Journal of Theoretical and Applied Information Technology
31st October 2011. Vol. 32 No.2

ISSN: **1992-8645** www.jatit.org E-ISSN: **1817-3195**

ROTOR LEVITATION AND AUTOCENTERING BY ACTIVE MAGNETIC BEARINGS USING FUZZY LOGIC CONTROLLER

POLAMRAJU.V.S.SOBHAN[1], DR. G.V.NAGESH KUMAR[2], DR. J.AMARNATH[3], M.VINAY KUMAR[4]

[1]Assoc. Prof.,Vignan University, Vadlamudi, Guntur, Andhra Pradesh, INDIA
[2]Assoc. Prof., GITAM University, Visakhapatnam, Andhra Pradesh, INDIA
[3] Prof., JNTUH, Andhra Pradesh, INDIA

[4]Asst. Prof., GMRIT, Rajam, Andhra Pradesh, INDIA

ABSTRACT

Active Magnetic Bearings (AMB) have many advantages such as no friction loss, no abrasion, lubrication-free quality, and used for high rotational speed applications. A complete AMB system consists of an actuator, power amplifier, a rotor position sensor and a control system. In this paper, a closed loop decentralized Fuzzy Logic controller for Active magnetic Bearings is designed. For the numerical evaluation of control algorithm a MIMO (multiple input multiple output) mathematical model of the controlled plant is determined. The majority of industrial applications of active magnetic bearings were still based on conventional PID control system. The proposed control design is based on rule based procedure. It has been shown, that the presented FL control guarantees satisfactory high damping, low parameter variations and measurement noise of the overall system. The designed FL controller is able to maintain the rotor in center position in the final steady state. Simulations are provided to illustrate the performance of the controller.

Keywords: *Active Magnetic Bearings , Rotor Levitation , decentralized control , Fuzzy control*

1. INTRODUCTION

An active magnetic bearing (AMB) system is a collection of electromagnets that enable the contact-less suspension of a rotor and stabilization of the system is performed by feedback control. Two radial bearings and one axial bearing are used to control the five degrees of freedom of the rotor, while an independent driving motor is used to control the sixth degree of freedom. In comparison with mechanical and hydrostatic bearings the active magnetic bearings have many advantages. The most important benefits are [1]:

- the rotor can be allowed to rotate at high speed, circumferential speeds about 350 m/s are achievable,
- the contact-less operation and the absence of lubrication and contaminating wear allow the use of magnetic bearings in vacuum techniques and in clean and sterile rooms,
- the low bearing losses, at high operating speeds are 5 to 20 times less than in conventional bearings, result in lower operating costs,
- lower maintenance costs and higher life time due to the lack of mechanical wear,
- the bearings magnet can also intentionally excite vibrations of the rotor to identify unknown rotor characteristics.

The major drawbacks are the purchase price and not available necessary knowledge for the design and maintenance of magnetic bearings at the user side. Due to many advantages, active magnetic bearings have found usage in many industrial applications, such as machine tools, energy storage flywheels, electric auxiliaries for aircraft, as well as high-speed turbines, centrifuges, compressors, etc. Active magnetic bearings constitute an inherently unstable system. Therefore, control is required to stabilize the shaft position and to ensure an appropriate damping and stiffness of the overall system. In most cases linear control methods are employed along with the differential driving mode. Here, the same bias current is supplied into the windings of all the electromagnets, while the position control is achieved in the x and y-axis, independently [2]. A quasi-linearization of the bearing force, as well as the required current gain and position stiffness are obtained in this way. The existence of the bias current, on the other hand, even under no load, leads to higher energy consumption and additional eddy current losses in the rotors

2. MATHEMATICAL MODEL OF ACTIVE MAGNETIC BEARINGS

2.1 Magnetic Levitation

A typical magnetic bearing comprises a set of radially positioned electromagnets positioned in opposing pairs around a laminated magnetic bearing journal. For instance, for a magnetic bearing with four electromagnets there is one opposing pair for each perpendicular axis. Each electromagnet consists of a laminated core and one or more coil windings. The force produced by a single two pole electromagnet can be shown to be given by the following equation where I is the total current in the magnet coils, z is the gap distance, μ_o is the permeability of free space, A is the pole face area, and N is the number of coil turns:

$$F = \frac{\mu_o A N^2}{4} \frac{i^2}{z^2} \qquad (1)$$

A simplified magnetic bearing system, with two-poles, single degree-of-freedom (DOF) magnetic bearing shown in Figure1.This system is the fundamental building block for more complicated magnetic bearing systems and thus contains the essential design challenges of these systems without the added complexity. For the derivation of the model, the following assumptions about the system will be made. It is assumed that the levitated shaft or rotor moves only in the x-direction, that no bending of the shaft occurs, and that no gravity acts on the shaft (a satellite application).

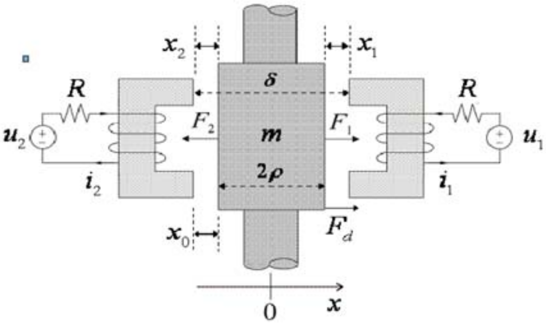

Fig 1. Schematic of a One-DOF Magnetic Bearing

The force in (1) is attractive and increases as the gap decreases. This attractive force produces an unstable system for an open loop magnetic bearing configuration. The net force, F produced by an opposing pair of identical two-pole electromagnets on a single axis is the sum of the forces produced by each electromagnet; taking account of the sign convention (see Fig l), the net force equation is given as follows:

$F_1$and F_2 denote the forces in the two counter – acting actuators respectively .whilst F_x denotes the resultant force in the x- direction. These values are thewn substituted ito equation (1) to give the non linear force equation for double acting actuator

$$F_x = F_1 - F_2 \qquad (2)$$

$$F_x = \frac{\mu_o A N^2}{4} \left[\frac{i_2^2}{z_2^2} - \frac{i_1^2}{z_1^2} \right] \qquad (3)$$

i_j is the current in magnet j, and z_j is the gap distance for magnet j.

A dynamical mathematical model for the AMB is shown in Fig. 1, where disturbances and external forces can be established as follows:

$$m\ddot{x} = \frac{\mu_o A N^2}{4} \left[\frac{i_2^2}{(x_o - x)^2} - \frac{i_1^2}{(x_o + x)^2} \right] \qquad (4)$$

Where

$x_1 = x_o + x$ air gap 1

$x_2 = x_o - x$ air gap 2

m mass of the rotor (kg);

x position displacement of the rotor (m);

x_o nominal air gap (m);

μ_o permeability of free space H/m;

A total pole-face area of each electromagnet (m);

N number of turns on each electromagnet coil;

i_1 , i_2 electromagnet coil currents (A);

u_1 and u_2 are the control voltages applied to the magnetic coils;

A linearization of the AMB's dynamics around operationg point at $[i_1, i_2, x] = [i_o, i_o, 0]$,where i_0 is a constant bias current and $i_1 = i_o + i_{bx}$, $i_2 = i_o - i_{bx}$ simplifies the nonlinear mechanical dynamic equation (4)into the linear equation

$$m\ddot{x} = k_i \, i_{bx} + k_x \, x \qquad (5)$$

Where i_{bx} is the force regulating current in the x-axis , k_i is the force – current factor and k_x is the force – displacement factor.

$$k_i = \frac{N^2 A\mu_o i_o}{x_o^2} \text{ and } k_x = \frac{N^2 A\mu_o i_o^2}{x_o^3} \quad (6)$$

When external disturbance F_d is present then the radial force can be expressed as follows:

$$m\ddot{x} = \frac{\mu_o A N^2}{4}\left[\frac{i_2^2}{(x_o - x)^2} - \frac{i_1^2}{(x_o + x)^2}\right] + F_d \quad (7)$$

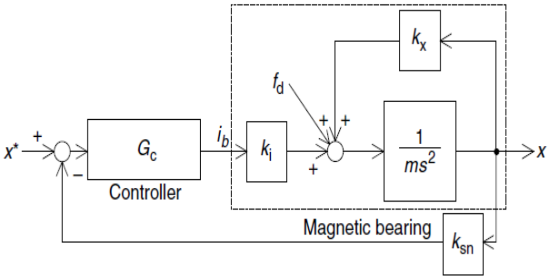

Fig 2. Block diagram of a One-dof Magnetic Bearing

The block diagram representation of a magnetic bearing as a linear actuator) and the mechanical system, including the mass of a rotor, is shown in fig 2. The radial force acting on the rotor due to radial magnetic bearing equation (5) is a function of both the current i_{bx} and rotor radial displacement x. The radial force F_x is the sum of these forces.

2.2 Radial force Interference in two-DOF AMB

In two -dof model, the generated radial forces are aligned on two perpendicular axes which usually coincide with the x- and y-axis displacements. However, there are some causes of radial force misalignment, i.e., when they may not be aligned with the x- and y-axes. Suppose that an electromagnet of a radial magnetic bearing is constructed with a misalignment at an angle with respect to the radial displacement sensors. The direction of the generated radial force has an angular position error, which results in interference of x- and y-axis force components. There are several other possible causes of interference, as listed below:

1. Flux due to eddy currents can generate a delay in the radial force. At high rotational speed and with a solid rotor, eddy currents flow on a rotor surface, which generates phase-delayed components in the flux wave distribution with respect to the rotor. This phase lag in the flux results in a direction error for the generated radial force.
2. The gyroscopic effect is apparent with short-axial-length machines with large radius rotors. The gyroscopic effect generates interference radial force.

The interference between the x- and y-axis radial forces can cause a serious problem. The feedback radial forces f_{NFBx} and f_{NFBy} have slightly delayed angular position. The rotor is rotating in a counter-clockwise direction. The direction angle error is defined as θ_{er} and the interference radial forces can be written as:

$$f_{dmy} = K_{mx}\, f_{NFBx} \text{ and } f_{dmx} = K_{my}\, f_{NFBy} \quad (8)$$

where

$$K_{mx} = -\sin\theta_{er} \text{ and } K_{my} = \sin\theta_{er} \quad (9)$$

Figure (3) shows a block diagram that includes the interference. The outputs are the radial positions and the inputs are the references. The upper and lower blocks are for x- and y-axis dynamic models. The interference is generated by K_{mx} and K_{my} .

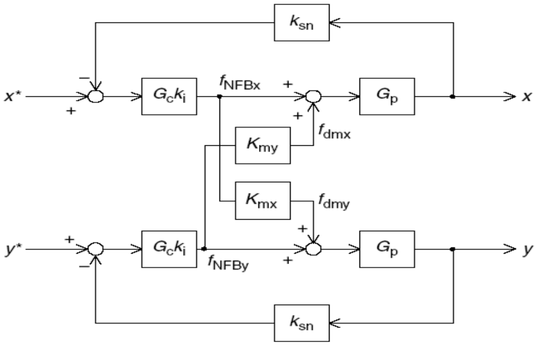

Fig 3. Block diagram of Interference in two-axis AMB.

3. FUZZY LOGIC CONTROLLER

The basis of Fuzzy Logic Controller is the representation of linguistic descriptions as membership functions. The basic Configuration of Fuzzy Logic Controller is shown in Figure 4. The Membership function indicates the degree to which a value belongs to the class labeled by linguistic description. In Fuzzy Logic control algorithms, degree of membership serve as inputs. The determination of appropriate degree of membership is the part of the design process. Once the membership functions are defined, the actual input values are transformed to degree of membership (varying from 0 to 1) of linguistic descriptors. This process is called fuzzification. The resulting fuzzified data is passed through an inference mechanism that contains the rules for the output. After the rules are applied, the combined effect of all rules will be evaluated according to a proper weightage for each rule. The weightage will be generally used to fine-tune the fuzzy controller and this process is defuzzification

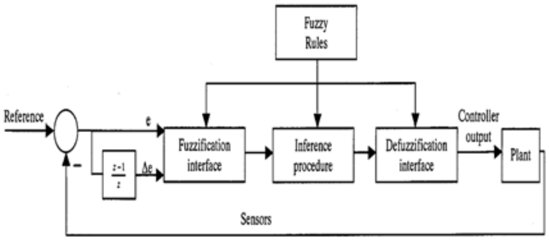

Fig4.Basic Configuration of Fuzzy Logic Controller

In the current application of Fuzzy Logic Controller, Error and Error Change are treated as the input variables. Triangular / Trapezoidal membership functions are assumed for mapping the input. The total Universe of discourse for each linguistic variable is portioned into 8 linguistic values (Large Positive (LP), Medium Positive (MP), Small Positive (SP), Positive Zero (PZ), Negative Zero (NZ), Small Negative (SN), Medium Negative (MN) and Large Positive (LP).

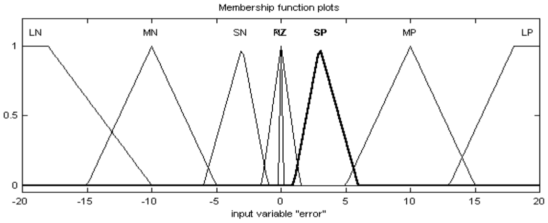

Fig 5. Membership Functions for Error and Error change

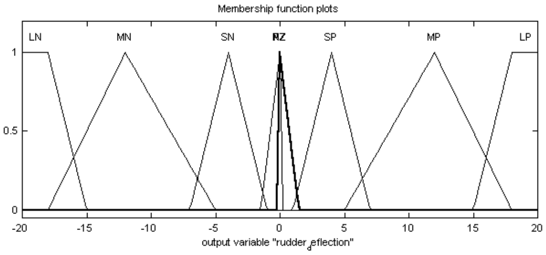

Fig 6. Membership Functions for Output – control current

The rules are chosen to get minimum overshoot and faster response. Rules applied in the Fuzzy Logic Controller are shown in table 1.

Table.1.Fuzzy Logic Control Rule Base

de\e	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

Table.2.Parameters of the AMB System

Symbol	Parameter	Optimum values
m	Mass of the rotor	3.14 kg
L_{rt}	Radius of the stator	0.09 m
h	Length of the rotor	0.15m
K_x	Force displacement factor	170000 N/m
I_i	Moment of inertia along i-axis	0.016 Kg m^2
I_k	Moment of inertia along k-axis	0.00023 Kg m^2
K_i	Force current factor	158N/A

4. SIMULATION RESULTS

To demonstrate the feasibility of the proposed fuzzy logic controller shown in fig 7 and the parameters of the AMB system shown in table 2 are used. In the simulation, the goal is to control the position of the rotor with respect to the center of the stator . The step responses of rotor position from the gap sensor in the AMB system using the fuzzy controller is shown in Figure 8. It shows that the fuzzy controller has remarkably reduced the overshoot and settling time. The fuzzy controller has achieved good performances in both transient and steady state periods.

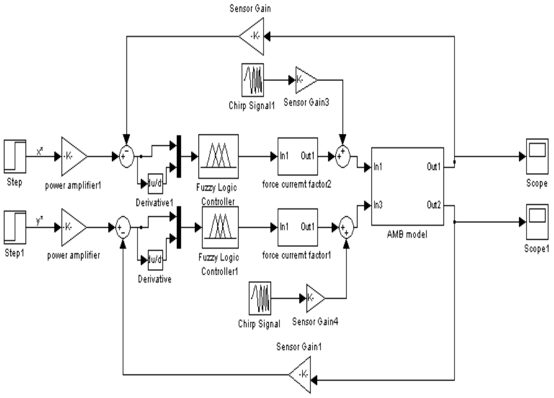

Fig 7. Block diagram of two-dof AMB with fuzzy controller

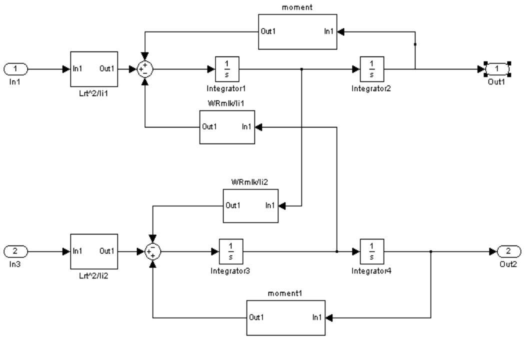

Fig 8. Block diagram of AMB System

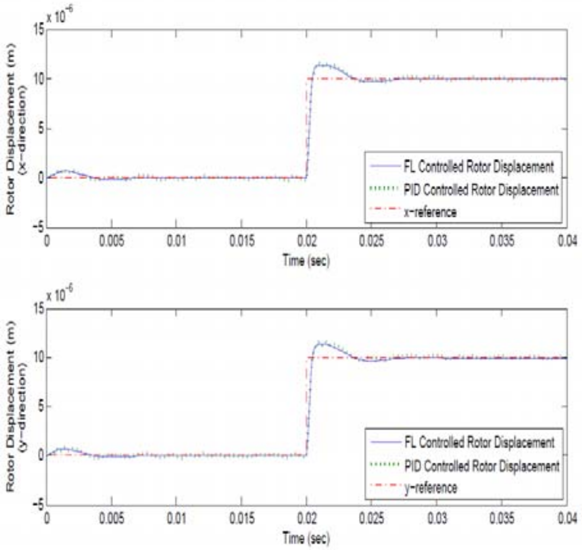

Fig 9. Time responses of rotor positions (2-dof)

5. CONCLUSIONS

This work has revealed the rich dynamics of the rotor response in active magnetic bearings. The control problem is to levitate and stabilize rotor shaft in the centre position of the magnetic bearings and to damp shaft vibration due to unbalance forces is addressed. Decoupled fuzzy logic controller, which uses the deflections of shaft from center position of the stator and its rate of change as the inputs results in an acceptable performance with respect to damping the deflection of the shaft, overshoot, settling time and the output current. The application of Decoupled Fuzzy Logic Controller looks to be a simple alternative for low performance applications. It is observed that Fuzzy logic systems are often superior than alternate approaches where in systems normally controlled by a human expert, in systems that have moderately very complex continuous inputs and outputs and in non-linear systems that use human observations as control rules or inputs. This fuzzy controller is simple in design and minimum calculation steps are required comparatively with other conventional (PID) controller. Numerical simulation revealed that the response of a rigid rotor displacement in air gap of AMB with fuzzy control is good at certain values of the governing parameters.

REFERENCES:

[1] F. Mazenc, M. S. de Queiroz, M. Malisoff, and F. Gao(2006), “Further Results on Active Magnetic Bearing Control With Input Saturation”, IEEE Transactions on Control Systems Technology, Vol 14, No. 5, September 2006.

[2] J.Shi, W.S.Lee, “ An Experimental Comparison of a Model Based Controller and a Fuzzy Logic Controller for Magnetic Bearing System Stabilization” 2009 IEEE International Conference on Control and Automation Christchurch, New Zealand, December 9-11, 2009 .

[3] Imoberdorf, P. Zwyssig, C. Round, S. D., Kolar, J.W., "Combined Radial-Axial Magnetic Bearing for a 1 kW, 500,000 rpm Permanent Magnet Machine," Applied Power Electronics Conference, APEC 2007 - Twenty Second Annual IEEE, Feb. 25 2007-March 1 2007, pp. 1434-1440.

[4] M. N. Sahinkaya and A. E. Hartavi, ”Variable Bias Current in Magnetic Bearings for Energy Optimization” IEEE Trans. on Magnetics, vol. 43, no. 3, pp. 1052-1060,March 2007.

[5] F. Mazenc M.Dde Queiroz ,M.malisoff, and Gao , "Further Results on Active Magnetic Bearing Control With input Saturation" IEEE Transactions control system technology Vol1 on 5-11-2006.

[6] Jugo, J., Lizarraga, I., and Arredondo, I.: ,“Nonlinear analysis of an AMB system using harmonic domain LTV models”. IEEE Int. Conf. Control Applications, October 2006, Munich, Germany

[7] Md. Emdadul Hoque, Masaya Takasaki, Yuji Ishino, “Development of a Three-Axis Active Vibration Isolator Using Zero-Power Control,” IEEE Transactions on Mechatronics, Vol. 11, No. 4, pp. 462-470, August 2006.

[8] Bostjan Polajžer, Gorazd ˇStumberger, Member, IEEE, Jože Ritonja, Member, IEEE, Oto Težak, Drago Dolinar, Senior Member, IEEE, and Kay Hameyer, Member, IEEE ,” Impact of Magnetic Nonlinearities and Cross-Coupling Effects on Properties of Radial Active Magnetic Bearings”, IEEE transactions on magnetics, vol. 40, no. 2, march 2004

[9] S. J. Huang and L. C. Lin, ”Fuzzy Dynamic Output Feedback Control With Adaptive Rotor Imbalance Compensation for Magnetic Bearing Systems,” IEEE Trans. on Sys., Man and Cybernatics – PART B: Cybern., vol. 37, no. 4, pp. 1854–1864, August 2004