Magnetic Bearings Control Using Fuzzy Logic and a Single Neuron

Zhang Danhong, Tang Ling, Su Yixin,
School of Automation, Wuhan University of Technology,
Wuhan 430070, P.R.China
Email: zhangdh@mail.whut.edu.cn,
Christint18128@163.com, suyixin@mail.whut.edu.cn,

Hu Yefa
School of Mechanical and Electronic Engineering, Wuhan
University of Technology,
Wuhan 430070, P.R.China
Email: huyefa@mail.whut.edu.cn,

***Abstract*—Linear controllers cannot get satisfactory results for active magnetic bearings (AMB) due to the highly nonlinear and open-loop unstable electromechanical dynamics. This paper proposes a combined controller which integrates a fuzzy logic controller (FLC) with a single neuron controller for AMB. The FLC operates with a small single neuron control component when the system error is big; the FLC and the single neuron controller operate simultaneously when the system error is small. The proposed controller overcomes the defect of the FLC which has a steady state error, and the defect of a single neuron controller which has unsatisfied dynamic performance. Simulation results demonstrate that the proposed controller has improved the dynamic performance and the disturbance rejection ability of AMB.**

***Keywords*—active magnetic bearings, proportional-integral-derivative, fuzzy logic controller, single neuron**

I. INTRODUCTION

Active Magnetic Bearings (AMB) are being increasingly used in many industrial applications. Typical applications for AMB include turbo molecular vacuum pumps, gas pipeline centrifugal compressors, sealed pumps and linear induction motors. The main advantage of AMB over traditional mechanical bearings lies in that the former support moving machinery without physical contact. For example, they can levitate a rotor and permit relative motion without friction. With this advantage AMB can be widely used in industrial applications where minimum friction is desired, or in harsh environments where traditional bearings and the associated lubrication systems are considered unacceptable.

Despite the great potential, the highly nonlinear and naturally unstable dynamic characteristics make AMB systems difficult to control. Initial studies were concentrated firstly on the classical linear control techniques which were based on proportional-integral-derivative (PID) or proportional derivative (PD) type controllers and then followed by the modern controllers such as LQG and H_∞ which were also based on linear control theory. These linear controllers are designed by linearizing the dynamic model of a magnetic bearing about a nominal equilibrium point [1], [2]. The main controllers used for AMB in most practical installation are the traditional PID type. Whilst the performance of the PID controller is generally satisfactory for most practical applications, this type of controller becomes ineffective when the rotor is subjected to extreme operating conditions. Thus, several non-linear control techniques have been proposed to deal with the non-linear dynamics of the AMB.

Research work on non-linear control of AMB has been undertaken by several authors to overcome the shortcoming of the linear PID controllers. Yeh proposed a sliding control scheme to deal with the non-linear dynamics of AMB systems [3]. Marcio S. used a backstepping approach as compensation for parametric uncertainty and eliminating state measurements [4]. However, these controllers are more complicated compared with their linear counterparts. At this point, a fuzzy logic controller (FLC) is seen as a solution for both of these problems. Hong S.K. used a robust fuzzy control scheme for magnetic bearing (MB) systems [5]. Hung J.Y. combined an FLC with a PID controller for adjusting the output of the PID controller in such a way that nonlinear effects are better compensated [6]. Maki K.H. used an FLC to tune the gains of the linear PD controller to improve the performance of the AMB control system [7].

In this paper, a combined controller, which integrates the fuzzy control with a single neuron control, is proposed to compensate the nonlinearity and improve the dynamic performance of AMB control systems.

II. ACTIVE MAGNETIC BEARINGS MODEL

A typical AMB configuration consists of a stator and a rotor. The coils are wound around each pole of the stator. Each rotor axis has a pair of amplifiers to provide current to the bearing coils and an attractive force to adjust the position of the rotor along the particular axis. The current carrying coil wrapped around the stator of an AMB system creates a magnetic field within the stator, the rotor and air gap between the rotor and the stator.

In the derivation of the forces that are generated in the magnetic field, the following assumptions hold.

- Leakage of magnetic flux is neglected.
- Fringing effect i.e. the spreading of magnetic flux in the air gap is neglected.
- The magnetic iron is operating below saturation level.

The expression for the electromagnetic force that is generated in a single-acting actuator is given in (1), where μ_0 is the permeability of air, N is the number of the coil turns on the magnetic actuator, A_l is the area of the one magnetic pole, i is the coil current, and s is the length of one air gap.

$$F = \frac{\mu_0 N^2 A_l i^2}{4s^2} \quad . \tag{1}$$

In the actual operation of the AMB, a pair of magnetic actuators counter-acting each other is used. This configuration is known as the difference driving mode. Fig. 1 shows the basic principle of an active magnetic bearing.

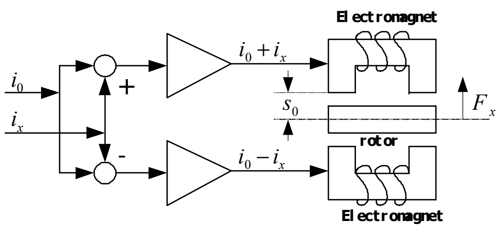


Figure 1. Basic Principle of an Active Magnetic Bearing.

The force produced in this system can be determined by assuming that the current in the decreasing air gap is (i_0+i_x) and the current in the opposite side is (i_0− i_x). The air gap is (s_0−x) in the decreasing side, and (s_0+ x) in the opposite side. i_x is the control current and s_0 is the nominal air gap i.e. the gap at equilibrium position in the X-axis, and x is the displacement of the rotor from its equilibrium position in the X-direction. F_1 and F_2 denote the forces of the two counter-acting actuators respectively, whilst F_x denotes the resultant force, then the non-linear force equation for the difference driving mode is (2).

$$F_x = F_1 - F_2 = \frac{\mu_0 N^2 A_l}{4}\left[\frac{(i_0+i_x)^2}{(s_0-x)^2} - \frac{(i_0-i_x)^2}{(s_0+x)^2}\right] . \tag{2}$$

Application of the Newton's second law to the AMB systems gives (3).

$$m\ddot{x} = k\left[\frac{(i_0+i_x)^2}{(s_0-x)^2} - \frac{(i_0-i_x)^2}{(s_0+x)^2}\right] , \tag{3}$$

where m is the mass of the rotor; $k=\mu_0 N^2 A_l / 4$, which is the force constant. Equation (3) is the model used in the simulations, and plant parameters are shown in Table I.

TABLE I. PARAMETERS OF THE AMB SIMULATION MODEL

m	The mass of the rotor	0.065kg
N	The number of turns in a winding	288
A_l	The cross sectional area of pole face	150.45mm^2
μ_0	Permeability of air	$4\pi\times10^{-7}$ H/M
k	The force constant	3.92×10^{-6} N·m^2/A^2
s_0	The air gap	0.4mm
i_0	The bias current	0.5A

III. SIMULATION MODEL OF ACTIVE MAGNETIC BEARINGS WITH LINEAR CONTROLLERS

The mathematical model that has been developed in section II is implemented using Matlab/Simulink development environment. The critical issue that surrounds the operation of AMB is the instability of the rotor. The most common PID controller is used to calculate the control current.

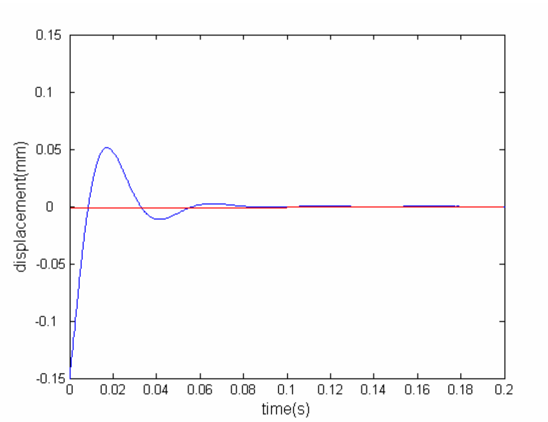
Usually, the relationship between the output and input of a PID controller in time-domain can be written as

$$u(t) = k_P[e(t) + \frac{1}{\tau_I}\int_0^t e(t)dt + \tau_D \frac{de(t)}{dt}] , \tag{4}$$

where k_P is the gain of proportional, τ_I is the time constant of integral, τ_D is the time constant of differential. Since the computer control is sampling control, it can just compute the control variables according to the sampling value. Therefore the computation of the integral and differential cannot be performed directly. In such case difference and sum operation are used to replace the differential and the integral, then the discrete format of (4) is written as

$$u(k) = k_P e(k) + k_I \sum_{j=0}^{k} e(j) + k_D[e(k) - e(k-1)] , \tag{5}$$

where $k_I = k_P T/\tau_I$, $k_D = k_P \tau_D /T$, T is the sampling period, k is the sampling serial number. Proportional gain determines the dynamic stiffness of the rotor, while derivative action is necessary for stabilization and reducing overshoots. Integral action is not necessary for stability, but is often used to improve the steady-state accuracy of AMB systems. The PID controller can get ideal performance only in a small region around the equilibrium point. When the rotor deviating far away from the equilibrium point or subjected to extreme operating conditions, the dynamic performance deteriorates quickly due to the nonlinearity of AMB. Fig. 2 shows the step response curve of PID control.



IV. DESIGN OF THE F-N CONTROLLER

FLC design is based upon an "expert" linguistic description of the system behavior; it fits to nonlinear object and the object which has uncertain mathematical model. With FLC, the response speed and the overshoot of AMB can be improved considerably. However, fuzzy control has its limitation; it has only inputs of controlled object's error and error variance ratio but with no integral effect. The lack of integral effect together with the fuzzy quantization effect has weakened the steady-state accuracy of the AMB system. A single neuron which is the basic unit of neural networks has self-learning and self-adaptation abilities. Combining a single neuron with PID control, it is able to adjust the parameters in real time and to compensate the control deficiency of complicated systems which cannot be solved by traditional PID controllers. Since the essence of the single neuron control is PID control, therefore there is a contradiction between tracking ability and disturbance rejection ability. This limitation has affected the ideality of the control result. In this paper an F-N control strategy is proposed for the AMB control system, which combines the fuzzy control with single neuron control according to their own control characteristics.

The configuration of the controller is shown in Fig. 3. $u_{FLC}(t)$ is the output of the FLC, $u_{NNC}(t)$ is the output of the single neuron controller, $u(t)$ is the output of the F-N controller and the combination is shown in (6).

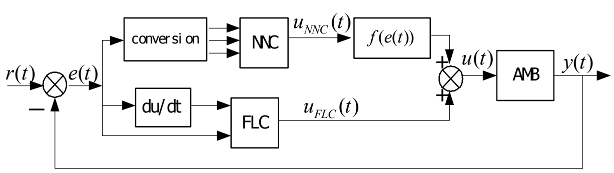


Figure 3. Configuration of F-N Controller.

$$u(t) = u_{FLC}(t) + f(e(t))u_{NNC}(t)\,, \tag{6}$$

where $f(e(t))$ is a non-linear function of the system error $e(t)$ as follows

$$f(e(t)) = b\exp(-a|e(t)|)\,, \tag{7}$$

where a and b are positive constants. When the value of the error $e(t)$ is small, the function $f(e(t))$ will approach b; on the other hand, when the value of the error $e(t)$ is large, the result of function $f(e(t))$ will be close to zero. With these, we can conclude the characteristics of the controller based on (6) and (7): at the beginning, the rotor produces a very big system error $e(t)$ and the value of the function $f(e(t))$ is very small, and the FLC plays a main role. When the system approaches the steady state, the value of the system error $e(t)$ will become very small and the function $f(e(t))$ will be close to one, then the fuzzy controller and the single neuron controller are combined to overcome the defect of the fuzzy controller which has the steady state error. Thus, the response of rotor can be very fast and there is no steady state error.

A. The Single Neuron Controller

According to (5), we can construct a single neuron controller as shown in Fig. 4.

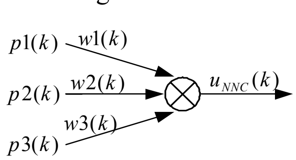


Figure 4. Configuration of a Single Neuron Controller.

The inputs of the neuron are

$$\begin{aligned} p1(k) &= e(k)\,, \\ p2(k) &= \sum_{j=0}^{k} e(j)\,, \\ p3(k) &= e(k) - e(k-1)\,. \end{aligned} \tag{8}$$

The output of the neuron can be expressed by

$$u_{NNC}(k) = w1(k)p1(k) + w2(k)p2(k) + w3(k)p3(k)\,, \tag{9}$$

where $\{wi(k)\}$ are adjustable coefficients, and the performance index function is chosen as

$$J = \frac{1}{2}[r(k+1) - y(k+1)]^2\,. \tag{10}$$

Using the gradient descent method, the coefficients of the controller are optimized as follows

$$\Delta wi(k) = \eta \cdot [r(k+1) - y(k+1)] \cdot pi(k)(\partial y(k+1)/\partial u_{NNC}(k))\,, \tag{11}$$

where η is the learning rate, which is a coefficient between 0 and 1. i is the input serial number. $\partial y(k+1)/\partial u_{NNC}(k)$ is an unknown part which just decides the adjustment direction, so it can be approximated by the sign function $sign\,((y(k+1) - y(k))/(u_{NNC}(k) - u_{NNC}(k-1)))$, and the learning rate η can be adjusted to compensate the influence of the approximate value.

The initial values of the adjustable coefficients $\{wi(k)\}$ are selected according to the parameters of the corresponding PID controller. They are very critical because the learning time is affected by the initial values.

B. The Fuzzy Controller

Fuzzy logic control provides a means of converting a linguistic control strategy based on expert knowledge into an automatic control strategy. It is a nonlinear control strategy. By using fuzzy logic control, the nonlinearity of AMB can be better compensated. The aim of a fuzzy logic controller is to improve the response of the system in terms of faster settling time and decreasing of overshoot.

The inputs of the fuzzy logic controller are the error, E and the error variance ratio, EC. The range for E is between –0.25 and 0.25, and EC is between –400 and 400. The output of it is the control variable, ranging from –1.2 to 1.2. The membership function used for E, EC and U is the triangular function because of its simple formulas and higher computational efficiencies. Seven labels are used to describe each linguistic variable. These levels are NB, NM, NS, ZE, PS, PM, and PB. NB implies negative big, NM negative medium, NS negative small, ZE zero and so on. The IF-THEN rules are generated to infer the proper value for the output variable. The rules are arranged in one (7×7) matrix table in Table Ⅱ. The fuzzy rule outputs are composed using the max-min composition, and a crisp value of the control variable is derived using the centroid method in which the value of the control variable is determined by finding the value of the center of gravity of the membership function.

TABLE II. FUZZY CONTROL RULES

ec \ e (u)	PB	PM	PS	ZE	NS	NM	NB
PB	PB	PB	PM	PM	PS	ZE	ZE
PM	PB	PB	PM	PM	PS	ZE	ZE
PS	PB	PB	PM	PS	ZE	NM	NM
ZE	PM	PM	PS	ZE	NS	NM	NM
NS	PM	PM	ZE	NS	NM	NB	NB
NM	ZE	ZE	NS	NM	NM	NB	NB
NB	ZE	ZE	NS	NM	NM	NB	NB

V. SIMULATION ANALYSIS

The AMB whose parameters are shown in Table I is simulated by using Matlab. For the simulation, equation (3) of the magnetic bearing system is built with S-function of MATLAB, and the basic fuzzy logic controller is built with the Fuzzy Inference System toolbox of MATLAB. Fig. 5 shows the comparison between the responses of the traditional PID controller and the F-N controller when the rotor rises from –0.15mm. Curve (1) shows the response of the traditional PID controller, while curve (2) showing the response of the F-N controller. It can be seen from Fig. 5 that when the F-N control method is adopted, the overshoot of the rotor displacement is less than 10% and the rising time is less than 0.01 second. In contrast, the overshoot is bigger and the rising time is longer when the traditional PID method is adopted.

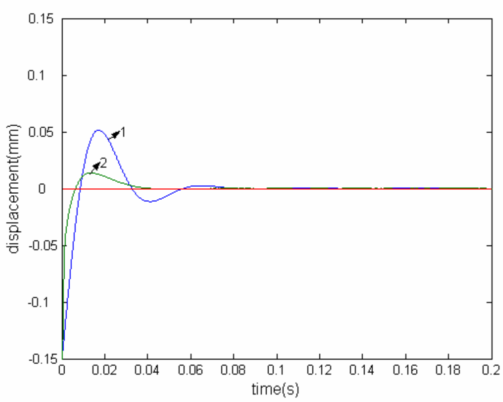
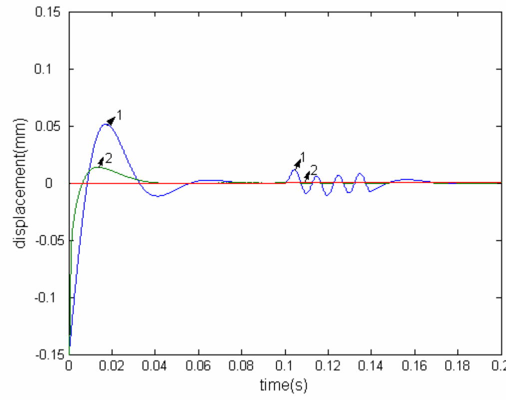
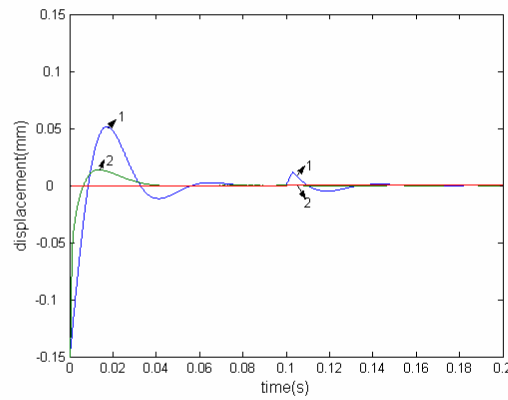


Figure 5. Step Responses of AMB with PID Control and F-N Control.

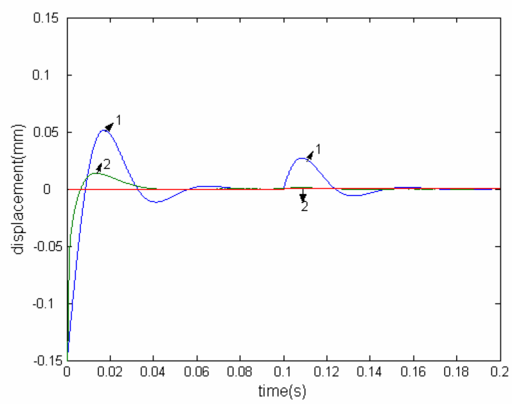
In the AMB system, when the rotor deviating from the equilibrium position about –0.1mm and the control current is 0.2A, the current will produce a force about 20N. At this point, proper disturbance forces are put on the rotor and the response of the rotor is shown in Fig. 6. In Fig. 6(a), a sine-force (8N, 100Hz) is put on the rotor at 0.1s and lasts for 0.03s; in Fig. 6(b), a impulse force about 30N is put on the rotor at 0.1s and lasts for 0.3ms; in Fig. 6(c), a step force about 8N is put on the rotor at 0.1s. In all figures, curve (1) denotes the response curve of the traditional PID controller; curve (2) denotes the response curve of the F-N controller. It can be seen that the F-N controller has stronger disturbance rejection ability compared with the traditional PID controller.



(a)



(b)



(c)

Figure 6. Responses of AMB to Different Disturbances (a) sine-force disturbance (b) impulse force disturbance (c) step force disturbance.

VI. CONCLUSIONS

In this paper a combined controller of AMB systems by using fuzzy logic and single neuron control is proposed. The PID controller can perform well when the system state is close to the design conditions, but it cannot give the ideal performance when the rotor deviating far away from equilibrium point. In order to have a better performance, the fuzzy logic control is integrated with a single neuron control. A fuzzy logic controller with a small single neuron control component is adopted when the system error is big; the fuzzy logic controller and the single neuron controller operate simultaneously when the system error is small. Simulation results show that the proposed controller has improved the dynamic responses as compared with the traditional PID control. This controller is able to overcome the shortcoming of fuzzy controller which has steady state error. And it also has strong disturbance rejection ability.

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