PD-FUZZY LOGIC CONTROLLED ON A MAGNETIC BEARING SYSTEM

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ABSTRACT

A magnetic bearing system is a device that uses electromagnetic forces to support a rotor without mechanical contact. The force exerted on the rotor is determined by the current flow in the magnet coil. This project will be focused on the stability and control of the MBC 500 system test bed constructed by Magnetic Moments Incorporated. The MBC 500 system contains a stainless steel shaft or rotor which can be levitated using eight horseshoe electromagnets. A controller which is able to stabilize the position of the rotor by varying the electromagnet force produced by the electromagnets at each end of the shaft will be developed. Here, direct fuzzy logic controller and proportional derivative fuzzy logic controller with Mamdani's inference method are designed.

KEYWORDS*: Fuzzy control, magnetic bearing system.*

1.0 BACKGROUND ON MAGNETIC BEARING SYSTEM

1.1 Introduction to MBC 500

The MBC 500 is a desktop test bed made by Magnetic Moments Incorporation and the system can be seen as shown as in Figure 1. It consist of a horizontal stainless steel shaft or rotor which can be levitated using eight horseshoe electromagnets, four at each end of the rotor (Paden *et al*.) (Morse *et al*., 1996). The shaft never even touches the bearings when it is operating since there are two silver housings that hold the electromagnetic bearings which levitate the spindle.

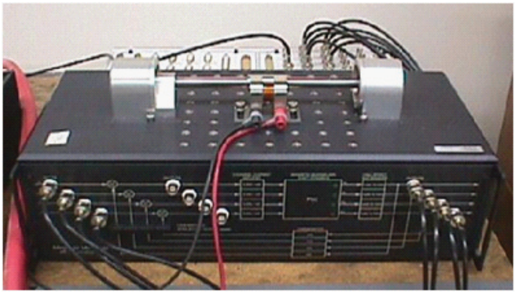

FIGURE 1
MBC 500 Magnetic Bearing Systems

Figure 2 shows the location of magnetic bearing. The copper-colored are the coils of wire that make up the electromagnet. Meanwhile, Figure 3 represents an attractive force exerted by electromagnet.

FIGURE 2
Magnetic bearing

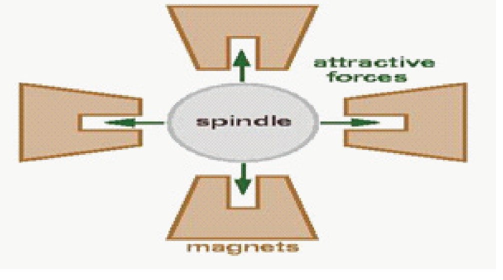

FIGURE 3
Attractive force exerted by electromagnet

One problem when using electromagnets is that they can only produce an attractive force. The force is stronger when the spindle is closer to the magnet, which in turn brings the spindle more close and makes the force even stronger. This leads to an unstable system. As a result, the magnets must be arranged radially around a spindle, so that a magnet on one side of the spindle can counteract the force exerted by a magnet on the other side of the spindle. Moreover, a control system is required to make the spindle levitate. The force exerted by the magnets can be controlled by changing the current flowing through the coils of wire. Equation (1) shows that a greater current increases the force exerted by the magnet.

$$f \; \alpha \; \frac{i^2}{g^2} \quad (1)$$

where

f = exerted force
i = current flowing through the coils of wire
g = distance between spindle and magnetic bearing

1.2 Advantages and Disadvantages of a Magnetic Bearing System

Magnetic bearing offer significant advantages because they do not come into contact with other parts during operation, which can reduce the maintenance. Higher speeds, no friction, no lubrication, weight reduction, precise position control, and active damping make them far superior to conventional contact bearings (Rebecca *et al*., 2000). However, there are rephrase that limit the application of the magnetic bearing such as to balance the electromagnets forces which are exerted on the magnetic bearing and to maintain the position of the rotor at the equilibrium point (Rebecca *et al*., 2000). Thus, magnetic bearing needs a controller which is able to stabilize the position of the rotor during operation before it works effectively.

2.0 ANALYSIS AND SYSTEM MODELING FOR MAGNETIC BEARING SYSTEM

The target system for this project is the Magnetic Moments MBC 500 Magnetic Bearing System. A diagram of this system is shown in Figure 4. It has a stainless steel shaft or rotor which is levitated using eight horseshoe electromagnets at each end of the rotor. Hall Effect Sensors are placed just outside of the electromagnets at each end of the rotor to measure the rotor end displacement. This system is a four degree of freedom system with two degrees of freedom at each end of the rotor. These two degrees of freedom are translation in the horizontal direction, perpendicular to the z axis (x_1 and x_2) and translation in the vertical direction (y_1 and y_2) (Paden *et al.*) (Morse *et al.*, 1996).

In this project, the rotor is assumed as as a rigid body. A rigid body is considered as it does not change its shape. Therefore, it is assumed that the rotor does not bend but rather experiences only translational or rotational motion. In addition, it is assumed that the horizontal and vertical dynamics (x and y directions) are uncoupled. The system in theory operates identically in the x and y directions except for the additional constant force due to gravity acting in the y direction. Here, gravity in the linear y direction analysis is neglected. Thus, analysis of the x and y directions is identical and the focus of analysis is strictly on the horizontal or x direction motion (Morse *et al.*, 1996).

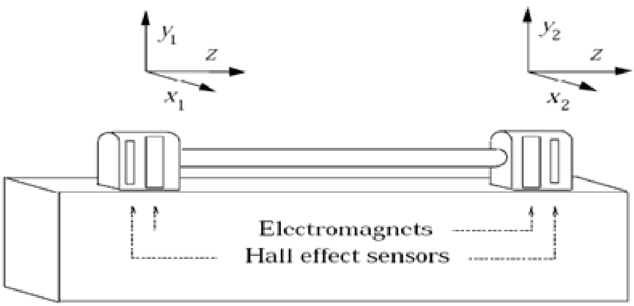

FIGURE 4
MBC500 system

Figure 5 shows rotor configuration of MBC 500 magnetic bearing system. Meanwhile, Table 1 and 2 represent system variables and parameters. The nominal or desired rotor position corresponds to x_1=0, and x_2=0 or (equivalently X_1=0 and X_2=0 or x_0=0 and θ=0). In this position, the rotor is centered horizontally with respect to the front and back electromagnets on each end and its long axis is parallel to the z axis (Morse *et a*l., 1996).

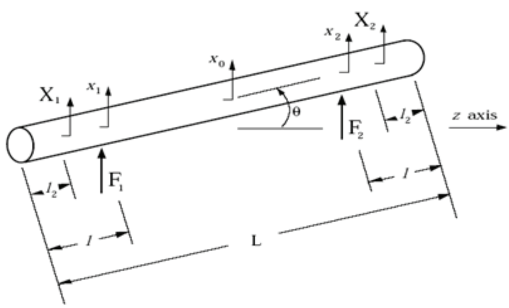

FIGURE 5
Rotor configuration

TABLE 1
System Variables

Symbol	Description
x_0	The displacement of center of mass of rotor
x_1 and x_2	The displacement of rotor at left and right bearings
X_1 and X_2	The displacement of rotor at Hall Effect sensor
θ	The angle that the long axis of the rotor makes with the z axis
F_1 and F_2	The forces exerted on the rotor by left and right bearing

TABLE 2
System Parameters

Symbol	Description	Value
L	Total length of the rotor	0.269m
l	Distance from each bearing to the end of the rotor	0.024m
l_2	Distance from each Hall-effect sensor to the end of the rotor	0.0028m
l_0	Moment of inertia of the rotor with respect to rotation about an axis in the y direction	1.5884 x 10^{-3} kg m^2
m	Mass of the rotor	0.2629kg

The state-space model of the magnetic bearing system can be represented as

$$\dot{x}_r = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ \frac{8750}{m} & 0 & 0 & 0 & \frac{3.5}{m} & \frac{3.5}{m} \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{8750(\frac{L}{2}-l)^2}{I_o} & 0 & -\frac{3.5}{I_0}(\frac{L}{2}-l) & \frac{3.5}{I_0}(\frac{L}{2}-l) \\ 0 & 0 & 0 & 0 & \frac{-1}{2.2\times10^{-4}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-1}{2.2\times10^{-4}} \end{bmatrix} x_r + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{0.25}{2.2\times10^{-4}} & 0 \\ 0 & \frac{0.25}{2.2\times10^{-4}} \end{bmatrix} \begin{bmatrix} V_{control1} \\ V_{control2} \end{bmatrix} \cdot \tag{2}$$

where

$$\dot{x}_r = \begin{bmatrix} \dot{x}_0 \\ \ddot{x}_0 \\ \dot{\theta} \\ \ddot{\theta} \\ i_{control1} \\ i_{control2} \end{bmatrix} \text{ and } x_r = \begin{bmatrix} x_0 \\ \dot{x}_0 \\ \theta \\ \dot{\theta} \\ i_{control1} \\ i_{control2} \end{bmatrix}$$

And the output equation can be written as

$$\begin{bmatrix} V_{sense1} \\ V_{sense2} \end{bmatrix} = 5000 \begin{bmatrix} 1 & 0 & -(\frac{L}{2}-l_2) & 0 & 0 & 0 \\ 1 & 0 & (\frac{L}{2}-l_2) & 0 & 0 & 0 \end{bmatrix} x_r \tag{3}$$

In control engineering, experimental determination of a system model is an important part of the modeling process. This is referred as a system identification. The transfer function of the MBC 500 magnetic bearing system was obtained by measuring the frequency response of the closed loop system (Shi *et al*., 2002). The toolboxes of MATLAB are used as to fit the transfer function model from the data collected. Figure 6 shows a general block diagram for a closed loop system identification. Here, r is the input signal, u is the input signal to the plant G, n is the measurement of noise, and y is the output signal.

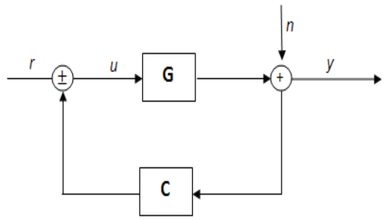

FIGURE 6
Closed loop system identification

For negative feedback of a closed loop system, the input signal, u and the output signal, y can be described as in equation (4) and (5).

$$u = \frac{1}{1+GC}r - \frac{C}{1+GC}n \tag{4}$$

$$y = \frac{G}{1+GC}r + \frac{1}{1+GC}n \tag{5}$$

Hence, the transfer function of the MBC 500 magnetic bearing system can be represented as

$$G(s) = \frac{-105.2s^2 + 4.038e005s^4 - 1.961e010s^3 + 6.086e013s^2 - 3.814e017s + 7.938e020}{s^6 + 334.6s^5 + 1.899e008s^4 + 5.897e010s^3 + 3.881e015s^2 + 1.086e018s - 5.8e020} \tag{6}$$

3.0 FUZZY LOGIC CONTROL DESIGN APPROACH

3.1 Introduction to Fuzzy Logic Controller

Fuzzy concepts derive from fuzzy phenomena that commonly occur in the natural world. The concepts formed in human brains for perceiving, recognizing, and categorizing natural phenomena are often fuzzy concepts. One such control strategy is the use of fuzzy logic based control. Figure 7 shows the typical structure of a fuzzy logic controller. Basically, a fuzzy logic controller consists of fuzzifier, knowledge base, inference engine and defuzzifier.

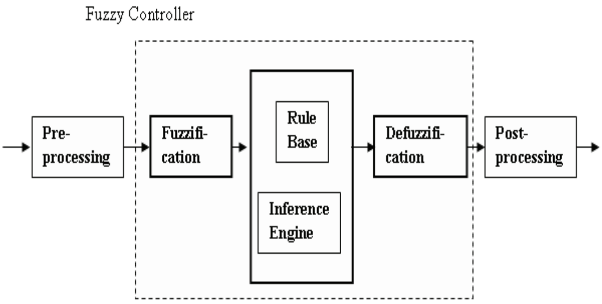

FIGURE 7
Block diagram of fuzzy controller

3.2 Fuzzy Logic Controller

Fuzzy controllers are being used in various control schemes. The most obvious one is a direct control, where the fuzzy controller is in the forward path in a feedback control system. The process output is compared with a reference, and if there is a deviation, the controller takes an action according to the control strategy. The block diagram of a direct fuzzy control can be shown as in Figure 8.

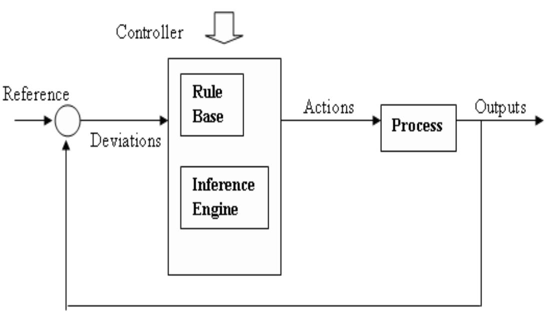

FIGURE 8
Fuzzy Logic Controllers

4.0 RESULT ON FUZZY CONTROLLED

4.1 Stability Test on Magnetic Bearing System

Before starting this project, the stability of the magnetic bearing system is identified. For this purpose, the locations of poles of the system were considered. Location of poles can be determined from the Eigen values of system matrix. It was observed that system is unstable since there have positive poles. It was observed too that the uncontrolled plant of the system is unstable since the output response goes to infinity. These proved that the system under test is unstable and requires a controller.

4.2 Description of Fuzzy Logic Controller

The project aims to present the implementation of a fuzzy logic control, FLC strategy for stabilizing the unstable response in MBC 500. This control strategy is expected to stabilize the position of the rotor of magnetic bearing system. Simulation of the non-linear system shows that for certain operating parameters, the MBC 500 exhibits unstable response for a rotor position. However, the use of fuzzy logic control has been able to eliminate this instability and improve the rotor stability performance. Uncontrolled MBC 500 plant was developed using MATLAB. Since MBC 500 is a non-linear system, the deployment of FLC is highly commendable. The non-linearity of the system is expressed using fuzzy principles in linguistic variable descriptions.

The implementation of fuzzy control in MATLAB was done in two stages analysis. The first stage covers the controlled action of direct fuzzy logic controller, FLC while the second analysis covers the controlled action of proportional derivative fuzzy logic controller, PD-FLC. Figure 9 shows the block diagram of direct FLC while Figure 10 shows the PD-FLC.

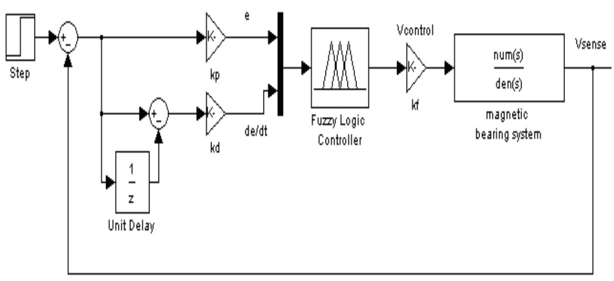

FIGURE 9
Direct Fuzzy Logic Controllers

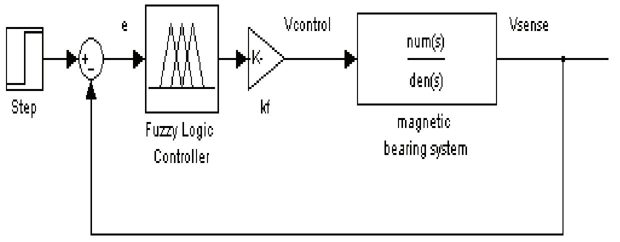

FIGURE 10
PD Fuzzy Logic Controllers

For this purpose, input for the fuzzy properties referring as error, e(t) and the output referring as $V_{control}$, are applied in direct fuzzy controlled. On the other hand, the change-of-error, d(e)/d(t) is applied as derivative input in PD-FLC. The output, $V_{control}$ will regulates the current into the bearing which then regulate the magnetic bearing force. Channel x1 is considered. The displacement output is sensed by the Hall-effect sensor with the output voltage, Vsense. For the magnetic bearing stabilization problem, the reference input is set to 0. Figure 11 shows the interface of direct FLC while Figure 12 indicates the interface of PD-FLC.

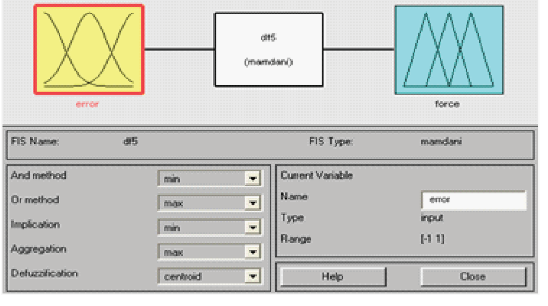

FIGURE 11
Interface of direct FLC

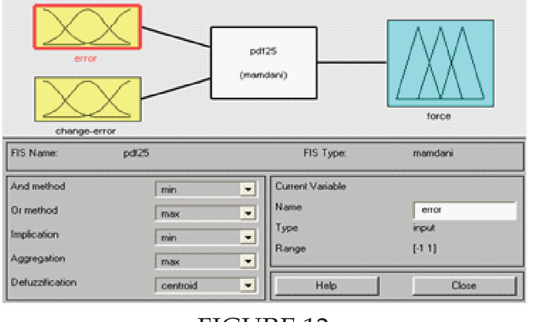

FIGURE 12
Interface of PD-FLC

The linguistic values have been used to describe the inputs and output of the FLC to specify a set of rules how to control the plant. Initially, five linguistic values are considered in fuzzy controlled analysis includes Negative Big, Negative Small, Zero, Positive Small and Positive Big. In addition, seven linguistic values have been used include Negative Big, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium and Positive Big. The triangular membership function (trimf) is used in mapping the input point to membership values and it was normalized universe of discourse at [-1, 1].

The IF-THEN rules are generated to infer the proper value for each of the output variables. For this purpose, 5 rules based on Mamdani's approach are applied to direct FLC while 25 rules are applied to PD-FLC. It then followed by developing 7 rules based on direct FLC and 49 rules based on PD-FLC.

The 5 rules base developed in direct FLC include;

If error is NB then force is NB
If error is NS then force is NS
If error is ZE then force is ZE
If error is PB then force is PB
If error is PS then force is PS

The 25 rules base developed in PD-FLC represented as in Table 3;
‘

TABLE 3
25 Rules Base of PD-FLC

$e(t)$ \ $\Delta e(t)$	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

Meanwhile, the 7 rules base developed in direct FLC include:

If error is NB then force is NB
If error is NM then force is NM
If error is NS then force is NS
If error is ZE then force is ZE
If error is PS then force is PS

If error is PM then force is PM
If error is PB then force is PB

Table 4 represents the 49 rules base developed in PD-FLC;

TABLE 4
49 Rules Base of PD-FLC

e(t) \ Δe(t)	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Figure 13 shows the response of a direct FLC with 5 linguistic values includes Negative Big, Negative Small, Zero, Positive Small and Positive Big. This response indicates that the position of the rotor is able to be stabilized at 0.145s. On the other hand, Figure 14 represents the response of controlled PD-FLC and the system was able to be controlled at 0.1s. These were proved that the unstable position of the rotor of MBC 500 is able to be stabilized at desired position using fuzzy logic controller. Thus, the position of rotor would be maintained and capable to return to its reference position successfully.

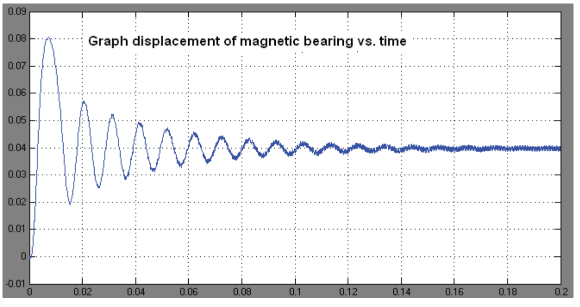

FIGURE 13
Output controlled by direct FLC with 5 linguistic values

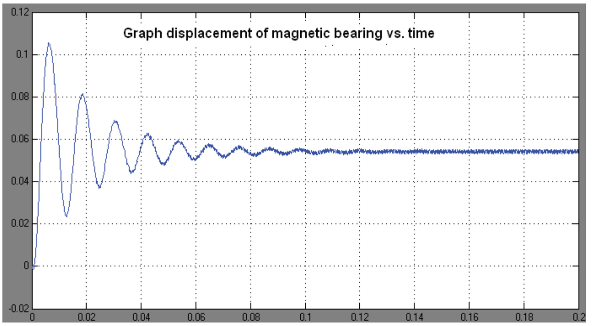

FIGURE 14
Output controlled by PD-FLC with 25 linguistic values

Figure 15 shows the response of a direct FLC with 7 linguistic values includes Negative Big, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium and Positive Big. This response indicates that the position of the rotor is able to be stabilized at 0.08s. On the other hand, figure 16 represents the response of controlled PD-FLC and the system was able to be controlled at 0.18s. Again, these were proved that both fuzzy logic control strategy are able to stabilize an unstable position of the rotor of MBC 500. Thus, the position of rotor would be maintained and capable to return to its reference position effectively.

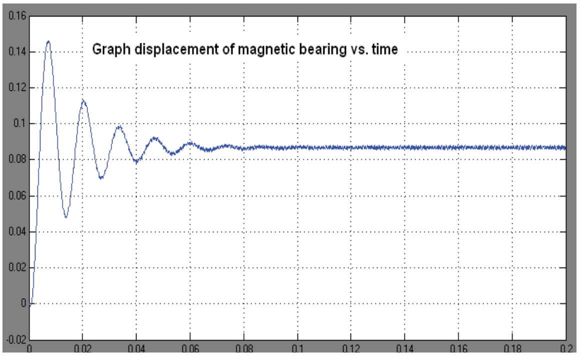

FIGURE 15
Output controlled by direct FLC with 7 linguistic values

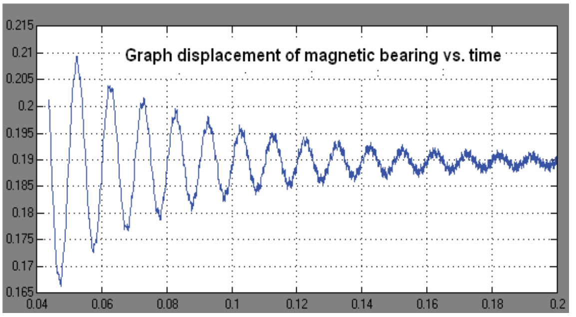

FIGURE 16
Output controlled by PD-FLC with 49 linguistic values

By referring to Figure 13-16, these were proved that the rotor's position was able to be controlled at 0.145s with direct FLC and 5 linguistic values compared to 0.08s with 7 linguistic values. On the other hand, the position of the rotor is stabilized at 0.1s with PD-FLC and 25 linguistic values compared to 0.18s with 49 linguistic values.

5.0 CONCLUSION

The system wish to be controlled is MBC 500 magnetic bearing system with a fuzzy logic controller. Both techniques are explored which direct FLC and proportional derivative FLC. The incorporation of developed fuzzy logic controllers into the existing system shows successful results in stabilization a non-linear behavior in the rotor response of the MBC 500 within the range of operating parameters. It was observed that the shaft is returned to its reference position at the end of control process and these were proved by the responses of controlled output of direct FLC and PD- FLC.

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