Design and Simulation of a Fuzzy-Supervised PID Controller for a Magnetic Levitation System

Faissal Abdel-Hady[1], **Sherif Abuelenin**[2]

[1]Bemidji State University, Bemidji, MN 56601 USA

E-mail: fabdelhady@bemidjistate.edu

[2]Sinai University, Arish, Egypt

(Corresponding author)

E-mail: sherif217@ieee.org

Abstract: In this paper, we present the design and simulation of a new fuzzy logic supervisory control approach that is designed to improve the performance of a PID controlled magnetic levitation system, such systems are inherently unstable and require means of control to stabilize their operation; the fuzzy logic controller continuously monitors system variables (error signal, and its derivative) and modifies the parameters of the PID controller to better introduce better system response. Using magnetic levitation eliminates metal friction, and the problems associated with heat dissipation and enables higher speeds, which, in industrial systems, can increase the production rate. The controller is kept as simple as possible so that it can be easily implemented on a low-cost microcontroller chip in the future. A Simulink® model of the magnetic levitation system with the controller is used to simulate and examine the system performance. A noticeable improvement in the performance has been recorded with the integrated controller over the PID alone.

Keywords: Fuzzy supervisory control, Magnetic Levitation, Fuzzy Control, PID Control, Fuzzy Tuning.

Faissal Elsayed Abdel-Hady: received his B.Sc. degree in 1975 and an M.S. in 1981 both from Ain-Shams University Egypt, and a Ph.D. in 1988 at Ecole Nationale Superieure des Mines de Saint Etienne France, all in mechanical engineering. He is currently an Assistant Professor of Physics/Technology Studies in the Department of Industrial Technology, Physics Department at Bemidji State University MN USA and an Associate Professor of Mechanical Engineering at Ain Shams (Egypt). His research interests include thermal analysis, Stress simulation, Automatic control and mechatronics, mechanical components, CAD/CAM for filament wound structures, dynamic signal processing and software development.

Sherif Mohamed AbuElenin received his B.Sc. degree in Electronics in 1999 from Suez Canal University Port-Said Egypt. He received his M.S. degree in Electrical Engineering in 2002 from Tuskegee University AL USA and Ph.D. degree in 2005 from Auburn University AL USA. Now, he is a Assistant Professor at Tuskegee Univeristy (on leave), and an Assistant professor in Sinai University Egypt. His research interests are focused on: Signal Processing, Fuzzy Systems, and Nonlinear Systems.

1. Introduction

Magnetic levitation systems are systems in which a rotor or a stationary object is suspended in magnetic field. Magnetic levitation of a rotating disk typically incorporates four or more electromagnets to levitate a ferromagnetic disk without contact with the surroundings, where levitation is accomplished through automatic control of the electromagnet coils currents. Position sensors are required to sense the position of the disk, and a controller uses position sensor outputs to apply stiffness and damping forces to the rotor to achieve a desired dynamic response.

Active magnetic levitation systems are being increasingly used in industrial applications where minimum friction is desired or in harsh environments where traditional bearings and their associated lubrication systems are considered unacceptable, as discussed in [6, 10]. Such systems are inherently open-loop unstable, and require means of control to stabilize their operation; this is generally done by creating a closed loop system through using feedback control. The requirement of controllers brings flexibility into the dynamic response of the systems, which can also be designed to compensate for noises and vibrations that would affect the operation. Also, these systems are highly nonlinear, and in order to obtain a transfer function to describe them, number of approximations has to be made; hence, the design of linear controllers can produce the desired dynamic response only for the region in which the linear model was created. Many non-linear control algorithms were introduced in earlier research [7, 8, 9, 10, 11], and a comparison between using linear and non-linear methods of controlling magnetic levitation systems was discussed in [4].

In this paper we introduce the design and simulation of a new supervisory control strategy for magnetic levitation systems that incorporates a fuzzy controller to tune the gains of a discrete PID controller.

Supervisory control is a type of adaptive control since it seeks to observe the current behavior of the control system and modify the controller to improve the performance. It is a multilayer (hierarchical) controller with the supervisory at the highest level; the supervisor controller can use any available data from the control system to characterize the system's current behavior and generate outputs that are not direct command inputs to the plant. Rather, they dictate changes to another controller that generates these command inputs [17]. Over 90% of the controllers in operation today are PID controllers. This is because PID controllers are easy to understand, easy to explain to others, and easy to implement. Because PID controllers are often not properly tuned (e.g., due to plant parameter variations or operating condition changes), there is a significant need to develop methods for the automatic tuning of PID controllers. The supervisor is trying to recognize when the controller is not properly tuned and then seeks to adjust the PID gains to obtain improved performance. When there is heuristic knowledge available on how to tune PID controllers while in operation, there is the opportunity to utilize fuzzy control methods as the supervisor that tunes or coordinates the application of conventional controllers, this approach shouldn't be confused with Fuzzy-PID controllers, which are PID controllers realized by fuzzy control methods [16].

Overall, fuzzy PID auto-tuners tend to be very application dependent and it is difficult to present a general approach to on-line fuzzy PID auto-tuning that will work for a wide variety of applications [17]. There are different configurations that incorporating fuzzy controllers with PID controllers, examples are: replacing PID with fuzzy controller, using fuzzy controller to adjust PID parameters, and using fuzzy controller to add to PID output [5, 8, 12, 13, 15, 18].

In the method presented here, we use a PID controller to create a stable equilibrium point of the position of a magnetically levitated rotor, and a fuzzy controller to adjust gains of the PID controller based on the operating conditions to improve the performance of the system. Two sets of this controller are used, one for each axis of freedom in the X-Y plane.

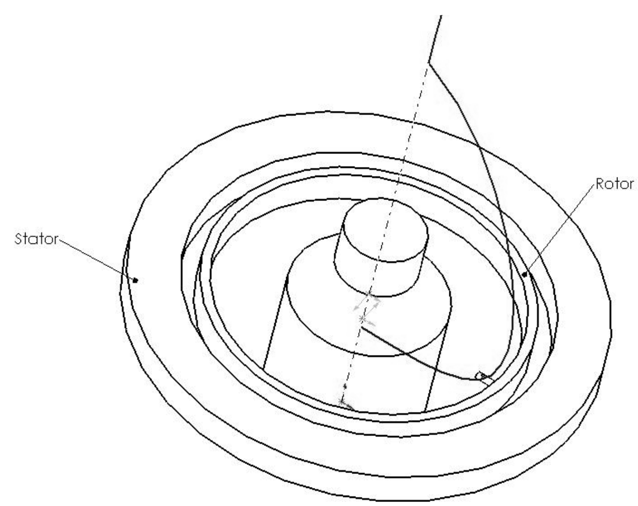

Figure 1. Illustration of magnetic ring spinning

This method was introduced as part of research effort started by designing a new magnetic levitation system intended to increase the production rate of yarn spinning machines, the new system replaces the traditional ring-spinning mechanism that dictates a continuous ring-traveler contact. In the traditional system, higher traveler speed will result in traveler burning out because of the frictional heat initiated during traveler rotation. The new magnetic levitation mechanism, named magnetic-ring spinning, would not have friction, enabling higher production speeds. The concept was introduced in [1, 2, 3], see Figure 1 for illustration. Because the new system is intended to be used in large scale in industry, one of the goals of the research was to be able to implement the designed controller in a low-cost single microcontroller chip.

The controller is simulated using SIMULINK®, and the performance of the PID controller alone is compared to the performance of the hybrid controller.

2. System Model

Figure 2 shows a schematic cross section view of the magnetic system (X-Z plan view). Permanent magnets create a bias flux, shown in dotted paths, across the air gaps (g_1, and g_2), supporting the weight of the rotating disk in the axial direction. When the ring (rotor) is exactly in the center, and assuming that all permanent magnets provide equal magnetic field intensities, the rotor will remain in the center, but this is a highly unstable state. In case the floating rotor is displaced from its central position to any direction, the permanent magnets will create a destabilizing force that attracts the rotor even further away from the center towards the same direction, because the attracting force between the magnet and the rotor is a function of the square of the distance between them, the closer the distance the higher the force. A set of inductive sensors will read out the deviation from the center position as a change in the inductance of the sensors, using two displacement sensors mounted radially to the rotor, the change in the inductance will be transformed to a voltage signal through control circuit. A control system will read this signal and generate a corrective current signal to power amplifiers, which in turn will supply the electromagnetic coils (the actuators) with current to generate the corrective flux (shown in Figure 2 by solid path). This corrective flux adds to the flux caused by the permanent magnets in the large gap and subtracts from the permanent magnets flux in the small gap, causing the magnetic flux to increase in the large gap and decrease in the small gap. Accordingly, the total magnetic force will tend to bring the rotor to its central position.

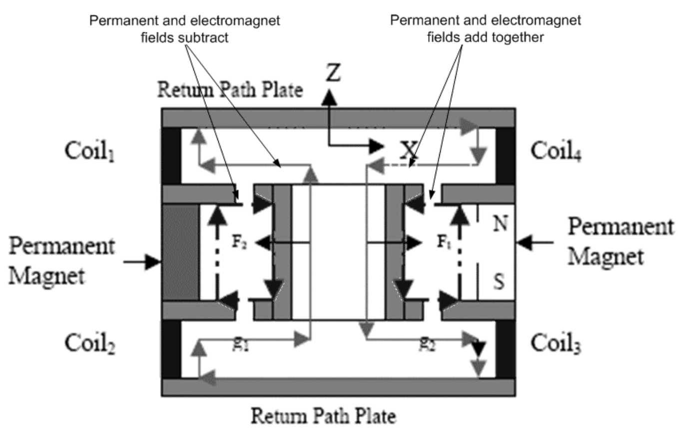

Figure 2. Schematic cross-section view of the magnetic system

A general model of the open loop system was found to be:

$$m\ddot{x}_i = C_1\left[\frac{(I-i_i)^2}{(L-x_i)^2} - \frac{(I+i_i)^2}{(L+x_i)^2}\right]$$

Where:

"m" is the mass of the rotor,

"*xi*", *the distance between any actuator 'i', and the facing surface of the rotor.*

"I" is the excitation current, and in this design, its value depends on both the DC component of the actuator current and the value of the flux produced from the permanent magnets, different values were used in our work.

"L" is equal to the distance between sensor surface and the center of the rotation.
"C_1" is a constant that depend on the parameters of the system, different values were used in our work.

3. Control

Two identical PID (Proportional, Integral, Derivative) controllers are used; one for each axis of the horizontal plane (X-Y). In this work, we show the results of simulating the system behavior with the PID controller alone, and the hybrid controler.

3.1 PID Controller

The PID controller is often referred to as a 'three-term' controller. It is currently one of the most frequently used controllers in the process industry. In a PID controller the control variable is generated from a term proportional to the error multiplied by a gain K_p, a term which is the integral of the error multiplied by a gain K_i, and a term which is the derivative of the error multiplied by a gain K_d; The controller output varies linearly according to the input signal, its derivative, and its integral, each weighted by a gain, these values are added together to provide the controller output. A very high K_p gain may cause instability, and a very low gain may cause the system to drift away. The K_i gain can be adjusted to drive the error to zero in the required time, a too high gain may cause oscillations and a too low gain may result in a sluggish response. Again, if the K_d gain is too high the system may oscillate and if the gain is too low the response may be sluggish [14]

The input signal for each PID controller is the voltage reading from the displacement sensor located on one axis, and is linearly proportional to "x_i", the distance between an actuator "i", and the surface of the rotor. Figure 3.a shows a block diagram of the system with the PID controller. The controller gains "K_p, K_d, and K_i" are initially calculated based on the mathematical model of the system, and later adjusted iteratively according to the results of the simulation.

3.2 Fuzzy Control

Fuzzy control is a control method based on fuzzy logic; a set of "if-then" statements called the fuzzy rules is responsible for making decisions; these linguistic rules are generally written based on observations the designer of the controller and the expertise of the operators of the system.

3.2.1 Fuzzy Supervision Controller

Figure 3.b shows a block diagram of the configuration, as shown in the figure, the inputs to the fuzzy controller are the *error* signal, which is the difference between the actual position of the rotor and the set point, and the *rate* of the change of this error (the derivative of the *error* signal). The *error* signal tells the controller how far the rotor is from the set point, and the *rate* signal is required as an input to tell the controller how fast the rotor is moving to or away from the set point.

The output of the PID controller modulates both the K_d, and K_p parameters of the PID controller. In extreme conditions, such as overshoots caused by disturbances, or great change in the position of the rotor, the fuzzy controller outputs a value greater than one, which modulates both K_d, and K_p, hence, changing the system response to better adapt to the current situation.

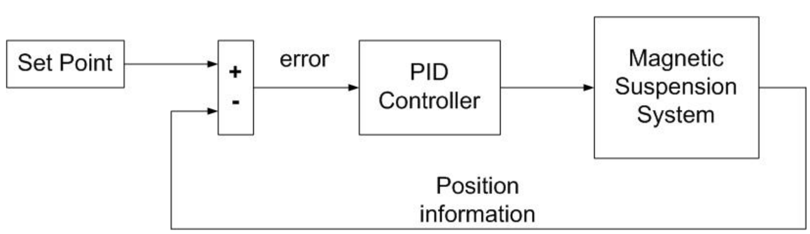

Figure 3.a. Block Diagram of the System with the PID Controller

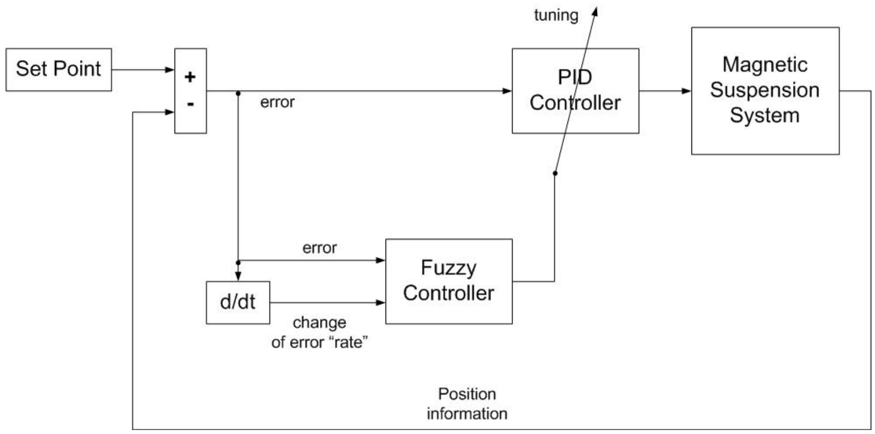

Figure 3.b. Block Diagram of the System with the Supervisory Controller

3.2.2 Design and Operation of the Fuzzy Controller

The relationship between the input and output variables is defined using the fuzzy rules set, shown in Figure 4.a, and which can be interpreted to the linguistic statements that are shown in Figure 4.b. These rules describe the output of the fuzzy controller in relation to its inputs. For example, the first rule *"if error is neg and rate is neg then output is hi"* is interpreted as: "when the rotor is displaced from its equilibrium point with a negative value, and is moving further away from the equilibrium position, then the output of the fuzzy controller should be high."

rate \ *error*	Neg.	Zero.	Pos.
Neg.	*hi*	*mid*	*norm*
Zero.	*mid*	*norm*	*mid*
Pos.	*norm*	*mid*	*hi*

Figure 4.a. Fuzzy controller rules

1. If (error is neg) and (rate is neg) then (2kd is hi) (1)
2. If (error is neg) and (rate is zero) then (2kd is mid) (1)
3. If (error is neg) and (rate is pos) then (2kd is norm) (1)
4. If (error is zero) and (rate is pos) then (2kd is mid) (1)
5. If (error is zero) and (rate is zero) then (2kd is norm) (1)
6. If (error is zero) and (rate is neg) then (2kd is mid) (1)
7. If (error is pos) and (rate is neg) then (2kd is norm) (1)
8. If (error is pos) and (rate is zero) then (2kd is mid) (1)
9. If (error is pos) and (rate is pos) then (2kd is hi) (1)

Figure 4.b. Fuzzy controller rules in linguistic format

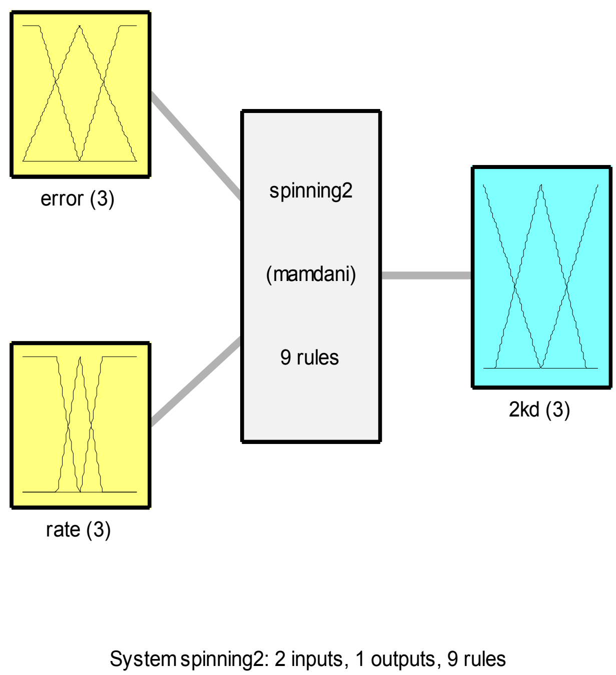

Figure 4.c. Block Diagram of the Fuzzy Controller

Three linguistic variables are used to describe each of the input and output variables of the fuzzy controller; this choice was made to minimize the calculations required by the fuzzy controller, which enables us to implement it on a low-cost microcontroller chip, and also to minimize the required memory. The three linguistic variables used for each input signal are named: NEG (negative), ZERO (zero), and POS (positive), the membership functions associated with these linguistic variables for the input variables "*error*", and *"rate"* are shown in Figures 5.a and 5.b. For each of the inputs, triangular membership function was used in the middle of the data range, and Z-shaped membership functions were used in the ends. Following the same manner, Figure 5.c shows the membership functions for the output variable "*output*". Again, we chose simple triangular and Z-shaped membership functions to minimize the calculations required by the microcontroller. The minimum, center, and maximum values for the different membership functions were chosen based on observations from simulating the system with the PID controller alone.

These figures show how the input signals are *fuzzified* i.e. converted into linguistic variables. Normally, for any value for an input variable, there are two overlapping memberships; using these with the rule set (shown in Figure 4.a) we get an output, the output is found using *min-max* method. In *the defuzzification* process, the output is converted from the linguistic rules into a numerical value, this value is found using the *centroid* method. Figure 5.d shows the fuzzy controller surface, which is a 3-D plot of the input-output relationship.

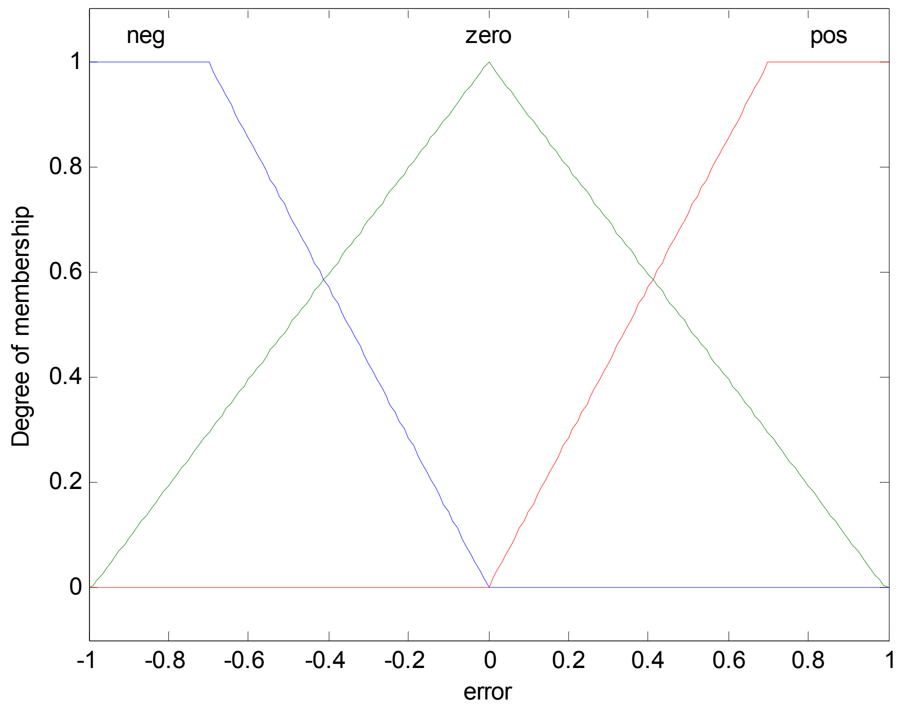

Figure 5.a. Membership functions of fuzzy input variable '*error*'

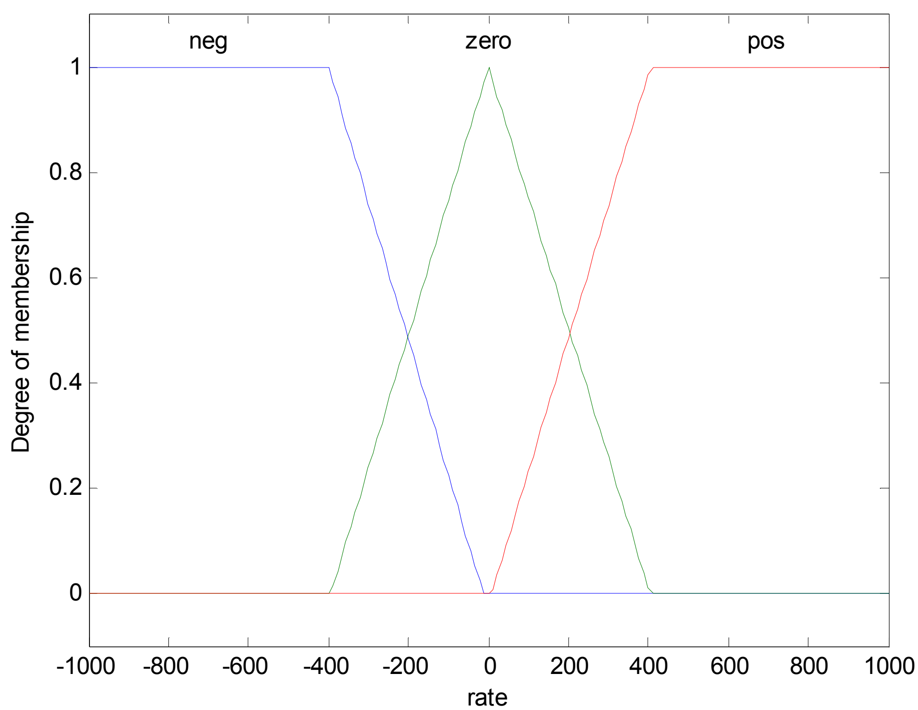

Figure 5.b. Membership functions of fuzzy input variable '*rate*'

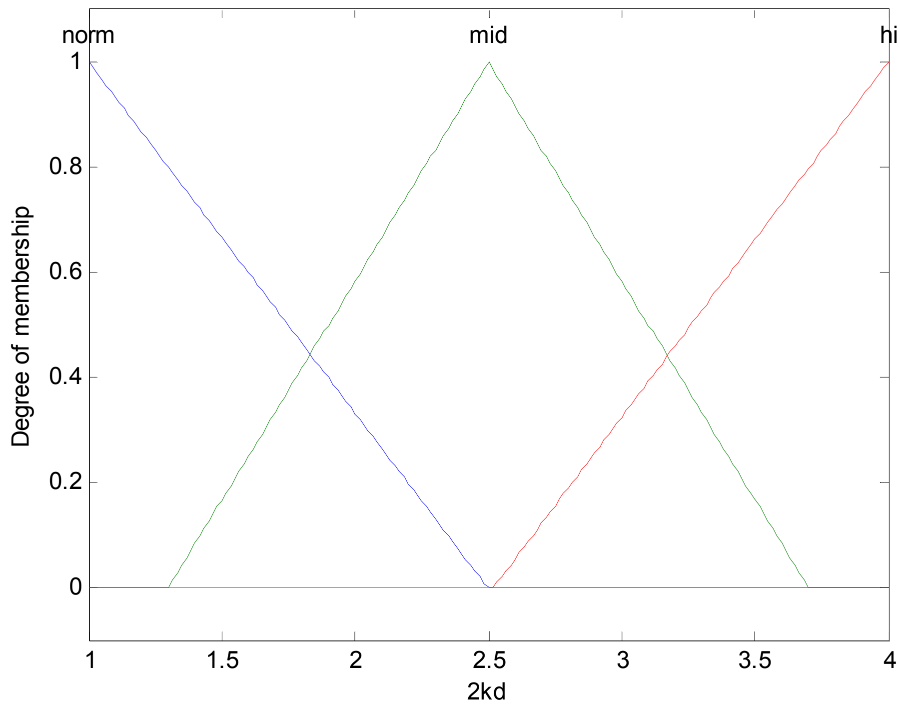

Figure 5.c. Membership functions of fuzzy output variable

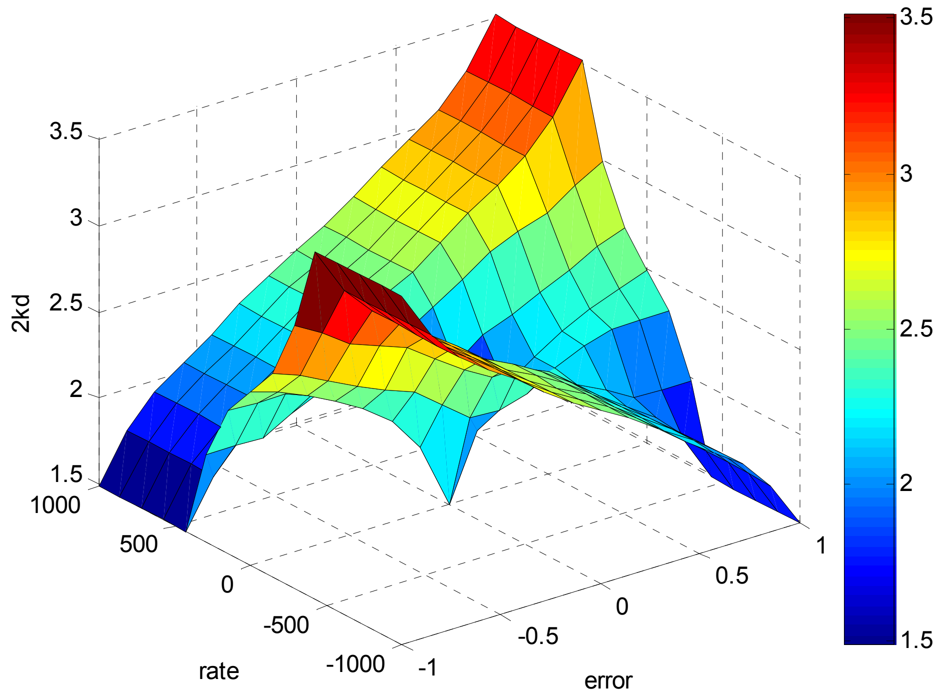

Figure 5.d. Fuzzy controller surface

The operation of the fuzzy controller can be summarized as follows; the output is chosen to be:

1. "*Norm*": when the rotor is displaced from the set-point but moving towards it, or when the rotor is at the set-point and not moving away from it.
2. "*Mid*": when the rotor is at the set-point, and moving away from it, or when the rotor is displaced from the set point and not moving towards it.
3. "*High*": when the rotor is displaced from the set-point and moving away from it.

4. Simulation

To simulate the controller, we constructed a Simulink® model –shown in Figure 6- that takes into account all the components of the system; in this model we avoided using linearised mathematical models to describe the mechanical components, instead we used the Simulink SimMechanics toolbox to numerically model the various components, in order to achieve a more accurate simulation. A detailed description of the model was introduced in [3]. In this model, different blocks represent the components of the designed magnetic spinning system; this includes the mechanical parts of the system, the electrical circuitry, the sensors, the actuators, and also the effects of air-drag on both the yarn and on the rotor. In this model, two discrete PID controllers are used, one for each axis of the movement of the rotor.

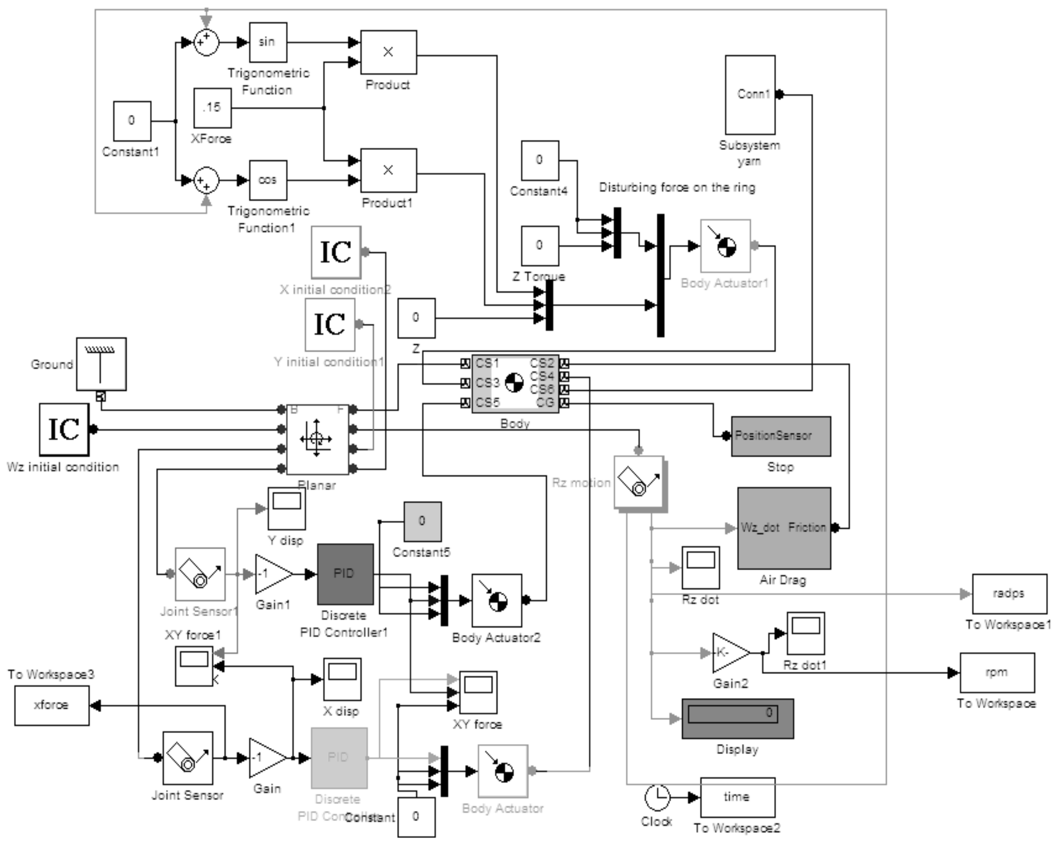

Figure 6. Simulink Model of the System

In this model, the rotor is driven by a force applied to the actuators. The input named "Constant4" allows the insertion of force signal to simulate disturbances affecting the rotor.

Block diagram of the PID controller used in this model shown in Figure 7. In the model, the mass of the rotor M = 32 g, we started by setting K_p=1.5, the integral gain K_i=4, and the derivative gain K_d=0.1.

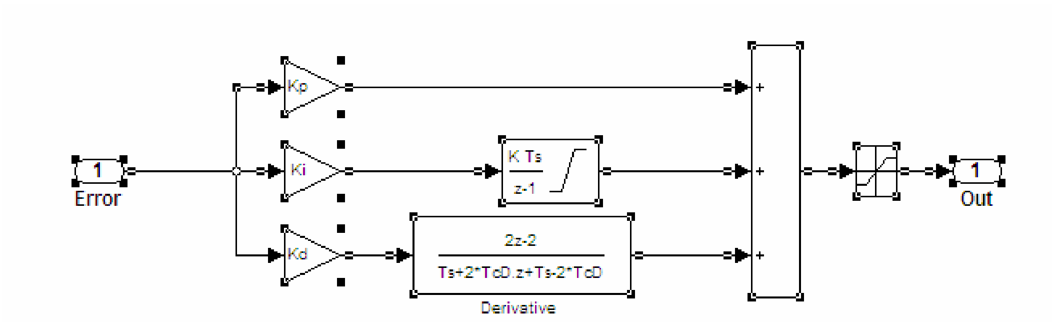

Figure 7. Simulink Discrete PID Controller

In order to implement the hybrid controller, the block diagram of the PID controller was modified as shown in Figure 8. In this figure, the output of the *fuzzy logic controller* modulates the both K_p, and K_d (Constant6, and Constant3 consecutively). So, the input of the discrete derivative becomes the *error* signal multiplied by the value of K_d (Constant 3,) and the output of the fuzzy controller. Similarly, the proportional input is changed.

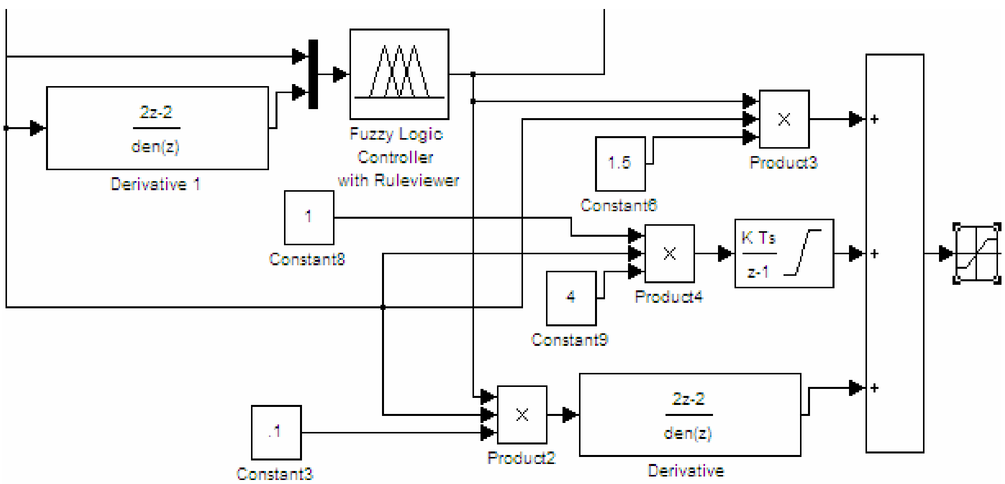

Figure 8. Simulink Model of Fuzzy Controller for Parameter Adaptation Configuration

5. Results

5.1 Discrete PID Controller Response

The response of the PID controller is shown in Figures 9; this graph shows the change in rotor position with time. In this simulation, the rotor started with an off-center initial position of -1mm, and settled in about 4 ms to .1 mm (90%), and to .01 (99%) in 8 ms. The PID controller works as designed, was able to stabilize the operation of the system.

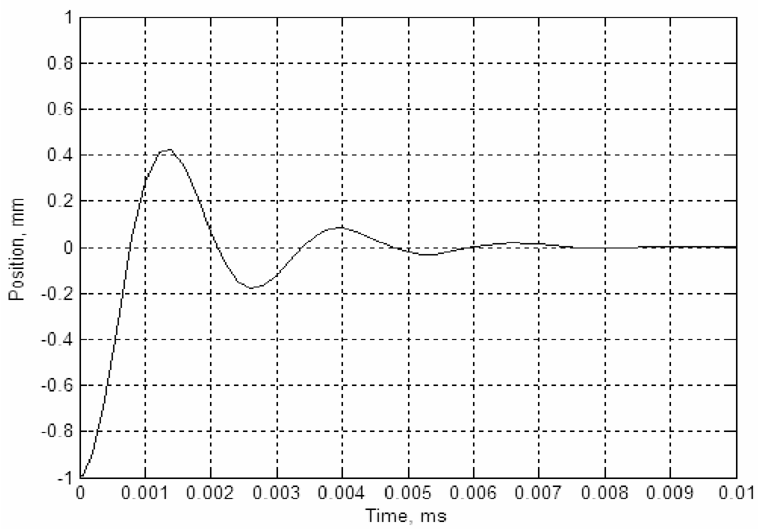

Figure 9. Change in the rotor position with time

5.2 Fuzzy Controller Response

To study the effect of the fuzzy controller, two sets of simulation were performed; first, the system was simulated with a disturbance force added to the actuators, then it was simulated with limited bandwidth white noise applied to the position of the rotor.

The signal shown in Figure 10 was inserted as a disturbance force applied to the actuators; this signal replaced the *constant4* input, which was set in the earlier simulation to be equal to *zero* in Figure 6.

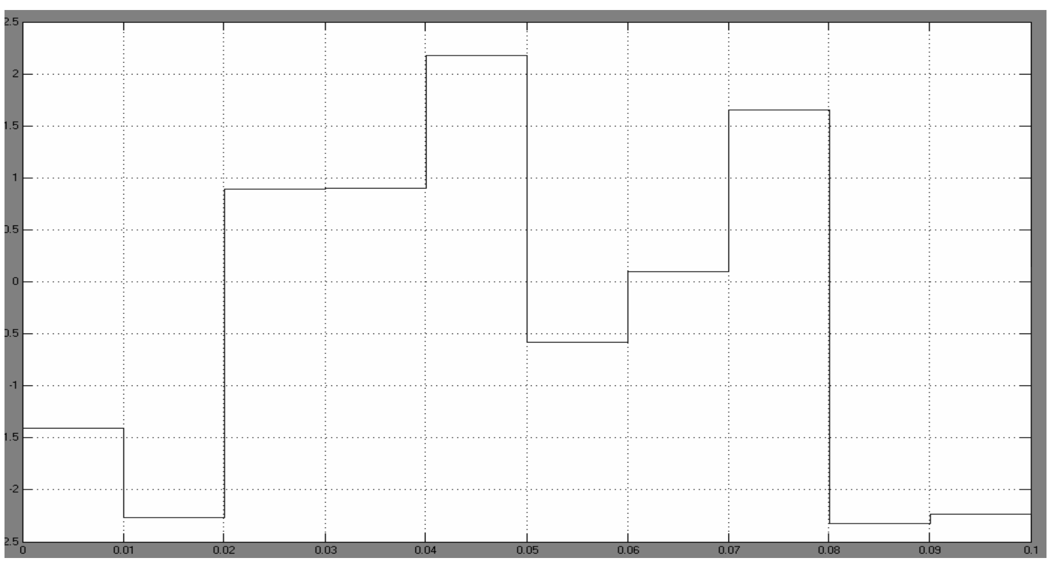

Figure 10. Inserted disturbance signal

Figure 11 shows the response of the system with the integrated controller (top), and with only the PID controller (bottom). The figure shows that the system responded better to the disturbances with the fuzzy controller; the position of the rotor was always closer to the set point (the *zero* line) in the case of the fuzzy controller.

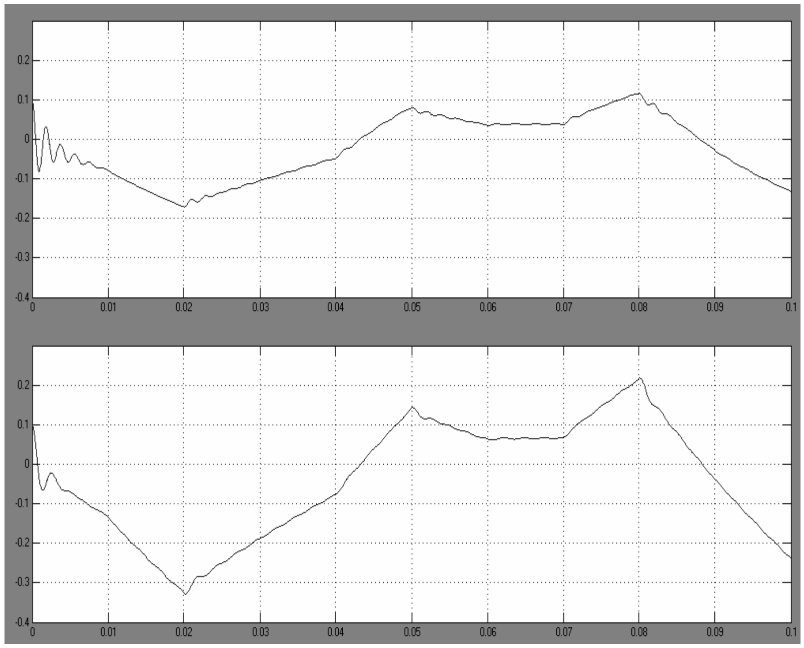

Figure 11. Hybrid (top) compared with PID response (bottom)

Figure 12 shows the response of the PID with the integrated fuzzy + PID (blue) compared with the response of the PID controller alone (green), when limited bandwidth white noise was applied directly to the position of the rotor. It is clear that the system responded better with the insertion of the fuzzy controller. The displacement of the rotor, due to white noise, was reduced by as much as 58%. Figure 13 shows the applied disturbance signal, the system response to the PID controller alone, the system response to the fuzzy + PID controller, and the output of the fuzzy controller (the tuning signal).

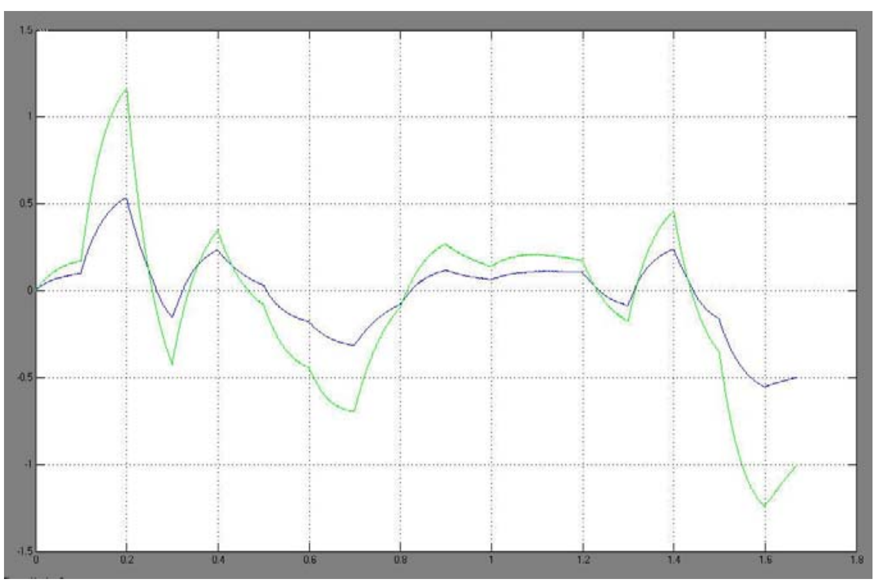

Figure 12. Response of the hybrid controller (blue) vs. PID alone (green), with Noise Applied

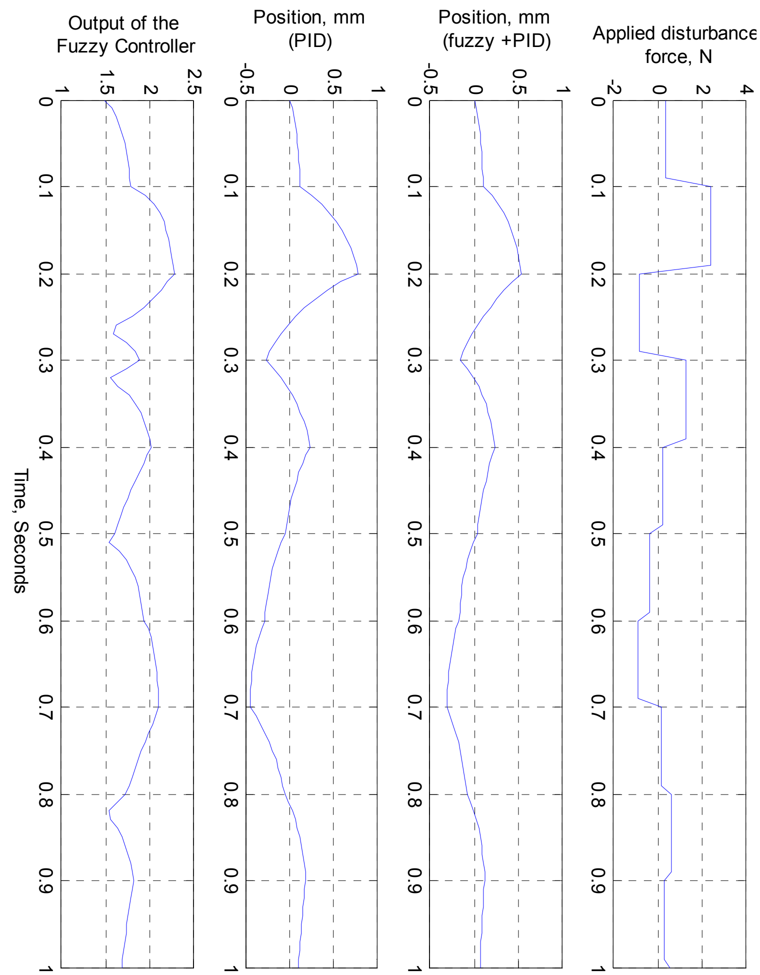

Figure 13. The applied disturbance signal, the system response to the PID controller alone, the system response to the Fuzzy + PID controller, and the output of the Fuzzy controller.

6. Conclusions

A design of a fuzzy-tuned PID controller that is intended to control magnetic levitation systems is introduced. The design aims at enhancing the performance of magnetic levitation systems, by using the output from a fuzzy controller to tune the parameters of a simple PID controller to adjust to different operating conditions. The control of the developed system is done in single input-single output manner.

First, the PID controller was designed to control the system, then fuzzy control was used as supervisory controller over the PID controller; a fuzzy controller supervises the operation of the PID controller, by tuning the PID controller gains, and optimizing them according to the operating conditions of the system.

The simulation showed that the fuzzy-PID controller performed better in the sense of keeping the rotor closer to the set point when compared to performance of the PID controller. This improvement in performance satisfies the objective of the design; when the error signal and its derivative indicate that the rotor is moving away from the set point, the fuzzy controller improves the performance of the system. The fuzzy controller was kept as simple as possible – three triangular membership functions for each of the input and output variables- to enable the future step of implementing the control algorithm on a low-cost single-chip microcontroller.

REFERENCES

1. ABDEL-HADY, F., ABUELENIN S., **Numerical simulation of magnetic ring spinning process.** In: Proceedings of the 5th AUTEX Conference, Portorož, Slovenia. 2005; pp. 872-877.
2. ABDEL-HADY, F., EL-MOGAHZY Y., ABUELENIN S, ABDEL-KADER, R., I**nnovative approach to high-speed spinning using magnetically-elevated spinning ring AUTEX** Res J, 2006; 6:113-121.
3. ABUELENIN, S., **Developing a magnetically suspended disc system for industrial applications, with application on ring spinning.** Dissertation, Auburn University Alabama 2002.
4. CHARARA, A, CARON B., **Magnetic bearing: comparison between linear and nonlinear functioning.** In: Proceedings of the third international symposium on magnetic bearings, Alexandria Virginia. 1992; pp. 451-460.
5. COPELAND, R.P., RATTAN K.S., **A Fuzzy Logic Supervisor for PID Control of Unknown Systems.** In: Proceedings of IEEE international Symposium of Intelligent Control, Ohio, USA. 1994; pp. 22-26.
6. DE QUEIROZ, M.S., DAWSON D.M., **Nonlinear control of active magnetic bearings: a backstepping approach**, IEEE Trans Control Sys Tech, 1996; 4:545-552.
7. DHAR, D, BARRETT L.E., KNOSPE C. R., **Optimum design of decentralized magnetic bearings for rotor systems.** In: Proceedings of the third international symposium on magnetic bearings, Alexandria Virginia. 1992; pp. 47-59.
8. GARCIA-BENITEZ, E., YURKOVICH S, PASSINO K.M., R**ule-based supervisory control of a two-link flexible manipulator.** Journal of Intelligent and Robotic Systems 1993; 7(2):195–213.
9. HERZOG, R., **A comparison between passively and actively controlled magnetic bearings.** In: Proceedings of the third international symposium on magnetic bearings, Alexandria Virginia. 1992; pp. 223-231.
10. HUNG, J.Y., Magnetic bearing control using fuzzy logic. IEEE Trans Indus Appl 1995; 31: 1492-1497.
11. IBRAHIM, D., **Microcontroller Based Applied Digital Control.** John Wiley & Sons Ltd. 2006, ISBN: 0-470-86335-8.
12. JANTZEN, J., **Fuzzy Supervisory Control**, Technical University of Denmark, Denmark. Tech. report no 98-H-875 (proc), Nov. 1998.
13. JIAN, L., YONG K, JIAN C., **Fuzzy-Tuning PID Control of an Inverter with Rectifier-Type Nonlinear Loads**. In: Proceedings of The Third International Power Electronics and Motion Control Conference, Beijing, China. 2000; v1:381-384.
14. LI, L., SHINSHI T, SHIMOKOHBE A., **State feedback control for active magnetic bearings based on current change rate alone**. IEEE Trans Magnetics 2004; 40:3512-3517.
15. LOU, K.N., KUO CY, SHEU L.T., A **Novel Method for Fuzzy Self-Tuning PID Controllers.** In: Proceedings of the Asian Fuzzy Systems Symposium 'Soft Computing in Intelligent Systems and Information Processing'. Kenting, Taiwan, 1996; pp. 194-199.
16. MIZUMOTO, M., **Realization of PID controls by fuzzy control methods.** ELSEVIER Fuzzy Sets and Systems 1995; 70:171-182.
17. PASSINO, K.M., STEPHEN Y., **Fuzzy Control**, Book; Addison Wesley Longman, Inc. 1997 ISBN 0-201-18074-X.
18. SONG, S., LIU W., **Fuzzy Parameters Self-Tuning PID Control of Switched Reluctance Motor based on Simulink/NCD.** In: Proceedings of International Conference on Computational Intelligence for Modelling, Control and Automation, 2006 and International Conference on Intelligent Agents, Web Technologies and Internet Commerce. 2006; pp. 73 – 73.