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Stabilization and Control of Three Pole Active Magnetic Bearing: A Sliding mode control Approach on Extended System Dynamics

V. A. Sherine Jesna*, and Winston Netto

Abstract: A magnetic bearing is a bearing which supports the load using magnetic levitation, which could provide a contact-less, low frictional losses, lubrication free, high speed operations compared to the conventional bearings. The contact forces are generated by actively controlling the dynamics of an electromagnet. An Active Magnetic Bearing (AMB) system is inherently nonlinear on account of the nonlinearities of its electromagnetic field, which considerably make difficulties in designing efficient and effective system controllers. More over the cost of the AMB is obstructing the industry from implementing an AMB. The possible solution is to reduce the number of magnetic poles, and hence the three pole AMB system is devised. But it has the major disadvantage of magnetic flux coupling, an added nonlinearity. This paper studies the feasibility of an extended systems and sliding mode control scheme to design a robust controller to control the nonlinear three pole Active Magnetic Bearing (AMB). The simulation analysis is done to quantify the robustness of the proposed controller.

Keywords: Three Pole Active Magnetic Bearing; Current mode control; Sliding mode control: Extended Systems.

1. INTRODUCTION

The concept of stable levitation of a static magnetic body in a magnetic field was identified in 1842 by Earshaw[1].The later century had seen tremendous efforts to make use of magnetic suspension. The advancements in power electronics, signal processing, identification and control of rotor dynamics has resulted in developing magnetic suspension of rotors for industrial purposes. The first of its kind commercial use of an Active Magnetic Bearing (AMB) was the suspension system for the COMSAT satellite developed by the Societe Europenne de Propulsion, a French firm in 1976 [20]. An active magnetic bearing (AMB) system is a bearing system in which there is a collection of electromagnets used to suspend an object. The stabilization of the highly inherent nonlinear system owing to its magnetic field is performed by feedback control. The AMB systems are composed of a floating mechanical rotor, coated with coated with ferromagnetic substance and electromagnetic coils on the stator provide the controlled dynamic forces and thus allowing the suspended object to move in its predefined functionality [5]. Some of the recent developments in application of active magnetic bearings include: (i) high speed machining such as milling, (ii) high temperature applications such as blowers, (iii) vacuum pumps and (iv) turbo-machinery (v) cryogenic turbo expanders.

Since the magnetically suspended rotor system is inherently unstable, stabilization and compensation of the adverse effects of system nonlinearity, rotor dynamics and external disturbances are addressed with feedback controllers which could render robustness also. The eight pole AMBs, which are common in

Manipal Institute of Technology, Manipal University, Karnataka- 576104, India.
* e-mail: sherine.jesna@manipal.edu (or) sherine.jesna@gmail.com

literature, have been modeled and controlled with various aspects stemming from classical control theory and further techniques [3] - [5]. The controller modes can be classified as i) current controlled mode and, ii) voltage controlled mode [6]. Three class of controllers; class A, class B, class C; depending upon the distribution approach of the control current and bias current in the actuator coils of AMB has been discussed in [7]. Power amplifiers and sensors have contributed to make the AMB an expensive and rarely used mechatronic device in industry. One among the possible ways to cost down the AMB is the reduction in the number of magnetic poles. The reduction in poles will reduce the driver requirements and number and also leave more room for heat transfer, coil winding and sensor installation. The concept of three pole AMB system has been put forward by S.L Chen and others [6] - [11]. The reduction in poles will also leave more room for heat transfer, coil winding and sensor installation. But the major shortcoming of the three-pole AMB is its magnetic flux coupling.

The feasibility of design and implementation of the controllers for both the current-controlled and voltage controlled three-pole AMB systems are discussed [8] - [10], [20]. Hsu and Chen used integral sliding mode controllers designed for the linearized systems and an experimental validation is shown in [8]. The nonlinear smooth feedback control, pole placement controls, and inverter fed control of AMB systems etc. can be seen in [11]-[12]. The objective of this work is to design a nonlinear stabilizing controller obtained by applying the concept of extended systems and feedback linearization. The aim is synthesize a controller law to ensure the stability and performance with global convergence.

2. THE THREE POLE AMB SYSTEM MODEL

2.1 The System Description

An optimal configuration of a three pole AMB [Fig.1] from the viewpoint of energy and cost is discussed in [9]. Assuming that the gravitational field acts in the y-direction, the system has its poles been arranged at 120^o radially displaced to produce an even force distribution in the two-dimensional configuration space. The magnetic poles *#2* and *#3* have opposite winding schemes and share the same current amplifier [10]. Hence, the two poles will have equal and opposite coil currents. The rotor position control in x and y directions are rendered with the two coil currents i_2 and i_1 respectively The vertical position is controlled by the coil current i_1 whereas the rotor's horizontal position is maintained by coil current i_2. To emphasis on the nonlinear control, a single three pole AMB system supporting a rigid, disk-like rotating rotor is considered [9]. The axial motions are restricted by the thrust bearing and the overall system has two degrees of freedom only. At steady state the constant current i_{20} is provided to support the rotor weight.

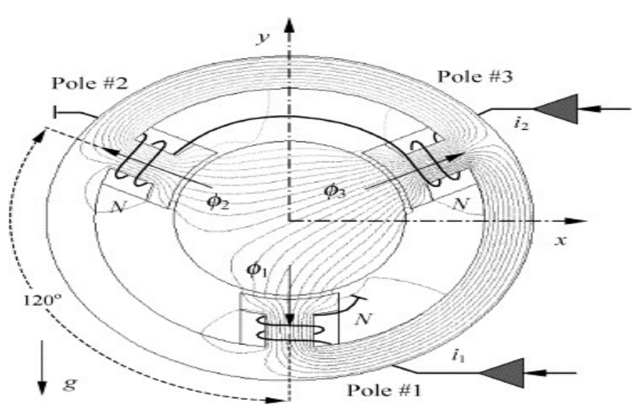

Figure 1: Three pole AMB system configuration and the coil currents

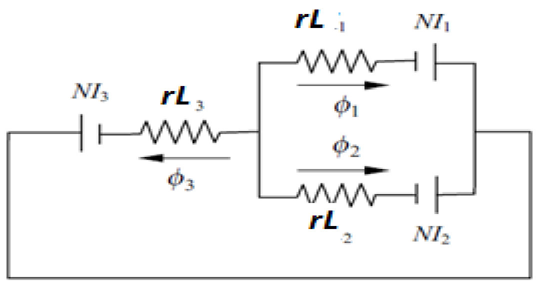

Figure 2: Three pole AMB system equivalent magnetic circuit magnetic circuit

2.2 Mathematical Model of the Three Pole Amb

The magnetic circuit equivalent of AMB is given in Fig. 2. The reluctances are assumed to be present only in the air gap, [Fig. 2] is analyzed and the flux passing through each pole can be obtained as,

$$\emptyset_1 = N\frac{(rL_1 + r_3)i_1 + (r_2 - r_3)i_2}{r_1r_2 + r_2r_3 + r_3r_1} \quad (1)$$

$$\emptyset_2 = N\frac{(-rL_3)i_1 + (2rL_1 + rL_3)i_2}{r_1r_2 + r_2r_3 + r_3r_1} \quad (2)$$

$$\emptyset_3 = N\frac{(-r_2)i_1 - (2r_1 + r_2)i_2}{r_1r_2 + r_2r_3 + r_3r_1} \quad (3)$$

The number of coil turns is indicated by N and rL_i, i = 1, 2, 3, are the air gap reluctances (H^{-1}) existing between the rotor and the magnetic actuator poles [8].

The variation in the position of the rotor results in variation in the reluctances as well.

$$\begin{bmatrix} rL_1 \\ rL_2 \\ rL_3 \end{bmatrix} = \frac{1}{\mu A}\begin{bmatrix} 1 & 0 & 1 \\ 1 & \frac{\sqrt{3}}{2} & -\frac{1}{2} \\ 1 & \frac{\sqrt{3}}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} l_0 \\ x_r \\ y_r \end{bmatrix} \quad (4)$$

Assuming linear magnetic (*B-H)* characteristics, and neglecting the flux leakage and the fringing effects, then the magnetic force is a function of flux [1] and is given by

$$F = \frac{B^2}{2\mu}A = \frac{\emptyset^2}{2\mu A} \quad (5)$$

where μ is the magnetic permeability of the air (Hm^{-1}), *B* is the magnetic field (T) and *A* is the pole face area (m^2).

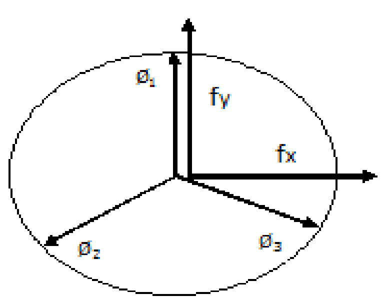

Figure 3: The resultant magnetic force in horizontal and vertical directions

Relating to Fig.3, the resultant magnetic forces generated can be resolved in both vertical and horizontal directions and could be given by

$$f_x = (F_3 - F_1)\cos 30 = \frac{4\gamma}{3}\overline{\emptyset}_1\overline{\emptyset}_2 \tag{6}$$

$$f_y = (F_3 + F_1)\sin 30 - F_1 = \frac{2\gamma}{3}(\overline{\emptyset}_1^2 - \overline{\emptyset}_2^2) \tag{7}$$

Where $\overline{\emptyset}_1 \equiv \frac{\sqrt{3}}{4\mu AN}(\emptyset_3 - \emptyset_2)$ and $\overline{\emptyset}_2 \equiv \frac{\sqrt{3}}{4\mu AN}(\emptyset_3 + \emptyset_2)$

By substituting Eq. (1) – (4) into eq.(6) and eq.(7) yields $(\overline{\emptyset}_1, \overline{\emptyset}_2)$ as a function of (i_1, i_2) as follows

$$\begin{bmatrix}\overline{\emptyset}_1\\ \overline{\emptyset}_2\end{bmatrix} = \frac{-1}{Z}\begin{bmatrix} x_r & \sqrt{3}(2l_0 + y_r)\\ 2l_0 - y_r & \sqrt{3}x_r\end{bmatrix}\begin{bmatrix} i_1\\ i_2\end{bmatrix} \tag{8}$$

where (x_r, y_r) are rotor position co-ordinates, l_o the nominal air gap (mm), $Z = 4l_0^2 - (x_r^2 + y_r^2)$ is always positive since (mm) $(x_r^2 + y_r^2) \leq l_0$. The determinant of the matrix $\sqrt{3}/Z$ is non-zero [8] and hence $(\overline{\emptyset}_1, \overline{\emptyset}_2)$ and (i_1, i_2) have bijective correspondence.

The dynamics equations of motion for the 3-pole AMB with simple disc like rotor are given by,

$$m\ddot{x}_r = f_x \text{ and } m\ddot{y}_r = f_y - mg \tag{9}$$

Where m is the mass of the rotor (kg) and g is the acceleration due to gravity (m/s^2). At the steady state, i.e. when the rotor is at the center $(x_r, y_r) = (0,0)$ and the air gap reluctances are hence equal to the nominal values, then

$$f_x = 0 \text{ and } f_y \equiv mg \tag{10}$$

Thus, the coil currents at the steady state will be current i_{10} and i_{20} are

$$i_{20} = l_0\sqrt{2mg/\gamma} \quad \text{and} \quad i_{10} = 0 \tag{11}$$

Now defining the states of the system as $x_1 = x_r, x_2 = \dot{x}_r, x_3 = y_r, x_4 = \dot{y}_r$ and the state space model is given by

$$\dot{x} = f(x,i) = \begin{bmatrix} x_2\\ c_0\overline{\emptyset}_1\overline{\emptyset}_2\\ x_4\\ 0.5c_0(\overline{\emptyset}_1^2 - \overline{\emptyset}_2^2) - g\end{bmatrix} \tag{12}$$

where $c_o = 4\gamma/3m$, $x = [x_1 \quad x_2 \quad x_3 \quad x_4]^T$ and $i = [i_1 \quad i_2]^T$.

3. SLIDING MODE CONTROL WITH GLOBAL INVARIANCE

3.1 Design preliminaries

For the design of the sliding mode controller [15]-[19], consider the general nonlinear system,

$$\dot{x} = f(x,t) + \Delta f(x,t) + [g(x,t) + \Delta g(x,t)]u + d(t)$$
$$y = h(x,u,t) \tag{13}$$

where $\in R^n$, the state vector and $u \in R^m$, $y \in R^m$, are the input and the output vectors respectively where $m \leq n$. $f: R^n \rightarrow R^n$, $h: R^n \rightarrow R^m$ are nonlinear vector fields , $g: R^n \rightarrow R^m$, is the nonlinear input gain matrix, $\Delta f, \Delta g$ are the uncertainties present in the model, which are continuously differentiable. $d \in R^n$ a continuous disturbance vector.

If an explicit relationship between the output y_i and the control input u can be established by differentiating y_i at least r_i times [19], that is,

$$L_g L_f^q h(x) = 0, for\ all\ q < r_i - 1$$
$$L_g L_f^{r_i-1} h(x) \neq 0 \tag{14}$$

Where, L represents the Lie derivative and r_i is the relative degree. Then the system is standardized considering $\sigma_{i1}, i = 1,2 \dots m$ outputs due to functional output controllability and the relative degree r_i for each output σ_{i1} is calculated. The standardized state space dynamic equations can be formulated using the feedback linearization technique and the concept of extended systems.

$$\dot{\sigma}_{ij} = \sigma_{ij+1},$$
$$\dot{\sigma}_{i(r_i+1)} = \frac{d}{dt}\left(L_f^{r_i} h(x) + L_g L_f^{r_i-1} h(x) u(t)\right) \tag{15}$$

Where, $j = 1,2 \dots r_i - 1$ and $i = 1,2..m \leq n$. The controllable canonical form system equations may have the order less than that of original systems. In those cases, the stability of the internal dynamics should be checked. If it is not internally stable, the order of the standardized equation should be incremented or the concerned outputs should be altered.

3.2 Sliding surface design

The sliding surface for the extended system in the proposed controller technique is given by,

$$S_i = \sigma_{ir_i+1} - \sigma_{ir_i+1}(0) + \int_0^t \sum_{j=1}^{r_i+1} k_i \sigma_{ij}\, dt = 0 \tag{16}$$

where $\sigma_{ir_i+1}(0)$ is the initial value of σ_{ir_i+1}. The equation can be reformulated as,

$$\dot{\sigma}_{ir_i+1} = -\sum_{j=1}^{r_i+1} k_i \sigma_{ij} \tag{17}$$

The sliding mode dynamics can be framed in matrix form as

$$\dot{\sigma}_i = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \vdots & \vdots & \ddots & \vdots \\ -k_{i1} & -k_{i2} \dots & \dots & -k_{i(r_i+1)} \end{bmatrix} \sigma_i = A_i \sigma_i \tag{18}$$

with k_{ij} are designed by the system performance specifications or eigen values of A such that Eq.(17) is Hurwitz.

3.3 Associated control law synthesis

The reaching law is chosen as,

$$\dot{S} = -\eta * sgn(S)$$

where sgn(•) is the sign function and the switching gain $\eta > 0$ is determined on the basis of the system robustness and required performances, such that the sliding condition is satisfied and the sliding mode motion is reached. The control law can be synthesized using,

$$\frac{d}{dt}\left(L_f^{r_i}h(x)+L_gL_f^{r_i-1}h(x)u(t)\right) = \eta * sgn(S) + y_d^{r_i} + \sum_{j=1}^{r_i+1} k_i\sigma_{ij} \tag{20}$$

so that

$$u(t) = \left(L_gL_f^{r_i-1}h(x)\right)^{-1}(y_d^{r_i} - y_d^{r_i}(0) - L_f^{r_i}h(x)) + \int_0^t \left(\sum_{j=1}^{r_i+1} k_i\sigma_{ij} + \eta * sgn(S)\right)dt \tag{21}$$

3.4 Design Features

(1) *Global Invariance* - The sliding surface is constructed so that the initial state itself falls on the sliding surface, by eq. (16). For chosen dynamics of sliding mode motion, the states will converge to zero exponentially. With the proposed control law, the sliding phase motion will occur immediately and the invariance property will always hold [19].

(2) *Chattering Reduction* - A continuous control input can be obtained from eq. (21), using the extended sliding mode control design scheme, resulting in a reasonably smooth system output response [19].

4. CONTROLLER DESIGN FOR THREE POLE AMB

4.1 Feedback Linearization

The preliminary step in the controller design is to find a state feedback $i = \Psi(x,\tilde{\imath})$ so that the closed loop system given by

$$\dot{x} = f(x,\Psi(x,\tilde{\imath})) = Ax + B\tilde{\imath} \tag{22}$$

where the pair (A,B) is controllable and $\tilde{\boldsymbol{\imath}}$ denotes the vector of new inputs. Although the modeled AMB system is a non-affine nonlinear system, there exists a bijective relation between $(\overline{\emptyset}_1,\overline{\emptyset}_2)$ and $(\tilde{\imath}_1,\tilde{\imath}_2)$ and hence the system can be linearized [17]. Defining $(\tilde{\imath}_1,\tilde{\imath}_2)$ as virtual inputs

$$\boldsymbol{c_0\overline{\emptyset}_1\overline{\emptyset}_2 = \tilde{\imath}_1}$$

$$0.5c_0(\overline{\emptyset}_1^2 - \overline{\emptyset}_2^2) - g = \tilde{\imath}_2 \tag{23}$$

Solving eq. (23) yields

$$\begin{bmatrix}\overline{\emptyset}_1\\ \overline{\emptyset}_2\end{bmatrix} = \frac{1}{\sqrt{c_0}} \times \begin{bmatrix}\sqrt{(\tilde{\imath}_2+g)+\sqrt{(\tilde{\imath}_2+g)^2+(\tilde{\imath}_1)^2}}\\ \sqrt{-(\tilde{\imath}_2+g)+\sqrt{(\tilde{\imath}_2+g)^2+(\tilde{\imath}_1)^2}}\end{bmatrix} \tag{24}$$

where $\tilde{\boldsymbol{\imath}} = [\tilde{\imath}_1,\tilde{\imath}_2]^T$ are the linearizing inputs in feedback. The physical system is always a nominal system with bounded uncertain part. The system model could be adapted as,

$$\dot{x} = f(x,\Psi(x,\tilde{\boldsymbol{\imath}}),t) + \Delta f(x,\Psi(x,\tilde{\boldsymbol{\imath}}),t) = Ax + B(\tilde{\imath} + \Delta(x,\tilde{\imath})) \tag{25}$$

where $f(x, \Psi(x, \tilde{\imath}), t)$ and $\Delta f(x, \Psi(x, \tilde{\imath}), t)$ represents the nominal part and the uncertainty part respectively. The primary task of the controller is to maintain the rotor disc at the projected center of AMB at (0,0) position inspite of uncertainities. The controller is required to keep the variations of the AMB inside the domain of interest, from the physical constraints is defined as within the limit of $\pm 0.5 \times 10^{-3}$mm.

$$D = \{x \in R^4; |x_1^2 + x_3^2| \le \left(\frac{i_0^2}{4}\right) \& \, x_2^2 + x_4^2 \le \frac{\omega l_0^2}{2}\} \tag{26}$$

The uncertainties can be coined as,

$$\Delta(x, \tilde{\imath}) = \begin{bmatrix} (c_0 \overline{\emptyset}_1 \overline{\emptyset}_2) - \tilde{\imath}_1 \\ (0.5c_0(\overline{\emptyset}_1^2 - \overline{\emptyset}_2^2) - g) - \tilde{\imath}_2 \end{bmatrix} \tag{27}$$

The perturbed linearized system could be redefined as:

$$\dot{x} = \begin{bmatrix} x_2 \\ \tilde{\imath}_1 + \delta f_x \\ x_4 \\ \tilde{\imath}_2 + \delta f_y \end{bmatrix} \tag{28}$$

Now $d = \left[\delta f_x, \delta f_y\right]^T$ is coined as disturbances.

4.2 Extended Sliding Mode Controller Design

Defining the new system states as, $[\sigma_{11}, \sigma_{12}, \sigma_{13}, \sigma_{21}, \sigma_{22}, \sigma_{23}]^T = \left[x_1, x_2, \dot{x}_2, x_3, x_{4,} \dot{x}_4\right]^T$ the controllable canonical form is given by

$$\begin{aligned} \dot{\sigma}_{11} &= \sigma_{12} \\ \dot{\sigma}_{12} &= \sigma_{13} \\ \dot{\sigma}_{13} &= \dot{\tilde{\imath}}_1 + \delta \dot{f}_x + \dot{d}_1 \\ \dot{\sigma}_{21} &= \sigma_{22} \\ \dot{\sigma}_{22} &= \sigma_{23} \\ \dot{\sigma}_{23} &= \dot{\tilde{\imath}}_2 + \delta \dot{f}_v + \dot{d}_2 \end{aligned} \tag{29}$$

The desired states are represented by $(\tilde{x}_{1d}, \tilde{x}_{3d})$. Then error states in x direction can be defined as in eq.(30). The vertical error states can be also defined similarlv.

$$\begin{aligned} \dot{e}_{11} &= \sigma_{12} - \dot{\tilde{x}}_{1d} \\ \dot{e}_{12} &= \sigma_{13} - \ddot{\tilde{x}}_{1d} = \tilde{\imath}_1 + \delta f_x + d_1 - \ddot{\tilde{x}}_{1d} \\ \dot{e}_{13} &= \dot{\sigma}_{13} - \dddot{\tilde{x}}_{1d} = \dot{\tilde{\imath}}_1 + \delta \dot{f}_x + \dot{d}_1 - \dddot{\tilde{x}}_{1d} \end{aligned} \tag{30}$$

Designing the sliding surface as defined in Eq.(16) for dynamics in x direction,

$$S_1 = e_{13} - \dddot{\tilde{x}}_{1d}(0) + \int_0^t (k_{11}e_{11} + k_{12}e_{12} + k_{13}e_{13})\, dt \tag{31}$$

The resulting control input can be obtained as,

$$\dot{\tilde{\imath}}_1 = -\dot{d}_1 - W_1 sgn(S_1) - (k_{11}e_{11} + k_{12}e_{12} + k_{13}e_{13}) + \dddot{\tilde{x}}_1 \tag{32}$$

The system dynamics in sliding motion is achieved as,

$$\begin{aligned}
\dot{\sigma}_{11} &= \sigma_{12} \\
\dot{\sigma}_{12} &= \sigma_{13} \\
\dot{\sigma}_{13} &= -W_1 sgn(S_1) + \dddot{\tilde{x}}_1 - (k_{11}e_{11} + k_{12}e_{12} + k_{13}e_{13}) + \dot{d}_1 \\
\dot{\sigma}_{21} &= \sigma_{22} \\
\dot{\sigma}_{22} &= \sigma_{23} \\
\dot{\sigma}_{23} &= -W_2 sgn(S_2) + \dddot{\tilde{x}}_3 - (k_{21}e_{21} + k_{22}e_{22} + k_{23}e_{23}) + \dot{d}_2
\end{aligned} \tag{33}$$

4.3 Robust Stability Analysis

Let the choice of candidate Lyapunov function of the system be $V = \frac{1}{2}S^T S$, and then $\dot{V} \leq 0$ can be ensured by proper choice of η. i.e, for the horizontal dynamics

$$\dot{V}_1 = S_1{}^T\left[\dot{\sigma}_{13} + \sum_{j=1}^{3} k_i \sigma_{1j}\right] = S_1{}^T\left[-\frac{d}{dt}(\Delta(x,\tilde{\imath})) - \eta * sgn(S)\right] \leq \left(\left|\frac{d}{dt}(\Delta(x,\tilde{\imath}))\right| - \eta\right)|S_1| \tag{34}$$

Hence choosing the switching gain η larger enough than the uncertainties, ensure that the first derivative of the Lyapunov function *V* with respect to time is certainly negative.

5. SIMULATION ANALYSIS AND VALIDATION OF THE CONTROLLER

The initial states are $(x_1 = 0, x_2 = 0, x_3 = 0, x_4 = 0)$ and the desired controlled states are given as $(\tilde{x}_{1d} = 0, \tilde{x}_{2d} = 0, \tilde{x}_{3d} = 0, \tilde{x}_{4d} = 0)$. Fourth order Runga-Kutta method is used for numerical analysis. The eigen values for critical damping response, corresponding to the Hurwitz polynomial or the sliding surface are fixed as [-6.5, -5.5, -5]. The switching gains are fixed as $W_1 = 10$ and $W_2 = 10$.

The simulation analysis is conducted on three pole AMB bearing with system parameters as in Table I

Table 1

Simulation parameters

Parameters	*Symbol*	*Value*	*Unit*
Mass	m	0.556	kg
Nominal Air Gap	l_0	2×10^{-3}	m
Clearance between Auxiliary bearing and Shaft	¼ l_0	0.5×10^{-3}	m
Pole Face Area	A	4×10^{-4}	m^2
Acceleration due to gravity	g	9.81	m/s^2
No. of Turns in coil	N	300	
Magnetic Permeability of airgap	μ	$4\pi\times10^{-7}$	H/m
Bias current	i_{20}	1.8	A

Since the system is open loop unstable, feedback controllers are to be implemented by default. Fig.4 indicates the nominal response of the system. The simulation response of the system for the normal running conditions with sliding mode controller is equivalent to the nominal response of the AMB with state feedback controllers implemented for the given pole locations. The rotor, in the beginning is at rest on the auxiliary bearings (0,-0.5mm) and then it traces its position to (0, 0), with rise time: 0.5646 s, settling time: 0.982, and minimal overshoot.

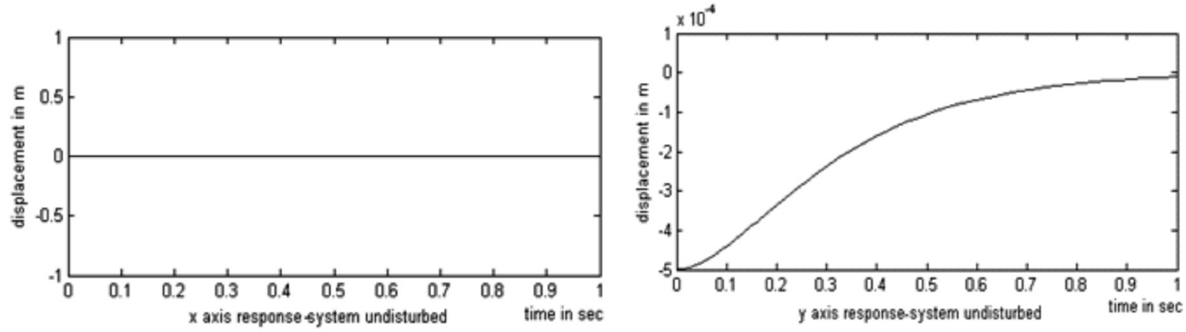

Figure 4: The displacement of rotor of undisturbed AMB with sliding mode controller in horizontal and vertical directions respectively

The simulation response of the system for the perturbed conditions is compared with the response of state feedback controlled system. The disturbance vector is as a vector of periodical signals with known bounds, and is given by . The initial condition is (0,-0.0005) and the response is shown in Fig. 5.

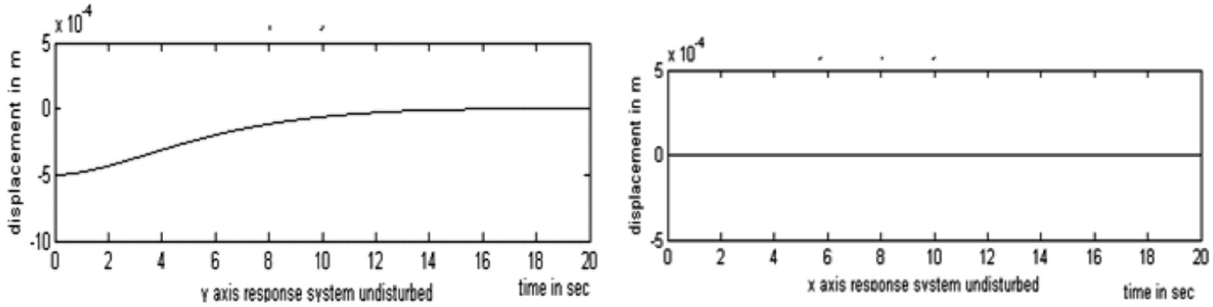

Figure 5: The displacement of rotor of perturbed AMB system with sliding mode controller in vertical and horizontal directions respectively

The response of the system has considerable reduction chattering which is often present in regular sliding mode controllers and the system response falls into the sliding surface specifications instantaneously thereby wearying the time spend in reaching phase to a large extent. The proposed sliding mode controller pushes the system into the sliding surface designed for the specifications as soon as the control input is switched on.

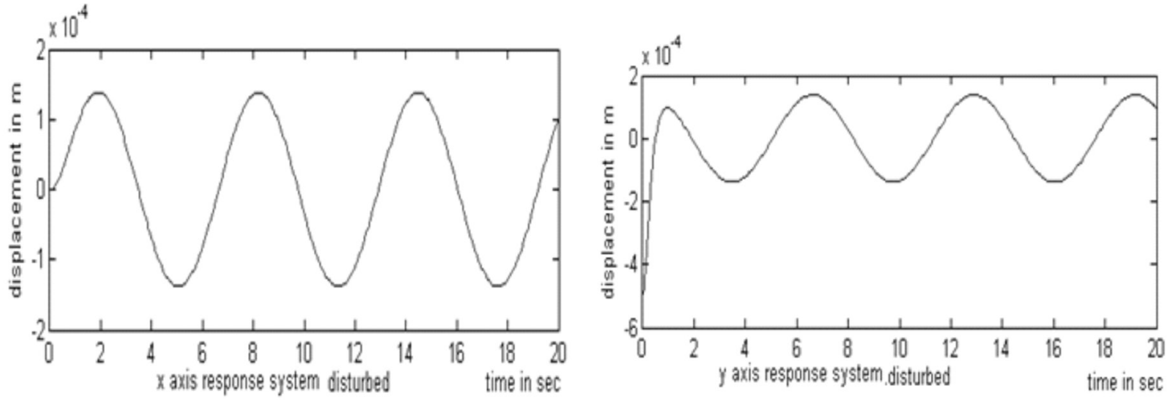

Figure 6: The response of state feedback controlled system with perturbations in horizontal and vertical directions respectively

The performance of the proposed controller is compared with state feedback controller designed for the same system specifications, i.e., to minimize the position error less than 0.01mm. and the velocity error and the position error converge within 2 seconds. Fig.6 shows the response of the state feedback controlled AMB system. Comparison of the responses Fig.5 and Fig. 6 clearly indicates that the proposed controller is superior in handling disturbances.

The extended sliding mode controller shows a critically damped response without any sort of overshoot or oscillations despite of the perturbations given to the system, but the settling time lags from that specified. The state feedback controller response for a perturbed condition is oscillatory and the amplitude of oscillations are considerably large. But the system settles within 2sec, which is desired.

A continuous control input, the coil current i_2 for both the normal AMB system and perturbed system AMB system can be obtained as shown in Fig.7 using the extended sliding mode control design scheme, which results in a reasonably smooth system output response as shown in Fig.5. The magnitude of the control current is within the neighborhood of bias current 1.8A in y direction.

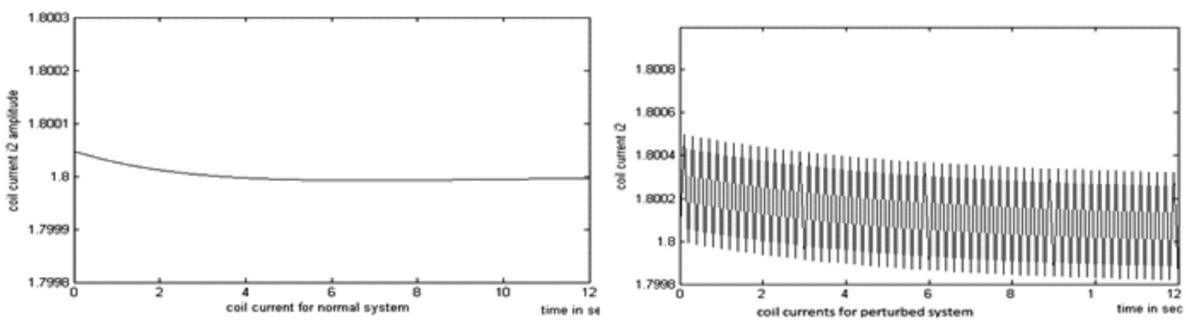

Figure 7: The coil current i_2 generated for sliding mode controller scheme in the normal system and the perturbed system respectively

6. CONCLUSIONS

The three pole AMB is a high speed cost effective and efficient bearing system. The stabilization and control of a nonlinear three pole AMB model is prerequisite for the rotor to give a desired performance. The non-linear, magnetically coupled, current controlled AMB is linearized using feedback linearization. The feedback controllers, *viz.* extended sliding mode and state feedback method, are designed. From the simulation analysis, the extended sliding mode controller has obtained a better error convergence. The discrete time implementation of sliding mode controllers is the future extend of the work.

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