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Improvement of Operational Performance of Active Magnetic Bearing using Nonlinear LQG Controller

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***Abstract* -Active Magnetic Bearing provides a means of supporting the body by magnetic forces without physical contact. Active magnetic bearings are inherently unstable systems due to the indirect proportionality between the attractive force and the length of the air gap. Thus, to stabilize the rotor position, a closed-loop control has to be implemented. The aim of this paper is to design a LQG controller and a nonlinear LQG controller to control the position of rotating shaft. First AMB is modeled using mathematical equations. LQG controller is a combination of Linear Quadratic Regulator (LQR) and Kalman Filter which is an optimal estimator.Extended Kalman Filter (EKF) is an extension of LQG which can be applied to nonlinear systems. It itself linearizes the model about an operating point. Using these controllers the magnetic bearing is capable to maintain the rotor position and in turn maintain the position of shaft connected to it.The performance of system with each controller is compared. This can be implemented using MATLAB/SIMULINK software.**

IndexTerms:- Nonlinearity,tracking,KalmanFilter,Extended Kalman Filter.

I.INTRODUCTION

Now a days application of Active Magnetic Bearings (AMB) are increasing and there is a wide tremendous increase in the application and usage of these. AMB's are now used in various application such as Turbo molecular pumps, Blood pumps, Epitaxy centrifuges, Contact free linear guides,Variable speed spindles, Pipeline compressor etc. Its operation is based on the suitable utilisation of magnetic forces that are acting on the system. But during the operation, they undergo various disadvantages such as in high temperature areas they cannot withstand and they will get wear easily and need to often change them. In vacuum also normal bearing cannot perform since vacuum may suck air out from the place which means that the oil from the air will get suck out and thus the friction between the moving and the stationary part will increase. Moreover they are highly unstable due to the indirective proportionality between attractive force and air gap. To overcome these situations suitable controllers are to be used to control the rotor position of AMB's and thus a closed loop system is obtained. Thus they include so many advantages such as it will give best solution to attain zero friction and thus to achieve contactless operation, they can operate in high speed, high efficiency and with less noise and low maintenance cost. They have the ability to compensate the unbalanced forces that are acting on the system and provide indications about changes in shaft dynamics with low vibrational level. Magnetic properties of the materials used are highly resistive or immune to changes in temperature, pressure, and the presence of chemicals, further reasons for use in extreme conditions and highly sensitive applications [3].

There are many controllers that can be used to track the rotor position to the symmetrical position. Conventional Proportional Integral Derivative (PID) controller can be used [1]. But they require information about more than one measurable system state which is usually the rotor position and the use of sensors will complicate the system and it will not be able to track the system even in the presence of disturbances.
Thus in the literature a variety of different solutions are found out. They include Linear Quadratic Gaussian Controller (LQR). It will provide better performance when compared to conventional PID controller but they do not possess the ability of disturbance rejection. Then Linear Quadratic Gaussian Controller is used which is a combination of LQR controller and an observer. It possess disturbance rejection capability and the rotor will be able to maintain the position even in the presence of disturbances. LQR and LQG controller can be used only in linear systems. But here the AMB system is highly nonlinear so we have to linearise the system to apply these controllers. To implement the controller in nonlinear system itself, we use Nonlinear LQG controller. Here the observer used is extended Kalman Filter. It is not an optimal controller like LQG.The response of these controllers on controlling rotor position is estimated in this paper.

II.ACTIVE MAGNETIC BEARING MODELING

Active Magnetic Bearing consists of Stator and rotor and air gap as its main parts. Stator comprises of electromagnet usually made of a stack of laminations with copper coils wound around the north and south poles. A current is applied to each coil to produce attractive forces on laminated iron rotor parts so to levitate the shaft inside the bearing. The clearance or magnetic air-gap between the stator and the rotor is 0.5 to 1.0 mm, depending on the application, thus there is no contact friction, no component wear and no lubrication required [2].

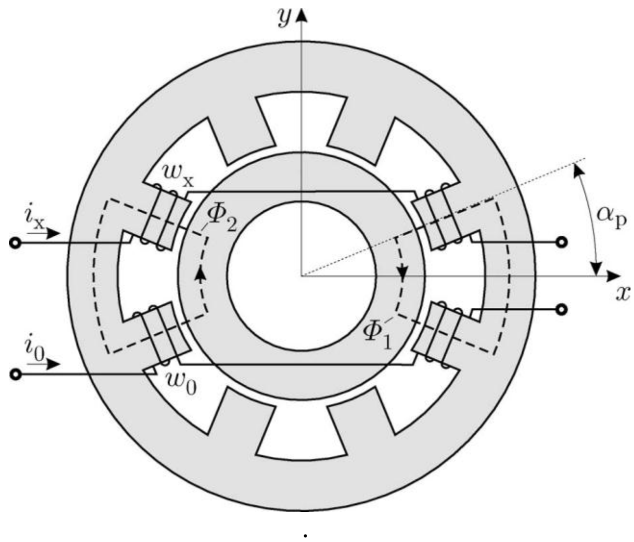

Fig 1: Constructional details of eight pole heteropolar radial active magnetic bearing.

Where $i_0$the exciting current is i_c is the controlling current is the air gap distance,d_0 is the air gap when the rotor is placed in the symmetric axis,$\propto_p$ is the pole angle. Ap is the area of one pole,w_0 no of turns of exciting winding and w_x is no of turns of the control winding.

Magnetic force acting on the system force is directly proportional to square of current supplied to stator and inversely proportional to square of air gap distance.

The state space variables defined are radial rotor position, delayed rotor velocity, delayed rotor position, control current, unbalanced force equation. The equations can be represented as given below [4]

The radial rotor position is refered to radial rotor velocity as

$$\dot{x} = v \tag{1}$$

Radial acceleration caused due to magnetic force acting on the system is given by

$$\mathrm{m}\frac{dv}{dt} = f_{mag}(i_x, x) + f_z \tag{2}$$

For generating desired control current power amplifier is used. The power amplifier will provide an output current which is constant and proportional to the input control voltage.

The Transfer function between reference current and control current is given by

$$T_a\frac{di_x}{dt} + i_x = K_a \tag{3}$$

There may be some measurement delay due to delayed rotor position. It will be taken as the fourth state x_d

$$T_{mx}\frac{dx_d}{dt} + x_d = x \tag{4}$$

Undisturbed forces that are acting on the system should be zero,hence

$$\frac{df_z}{dt} = 0 \tag{5}$$

The nonlinear magnetic force acting on the system is given by

$$f_{mag}(i_x, x) = \frac{1}{4}\mu_0 A_p \cos\alpha_p \left[\frac{(w_0 i_0 + w_x i_x)^2}{(d_0 - x\cos\propto_p)^2} - \frac{(w_0 i_0 - w_x i_x)^2}{(d_0 + x\cos\propto_p)^2}\right] \tag{6}$$

The given system is highly nonlinear and have to linearise the system about an operating point and to do so, the effects of position and current on the magnetic force should evaluated independently. With constant current dependence of position on the force is determined as deviation from the operating point. [5] A tangent is drawn to the magnetic force-position curve at the operating point is drawn as seen in Fig 2.

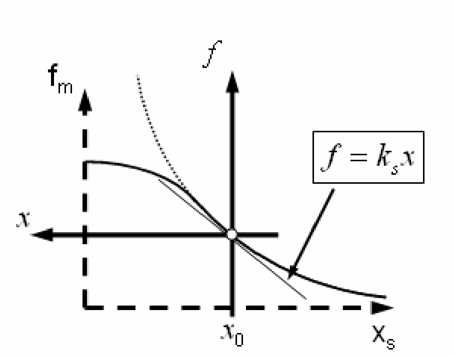

Fig 2. Dependence of magnetic force on position.

The force-displacement factor k_s describes the slope of the tangent line.

With constant position dependence of current on the force is determined as deviation from the operating point. A tangent is drawn to the magnetic force-current curve at the operation point is drawn as seen in Fig 3

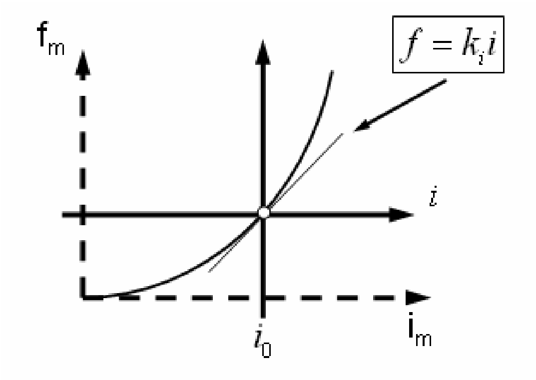

Fig 3. Dependence of magnetic force on current.

The force-current factor *ki* is used to describe the slope of the tangent line. Adding both independent correlations leads toequation (7) where the magnetic force acting on the system has been simplified to a linear dependence on both the current and the position.

f(x,i)=$k_s x + k_i i$ (7)

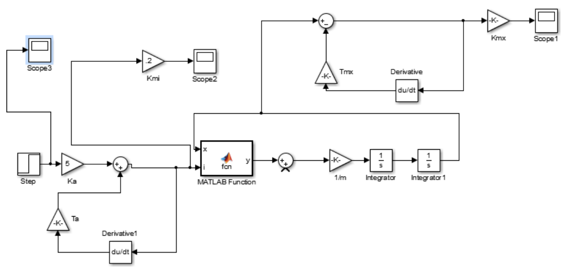

Fig 4:Nonlinear model of magnetic bearing

III. CONTROLLER

A.Linear Quadratic Guassian Controller

It is a linear controller and is a combination of Linear Quadratic Regulator as controller and Kaman filter as observer. LQR is the controller and it assumes full state information while Kalman Filter estimates states from output measurement. LQG control is based on Separation Principle

Consider a linear system,

$\dot{x} = Ax + Bu$
y=Cx+Du (8)

Design a control law u=$k_r x$ such that the performance measure is minimised. k_r is the controller gain. Performance measure depends on deviation of rotor position from the equilibrium position with less control effort.

Kalman Filter

It is an optimal estimator. Availability of all states for control at a time is not realistic hence have to use an estimator for this purpose. It works based on recursion principle and thus it will find out the best estimate among the past present and future estimates [5].

Consider the system with process noise and measurement noise acting on the system as

$\dot{x} = Ax + Bu + w$
y=Cx+Du+v (9)

Where w and v represents process noise and measurement noise respetively.It works based on three steps predicton correction and updation.

1.Prediction based on last estimate is
$\hat{x}(t+1|t = Ax(t) + Bu(t)$
y(t)=C$\hat{x}$(t+1|t) (10)

2.Calculate correction based on prediction and last estimate
Δx=f(y(t+1),$\hat{x}(t+1|t)$) (11)

3.Update prediction
$\hat{x}(t+1|t+1) = \hat{x}(t+1|t) + \Delta x$ (12)

B. Extended Kalman Filter

In case of a simple Kalman filter the range of application is limited to a narrow region around operating point. It cannot be used for nonlinear systems or operation over wide operating range. EKF is widely used for non-linear filtering problem. EKF basically linearizes the system dynamics at each sampling instant online and helps to capture the system dynamics of the system better. EKF extends the scope of simple Kalman Filter by performing Gaussians approximation of the joint distribution. It linearizes the system about an operating point online and the linearized equations are used in similar way as that of ordinary Kalman filter. If the linear approximation of the nonlinearity occurred is too decrimental then EKF will give better results when compared to ordinary Kalman Filter[6].

Nonlinear dynamics are given by
$\dot{x} = f(x,u) + v_x$
y=g(x) + n_x (13)

$v_x$and n_x are guassian white noise independent random process with zero mean and covariance.

EKF gives an approximation of the optimal estimate. The nonlinearities of the system's dynamics are approximated by a linearized version of the nonlinear system model around the last state estimate. Forthis approximation to be valid, the linearization performed should be a good approximationof the nonlinear model of the system[7].

The EKF uses a replica of the nonlinear plant, correcting the state-estimate by a linear gain matrix,H(t),multiplying the residual vector, r(t)

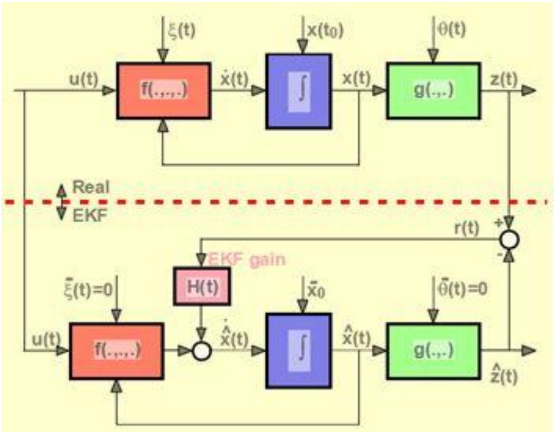

Fig 5:Block diagram of extended Kalman Filter

The state estimate vector $\hat{x}$ is determined by solving the non linear differential equations[8].

$$\frac{d\hat{x}(t)}{dt}=f(\hat{x}(t),u(t),0)+H(t)[z(t)-g(\hat{x}(t))] \qquad (14)$$

Iterative steps of ExtendedKalman filter include

1.With respect to last filtered estimate $\hat{x}(t|t)$ linearise the system x(t+1)

2.Apply prediction step to the linearised system and find predicted estimate $\hat{x}(t+1|t)$

3.With respect to the above predicted estimate linearise the observation dynamics y

4.The update cycle of kalmanfiter is applied to the linearised model of observation dynamics and then find out $\hat{x}(k+1|k+1)$

IV.SIMULATION RESULTS

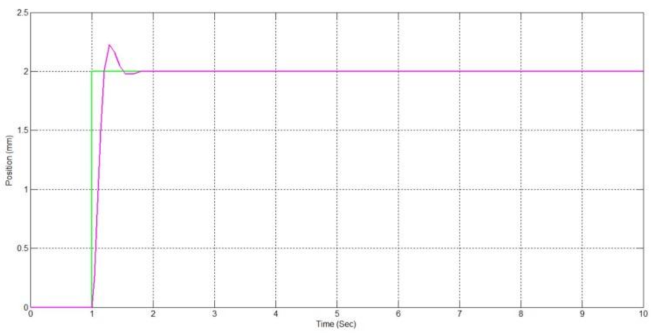

Fig 6:Response of rotor position controlled using LQG controller

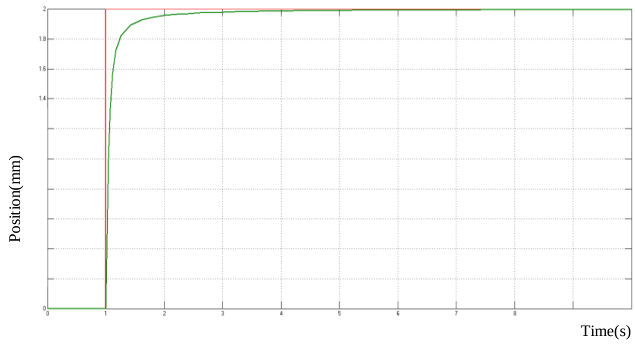

Fig 7:Response of rotor position controlled using EKF controller

Table 1:Comparison of different controllers

	PID	LQG	EXT-kalman
Delay time	0	1.105s	1.2s
Rise time	3s	1.2s	2s
Peak time	3.6s	2.22s	4.5s
%Mp	2.25%	9%	0
Setting time	4.8s	1.7s	4.5s
ess	.25	0	0

Parameter	Rig test
∂_0	500µm
m	250Kg
$\tilde{m}$	56Kg
i_0	5A
w_0	68
w_x	22
$\propto_p$	$\Pi/8$
A_p	$6158mm^2$
K_{mx}	200000V/m
T_{mx}	100µm
K_{mi}	0.2V/A
K_a	5A/V
T_a	$100\mu s$
f_a	50KHz
U_{DC}	160V

Table 2:RID test parameters

V.CONCLUSION

In this paper active magnetic bearing is analyzed and modeled using Simulink. Rotor position is controlled using different controllers PID, LQG and Extended Kalman Filter. The results were compared. LQG gives better performance compared to PID and Ext-Kalman Filter. Even though rotor position controlled using LQG gives peak overshoot when compared to other controllers it is with in permissible limits. LQG controlled system has the ability of disturbance rejection ie they can show improved response even in the presence of disturbance.

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