Experimental Verification of Adaptive Control in Active Magnetic Bearings

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Abstract

The strong nonlinearity and uncertainty of the active magnetic bearing (AMB) makes the controller difficult to design. In many applications the design of the control is performed under the assumption that all system parameters are exactly measured in advance and do not change during operation. For these plants, it is sufficient to design a robust controller for a limited range of operation (Peter Wurmsdobler, 1997). In high performance machinery, however, a change in operation condition may easily occur. This event may lead to destabilizing finally. This paper presents a concept of adaptive control in combination with KALMAN filter, in order to guarantee the optimal control behavior in various operating condition and a desired performance for a wide range of operation. This paper extends this tropic from the former experiment to a test facility with strong nonlinearity / uncertainty and draws a brief comparison to a fixed control design.

Keywords : adaptive control, KALMAN filter, soft computing

1. Introduction

The position controller faces many challenges because AMB systems are multivariable, nonlinear, dynamic and inherently unstable systems. Nonlinear systems with unknown or partially known dynamics can exhibit time-varying behavior. It is no wonder that the existing AMB models were poorly approximated from reality.

An expert system consisting of control laws is able to adjust the controller, to ensure the optimal control behavior. As opposed to a fixed or a robust controller, this concept aims at a wide range of operations area.

This chapter starts with a brief review of AMB system operation and the challenges associated with AMB system control. In magnetic bearing system, the single degree magnetic poles are usually assembled symmetrically. Without regarding the additional current caused by iron hysteresis, the resultant linearized magnetic force generated by this pair of magnet poles will be described as:

$$F = k_{Magnet} \cdot \frac{i^2}{x^2} \Rightarrow k_i \cdot i + k_s \cdot s \tag{1}$$

The transfer function of the rotor behavior is:

$$\frac{x(p)}{i(p)} = \frac{k_i / m}{p^2 - k_s / m} \tag{2}$$

Where m is the mass of the rotor, k_i and k_s are stiffness parameters.

A 1-DOF AMB control system with PD control is normally under consideration. The transfer function of the plant is defined in the Laplace domain and approximated as a spring-masse-system.

$$m_{Rotor} \cdot x \cdot p^2 + k_i \cdot k_d \cdot x \cdot p + \left(k_i \cdot k_p - k_s\right) = 0 \tag{3}$$

Simply note that most applied PD-control of an AMB system with nonlinearity and uncertainty can be attributed to the bellow mentioned system characteristics.

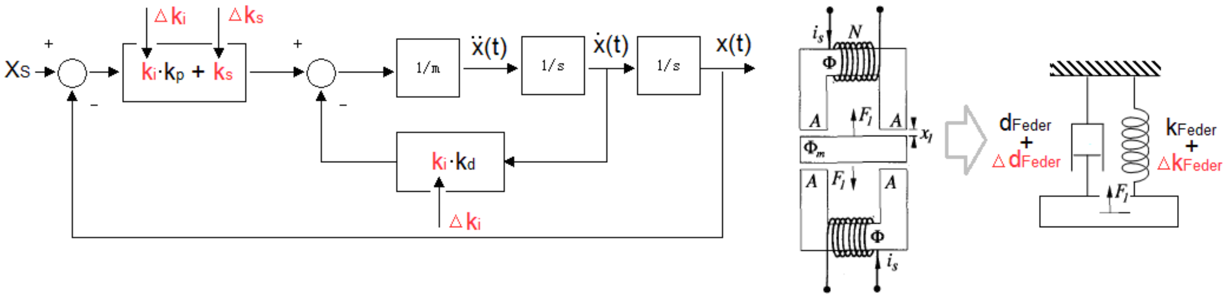


Fig.1 Illustration of the PD regulated closed loop of AMB

In model-based control design methods, the accuracy of the model has the most significant influence on the success of the design. It is therefore crucial to have a high quality model (Angelique Combrinck, 2010).

In the previews works (Dapeng Wang, Fengxiang Wang, 2010) (Heeju Choi, Gregory Buckner, Nathan Gibson, 2006) it overcame the nonlinearity problem of air gap and current for the entire available working area via a fuzzy-logic-based model, and focused on the nonlinear control scheme and provided stability analysis for this scheme. Furthermore, a fuzzy-model-based PID control in works (Sung Kyung Hong, Reza Langari, 2000) (Wang Jun, Zeng Li, 2011) and a fuzzy-model-based state control in works (Sharatul Izah Samsudin, Shahrom Shah Abdullah, 2009) (Sung Kyung Hong, Reza Langari, Joongseon Joh, 1997), are proposed to deal with the difficulty in control with the nonlinearity problem.

In this paper, an adaptive optimal state control of a sensor based active axial magnetic bearing with using a KALMAN filter will be implemented. The basic idea behind adaptive control involves updating a controller using previous achieved control laws. In contrast to the previous relevant works (Li Li, Frank Worlitz 03, 2016), (Li Li, 2015), (Li Li, Wolfgang Kästner, Frank Worlitz, 08,2014), this paper is focused on the experimental verification of this design on a test platform.

2. Test Platform

The MECHATRONICS research group at the IPM made an AMB system with a rotor available for this study. The system serves as AMB of modern high-temperature reactors (HTR) because AMB is considered as a key technology for safety and competitiveness within these concepts. The problem of admitting helium into the lubricants of the bearing would be solved with magnetic bearings. Particularly affected are components which are directly integrated in the helium cycle, e. g. helium compressors. Moreover, the use of magnetic bearings instead of lubricated bearings reduces the amount of flammable mass in safety-relevant facilities. This AMB system is accordingly called the FLP500. (F.Worlitz, M.Gronek, S.Duesterhaupt,1997)

Fig.2 Illustration of the test stand “FLP500”

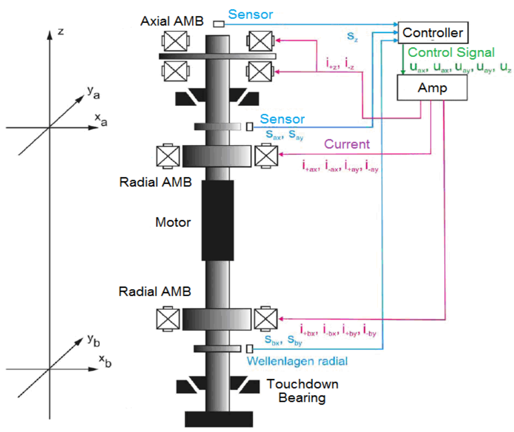
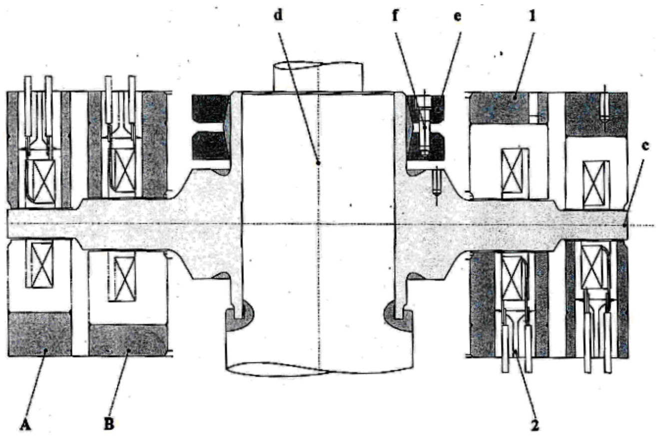


Fig.3 Description of the inside structure of “FLP500”

The system was designed to deliver the magnetic force to levitate a rotor about 1300 kg. The AMBs were designed to suspend the rotor up to an operating speed of 7200 r/min. It employs two radial AMBs and one axial AMB resulting in a 5-DOF system as shown in figure 3.



A...Outside MB, B...Inside MB, 1...Upper Coil,
2...Under Coil, c...Axial Disc, d...Rotor

Fig.4 Inside structure of the axial AMB (R.Hampel, F.Worlitz, A.Doerrer, S.Gaertner, T.Rottenbach, H.Stegemann 1997)

Active magnetic bearings consist of numerous mechanical, electrical and information-processing components which make them an integrated MECHATRONIC product. As can be seen in figure 3, the electronic system consists of the controller, power amplifiers and sensors. The axial and radial suspensions can be considered separately and independently.

The axial bearing (figure 4) consists of the ring coil A and B, which are aligned vertically. Between the ring coils locates the axial bearing disc of rotor. The ring coils are made of Round copper wires with diameter 3.55 mm. The geometric data will be listed.

Table 1 Geometric parameter of the AMB structure
(R.Hampel, F.Worlitz, A.Doerrer, S.Gaertner, T.Rottenbach, H.Stegemann 1997)

Meaning	Value	Meaning	Value
Material of the axial bearing disc	27NiCrMoV155	Air gap upside of bearing disc	$\delta_o = 1.0(\pm 0.05)mm$
Diameter of bearing disc	$d_a = 690mm$ $d_i = 170mm$	Air gap underside of bearing disc	$\delta_u = 1.2(\pm 0.05)mm$
Height of axial bearing	$h_{ges} = 278.5mm$	Thickness of the disc in bearing 1	$h_1 = 32mm$
Height of bearing ring 1 (A, B)	$h = 122mm$	Thickness of the disc in bearing 2	$h_2 = 55mm$
Height of bearing ring 2 (A,B)	$h = 110.5mm$		

To realize the linear relationship between the control signal and the coil current, an amplifier (AMP) with intern current controller, PWM, H-bridge as a switch circuit and current measurement will be constructed as shown in Fig 5. Two opposing actuators each consisting of an axial AMB and AMP are used in this experiment.

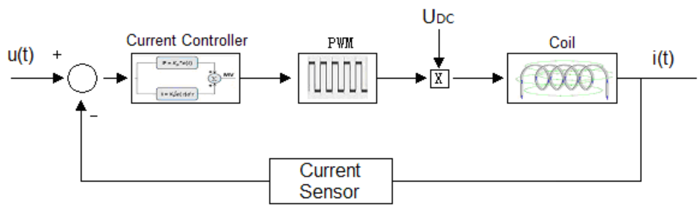


Fig.5 Illustration of the amplifier (AMP) structure

The research and development goals were to improve the control behavior of axial suspension with the help of theoretical and experimental investigations.

3. Adaptive Control Design

An adaptive control concept which allows for the use of actual model information to update the controller parameter is required. A comparison of the various analytical proofs will reveal the most appropriate method.

3.1 Identification of Local Model

The static magnetic force of the bearing “A” and “B” will be illustrated by the characteristic maps F~(i,s). The linearization method of the magnetic force will be used to obtain the necessary data required for implementation of linear local model. The implementation of the various local linear models with using LSM will be described in Fig. Detail can be found in (Li Li, Frank Worlitz, 03, 2016) (Li Li, Wolfgang Kästner, Frank Worlitz, 08,2014).

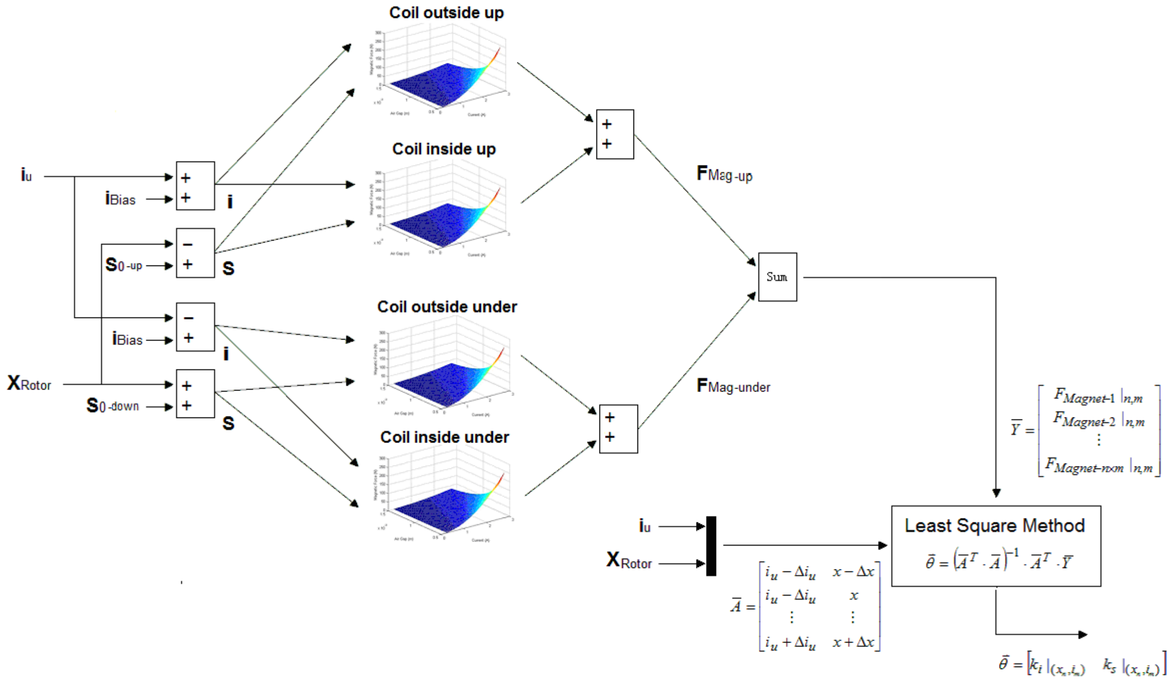


Fig.6 Linearization method of the nonlinear magnetic force

3.2 Design of State Controller

An AMB system requires feedback stabilization because it is open-loop unstable. SISO (single-input single-output) control design methods have been proven to be inadequate even though these methods are easier to implement. The only solution is to use more complex multivariable or MIMO (multiple-input multiple-output) control design methods (Angelique Combrinck, 2010).

Besides the measured object, the state observer captures the remaining state variables. The combination of an optimal state observer with an optimal state feedback regulator is known as LQG-regulator (Th.Schuhmann, W.Hoffmann, R.Werner, 2006 IEEE). The system structure is demonstrated in the figure 9.

The criterion function will be applied to obtain the optimal controller:

$$J = \sum_{k=0}^{\infty} \left(\bar{Y}^T(k) \cdot \bar{Q}_L \cdot \bar{Y}(k) + \bar{U}^T(k) \cdot \bar{R}_L \cdot \bar{U}(k) \right) \tag{4}$$

To calculate the feedback vector K in discrete function, the matrix-valued RICCATI equation will be applied:

$$\bar{A}^T \cdot \bar{P} \cdot \bar{A} - \bar{A}^T \cdot \bar{P} \cdot \bar{B} \cdot \left(\bar{R}_L + \bar{B}^T \cdot \bar{P} \cdot \bar{B} \right)^{-1} \cdot \bar{B}^T \cdot \bar{P} \cdot \bar{A} + \bar{H}^T \cdot \bar{Q}_L \cdot \bar{H} = \bar{P}$$

$$\Rightarrow \bar{U}^{optimal}(k) = \bar{K}_U \cdot \bar{X}(t) = \left(\bar{R}_L + \bar{B}^T \cdot \bar{P} \cdot \bar{B} \right)^{-1} \cdot \bar{B}^T \cdot \bar{P} \cdot \bar{A} \cdot \bar{X}(k) \tag{5}$$

The Q_L und R_L are named as weighing matrices. Detail of setting the matrices could be found in (Th.Schuhmann, W.Hoffmann, R.Werner, 2006 IEEE). Where A, B are system matrix and control matrix. Q_L and R_L are the weighting matrix. P is the RICCATI matrix. K_U is the state feedback vector. X is the state vector.

3.3 Design of Experts System

The two most common techniques used in soft computing are neural networks and fuzzy logic. In particular, this strong nonlinear system can be approximated by a fuzzy logic system with linear local models in logic rule. The logic architecture should have the ability to model the system characteristics as accurately as possible. It uses if-then rule to describe the discrete dynamic model, which presents the linear relation of the input and output with special system matrices $\overline{A}_i$ and $\overline{B}_i$ in each local model:

IF < control current $i_u(k)$ is in class 'm', rotor position $x_{Rotor}(k)$ is in class 'n' >

THEN < the local model is $\overline{X}(k+1) = \overline{A}_i \cdot \overline{X}(k) + \overline{B}_i \cdot \overline{U}(k)$ >

And < the feedback state control is $\overline{U}(k) = \overline{K}_U \cdot \overline{X}(k)$ >

Index $i = 1,2,\cdots,n$ is the number of rules. The special elements in the matrices $\overline{A}_i$ and $\overline{B}_i$, which are associated with the magnetic force, will be defined in LSM - approximation - method. The final output for the control signal is given by the equation below:

$$\overline{U}(k) = \frac{\sum_{i=1}^{n} W_i \cdot \{\overline{K}_{U-i} \cdot \overline{X}(k)\}}{\sum_{i=1}^{n} W_i} \tag{6}$$

Where W_i means the membership grade of the i-te local model.

The Radial-Basis-Function-Neural-Network will implement the logic rule in this approach. The RBFNN is derived from the fuzzy logic which has "if" part in the radial basis function and "then" part in the weighting of node connection. In this application, the input layer receives the data of the actual working point. The hidden layer is a basis function, which can transfer the input data into the weighted membership grade. The output layer is a linear combination for the hidden layer outputs and realizes the defuzzification function. The network uses 2 input nodes, 25 hidden nodes and 1 output node, and the detail implementation is shown in figure.

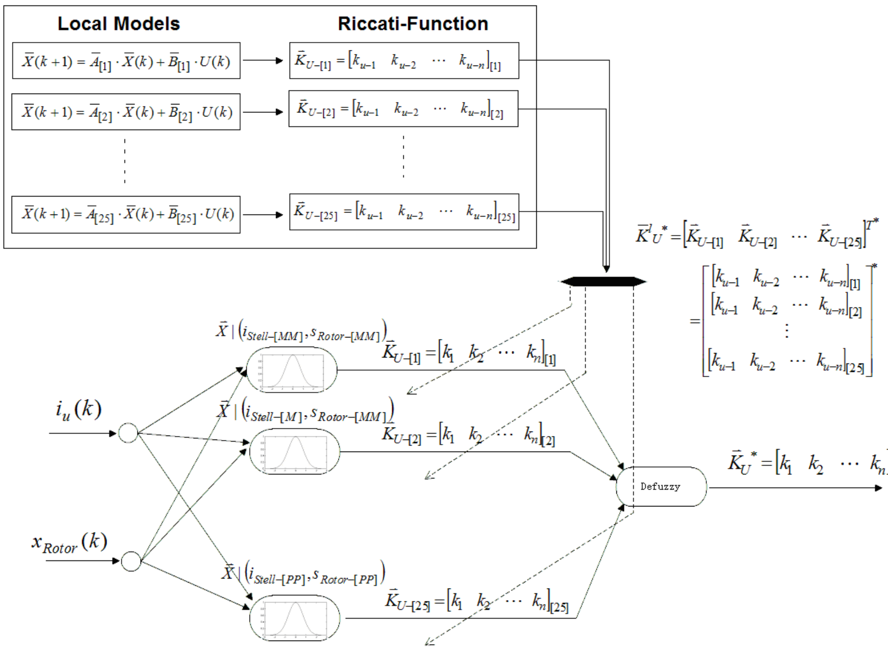


Fig.7 Structure and implementation of RBFNN

Detail for the setting of KALMAN filter for axial position control will be given in (Li Li, Wolfgang Kästner, Frank Worlitz, 08,2014) and (Li Li, 2015).

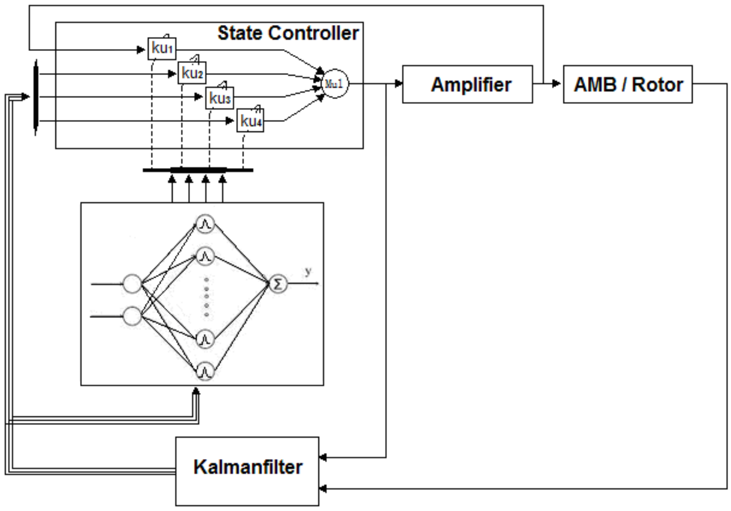


Fig.8 Closed control loop with KALMAN filter and adaptive state controller

4. Experiments and Result

This chapter contains the implementation and experimental results of the chosen adaptive controller. The stability analysis results are presented first. Performance verification continues with robustness and stability analysis.

4.1 Stability and Robust Analysis

The stability and the dynamic behavior of the adaptive controlled system will be determined. This will provide a way of verifying the performance of the adaptive control system. The eigenvalues of the regulated state equation are negative

$\lambda_1 = -3.6513 \cdot 10^4$, $\lambda_2 = -0.0041 \cdot 10^4$, $\lambda_3 = -0.0342 \cdot 10^4$

The equilibrium of a state regulated system is asymptotically stable in the large if there exists a common positive definite HERMITIAN matrix P such that:

$$(\overline{A} - \overline{B} \cdot \vec{K}_{UI})^T \cdot \overline{P} + \overline{P} \cdot (\overline{A} - \overline{B} \cdot K_{UI}) = -\overline{Q} \tag{7}$$

The LYAPUNOV matrix P for this state-regulated system is a positive defined matrix:

$$\overline{P} = \begin{bmatrix} 5.6006 \cdot 10^6 & 2.2770 \cdot 10^4 & 0.9812 \\ 2.2770 \cdot 10^4 & 101.3294 & 0.0035 \\ 0.9812 & 0.0035 & 1.3753 \cdot 10^{-5} \end{bmatrix}$$

with $|p_{1,1}| = 5.6006 \cdot 10^6 > 0$, and determinant of LYAPUNOV matrix $\det(P) = 664.3419 > 0$.

The closed loop poles must be located at a prescribed region in the open left half plane. The root locus is with negative pole ($d_1 = -404.4839$, $d_2 = -3.0867$).

The reference transfer function of the PD regulated rotor dynamic can be calculated as a spring-masse-system:

$$p^2 + 2 \cdot \xi \cdot \omega_n \cdot p + \omega_n{}^2 = 0 \tag{8}$$

with the relation between the eigenfrequency (natural frequency) ω_n and the damping factor ξ respectively. The eigenvalues of the spring-mass-system are: $\lambda_1 = -61.0702$ and $\lambda_2 = -20.4439$, which means a over critically damped system.

4.2 Result

Performance verification enables a comparison between the adaptive state control concept and original PID control concept. The verification consists of step response, robustness analysis and stability analysis. Standard performance defined in terms of the step response includes: percentage of overshoot (P.O.) and settling time (Ts).

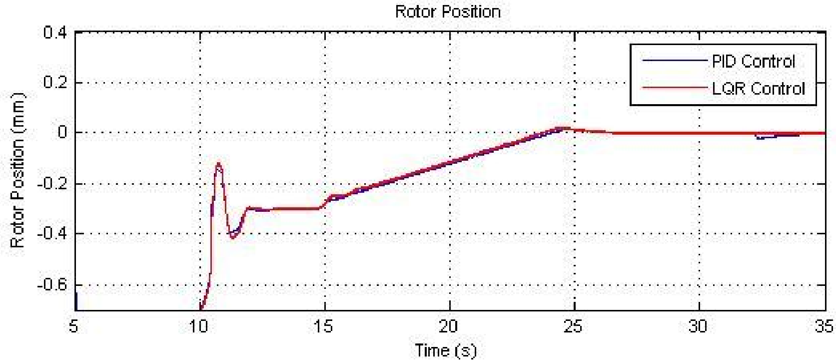


Fig.9 Comparison of step response

Figure 10 shows the experimental results when a component hits once the rotor. As observed, the proposed method is robust against disturbance, and able to reduce the maximal displacement of rotor remarkably.

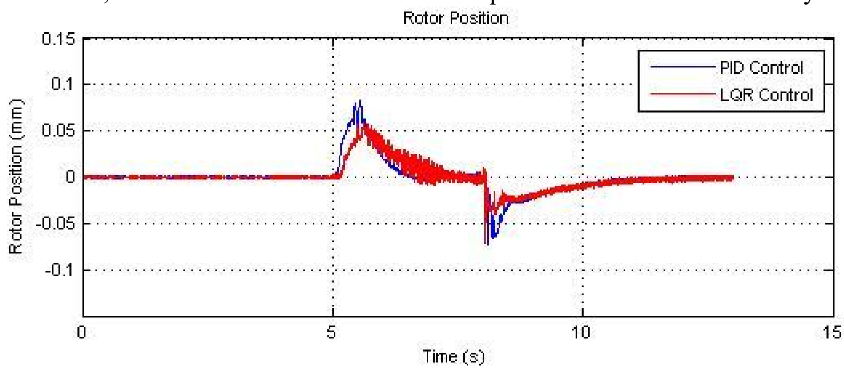


Fig.10 Comparison of disturbance performance

Figure 11 and 12 display the frequency response and normal distribution of the coil current. The proposed KALMAN filter is applied to reduce the fluctuation, amplitude and distribution of the control current.

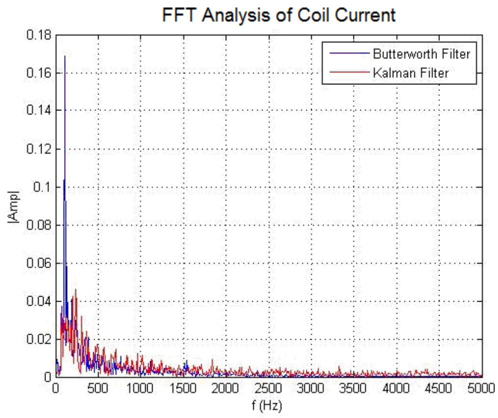


Fig.11 FFT analysis of the coil current

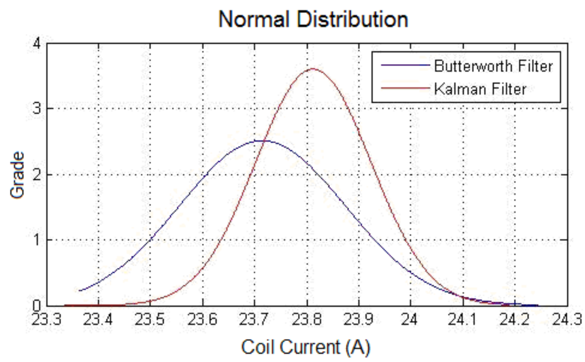


Fig. 12 Normal distribution of the coil current

5. Conclusion

In this paper, a fuzzy model based state control scheme is proposed to overcome nonlinearity, uncertainty, maximize the stable operation region and reduce the signal noise. Finally, experimental results showed that the adaptive state controller proposed in this paper yields not only maximized stability boundary but also better performance and response than a traditional fixed designed controller.

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