

Designing Two Control Methods For Active Magnetic Bearing System

Ayyob Asadbeigi*ⁱ

Abstract

At the present study, two methods would be presented to control active magnetic bearing. Results of the two methods would be compared and would be simulated using MATLAB Simulating software. Finally, one of the two methods would be proposed as the most efficient method. The methods include 1- adaptive back-stepping control (ABS), which can be applied for controlling linear model of active magnetic bearing (AMB) and 2- pole placement control, which is applicable for controlling system linear model. In both methods, error level around working point can be measured in presence of improper external disturbances. Through control using the two methods, it could be indicated that magnetic bearing around work point is asymptotically stable. Simulations indicate efficiency of the control methods properly in presence of external disturbances.

Key words:

Introduction

Over the decades, magnetic bearings have been applied for purpose of achieving optimal efficiency, high accuracy and controlling vibrations of rotating machines in the industry. Through eliminating physical contact between the bearing and rotating elements, it would be possible to have access to high rotating speed, which has been previously along with many difficulties using common industrial bearings. Magnetic bearings can be divided to two general categories including active and inactive. Inactive magnetic bearings have been formed of permanent magnets and in this type of bearing, outlet flux can't be controlled; although active magnetic bearings are formed of electromagnetic materials, in which outlet flux can be controlled using changing the current of

coils. Therefore, active magnetic bearings are more common than inactive types because of their controllability.

Because of high speed and low space between rotor and stator, high error in performance of the rotor may cause problem in performance of the machine. Hence, controlling status of the rotor is a very important issue; although controlling location of rotor is a hard action to do. PID controller in [3-5] is very common, which can cause stability of the system. In addition to PID, LQR controller has been also presented for smaller sizes of magnetic bearings in [6]. Displacement of location of rotor needs control, which would be conducted through measurement of bearing current. A new perspective named Active Disturbance Rejection Control (ADRC) developed over the years has been simulated on active magnetic bearing system in [2 and 12]. ADRC has the capability to reject strong power of external disturbances, when location sensor is not applied and it is just adapted with regulation of bandwidth of the controller and observation. However, inefficiency of ADRC controller can be predicted for controlling active magnetic bearing in the steady state for location of rotor [12].

In this study, ABC controlling method has been added to AMB for controlling system linear model. Adaptive Back-stepping Control (ABC) has been developed considerably over the decades [13]. ABC control has been composed of three general parts including control feedback, Lyapunov stability and adaptive control (or resistant). Moreover, ABC can be applied in helicopters, inverted pendulum, jet engineering and induction motor drive systems [13-20]. It has been depicted in [17] that ABC is more efficient than PI controller in terms of robot. The study has investigated effect of ABC on AMB generally. Controlling overall resistance of the system using direct Lyapunov method would be conducted while the process of designing control rules.

In addition, proposed ABC in this study is resistant against external disturbances and changes in parameters. However, in [14-20], change in parameters have been just estimated and compensated. In this study, in addition to ABC method, another method has been also proposed named Pole Placement for active magnetic bearing control, which is applicable for controlling linear systems. In pole placement method, displacement error of rotor would be measured and location of rotor would be controlled.

The study has been designed as follows: at the first section, mechanical model of system is constructed and presented. In the next section, ABC controllers are designed and next, results of ABC simulation would be presented. In the section 4, pole placement controller would be designed. Next, results of simulation for pole placement controller would be displayed. At the final step, controlling methods would be compared to each other and a method would be proposed.

System's mechanical modeling

Figure 1 illustrates simple model of magnetic actuator. In figure 1, I indicates coil current, g is air gap, N is number of coil laps to core laps, A_g indicates cross section. Magnetic field can be produced by the current and in upward current.

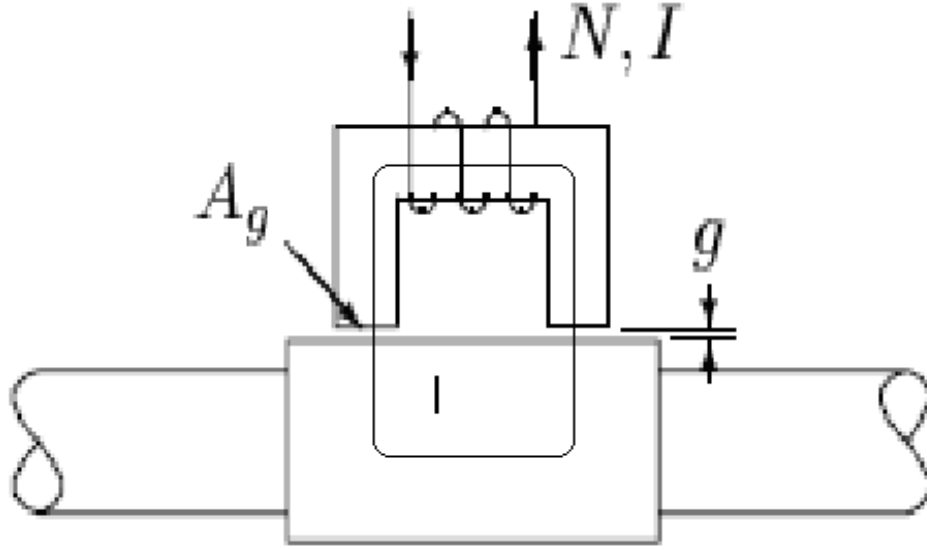


Figure 1: magnetic actuator

According to ampere in nodes (Kirchhoff) rule, equation 1 would be obtained. In this equation, H is magnetic field, B is flux density, n_s is number of loops in path 1 when H is constant, n_c is number of the other coil.

$$\sum_{i=1}^{n_s} H_i l_i = \sum_{i=1}^{n_c} N_i I_i \quad (1)$$

With the assumption that average permeability of μ is each loop is constant, magnetic flux density would be as follows:

$$B_i = \mu_i H_i \quad (2)$$

Through combining 1 and 2, the equation would be as follows:

$$\sum_{i=1}^{n_s} \frac{B_i l_i}{\mu_i} = \sum_{i=1}^{n_c} N_i I_i \quad (3)$$

For the system in figure 1, two air gaps are existed and air permeability rate (μ_g) is very lower than iron (μ_0). Therefore:

$$\frac{2B_g g}{\mu_g} = NI \Rightarrow B_g = \frac{\mu_g NI}{2g} \quad (4)$$

Stored energy (E) in air gap is as follows:

$$E = \frac{1}{2} B_g H_g A_g 2g \quad (5)$$

Electromagnetic energy (f) is equal to energy derivative (E) due to the air gap that can be expressed as follows:

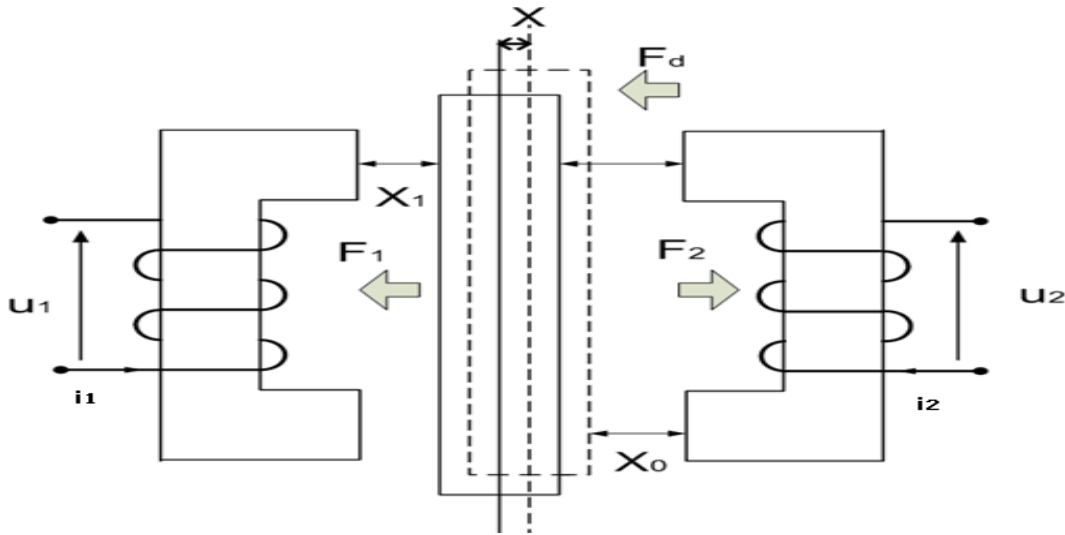
$$f = \frac{dE}{dg} = B_g H_g A_g = \frac{1}{\mu_g} B_g^2 A_g \quad (6)$$

According to flux density equation in eq. 4 and other equations, the next equation would be:

$$f = \frac{1}{\mu_g} A_g \left(\frac{\mu_g N I}{2g} \right)^2 = \frac{\mu_g N^2 I^2 A_g}{4g^2} \quad (7)$$

AMB with a degree of freedom (df) has been illustrated in figure 2.

Figure 2: AMB model



In figure 2, F_d is force of the disturbances on the rotor and F_1 and F_2 are two electromagnetic forces opposite to each other, which can be measured by equation 7. Through determining input voltages of u_1 and u_2 , value of i_1 and i_2 currents can be controlled and as a result, output energy can be measured.

In figure 2, displacement of rotor from its initial place (x_0) is equal to x . Hence, the equation, according to Newton's Law, is as follows:

$$m\ddot{x} = F_1 + F_d - F_2 \quad (8)$$

In figure 2, x_1 and x_2 are respectively the distance of the rotor from the left and right stator. Through replacing x_1 and x_2 separately instead of g in equation 7, electromagnetic forces F_1 and F_2 can be calculated. Hence, the equation would be as follows:

$$F_1 = \frac{\mu_g N^2 i_1^2 A_g}{4x_1^2} = \frac{K}{4} \left(\frac{i_1}{x_1}\right)^2, \quad F_2 = \frac{\mu_g N^2 i_2^2 A_g}{4x_2^2} = \frac{K}{4} \left(\frac{i_2}{x_2}\right)^2 \quad (9)$$

If $K = \mu_g N^2 A_g$, the equation according to Kirchhoff's law would be as follows:

$$u_1 = Ri_1 + L_s \frac{di_1}{dt} + \frac{K}{2} \frac{d}{dt} \left(\frac{i_1}{x_1}\right), \quad u_2 = Ri_2 + L_s \frac{di_2}{dt} + \frac{K}{2} \frac{d}{dt} \left(\frac{i_2}{x_2}\right) \quad (10)$$

In eq. 10, R refers to electric resistance of coil, L_s is inductance coefficient of coil and $\frac{K}{2} \frac{d}{dt} \left(\frac{i_1}{x_1}\right)$ and $\frac{K}{2} \frac{d}{dt} \left(\frac{i_2}{x_2}\right)$ are Electromotive force (EMF) of power, which can be created as a result of changing flux density.

It is assumed that (i_0, x_0, u_0) are nominal values of state variable and x_1, i_1, u_1 are respectively equal to place, current and voltage in left side of AMB in figure 2. Hence, the equation would be:

$$x_1 = x_0 - x, \quad x_2 = x_0 + x \quad (11)$$

$$i_1 = i_0 + i, \quad i_2 = i_0 - i \quad (12)$$

$$u_1 = u_0 + u, \quad u_2 = u_0 - u \quad (13)$$

Through replacing equations 11 and 13 in eq. 10 and through replacing 9 in 8, system's nonlinear model would be obtained as follows:

$$\dot{x} = v$$

$$\begin{aligned}
\dot{v} &= \frac{K}{4m} \left(\frac{i_1}{x_0 - x} \right)^2 - \frac{K}{4m} \left(\frac{i_1}{x_0 + x} \right)^2 + \frac{F_d}{m} \\
i_1 &= \frac{2(x_0 - x)}{2L_s(x_0 - x) + K} \left[-Ri_1 - \frac{K}{2(x_0 + x)^2} vi_0 + u_1 \right] \\
i_2 &= \frac{2(x_0 - x)}{2L_s(x_0 - x) + K} \left[-Ri_2 - \frac{K}{2(x_0 + x)^2} vi_1 + u_2 \right]
\end{aligned} \tag{14}$$

Using Jacobian transformation, one can obtain nonlinear equations of the system in linear form around work point. Equations of linear state have been presented below. State matrix has been displayed by A.

$$\begin{bmatrix} \dot{x} \\ \dot{v} \\ \dot{i} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{2k_s}{m} & 0 & \frac{2k_i}{m} \\ 0 & \frac{-k_i}{L_0 + L_s} & \frac{-R}{L_0 + L_s} \end{bmatrix} \begin{bmatrix} x \\ v \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u + \begin{bmatrix} 0 \\ \frac{1}{m} \\ 0 \end{bmatrix} f_d \tag{15}$$

According to equation 9, when i_0 is constant, bias voltage can be obtained as $u_0 = Ri_0$ due to resistance of coil and when i_0 is variable, the equation between u_0 and i_0 would be as follows:

$$\frac{d}{dt} i_0 = \frac{-R}{L_0 + L_s} i_0 + \frac{1}{L_0 + L_s} u_0 \tag{16}$$

Where; $k_s = \frac{K}{2} \frac{i_0^2}{x_0^3}$, $k_i = \frac{K}{2} \frac{i_0}{x_0^2}$, $L_0 = \frac{K}{2x_0}$

Values of system parameters have been presented in table1.

Table 1: system's parameters

Parameter	Symbol	Value(unit)
Force-Displacement Constant	K_s	153740 N/m
Force-Current Constant	K_i	3500 N/A

Coil Self Inductance	L_s	130mH
Air Gap Inductance	L_0	95mH
Weight of Rotor	m	4.6 kg
Coil Resistance	R	9.7 Ω
Nominal Air Gap	x_0	0.0033 m
Bias current	i_0	1 A
Disturbance Force	F_d	6.2 N

According to values in table 1 and equation 15, eigenvalues of A matrix can be obtained [207.7905, -207.7669, -0.0667]. Clearly, one of the eigenvalues is positive-valued, which indicates that the system is naturally unstable. It has been attempted to design a controller that is able to make the system stable.

Designing the controller

Until the time that active magnetic bearing is unstable, there is need to get help of the controller to control and stabilize location of rotor with presence of external disturbances and uncertain parameters of the system. For this purpose, it is necessary to estimate disturbances exactly, since taking action other than it can make control ineffective.

Firstly, Adaptive Back-Stepping controller has been designed for the system and then, pole placement controller has been designed.

Adaptive Back-stepping controller

ABC is relied on two main bases: 1- back-stepping controller and 2- adaptive law. Back-stepping controller can be applied for stabilizing and controlling rotor's location and adaptive law can be applied for estimating external disturbances.

In regard with designing ABC, it is assumed that system is in base state and as a result:

$$\begin{aligned}
 \dot{x} &= f(x) + g(x)\xi_1 \\
 \dot{\xi}_1 &= f_1(x) + g_1(x, \xi_1)\xi_2 \\
 \dot{\xi}_2 &= f_2(x, \xi_1, \xi_2) + g_2(x, \xi_1, \dots, \xi_2)\xi_3 \\
 &\vdots \\
 &\vdots \\
 &\vdots \\
 \dot{\xi}_{k-1} &= f_{k-1}(x, \xi_1, \dots, \xi_{k-1}) + g_{k-1}(x, \xi_1, \dots, \xi_{k-1})\xi_k \\
 \dot{\xi}_k &= f_k(x, \xi_1, \dots, \xi_k) + g_k(x, \xi_1, \dots, \xi_k)u
 \end{aligned} \tag{17}$$

In equation 17, $x \in \mathbb{R}^n$ and $\xi_i (i=1 \dots k)$ are scholar states. Functions f and g are depended on changes of previous state. When ABC was designed, equations of system state of AMB should be changed into eq. 17 and as a result, equation 15 can be rewritten as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{v} \\ \dot{i} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ a & 0 & b \\ 0 & c & d \end{bmatrix} \begin{bmatrix} x \\ v \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ e \end{bmatrix} u + \begin{bmatrix} 0 \\ f \\ 0 \end{bmatrix} F_s \tag{18}$$

Where; $a = \frac{2K_s}{m}$, $b = \frac{2K_i}{m}$, $c = \frac{-K_i}{L_s + L_0}$, $d = \frac{-R}{L_0 + L_s}$, $e = \frac{1}{L_0 + L_s}$, $f = \frac{1}{m}$. Equation 18 can be written in

form of equations 19, 20 and 21; where, $x_3 = ix_2 = \frac{1}{b}v$ and $x_1 = \frac{1}{b}x$:

$$\dot{x}_1 = x_2 \tag{19}$$

$$\dot{x}_2 = x_3 + \frac{a}{b}x_1 + \theta = x_3 + \varphi_1(\theta, x_1) \tag{20}$$

$$\dot{x}_2 = \dot{u} + cbx_2 + dx_3 = \dot{u} + \varphi_2 \quad (21)$$

In the above equations, disturbance force and control input are respectively equal to $\theta = (Fs/bm) = 0.023$ and $u' = eu_1$. φ_1 and φ_2 are equal to $\varphi_1(\theta, x_1) = \frac{a}{b}x_1 + \theta$ and $\varphi_2 = cbx_2 + dx_3$.

According to the equations and the goal of control that is measuring rotor's location, one can select Lyapunov function and state variables to obtain control function and adaptive law as follows:

If assume that: $z_1 = x_1$, $z_2 = x_2 - a_2$, $a_1 = -c_1x_1$, $z_3 = x_3 - a_2$

Following equations can be obtained:

Proposed Lyapunov function equation:

$$V_2 = \frac{1}{2}Z_1^2 + \frac{1}{2}Z_2^2 + \frac{1}{2}Z_3^2 \quad (22)$$

If in the eq.22, V_2 is differentiated, the equation would be:

$$\begin{aligned} \dot{V}_2 &= -C_1Z_1^2 - C_2Z_2^2 + Z_2Z_3 + Z_3(u + \varphi_2 - \dot{a}_2) \\ &= -C_1Z_1^2 - C_2Z_2^2 + Z_3(Z_2 + \dot{u} + \varphi_2 - \dot{a}_2) \end{aligned} \quad (23)$$

When u' is selected as $\dot{U} = -C_3Z_3 - Z_2 - \varphi_2 + \dot{a}_2$, differentiated equation of Lyapunov function can be rewritten as follows:

$$\dot{V}_2 = -C_1Z_1^2 - C_2Z_2^2 - C_3Z_3^2 \quad (24)$$

The equation indicates that derivative of the negative Lyapunov function is semi-certain. As a result, the objective of control is achievable. In this equation, no external disturbance is considered. However, if one is existed, adaptive laws should be codified, so that the disturbances can be estimated and eliminated. Estimation of the disturbances would be added to the control laws as feedback at the time of working. Details about estimation of disturbances would be explained here.

Here, θ is considered as disturbance and estimated disturbances can be shown by $\hat{\theta}$. Estimation error can be obtained as $\tilde{\theta}_1 = \theta - \hat{\theta}_1$. Quadratic form of the equation would be added to equation 22 and a new form of Lyapunov function would be obtained in equation 23.

$$V_2 = \frac{1}{2}Z_1^2 + \frac{1}{2}Z_2^2 + \frac{1}{2\gamma_1}\hat{\theta}_1^2 \quad (23)$$

Derivative of the above Lyapunov function would be obtained as follows:

$$\begin{aligned} \dot{V}_2 &= -C_1Z_1^2 - C_2Z_2^2 + Z_2Z_3 + Z_2\tilde{\theta}_1 + \frac{1}{\gamma_1}\dot{\hat{\theta}}_1\tilde{\theta}_1 \\ &= -C_1Z_1^2 - C_2Z_2^2 + Z_3Z_2 + \tilde{\theta}_1(Z_2 - \frac{1}{\gamma_1}\dot{\hat{\theta}}_1) \end{aligned} \quad (24)$$

In the equation 24, if adaptive law is selected as $\dot{\hat{\theta}}_1 = \gamma_1 Z_2$, negative V_1 would be determined and Z_2Z_3 can be also omitted from the equation. According to external disturbances, a_2 value can be selected as follows:

$$\begin{aligned} a_1 &= -Z_1 - C_2Z_2 - \varphi_1x_1 - \hat{\theta}_1 + \dot{a} = -Z_1 - C_2(x_2 - a_1) - \varphi_1Z_1 - \hat{\theta}_1 - C_1\dot{x}_1 \\ &= -(C_1C_2 + \varphi_1 + 1)Z_1 - (C_1 + C_2)x_2 - \hat{\theta}_1 \end{aligned} \quad (25)$$

Here, $z_1 = x_1$, $z_2 = x_2 - a_1$, $a_1 = -c_1x_1$ has been considered. As a result, a_2 equals:

$$\begin{aligned} \dot{a}_2 &= -\left(\frac{\partial a_2}{\partial Z_1}\dot{Z}_1 + \frac{\partial a_2}{\partial x_2}\dot{x}_2 + \frac{\partial a_2}{\partial \hat{\theta}_1}\dot{\hat{\theta}}_1\right) \\ &= -\left(\frac{\partial a_2}{\partial Z_1}\dot{Z}_1 + \frac{\partial a_2}{\partial x_2}(x_3 + \varphi_1x_1 + \theta) + \frac{\partial a_2}{\partial \hat{\theta}_1}\dot{\hat{\theta}}_1\right) \end{aligned} \quad (26)$$

It is assumed that $\hat{\theta}_2$ is an estimation of θ_1 and estimation error is equal to $\tilde{\theta}_2 = \theta_1 - \hat{\theta}_2$.

Consequently, Lyapunov function can be rewritten as follows:

$$V_2 = \frac{1}{2}Z_1^2 + \frac{1}{2}Z_2^2 + \frac{1}{2}Z_3^2 + \frac{1}{2\gamma_1}\hat{\theta}_1^2 + \frac{1}{2\gamma_2}\hat{\theta}_2^2 \quad (27)$$

If $z_3 = x_3 - a_2$, the control law, which was differentiated, would be expressed as follows:

$$\dot{u} = -C_3Z_3 - Z_2 - \varphi_2 + \dot{a}_2 \quad (28)$$

Through replacing 26 in 28, the equation would be as follows:

$$\begin{aligned} \dot{u} = & -(C_3 + d)x_3 - \left[C_3 \left(C_1C_2 + \frac{a}{b} + 1 \right) + C_1 \right] x_1 - [C_3(C_1 + C_2) + 1 + cb]x_2 \\ & - C_3\hat{\theta}_1 + \dot{a}_2 \end{aligned} \quad (29)$$

Finally, through differentiation of Lyapunov function in equation 27, the obtained equation would be:

$$\dot{V}_2 = -C_1Z_1^2 - C_2Z_2^2 - C_3Z_3^2 - \frac{1}{\gamma_2}\dot{\hat{\theta}}_2\tilde{\theta}_2 - Z_3\frac{\partial a_2}{\partial x_2}\tilde{\theta}_2 \quad (30)$$

To have semi-certain negative value for equation 30, there is need to eliminate existed error of

$\tilde{\theta}_2$ in the equation. If the adaptive law is selected as $\dot{\hat{\theta}}_2 = -\gamma_2\tilde{\theta}_2$, derivative of V_2 would be:

$$\dot{V}_2 = -C_1Z_1^2 - C_2Z_2^2 - C_3Z_3^2 \quad (31)$$

Now that derivative of Lyapunov function has gotten semi-certain negative value, system has been stabilized properly around its work point. Adaptive back-stepping control law can be obtained finally as follows:

$$\begin{aligned} \dot{u} = & -\left(\frac{a}{b}(C_1 + C_2 + C_3) + 2C_1 + C_3 + C_1C_2C_3\right)x_1 \\ & - (C_1C_2 + C_2C_3 + C_1C_3 + cb + \varphi_1 + C_1 + C_2 + 3)x_2 - (C_1 + C_2 \\ & + C_3 + d)x_3 \end{aligned} \quad (32)$$

The equation 32 displays final ABC controller, which includes 3 feedback states. According to Lyapunov function, AMB system has been controlled by ABC and has achieved to steady state. Closed loop circuit of system has been illustrated in figure 3.

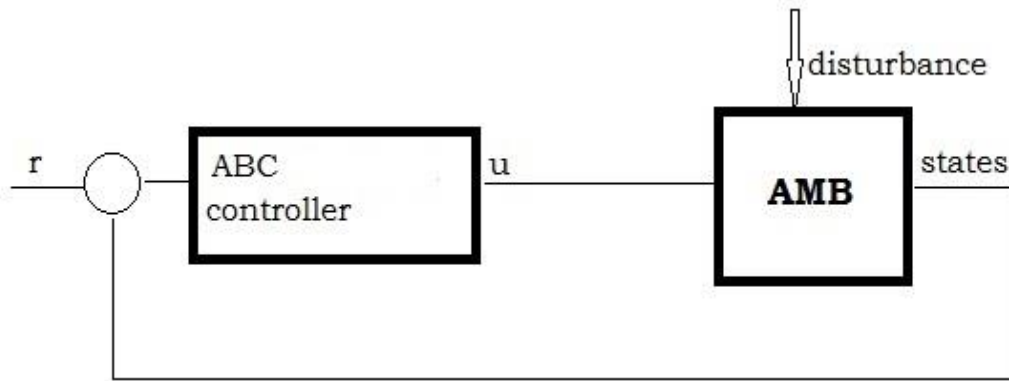


Figure 3: Closed loop circuit along with controller

Simulation results of controlled system by ABC

Simulation results have been presented below. An important issue is that amount of estimated disturbances has been considered to 0.023 ($\Theta=0.023$).

Figure 4 illustrates state variables with presence of estimated disturbance. Here, adaptive

coefficients have been considered constant $\gamma_1 = 1$ and $\gamma_2 = 1$; although back Lyapunov coefficients

of c_1 , c_2 and c_3 have been changed. It indicates that maximum value of rotor displacement is equal to 0.5mm, which can guarantee that rotor would never touch the stator. Through change in the parameters and coefficients, it could be found that the system still is stable and this indicates that controller system is resistant and effective against changes. Control function output is shown in figure 4.

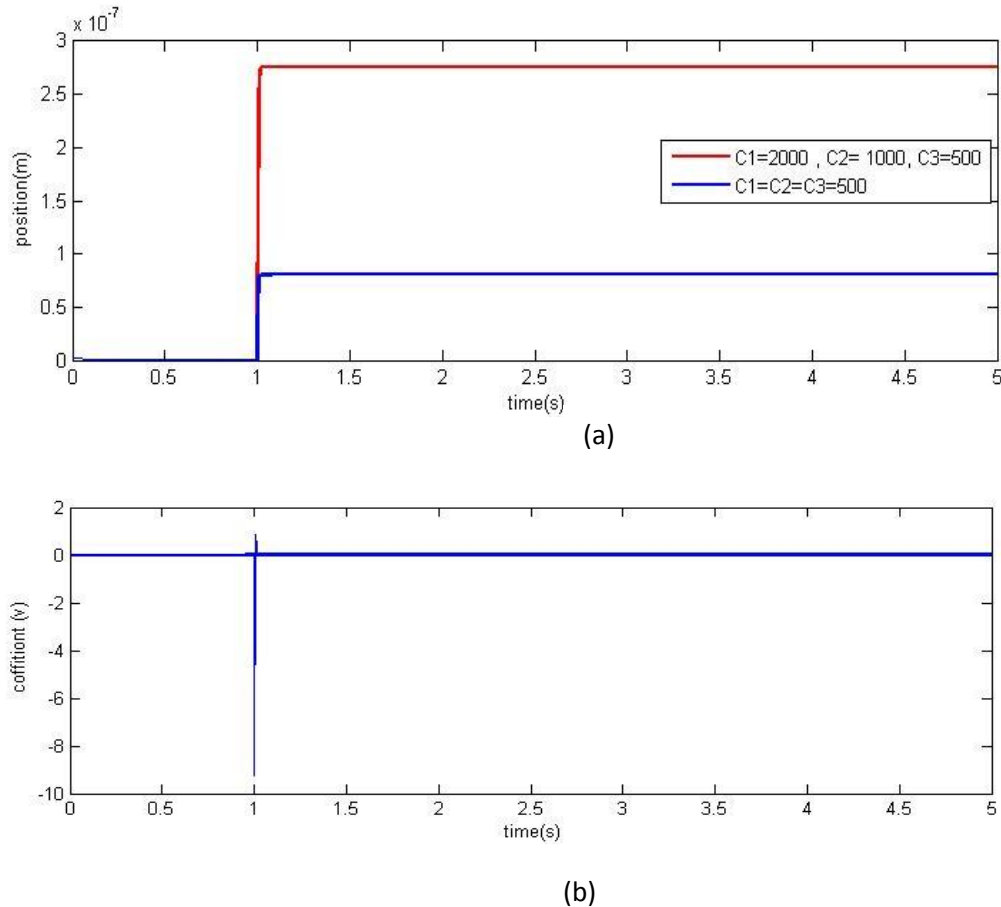


Figure 4: system output, along with ABC controller a) rotor displacement with different Lyapunov coefficients b) controller's output (control signal)

Controlling by pole placement method

In this method, one can transfer system's poles to the desired places. Hence, name of the method is pole placement control method. First, equations of the system should be transferred from state space to transfer function.

State space equations of the system are according to equation 18. Through transferring the equations to conversion function, the system would be changed into equation 33.

$$G(s) = \frac{0.06012}{s^3 + 0.04211s^2 - 3.889e4s - 1637} \quad (33)$$

Through calculating roots of conversion function, it could be found that system poles are equal to [207.7905, -207.7669, -and 0.0667]. Positive pole indicates instability of the system. In order to make system stable, the pole should be destroyed. In pole placement method, new places would be determined, to which previous poles of the system are being transferred. For example, it is desired to consider new poles equal to [-0.5, -1, -1.2]. Through selecting these poles, one can stabilize the system, since all roots of conversion function are placed in left hand of the coordinate axis. This type of controller can conduct estimation due to the system's poles and desired places, to which previous poles should be transferred. Through multiplying it in input signal, control signal would be produced and through applying it in system, new poles would be created.

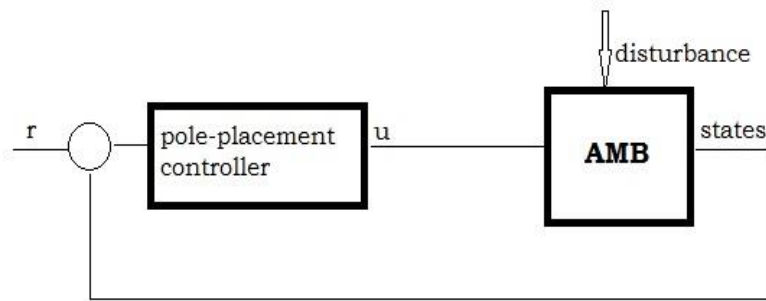


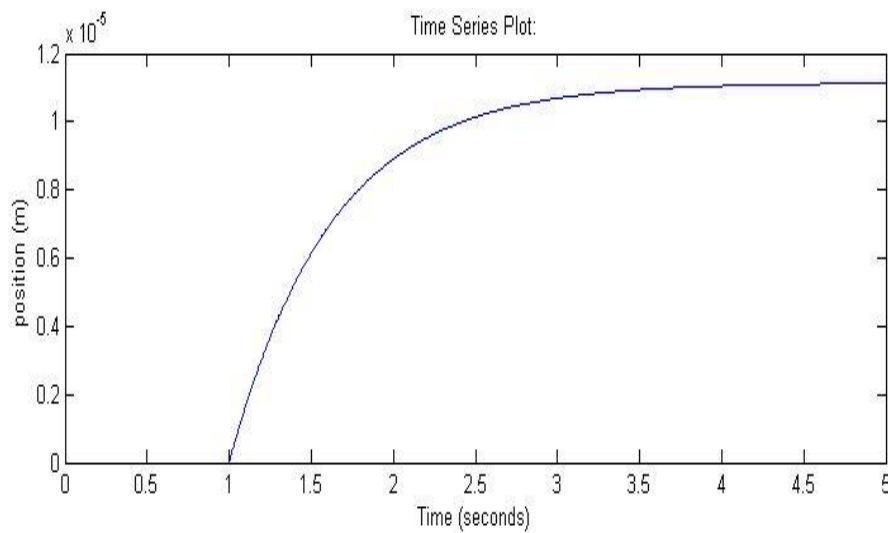
Figure 5: system's loop, along with pole placement controller

In this study, it has been assumed that source input is equal to 0.

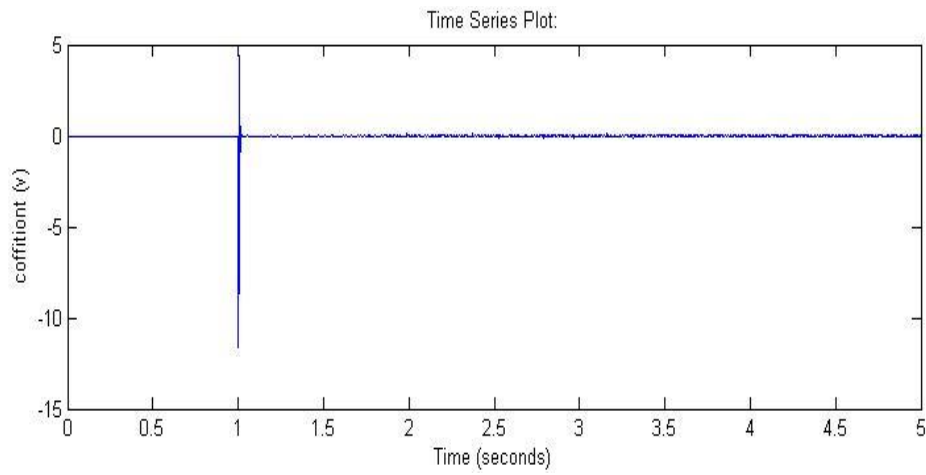
Simulation results of controlled system by pole placement controller

As it is assumed that new places of system's poles are equal to $[-0.5, -1, -1.2]$, gains of the controller would be equal to $[1.7466, 0.6469, 0.0005]e^{+6}$. Through multiplying the values in input signal, control signal would be produced and finally, the system would be stabilized through applying control signal.

Output of the system has been displayed in figure 6 after adding pole placement controller.



(a)



(b)

Figure 6: system output a) rotor displacement diagram, b) controller's output (control signal)

It could be observed that in this method, the system has been appeared properly in work point. Maximum displacement amount for rotor is also equal to 0.012mm, which indicates that rotor would never touch the stator.

Conclusion

At the present study, Active Magnetic Bearing system, which is naturally a nonlinear system, has become linear around working point using Lagrange. Then, two methods of adaptive backstepping control and pole placement control have been applied to control rotor's status and location

in ABC system. The main aim by conducting this is stabilizing the closed loop system and controlling rotor's displacement in presence of disturbance and uncertain parameters of the system. Here, performance of the two controllers is compared. As it is obvious from simulation results (figures 4-6), ABC controller is resistant against disturbances and performs properly through changing parameters of the system. The time for achieving response of steady state using ABC is shorter than the time of using pole-placement controller. In addition, control signal at the time of using ABC has more stability and has less fluctuations and changes than produced control signal by pole-placement controller. In addition, the distance of rotor and stator while using ABC is higher than pole placement and this can provide better safety margin for preventing contact of rotor and stator. All mentioned issues indicate that performance of ABC controller is better than pole-placement controller.

In future, it will be studied in this field that how Lyapunov coefficients can be selected in a manner that system can have better performance? Also, the aim is to implement ABC controller practically for controlling magnetic bearing system, since it was proved that the system has better action and performance than pole-placement controller system.

References

- [1] - S. C. Mukhopadhyay, C. Gooneratne and G. Sen Gupta “Magnetic bearing: an Integrated Platform for Teaching and Learning,” in *Proc. Of 2nd International Conference on Autonomous Robots and Agents*, Palmerston North, New Zealand, Dec. 2004, pp. 283-28

- [2] - Richard A. Rarick, Control of An Active Magnetic Bearing with and without Position Sensing, Master's Thesis, Department of Electrical and Computer Engineering, Cleveland State University, Cleveland, OH, 2007.
- [3] -B. Polajžer, J. Ritonja, G. Štumberger, D. Dolinar and J. P. Lecointe, "Decentralized PI/PD position control for active magnetic bearings," *Electrical Engineering*, vol. 89, no. 1, pp. 53–59, Oct. 2006.
- [4] - Bearing System, Bachelor's Honors Thesis, Department of Electrical and Computer Engineering, Cleveland State University, Cleveland, OH, 2009.
- [5] - Timothy P. Denver, Gerald V. Brown, Ralph H Jansen, "Estimator Based Controller For High Speed Flywheel Magnetic Bearing System," NASA internal report (NASA/TM—2002–211795), Aug. 2002.
- [6] - Ha-Yong Kim, Chong-Won Lee, "Design and Control of Active Magnetic Bearing System with Lorentz Force-Type Axial Actuator," *Mechatronics*, vol. 16, no. 1, pp. 13–20, Feb. 2006.
- [7] – Rafal Piotr Jastrzebski, Riku Pollanen, "Centralized Optimal Position Control for Active Magnetic Bearings: Comparison with Decentralized Control," *Electrical Engineering*, vol. 91, no. 2, pp. 101-114, Aug. 2009.
- [8] – Wojciech Grega, Adam Pilat, "Comparison of Linear Control Methods for an AMB system," *Int J Appl Math Comput Sci*, vol. 15, no. 2, pp. 245-25, 2005.
- [9] – Ladislav Kucera, "Robustness of Self-Sensing Magnetic Bearing," in *Proceedings of Magnetic Bearings Industrial Conference*, Alexandria, Virginia, 1991, pp. 261–270.

- [10] - Lichuan Li, Tadahiko Shinshi, and Akira Shimokohbe, "State Feedback Control for Active Magnetic Bearing Based on Current Change Rate Alone", *IEEE Transactions on Magnetics*, vol. 40, no. 6, pp. 3512-3517, Nov. 2004.
- [11] - Myounggyu D. Noh, Eric H. Maslen, "Self-Sensing Magnetic Bearings Using Parameter Estimation," *IEEE Transactions on Instrumentation and Measurement*, vol. 46, no. 1, pp. 45-50, Feb. 1997.
- [12] - Baixu Su Alexander, Control of Active Magnetic Bearings For Flywheel Energy Storage, Master's Thesis, Department of Electrical and Computer Engineering, Cleveland State University, Cleveland, OH, 2006.
- [13] – Miroslav Krstic, Ioannis Kanellakopoulos and Petar Kokotavic, Nonlinear and Adaptive Control Design, New York: Wiley-Interscience, 1995.
- [14] - ö.Tolga Altmöz, "Adaptive Integral Backstepping Motion Control for Inverted Pendulum," *International Journal of Computer and Information Science and Engineering*, vol. 1, no. 4, pp. 192-195, 2007.
- [15] - A.Benaskeur, A. Desbiens, "Application of Adaptive Backstepping to the Stabilization of the Inverted Pendulum," in *CCECE'98 Proceedings*, Waterloo, Ontario, 1998, pp. 113–116.
- [16] - Jung-Hua Yang, Wen-Chun Hsu, "Adaptive backstepping control for electrically driven unmanned helicopter," *Control Engineering Practice*, vol. 17, no. 8, pp. 903–913, Aug. 2009.
- [17] - R.R.Joshi, R.A.Gupta and A.K Wadhwani, "Adaptive Backstepping Controller Design and Implementation for a Matrix-Converter-Based IM Drive System," *Journal of Theoretical and Applied Information Technology*, vol. 3, no. 2, pp. 28–41, 2007.

- [18] - Kubota T & Toumi K.Y., (1998). *Limitation of Linear Controllers for The Precision Magnetic Bearing with Uncertainties*, Proc. the American Contr. Conf. Philadelphia, pp. 2204-2228.
- [19] - Gurleyen, F. (2006). *PID+Rule-Based Variable Structure Control of Active Magnetic Bearings for High Speed Rotors*, 9. IEEE Int. Workshop on AMC Proc., P 235-242.
- [20] - Changsheng Z., Zhiwei M. (2005). *A PWM Based Switching Power Amplifier for Active Magnetic Bearings*, IEEE Electrical Machines and Systems, V 2 P 1563 – 1568.

ⁱ Department of Electrical Engineering, Islamic Azad University, Hamedan Branch, Iran
asadbeigi.ayyob@gmail.com