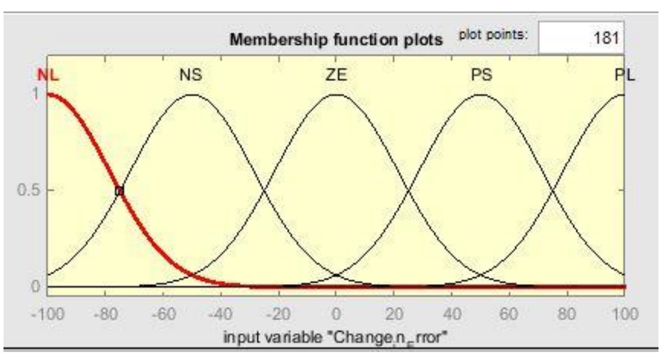

Fig. 8. Membership function plot for input variable i.e. change in error

Whereas, membership function plots for outputs, i.e. K_p, K_i and K_d are given in Figs. 9, 10 and 11 respectively. Gaussian membership functions were used to convert these values into corresponding fuzzy values. Rules have been defined after performing extensive simulations, whereas inputs have been mapped to corresponding outputs using Mamdani Inference Engine. Fuzzy rule is given in Table 2.

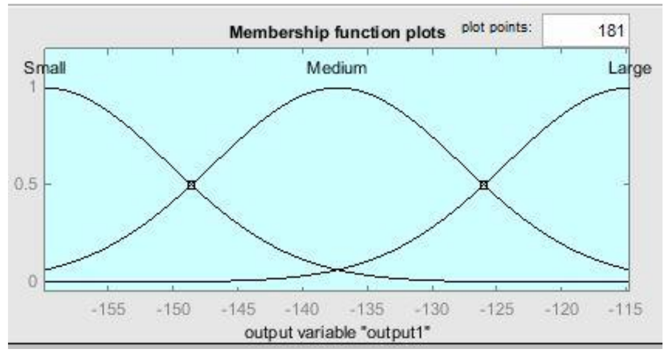

Fig. 9. Membership function for output K_p variable

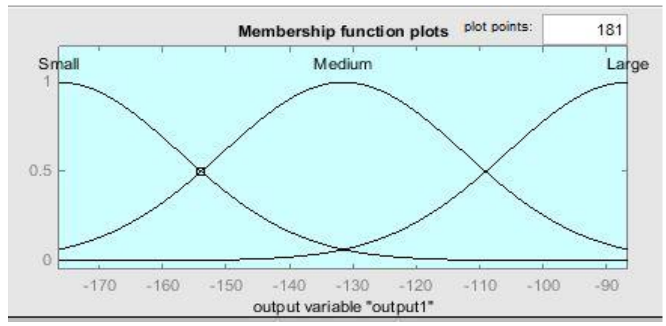

Fig. 10. Membership function for output K_i variable

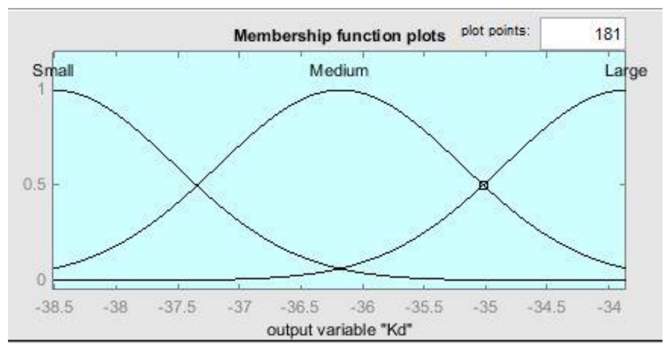

Fig. 11. Membership function for output K_d variable

Subsequently, Center of Average-Defuzzifier was used to get a crisp value. Fuzzy supervisory controller provides tuned values of K_p, K_i and K_d. The PID is now ready to these tunedK_p, K_i and K_d. All these steps were performed using MATLAB. This implemented fuzzy supervisory control system methodology has been shown in Fig. 6.

Table 2

Fuzzy rule table

K_p, K_i, K_d		Rate of Change of Error				
		NL	*NS*	*ZE*	*PS*	*PL*
Error	*NL*	L	L	L	M	M
	NS	L	L	M	M	M
	ZE	L	M	M	M	S
	PS	M	M	S	S	S
	PL	M	S	S	S	S

4. Simulation and Results

4.1 Response of PID Controlled System

The system was simulated without and then with a PID controller and those responses appear in Table 3. Fig. 12 depicts the step response of the system without a PID controller and Fig. 13 on the other hand shows the response of the system with PID controller.

Table 3

Comparison of system parameters

	Without PID controller	With PID controller
Rise time (s)	1.85	0.50
Settling time (s)	3.55	1.60
Overshoot (%)	0	0.40

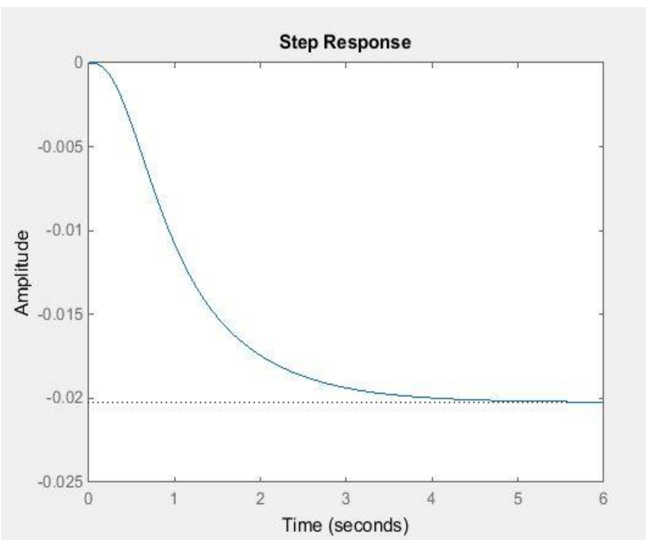

Fig. 12. Step Response of Mag Lev.

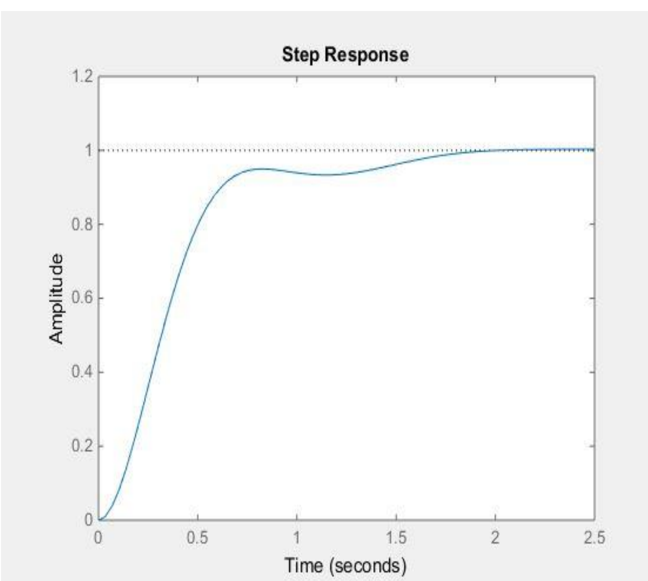

Fig. 13. Step Response of PID controller

The analysis indicate that rise time has decreased from 1.85 to 0.50 s and settling time has improved from 3.55 to 1.60 s and overshoot has increase from 0 to 0.40%. Hence, the response of the system has become fast.

4.2 Response of Fuzzy Supervisory Controller

By using the fuzzy logic based controller over the PID controller, the performance of closed loop operation of a magnetic levitation system has been improved as compared to that of just using a classical PID controller, as evident from the step response given in Fig. 14. The legends '*a*' to '*j*' in Fig. 14 represent the different step responses for different values of error and rate of change of error. The results in Table 4 show that whatever the values of Error (-100 to 100) and rate of Change of error (-100 to 100), the Fuzzy supervisory controller adjusts the parameters of PID controller to get desired performance.

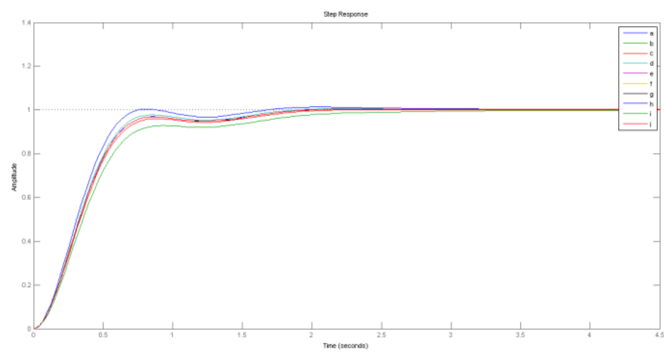

Fig. 14. Step response of Fuzzy Supervisory controller for Error and Change in Error (-100 to +100)

Table 4

Results of fuzzy supervisory controller

Error, Change in Error	K_P	K_I	K_D	Rise Time, T_S (s)	Settling Time, T_S (s)	Max. Percent Overshoot, M_p (%)
[0, 100]	-149.73	-155.97	-35.87	0.44	1.46	1.33
[-100, 0]	-124.93	-106.89	-29.48	0.60	2.04	0
[-75, 0]	-134.51	-125.82	-31.95	0.51	1.72	0.19
[0, 75]	-140.13	-137.02	-33.40	0.48	1.60	0.58
[-50, 0]	-137.24	-131.34	-32.66	0.5	1.66	0.32
[0, 50]	-137.36	-131.57	-32.69	0.5	1.66	0.90
[-25, 0]	-137.22	-131.30	-32.66	0.5	1.66	0.90
[0, 25]	-137.38	-131.61	-32.69	0.5	1.66	0.33
[-100, 100]	-137.30	-131.46	-32.68	0.5	1.66	0.32
[-50, 50]	-137.30	-131.46	-32.68	0.5	1.66	0.32

5. Conclusion

The performance of a simple PID controller and a Fuzzy Supervisory controller has been evaluated under realistic operating conditions. Furthermore, an elaborative comparative study of the conventional control and Fuzzy Supervisory control has been presented using the performance significant measures i.e. peak overshoot, settling time and rise Time. PID controller gives reasonably good performance for constant set point operations. However, due to parameters changes the gains of the controller have to be re-adjusted. To overcome this problem, a Fuzzy supervisory controller was designed to provide satisfactory solution. It is concluded that the performance of a closed loop operation of the mag-lev system has been improved by using a fuzzy supervisory controller over a classical PID controller. The performance in terms of rise time, setting time and maximum peak overshoot is improved. For a wide range of error and rate of change of error an improved a minimum rise time of 0.44s, a minimum settling time of 1.46s and a minimum value of peak overshoot 0% is achieved. Furthermore, the Fuzzy supervisory controller exhibits a robust performance in the transient period and also during arbitrary load changes when compared to a PID controller.

5. References

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