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Nonlinear Adaptive Sliding Mode Control of a Rigid Rotor via Contactless Active Bearing

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***Abstract*—Three-pole Active Magnetic Bearing AMB is a cost-effective method for implementing the principle of magnetic levitation in rotary devices as a bearing support. The nonlinear and unstable nature of three-pole AMB is a challenge for controller design. This study investigates the nonlinear characteristics of three-pole AMB and the design of a sliding mode controller to control AMB dynamics. The system is standardised into extended controllable canonical form, and the controller is designed. The inherent chattering of the sliding mode controller is also addressed with a solution of sliding gain adaptation. The simulation of the controller and the AMB analyses the performance of a system using the proposed controller.**

***Index Terms*—three-pole AMB, mechatronics, output feedback linearisation, extended dynamics, sliding mode control, sliding gain adaptation, adaptive control**

I. Introduction

An Active Magnetic Bearing, AMB system is a bearing system that has a collection of electromagnets that are used to suspend an object. A wide study on the feasibility and application of bearing support by magnetic levitation has been conducted by Earshaw, Schweitzer and many others [1,2]. An AMB system is composed of a floating mechanical rotor and electromagnetic coils that provide the controlled dynamic force and allow the suspended object to move in its predefined functionality [3]. AMB systems have the characteristics of noncontact suspension, wear prevention and long lifespan and do not require lubrication; these factors are essential for high-speed rotating devices. However, all the aforementioned advantages are adversely complemented by the fact that a magnetically suspended rotor system is inherently unstable. Therefore, controllers are necessary for stabilisation and compensating for the effects of system nonlinearity, the eccentricity and flexibility of the rotor and the external disturbances. There are two controller approaches for AMB: current-controlled method and voltage-controlled method [4]. Ref. [5] discusses three classifications of controllers, namely, class A, class B and class C, which depend on the supply scheme of the control current and bias current in the coils of the electromagnet of AMB.

The application of AMB in the industry is hindered by two factors. Firstly, currently available linear controllers are ineffective on the nonlinearities of AMB. To obtain a practical control solution, robust nonlinear controllers are required, but these controllers are inhibited by implementation issues. Given the advancement of studies on nonlinear control theory and the surge of computing and sampling speed in PC/DSP-based control knowledge, nonlinear controllers have become feasible today. Secondly, the high cost required owing to power amplifiers and coils is responsible for the limited use of AMB systems in industry. The possible ways to lower the cost of AMB systems include the use of sensor-less control or the reduction of the number of magnetic poles so that fewer drives will be required. Reducing the number of poles will also leave more spaces for heat transfer, coil winding and sensor installations [6]–[10]. The major disadvantage caused by reducing the number of poles in AMB is the strong nonlinearity due to magnetic flux coupling. Hsu and Chen [7]–[9] proposed nonlinear controllers for both current- and voltage-controlled three-pole AMB systems. The most recent works concentrate on the nonlinear smooth feedback control of AMB systems [10], as well as sliding mode control [12], $H_{infinity}$ control [13] and LQR control [14]. To reduce measurement noise and improve operational performance, Kalman filter–based estimation and state feedback control were proposed [15].

The objective of this work is to study the nonlinear model of three-pole AMB and the associated issues in

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controller design. The nonlinear stabilising controller was obtained by applying the extended sliding mode control method [16]–[18] to the output feedback linearised system. The sliding surface is assigned so that the sliding mode action at the instant control law can be applied. The sliding gain adaptation [19] is advantageous for reducing the task of deciding the proper sliding gain. Thus, an adaptive extended sliding mode controller is proposed as a method to improvise the control effort generated and guarantee a system performance with global invariance.

This paper is organised as follows. Section II discusses the nonlinear and linearised models in the neighbourhood of the projected AMB centre. Section III discusses the design of the extended sliding mode controller for three-pole AMB and an adaptive controller with sliding gain adaptation. Section IV shows the simulation analysis of the three-pole AMB and designed controllers, as well as the results that complement the design.

II. Dynamic Modelling of Three-Pole AMB Systems

Fig. 1 shows the energy-efficient and cost-effective optimal configuration of three-pole AMB proposed by Chen and Hsu [6–8]. Each pole has a surface area *A* and one coil with *N* turns of copper wires. ϕj is the magnetic flux produced in the electromagnetic pole *j*. Magnetic poles #2 and #3 have opposite winding schemes and share the same current amplifier [9]. The vertical position is controlled by coil current i_1, and the horizontal position is maintained by coil current i_2. At the equilibrium point, the control currents are given by the following:

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} \bar{\iota}_1 \\ \bar{\iota}_2 + i_{2B} \end{bmatrix}, \tag{1}$$

where $(\bar{\iota}_1, \bar{\iota}_2)$ refers to the control currents supplied to the actuators.

In analysing the AMB system, the following assumptions are made [12]:

- The coupling effects on vertical and horizontal displacement are neglected.
- The electromagnetic poles have linear magnetic (B-H) characteristics.
- The flux leakage and the fringing effects can be neglected.
- The field density and magnetic flux density are uniformly distributed throughout the core and the gap.
- The attractive forces of the electromagnets are governed by Maxwell's theorem.
- This study considers only the small vibrations that are evident near equilibrium and deliberately neglects torsional and axial vibration effects.

A. Mathematical Modelling of the Magnetic Circuit of AMB

On the basis of the assumptions stated and considering the air gap reluctances in the magnetic circuit diagram, the flux produced at each pole is given by (2), and the relation of air gap reluctance and position coordinates is shown in (3).

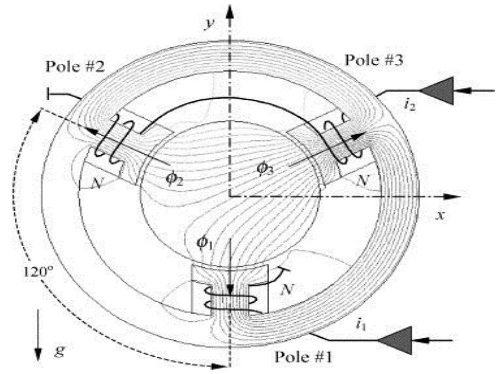

Figure 1. Planar configuration of three-pole AMB and coil currents.

$$\begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \end{bmatrix} = \frac{N}{rL_{tot}} \begin{bmatrix} rL_1 + rL_3 & rL_2 - rL_3 \\ -rL_3 & 2rL_1 + rL_3 \\ -rL_2 & -2rL_1 - rL_2 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}, \tag{2}$$

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

where the number of coil turns is *N*, rL_i, $i = 1, 2, 3$ refers to the air gap reluctances (H^{-1}) existing between the rotor and the magnetic actuator poles, and $rL_{tot} = rL_1\, rL_{2+}\, rL_2\, rL_{3+}\, rL_1\, rL_2$. The variation in the position of the rotor is also reflected in the reluctances.

Substituting the reluctances in Eq. (2) yields (φ_1, φ_2) as a function of (i_1, i_2):

$$\begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \end{bmatrix} = \frac{\gamma}{3Z} \begin{bmatrix} 2(2l_0 - y_r) & 2\sqrt{3}x_r) \\ -2l_0 + \sqrt{3}x_r + y_r & 6l_0 - \sqrt{3}x_r + 3y_r \\ 2l_0 + \sqrt{3}x_r - y_r & 6l_0 + \sqrt{3}x_r + 3y_r \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}, \tag{4}$$

where '$\gamma = 2\mu AN$', (x_r, y_r) refers to the Cartesian coordinates of the rotor position, and l_o is the nominal air gap (mm). $Z = 4l_0^2 - (x_r^2 + y_r^2)$ is always positive because (mm) $(x_r^2 + y_r^2) \leq l_0$.

On the basis of Maxwell's equations, the electromagnetic forces of attraction are given by the following:

$$F = \frac{B^2}{2\mu} A = \frac{\varphi^2}{2\mu A}, \tag{5}$$

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).

According to Fig. 1, the resultant magnetic forces generated can be resolved in both the vertical and horizontal directions and can be stated as follows:

$$f_{mx} = (F_3 - F_2)\cos 30 = \frac{\sqrt{3}}{4\mu A}(\varphi_3^2 - \varphi_2^2), \tag{6}$$

$$f_{my} = (F_3 + F_2)\sin 30 - F_1 = \frac{1}{4\mu A}(\varphi_3^2 + \varphi_2^2 - \varphi_1^2). \tag{7}$$

By substituting Eq. (4) into Eqs. (6) and (7),

$$f_{mx} = 1.5\gamma\big[2x_r(2l_0 - y_r)i_1^2 + 6x_r(2l_0 + y_r)(i_2)^2 + + 2\sqrt{3}Z(4l_0^2 + x_r^2 - y_r^2)(i_1 i_2)\big], \quad (8)$$

$$f_{my} = 1.5\gamma\big[(x_r^2 - (2l_0 - y_r)^2)i_1^2 + 4\sqrt{3}x_r y_r(i_1)(i_2) + 3(2l_0 + y_r)^2 - 3x_r^2(i_2)^2\big]. \quad (9)$$

According to Eqs. (8) and (9), the forces of the three-pole AMB are nonlinear, and the fractional functions of the coil currents and shaft displacements cause the nonlinear coupling of the shaft dynamic equations in the *x* and *y* directions.

B. *The Equations of Motion*

The dynamics equations of motion for a three-pole AMB system with a simple disc-like rotor having two degrees of freedom are given by the following equations:

$$m\ddot{x}_r = f_{mx} \quad (10)$$

$$m\ddot{y}_r = f_{my} - mg, \quad (11)$$

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 centre $(x_r, y_r) = (0,0)$ with no rotation and when the air gap reluctances are equal to the nominal values, the following is obtained:

$$f_{mx} = 0 \text{ and } f_{my} \cong mg. \quad (12)$$

Therefore, the coil currents at the steady state will be current i_{1B} and i_{2B}:

$$i_{2B} = l_0\sqrt{2mg/\gamma} \text{ and } i_{1B} = 0. \quad (13)$$

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

$$\dot{x} = g(x,i) = \frac{1}{m}\begin{bmatrix} mx_2 \\ f_{mx} \\ mx_4 \\ f_{my} - mg \end{bmatrix} \quad (14)$$

where $x = [x_1 \quad x_2 \quad x_3 \quad x_4]^T$ and $i = [i_1 \quad i_2]^T$.

III. Controller Design for Three-Pole AMB

In the process of developing the controller design, the nonlinearities of the magnetic force must be linearised with the system state equilibrium.

A. *System Linearisation*

Considering the relatively small displacement of the rigid disc and the decomposition of the small coil currents into bias and control currents, the magnetic forces can be expanded using Taylor's series expansion and truncated to first-order terms:

$$f_{mx} = \frac{\gamma i_{2B}^2}{2l_0^3} x_r + \frac{\gamma i_{2B}}{\sqrt{3}l_0^2}\bar{\imath}_1 + \Delta f_{mx}, \quad (15)$$

$$f_{my} = \frac{\gamma i_{2B}^2}{2l_0^3} y_r + \frac{\gamma i_{2B}}{\sqrt{3}l_0^2}\bar{\imath}_2 + \Delta f_{my}. \quad (16)$$

The primary task of the controller is to maintain the rotor disc at the projected AMB centre at (0, 0) regardless of the uncertainties. In addition to it, the controller is required to keep the variations in disc displacement inside the AMB within the domain of interest, which is defined by the following:

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

Hence, the linearised system dynamics, along with the bounded disturbances in the input channel, is given by the following:

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ K_{fx} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & K_{fy} & 0 \end{bmatrix} x + \begin{bmatrix} 0 & 0 \\ K_{ix} & 0 \\ 0 & 0 \\ 0 & K_{iy} \end{bmatrix} \bar{\imath} + \begin{bmatrix} 0 \\ d_1 \\ 0 \\ d_2 \end{bmatrix}, \quad (17)$$

where $x \in R^4$ is the state vector, and $\bar{\imath} \in R^2$ is the input vector. The constants ' $K_{fx} = \frac{\gamma i_{2B}^2}{2l_0^3}$, $K_{ix} = \frac{\gamma i_{2B}}{\sqrt{3}l_0^2}$, $K_{fy} = \frac{\gamma i_{2B}^2}{2l_0^3}$, $K_{iy} = \frac{\gamma i_{2B}}{\sqrt{3}l_0^2}$ ' and $d = [0 \ d_1 \ 0 \ d_2]^T$ are coined as disturbances sourced by linearisation, unknown dynamics and parametric uncertainties, which are bounded.

As explained in Ref. [20], the controller design is preceded with the system standardisation in extended controllable canonical form, and the new system states are now $[\sigma_{11}, \sigma_{12}, \sigma_{13}, \sigma_{21}, \sigma_{22}, \sigma_{23}]^T = [x_1, x_2, \dot{x}_2, x_3, x_4, \dot{x}_4]^T$.

$$\begin{aligned} \dot{\sigma}_{11} &= \sigma_{12} \\ \dot{\sigma}_{12} &= \sigma_{13} \\ \dot{\sigma}_{13} &= K_{ix}\dot{\bar{\imath}}_1 + K_{fx}\sigma_{12} + \dot{d}_1 \\ \dot{\sigma}_{21} &= \sigma_{22} \\ \dot{\sigma}_{22} &= \sigma_{23} \\ \dot{\sigma}_{23} &= K_{iy}\dot{\bar{\imath}}_2 + K_{fy}\sigma_{22} + \dot{d}_2. \end{aligned} \quad (18)$$

B. *Extended Sliding Mode Controller Design*

With the extended dynamics of AMB, the inherently nonlinear system is feedback linearised, and the pair (A, B) is controllable and can be decoupled for individual inputs.

The desired position of the rotor at the projected centre of the bearing is represented by $(\tilde{x}_{1d}, \tilde{x}_{3d})$. The error states corresponding to the horizontal displacement of the rotor is given by Eq. (19). The vertical error states can also be defined similarly [18].

$$\begin{aligned} \dot{e}_{11} &= \sigma_{12} - \dot{\tilde{x}}_{1d} \\ \dot{e}_{12} &= \sigma_{13} - \ddot{\tilde{x}}_{1d} = K_{ix}\bar{\imath}_1 + K_{fx}\sigma_{11} + d_1 - \ddot{\tilde{x}}_{1d} \\ \dot{e}_{13} &= \dot{\sigma}_{13} - \dddot{\tilde{x}}_{1d} = K_{ix}\dot{\bar{\imath}}_1 + K_{fx}\sigma_{12} + \dot{d}_1 - \dddot{\tilde{x}}_{1d}. \end{aligned} \quad (19)$$

By designing the sliding surfaces for dynamics in the x direction, the following is obtained:

$$S_1 = e_{13} - \dddot{\tilde{x}}_{1d}(0) + \int_0^t (k_{11}e_{11} + k_{12}e_{12} + k_{13}e_{13})\, dt. \quad (20)$$

The resulting control input can be obtained as follows:

$$\dot{i}_1 = \frac{1}{K_{ix}}\left[-K_{fx}\sigma_{12} - \dot{d}_1 - \eta_1 sgn(S_1) - (k_{11}e_{11} + k_{12}e_{12} + k_{13}e_{13}) + \dddot{\tilde{x}}_1\right]. \quad (21)$$

The system dynamics in sliding motion is achieved as follows:

$$\begin{aligned}\dot{\sigma}_{11} &= \sigma_{12}\\ \dot{\sigma}_{12} &= \sigma_{13}\\ \dot{\sigma}_{13} &= -\eta_1 sgn(S_1) + \dddot{\tilde{x}}_1 - (k_{11}e_{11} + k_{12}e_{12} + k_{13}e_{13}) + \dot{d}_1.\end{aligned} \quad (22)$$

C. Robustness and Stability of System Sliding Dynamics

Let the choice of candidate Lyapunov function of the system be $V = \frac{1}{2}S^T S$. For the horizontal dynamics,

$$\dot{V}_1 = {S_1}^T\left[\dot{\sigma}_{13} + \sum_{j=1}^{3} k_i \sigma_{1j}\right], \quad (23)$$

$$\dot{V}_1 = {S_1}^T\left[-\dot{d}_1 - \eta_1 * sgn(S)\right] \le \left(|\dot{d}_1| - \eta_1\right)|S_1| \le 0 \quad for\ |\dot{d}_1| \ll \eta_1. \quad (24)$$

Therefore, $\dot{V} \le 0$ can be ensured by the proper choice of η.

Hence, by choosing a switching gain η that is larger than the bounded matched uncertainties, the first derivative of the Lyapunov function *V* with respect to time is certainly negative. However, the term $\dot{d}_1$ is not measurable for designing the control input; thus, it is omitted, and the effect is negated by choosing a large enough value of η_1 to ensure stability in the sense of Lyapunov. The stability can also be proved in the vertical dynamics.

D. Proposed Adaptive Extended Sliding Mode Controller

The sliding mode controller in the preceding section gives robust system responses for the modelled dynamics and is equally robust when the unmodelled dynamics are activated. The robustness of the sliding mode controller depends largely on the choice of the switching gain η. Furthermore, a high control effort will be required to maintain the sliding phase. A modification of the control law is proposed to adaptively tune the controller gain imperative to the system uncertainty.

Differentiating the sliding surface in (20) provides the following output:

$$\dot{S}_1 = -\frac{d}{dt}\left(\Delta(x, f_{mx}, i)\right) - \eta * sgn(S), \quad (25)$$

where $\Delta(x, f_{mx}, i)$ is the lumped unbounded uncertainty in the magnetic forces and the parameters. The modified control law is

$$\dot{i}_1 = -\frac{d}{dt}\left(\Delta(x, f_{mx}, i)\right) - \hat{\Lambda}_1 sgn(S_1) - (k_{11}e_{11} + k_{12}e_{12} + k_{13}e_{13}) + \dddot{\tilde{x}}_1, \quad (26)$$

where $\hat{\Lambda}$ is an adjustable gain constant. The first two terms in the summation is the input that takes care of uncertainties, and the remaining terms are nominal system inputs.

The adaptation law is given by the following:

$$\dot{\hat{\Lambda}} = \frac{1}{\beta}|S|, \quad (27)$$

where β is the adaptation gain and is strictly positive, and the adaptation error is $\epsilon_a = \hat{\Lambda} - \Lambda_d$. The convergence of the error to zero, along with attaining the sliding mode, can be obtained by the Lyapunov approach:

$$V = \frac{1}{2}S^T S + \beta\frac{1}{2}\epsilon_a^T \epsilon_a \quad (28)$$

By taking the time derivative along the horizontal dynamics,

$$\dot{V}_1 = {S_1}^T\left[\dot{\sigma}_{13} + \sum_{j=1}^{3} k_i \sigma_{1j}\right] + \beta(\hat{\Lambda}_1 - \Lambda_{1d})\dot{\epsilon_a}, \quad (29)$$

$$\dot{V}_1 = S_1\left(-\frac{d}{dt}\left(\Delta(x, f_{mx}, i)\right) - \hat{\Lambda}_1 sgn(S_1)\right) + \beta(\hat{\Lambda}_1 - \Lambda_{1d})S_1 sgn(S_1). \quad (30)$$

For a finite time convergence,

$$\dot{V}_1 = -\frac{d}{dt}\left(\Delta(x, f_{mx}, i)\right) - \Lambda_{1d}|S_1| < 0. \quad (31)$$

IV. Validation of the Controller

The AMB system is modelled and analysed by simulations. The system parameters are chosen with literature support and are shown in Table I.

TABLE I. Simulation Parameters

	Parameters	*Symbol*	*Value*	*Unit*
1	Mass	m	1.4	Kg
2	Mass eccentricity	ε	$3 * 10^{-4}$	m
3	Nominal air gap	l_0	$2 * 10^{-3}$	m
4	Clearance between the backup bearing and the shaft	¼ l_0	$0.5 * 10^{-3}$	m
5	Acceleration due to gravity	g	9.81	m/s
6	No. of turns in the coil	N	350	
7	Magnetic permeability of air	μ	$4\pi * 10^{-7}$	H/m
8	Pole face area	A	$4.5 * 10^{-4}$	m
9	Bias current	I_0	1.8	A

The analysis considers that the rotor initially at rest on the auxiliary bearings has initial states of '$(x_1 = 0, x_2 = -0.0005, x_3 = 0, x_4 = 0)$', and the desired controlled states are given as '$(\tilde{x}_{1d} = 0, \tilde{x}_{2d} = 0, \tilde{x}_{3d} = 0, \tilde{x}_{4d} = 0)$'. The Eigen values for critical damping response are fixed, and the corresponding Hurwitz polynomial of the sliding surface is generated. The switching gains are initially tuned to $W_1 = 5$ and $W_2 = 5$ for the sliding mode controller with known bounded disturbances. For the normal running conditions and for the given desired pole locations, the sliding mode controller provides the output (Fig. 2). The control effort for the nominal case is given in Fig. 3.

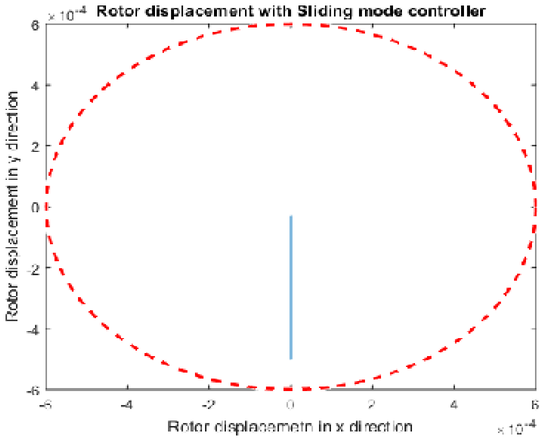

Figure 2. Rotor displacement (m) for a sliding mode controller in the nominal case

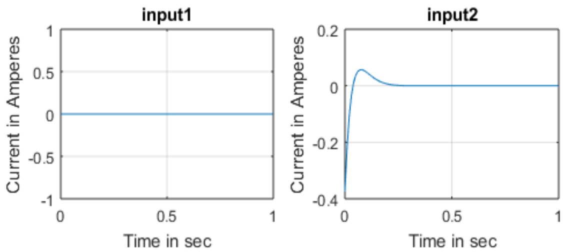

Figure 3. Control currents generated to bring the rotor in position in the normal case.

On the basis of the bounded disturbance in the input channels as $d = 0.0004[\,0\; cos\omega t\; 0\; sin\omega t]^T$ and the given sliding gain, the AMB will trace back to the desired positions with some reservations. The output of the system with a sliding mode controller is superior to that with a linear state feedback controller [18], but the performance highly depends on the chosen gain. An improper gain initiates a delay in settling time and causes unnecessary overshoot.

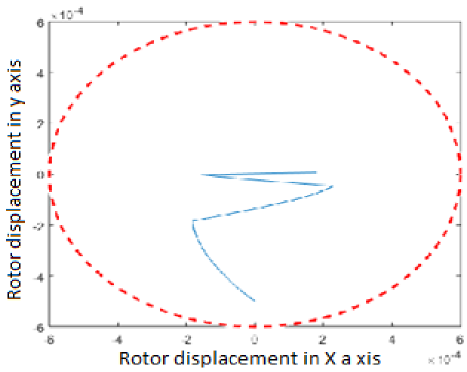

Figure 4. Rotor response to bounded disturbance with a sliding mode controller.

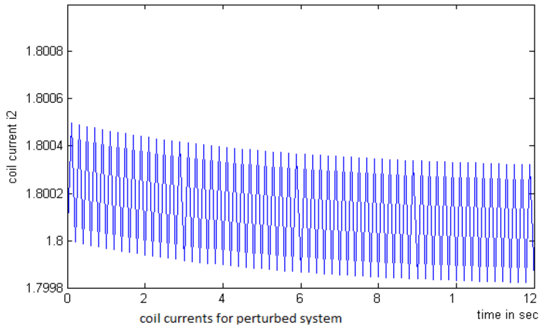

Figure 5. Coil currents in the y axis for tracking the rotor back to the desired position with a sliding mode controller.

Fig. 4 shows the response of a sliding mode controller for bounded disturbance, and Fig. 5 shows the control effort. The frequency in the control effort is a function of the chosen sliding gain. Without knowledge of the bounds, the tuning of the switching gains seems to be tedious. Compensating for very large gain values is a trade-off for system performance.

On the contrary, the proposed adaptive sliding mode controller tunes the required sliding gain automatically. The β value has to be $0 < \beta \leq 1$ to achieve a desirable performance. Figs. 7 and 8 show the AMB centre and the control currents in the vertical direction, respectively. The rate of gain adaptation is shown in Fig. 9 for the bounded case.

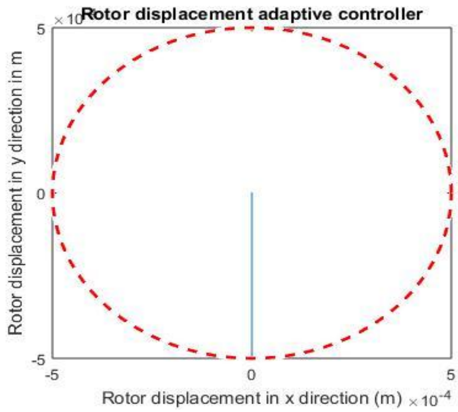

Figure 6. Rotor displacement with an adaptive sliding mode controller for bounded disturbance.

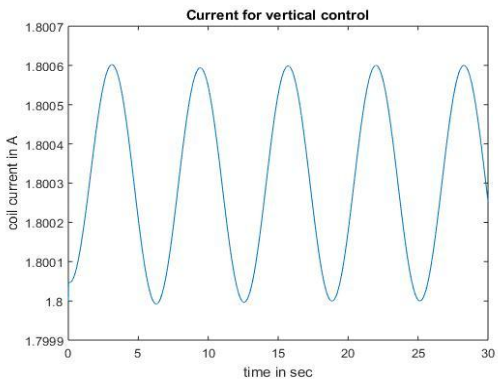

Figure 7. Coil current in vertical axis control for an adaptive sliding controller.

The coil current frequency, which is a function of sliding surface chattering, is low in an adaptive sliding mode controller. The performance of a sliding mode controller with gain adaptation is almost similar to the nominal case. The results confirm that the desired performance specified by the Hurwitz polynomial is achieved with minimal actuator cost in the proposed controller.

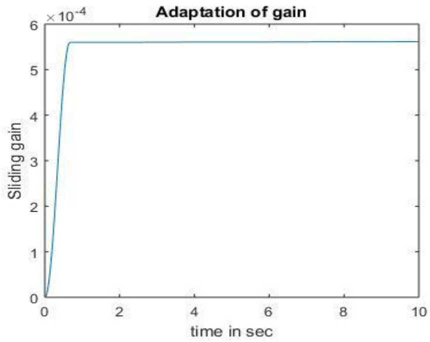

Figure 8. Adaptation of sliding gain for bounded disturbances.

V. Conclusion

The three-pole AMB is an eco-friendly, highly efficient and cost-effective bearing system. From the various models available, a current control model is chosen in this paper. The stabilisation and control of a nonlinear three-pole AMB model is required for the rotor to achieve the desired performance. The highly magnetically coupled nonlinear AMB is linearised using output state feedback linearisation, and the extended sliding mode is designed. The controller design is further improvised with sliding gain adaptation. The adaptive sliding mode controller is advantageous with respect to the control effort realised and the amount of chattering. The sliding mode controller is limited by the known bounds of system uncertainties. Studies should be made to design a sliding mode controller that could tackle unbounded perturbations with minimum cost on actuator effort. Further studies can also be conducted on the modelling and control of a flexible rotor with the proposed controller method.

A detailed modelling of the actuator dynamics and the performance of the controller on the improved system dynamics can be performed in an extended work

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