Genetic Algorithms Based Optimization Design of a PID Controller for an Active Magnetic Bearing

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Summary
The active magnetic bearing (AMB) using permanent magnet and electromagnet offers the advantage of higher lift-to-weight ratio and nearly zero ohmic loss of its control winding. Because of its inherent instability, AMB applications often require to overcome formidable control problems. This paper deals with the optimal design of a PID controller for an AMB using genetic algorithms (GA). The dynamic model for axial motion is also presented, together with experimental and simulation results to verify its availability and good dynamic response.

Key words:
Active Magnetic Bearing, PID Controller, Genetic Algorithms, Optimization Design

1. Introduction

Maglev systems with controlled-permanent magnet electromagnets have been reported elsewhere [1],[2]. The main advantages of such a system lie in its higher lift-to-weight ratio and lower power consumption as compared to the conventional magnetic suspension system [3],[4],[5]. Magnetic suspension offers a number of practical advantages over conventional bearings such as lower rotating losses, higher speeds, elimination of the lubrication system and lubricant contamination of the process, operation at temperature extremes and in vacuum, and longer life. However, AMB applications often require the solution of very interesting and formidable control problems because of the inherent instability and the nonlinear relationship between the lift force and the air gap distance [6],[7]. The characteristics of AMB depend on control system directly. In this paper, we propose a GA-based optimal design of a PID controller to solve the control problem of an AMB system with low power consumption. From both experiment and simulation results, the near-zero power consumption can be achieved with appropriate controller parameters tuning based on GAs.

2. Analysis of System Dynamic Model

Fig. 1 shows the schematics of the active magnetic bearing system. It consists of a levitated object (rotor) and a pair of opposing E-shaped controlled-PM electromagnets with coil winding. An attraction force acts between each pair of hybrid magnet and extremity of the rotor. The attractive force each electromagnet exerts on the levitated object is proportional to the square of the current in each coil and is inversely dependent on the square of the gap. Assuming a minimum distance to the length of the axis, the two attraction forces assure the restriction of radial motions of the axis in a stable way. The rotor position in axial direction is controlled by a closed loop control system, which is composed of a non-contact type gap sensor, a PID controller and an electromagnetic actuator (power amplifier). This control is necessary since it is impossible to reach the equilibrium only by permanent magnets.

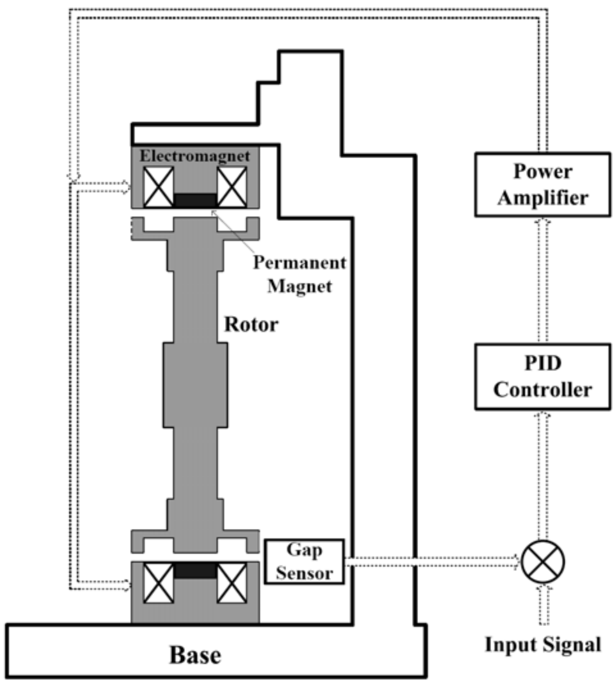

Fig. 1 Configuration of PM electromagnets active magnetic bearing.

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The rotor with mass m is suspended. Two attraction forces F_1. and F_2 are produced by the hybrid magnets. The applied voltage E from power amplifier to the coil will generate a current i which is necessary only when the system is subjected to an external disturbance w. Equations governing the dynamics of the system are

$$F_1(y,i) + F_2(y,i) - mg + w = m\frac{d^2y}{dt^2} \quad (1)$$

$$E = Ri + N\frac{d}{dt}(\phi_1(y,i) + \phi_2(y,i)) \quad (2)$$

Under small disturbance, the above equation becomes

$$\begin{aligned}\Delta E &= R\Delta i + N\frac{d}{dt}(\phi_1(y,i) + \phi_2(y,i)) \\ &= R\Delta i + N\left(\frac{\partial(\Delta\phi_1 + \Delta\phi_2)}{\partial \Delta y}\frac{d\Delta y}{dt} + \frac{\partial(\Delta\phi_1 + \Delta\phi_2)}{\partial \Delta i}\frac{d\Delta i}{dt}\right)\end{aligned} \quad (3)$$

If the weight of rotor is equal to the sum of these two attraction forces, the rotor will rotate on specific gap. According to Eq.(2), the disturbance equation at specific gap is calculated as follows

$$\Delta F_1(\Delta y, \Delta i) + \Delta F_2(\Delta y, \Delta i) + w = m\frac{d^2\Delta y}{dt^2} \quad (4)$$

and

$$\Delta F_1(\Delta y, \Delta i) = \frac{\partial \Delta F_1}{\partial \Delta y}\Delta y + \frac{\partial \Delta F_1}{\partial \Delta i}\Delta i \quad (5)$$

$$\Delta F_2(\Delta y, \Delta i) = \frac{\partial \Delta F_2}{\partial \Delta y}\Delta y + \frac{\partial \Delta F_2}{\partial \Delta i}\Delta i \quad (6)$$

Where y is the distance from gap sensor to bottom of rotor. R and N are the resistance and number of turns of the coil. ϕ_1 and ϕ_2 are the flux of the top and bottom air gap, respectively. We denote $\phi = \phi_1 + \phi_2$ and $F = F_1 + F_2$. The system is linearized at the operation point (y=y_o, i=0) and described as follows

$$\frac{d^2\Delta y}{dt^2} = \frac{1}{m}\frac{\partial \Delta F}{\partial \Delta y}\bigg|_{(y_o,0)}\Delta y + \frac{1}{m}\frac{\partial \Delta F}{\partial \Delta i}\Delta i \quad (7)$$

$$\frac{d\,\Delta i}{dt} = -\frac{R}{L}\Delta i - \frac{N}{L}\frac{\partial \Delta\phi}{\partial y}\bigg|_{(y_o,0)}\frac{d\,\Delta y}{dt} + \frac{1}{L}\Delta E \quad (8)$$

then

$$\frac{d}{dt}\begin{bmatrix}\Delta y \\ \Delta\dot{y} \\ \Delta i\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 \\ a_{21} & 0 & a_{23} \\ 0 & a_{32} & a_{33}\end{bmatrix}\begin{bmatrix}\Delta y \\ \Delta\dot{y} \\ \Delta i\end{bmatrix} + \begin{bmatrix}0 \\ 0 \\ b\end{bmatrix}E + \begin{bmatrix}0 \\ d \\ 0\end{bmatrix}w \quad (9)$$

where

$$a_{21} = \frac{1}{m}\frac{\partial \Delta F}{\partial y}, \quad a_{23} = \frac{1}{m}\frac{\partial \Delta F}{\partial \Delta i}, \quad a_{32} = -\frac{N}{L}\frac{\partial \Delta\phi}{\partial y}$$

$$a_{33} = -\frac{R}{L}, \quad b = \frac{1}{L}, \quad d = \frac{1}{m}, \quad L = N\frac{\partial \Delta\phi}{\partial \Delta i}$$

The partial derivatives are calculated from the experimental characteristics at the normal equilibrium operating point. It can be seen from the characteristic roots that the system is unstable. This system has to be stabilized by a PID controller with appropriate controller parameters tuning.

3. GA-Based PID Controller Tuning

As a mathematical means for optimization, GAs can naturally be applied to the optimal-tuning of PID controllers [8],[9]. With reference to a step input signal, the entire system will generate an output step response. The role of the PID controller is to drive this output response within the user's specifications. Obviously, the parameter settings of the PID controller should be fine-tuned so as to meet as high requirements as possible.

Optimization of PID controllers firstly needs design the optimization goal, and then encode the parameters to be searched. Genetic operator is running until the stop condition is satisfied. The decoding values of the last chromosome are optimized parameters of the PID controller. To obtain the optimal controller, the following implementations of the genetic algorithm are used.

3.1 Representation of Parameters

For most applications of genetic algorithms to optimization problems, the real coding technique is used to represent a solution to a given problem [10]. In real coding implementation, each chromosome is encoded as a vector of real numbers, of the same lengths as the solution vector. According to control objectives, three parameters K_P, K_I and K_D of a PID controller are required to be designed in this research. For a given problem with *3* decision variables, this paper adopts a real-valued vector [x_1, x_2, x_3] as a chromosome to represent a solution to the problem.

3.2 Crossover

Arithmetic crossover takes two parents and performs an interpolation along the line formed by the two parents. It is constructed by borrowing the concept of linear combination of vectors from the area of convex sets theory

[11]. According to the restriction on multipliers, it yields three kinds of crossovers, which can be called convex crossover, affine crossover, and linear crossover. Generally, when applying affine and linear crossovers to a particular problem, the absolute values of multipliers should be restricted to be below an upper bound according to the domain constraint in order to force genetic search within a reasonable area. Crossover uses the linear crossover with probability 0.85.

3.3 Mutation

Mutation adopts dynamic mutation, also called non-uniform mutation, with mutation probability 0.02. It is designed for fine-tuning capabilities aimed at achieving high precision. Non-uniform mutation changes one of the parameters of the parent based on a non-uniform probability distribution. This Gaussian distribution starts wide, and narrows to a point distribution as the current generation approaches the maximum generation [12].

3.4 Fitness Function

To evaluate the controller performance, there are always several criterions of control quality:

$$J_1 = \int_0^\infty e^2(t)\, dt \qquad (10)$$

$$J_2 = \int_0^\infty |e(t)|\, dt \qquad (11)$$

J_1 can track error quickly, but easily give rise to oscillation. J_2 can obtain good response, but its selection performance is not good. For getting good dynamic performance and avoiding long setting time, the following control quality criterion is used.

$$J = \int_0^\infty t\, e^2(t)\, dt \qquad (13)$$

The above control quality criterion J is adopted as the fitness function in this paper.

3.5 Select Probability

In proportional selection procedure, the selection probability of a chromosome is proportional to its fitness. This simple scheme exhibits some undesired properties. To maintain a reasonable differential between relative fitness ratings of chromosomes and to prevent a too-rapid takeover by some super chromosomes, the exponential ranking fitness assignment is selected in fitness calculations of reproduction operator, because its simplicity and robustness [13],[14]. The idea is straightforward: Sort the population from the best to the worst and assign the selection probability of each chromosome according to the ranking but not its raw fitness. Normalized geometric select is a ranking selection function based on the normalized geometric distribution, which is utilized in this research.

3.6 Termination Condition

Maximum generation termination method is used to decide whether the termination condition is satisfied or not.

4. Simulations and Experimental Results

Optimal parameters of the PID controller are designed based on genetic algorithm. After 200 generations of genetic operation, the optimal parameters obtained are K_P=4.598, K_I=2.538 and K_D=0.098. Using the determined controller, both simulation and experiment are conducted in an AMB system. The Simulink module frame utilized for simulation is shown in Fig. 2. The step responses of rotor position and feedback voltage signal are show in Fig. 3 and Fig. 4, respectively. We can observe that the controller gives a slight overshoot and settling time is less than 2.2 sec, when the rise time is less than 0.03 sec. Moreover, the rotor reaches to the commanded position and the steady state error is zero.

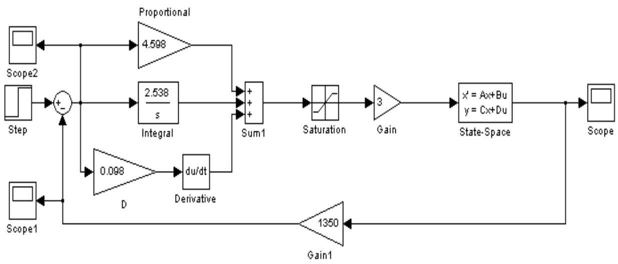
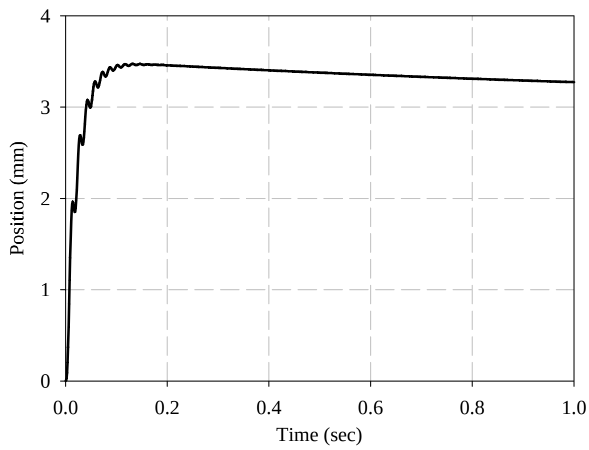
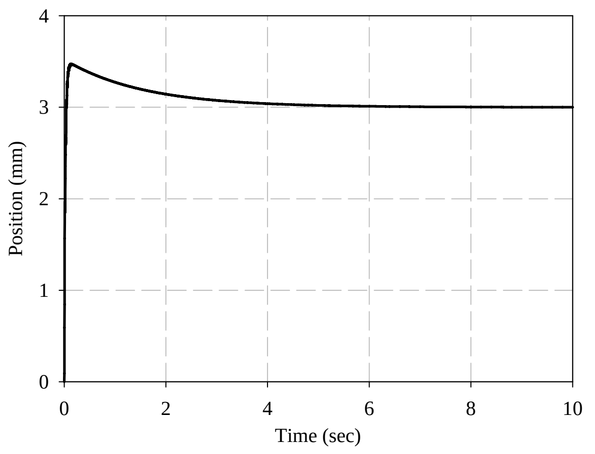


Fig. 2 Simulink module frame of PID controller.

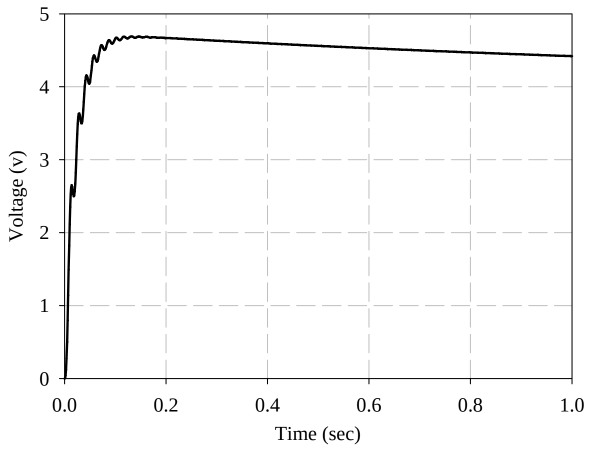


(a)

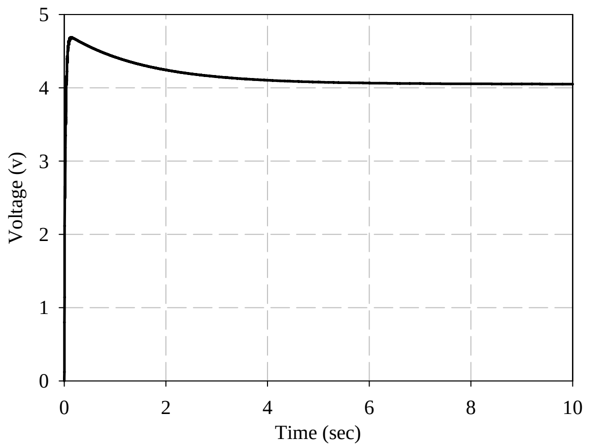


(b)

Fig. 3 Simulation responses of rotor position (a) simulation duration is 1.0 sec. (b) simulation duration is 10 sec.



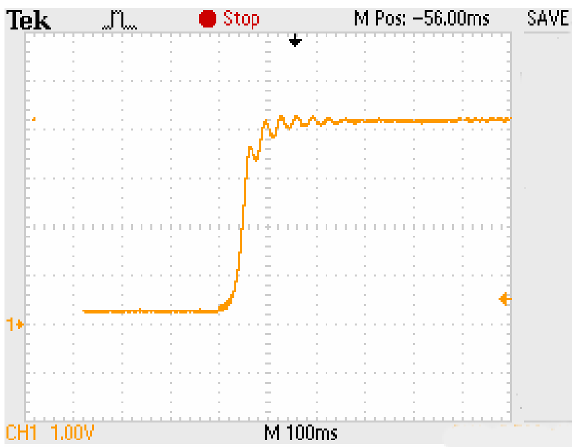
(a)



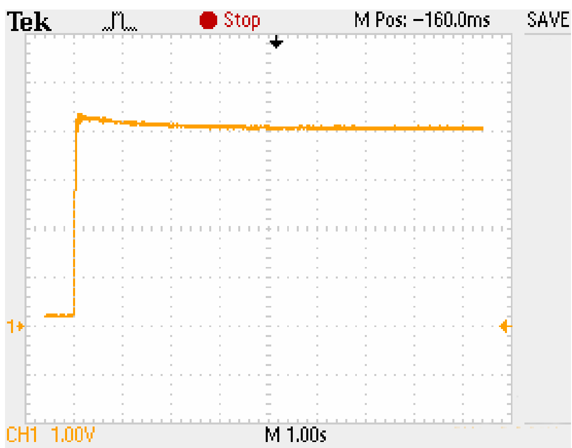
(b)

Fig. 4 Simulation responses of feedback voltage signal from the gap sensor (a) simulation duration is 1.0 sec. (b) simulation duration is 10 sec.

Fig. 5 and Fig. 6 show the experimental results. Fig. 5 shows the experimental position response measured from the output of gap sensor. It is very consistent with the simulation result shown in Fig. 4, which not only proves the performance of proposed genetic algorithm but also verifies the availability of the system model. The PID controller based on GA optimization techniques considerably suppresses down the undesired overshoot and attains short rise time as well as satisfactory settling time. Fig. 6 shows the waveform of the exciting current in the control winding of electromagnetic. A continuous oscillation of about ±0.1A range can be observed. The current peak value is approximately 0.1A. Therefore, the nearly zero power control is almost achieved.



(a)



(b)

Fig. 5 Experimental responses of feedback voltage signal from the gap sensor (a) measuring duration is 1.0 sec. (b) measuring duration is 10 sec.

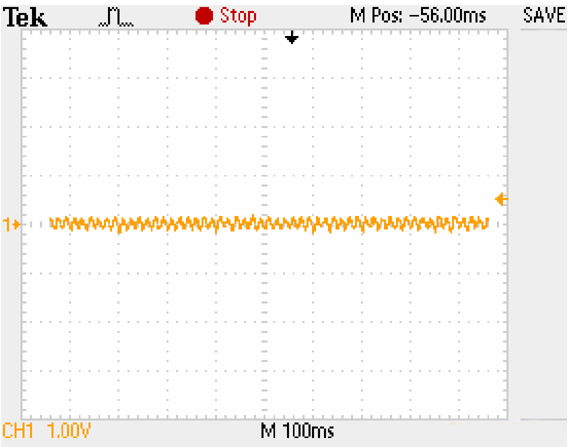


Fig. 6 Exciting current in the control winding of electromagnetic.

5. Conclusions

The main advantages of an AMB system lie in its lower power consumption as compared to the conventional bearing system. This paper has suggested a fine-tuning technology for optimal design of a PID controller of an AMB based on genetic algorithms. The position response has shown that the AMB has good static and dynamic performances. In addition, the PID controller parameters are designed well to satisfy performances of magnetic bearing. Both the experiment and simulation results are obtained which demonstrate the efficiency and effectiveness of the proposed tuning technology.

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