

Optimal Controller Design for Linear Magnetic Levitation Rail System

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Abstract—In many applications, magnetic suspension systems are required to operate over large variations in air gap. As a result, the nonlinearities inherent in most types of suspensions have a significant impact on performance. Specifically, it may be difficult to design a linear controller which gives satisfactory performance, stability, and disturbance rejection over a wide range of operating points. In this paper an optimal controller based on discontinuous mathematical model of the system for an electromagnetic suspension system which is applied in magnetic trains has been designed. Simulations show that the new controller can adapt well to the variance of suspension mass and gap, and keep its dynamic performance, thus it is superior to the classic controller.

Keywords—Magnetic Levitation, optimal controller, mass and gap

I. INTRODUCTION

NOWADAYS, magnetic levitation (maglev) techniques have been respected for eliminating friction due to mechanical contact, decreasing maintaining cost, and achieving high-precision positioning. Therefore, they are widely used in various fields, such as high-speed trains [1], [2], magnetic bearings [3], [4], vibration isolation systems [5], wind tunnel levitation [6] and photolithography steppers [7]. In general, maglev techniques can be classified into two categories: electrodynamic suspension (EDS) and electromagnetic suspension (EMS). EDS systems are commonly known as “repulsive levitation”, and the corresponding levitation sources are from superconductivity magnets [8] or permanent magnets [9]. On the other hand, EMS systems are commonly known as “attractive levitation”, and the magnetic levitation force is inherently unstable so that the control problem becomes more difficult. In this study, the EMS strategy is utilized for the fundamental levitation force of a linear maglev rail system, and the corresponding levitated positioning and stabilizing control of the maglev system is the major control objective to be manipulated via model-free control schemes. The absence of contact in these systems reduces noise, component wear, vibration, and maintenance costs [10]. However, they are nonlinear and have unstable dynamics and proper performance of these Systems greatly depend on their control strategy. The control of EMS is investigated in many researches so far. A wide variety of control methods are proposed ranging from PID and classical State feedback controls to complex nonlinear and adaptive controls. Many nonlinear control algorithms are applied in magnetic suspension system control, such as model reference control [11], robust control [12], slide mode control [13] and back

stepping control [14], Inter model control [15] etc. These control methods can overcome the uncertainties of model and improve characteristics of disturbance rejection and robustness in a certain degree. Jun-Ho Lee and et al have also proposed an integral sliding-mode control method to a magnetically suspended balance beam to achieve zero steady-state error under an external step disturbance and its robustness [16] In fact, the two groups of electromagnets embedded in a module are connected with a rigid body, and their motion states are coupling. At present the general control method controls the two groups of electromagnets separately using two independent controllers, and each acts according to the respective controlled object; the coupling between the two groups of electromagnets is regarded as disturbance and suppressed by enhancing the robustness of the controller [17]. However, this method cannot actively overcome the coupling question, and the control performance is not desirable when the system is adjusting due to the disturbance. In this paper, the module is modeled as a double-electromagnet (DEM) suspension system, and the method to solve the coupling problem of module suspension system is studied based on a DEM prototype (fig.1). The aim of this study is designing a controller for an electromagnetic suspension system which is applied in magnetic trains. Aforesaid system contains two magnets locating in two edges connected to the frame. Mentioned system has a nonlinear mathematical model. The models that is recommended for controlling the system is based on Discontinuous Mathematical Model this method is using system discontinuous mathematical model and each magnet is controlled separately with considering linearizing the system around work point, and flux of each magnet and air gap is control separately. In this model the equations of magnets are separately examined and distinct equations are written for each side having separated controller.

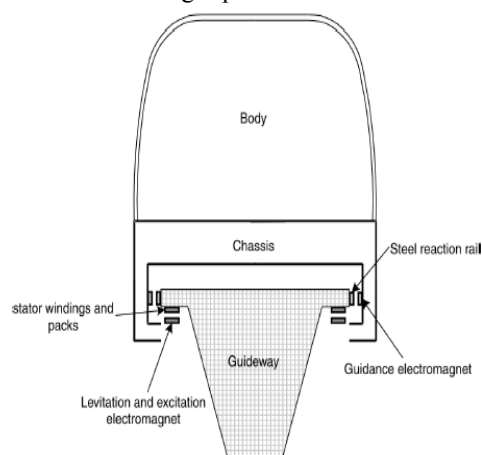


Fig. 1 structure of MAGLEV train

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II. SYSTEM MODELING

The system includes DC supply, a control block and sensors. The sensors are used to measure vertical acceleration of primary and the length of air gap. The vertical force in this system is calculated as follows:

$$F_1 = k \frac{i^2}{d^2} \quad (1)$$

$$u(t) = Ri + \frac{d\lambda}{dt} \quad (2)$$

$$\lambda = L \cdot I \quad (3)$$

$$m\ddot{d} = F_1 - mg - f_{ext} \quad (4)$$

Where, k is a constant coefficient depending on the system specifications. d is distance of magnets from rail. Above equations show system is nonlinear. Therefore, the system requires a nonlinear controller which increases the complexity and cost of the system. In order to avoid this problem, model linearization is applied to the system. As a result, the linear equations of the system are derived as follows:

$$F_1 = K(i - \beta d) \quad (5)$$

$$V = (R + L\sigma)i + \frac{Lp}{d_0}(i - \beta d)S \quad (6)$$

$$ms^2d = F_1 - mg - F_{ext} \quad (7)$$

$$K = \frac{2K'I_n}{d_0^2} \quad (8)$$

$$\beta = \frac{I_n}{d_0} \quad (9)$$

L_σ , L_p are leakage and constant inductances of coil respectively. d_0 is nominal air gap and I_n is nominal current. Linearized model of MAGLEV is shown in fig.2.

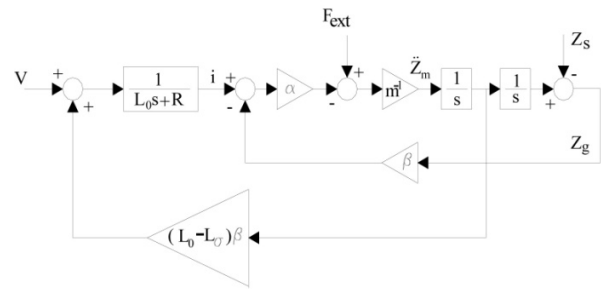


Fig. 2 linearized model of MAGLEV

III. DESIGNING OPTIMAL CONTROLLER

In this section optimal controller for discontinuous mathematical model has been designed. The aims of this controller include stabilizing the suspension system and controlling energy for transportation applications. In this method desirable controller mode is designed by optimizing location of the poles and using feedback technique.

The behavior of magnetic suspension system in mentioned controlling method is examined in Matlab/ Simulink. One of controlling methods is optimal control of linear systems. Proper and optimal choosing of the poles of a linear system is difficult for industrial process. Although an unstable system can be stabilized by feedback mode and place the poles in each surface point but studying linear optimal control is necessary.

State equations of open loop system are given by:

$$\dot{X} = Ax(t) + Bu(t) \quad (10)$$

$$y = cx(t) \quad (11)$$

$$X(t) = [d(t) \quad \dot{d}(t) \quad \ddot{d}(t)] \quad (12)$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ \frac{K\beta}{m} & \frac{K\beta - \frac{K}{L_0}}{m} & \frac{L_0}{R} \end{bmatrix} \quad (13)$$

$$\beta^T = \begin{bmatrix} 0 & 0 & \frac{-\alpha}{mL_0} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{-K}{mL_0} \end{bmatrix} \quad (14)$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (15)$$

The control objectives include desirable ride comfort, system stability and dynamic as well as good steady state performance. In order to achieve these goals an optimal controller is proposed based on enhanced classical state feedback. It consists of three parts, state feedback gains, an optimal gain calculator and an integral controller. To achieve desirable specifications, state feedback gains vector should be calculated optimally. Feedback signal is chosen as follows:

$$Z(t) = -Kx(t) \quad (16)$$

This signal should minimize the performance function at steady state defined by

$$\int_0^{\infty} (x^T(t)R_1 x(t) + u^T(t) Ru(t))dt \quad (17)$$

R_1 and R_2 are positive definite or semi definite matrices. Assuming that the stability of close loop system is achieved and $R_2 = T^T T$ (T is a nonsingular matrix), and by minimizing of (17) the optimal gain vector is calculated.

$$K = R_2^{-1} B^T P \quad (18)$$

where P can be obtained by solving Riccati equation :

$$A^T P + PA - PBR_2^{-1} B^T P + R_1 = 0 \quad (19)$$

In this paper R_1 and R_2 are selected as:

$$R_1^T = \begin{bmatrix} a^2 & 0 & b^2 \end{bmatrix} \quad (20)$$

$$R_2 = \begin{bmatrix} c^2 \end{bmatrix} \quad (21)$$

Therefore, the performance function can be presented as:

$$\tau = \frac{1}{2} \int_0^{\infty} (a^2 \dot{d}^2(t) + b^2 \ddot{d}^2(t) + c^2 u^2(t)) dt \quad (22)$$

The first part of Equation (22) limits the air gap variation and the second part limits the acceleration. The consumed energy is also considered in the control by the third part to have a more realistic design. The coefficients, a , b , and c are selected with regard to importance of each part as the value of each term in Equation (22) ($a^2 \dot{d}^2(t)$, $b^2 \ddot{d}^2(t)$, $c^2 u^2(t)$) become proportional to its importance. In this paper the coefficient, c is selected as unity; the coefficient, a , is selected as $a^2 \dot{d}^2 = c^2 u^2$ and b is selected to have $b^2 \ddot{d}^2 = b^2 (1 \text{ m/s}^2) = 2c^2 u^2$. d , u , \ddot{d} , are nominal air gap length, nominal input voltage and proper acceleration respectively. Therefore the input voltage and air gap variations have the same Importance, whereas the importance of acceleration is twice than those of air gap variations and input voltage.

The values of these coefficients are as follows: Designed controller will have steady state error. Therefore, an integral controller is employed to overcome this problem. The gain of integral controller should be regulated according to the desirable performance.

IV. SIMULATION RESULTS

A controller is designed for an EMS with specifications listed in table.1 and its uncontrolled Bode diagram is shown in Figure 3. It is clear from this diagram that the uncontrolled system is unstable. Optimal gain vector and integral controller gain regarding the previously mentioned rules are calculated as:

$$K = [400 \ 10700 \ 1.8 \times 10^5] \ \& \ h = 6.25$$

The value of integral controller gain is selected by try and error method. However, it can be incorporate in state feedback and calculated as optimal gain. The dynamic performance of the EMS is then simulated under the proposed control system. Effect of load changes on the air gap length is shown in fig.4. The results validate accuracy of proposed controller. The effect of integral gain on starting performance of system is also investigated in Figure 5. It is seen that the higher h value results in faster response of system but also increases the overshoot. Acceleration performance during the starting of system is also shown in figure 6. The, current and consumed energy are depicted in Figure 8 and Figure 9. It is observed that the current value is limited and its overshoot is reasonable. The proposed control system effectively reduces the acceleration during load disturbance, resulting better movement.

TABLE I
 SPECIFICATIONS ADOPTED FOR THE SIMULATED SYSTEM

Symbol	Quantity	Rating values
L_{σ}	2.497	mH
L_p	1.43	mH
R	Ohm	1
M	Kg	5000
d(t)	Cm	1.5
I_n	A	200
V_n	V	200
α	N/A	1492
β	A/m	13300

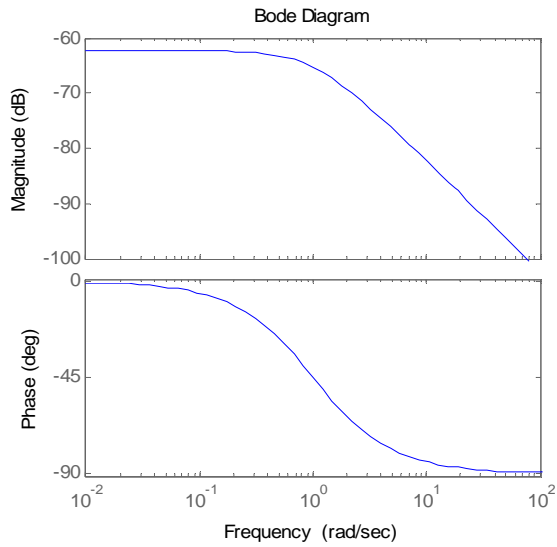


Fig. 3 Bode diagram of system

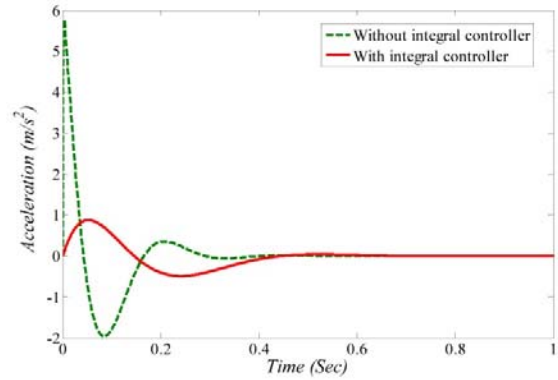


Fig. 6 Vertical acceleration during starting process

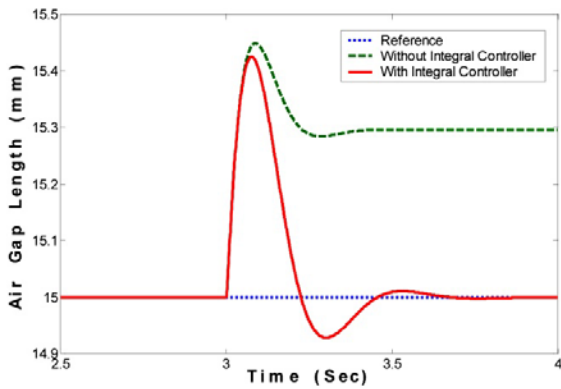


Fig. 4 Effect of load changes on the air gap length

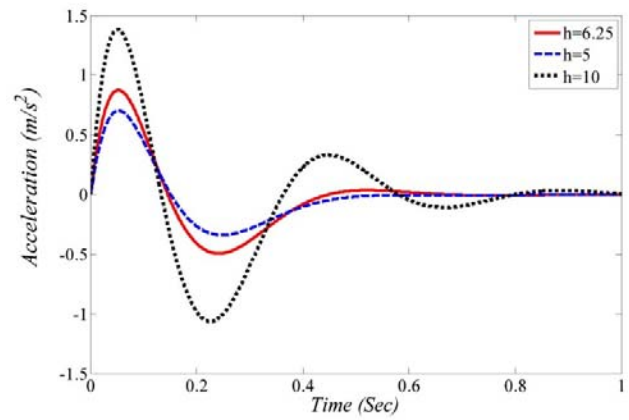


Fig. 7 The effect of integral controller gain on the vertical acceleration

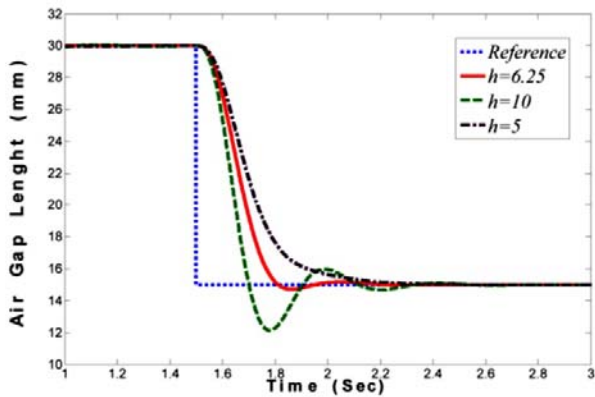


Fig. 5 The effect of integral controller gain on the system response

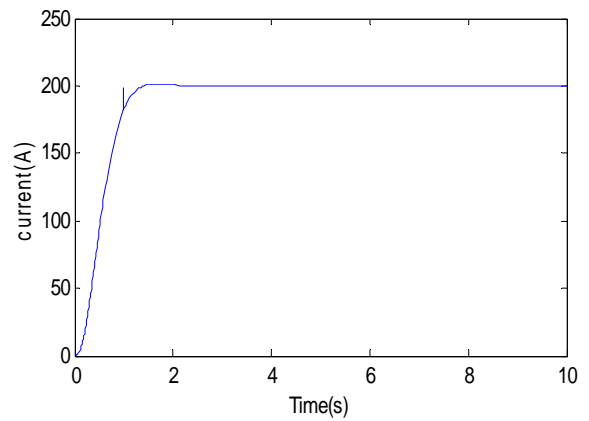


Fig. 8 Current of the simulated system

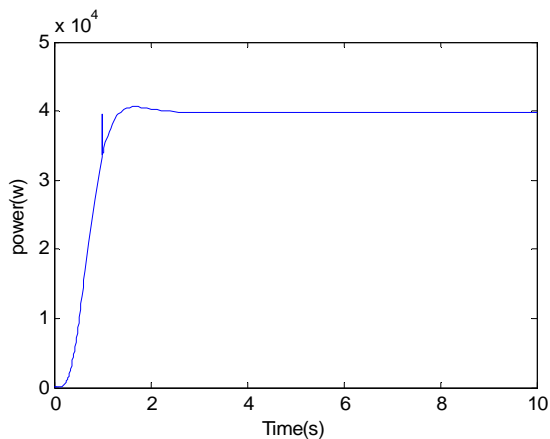


Fig. 9 Consumed energy of the simulated system

V. CONCLUSION

Magnetic suspension systems are basically unstable non linear system. There are different methods for controlling magnetic suspension distance (air gap) but in this paper optimal control method is considered.

In this method control signals causing non linear behavior in system can be prevented by optimizing poles location. Also desirable speed to acceptable amount of control signal can be achieved by optimal choosing close loop poles. As referred before; inappropriate open loop diagram shows that system is unstable which can be stabilized by choosing a proper controller. In this method we linearizing magnetic suspension nonlinearities by linearizing around work point then we control important parameters including rise time, overshoot, air gap, vertical acceleration and consuming energy amount and voltage and current by finding proper place of close loop poles. Vertical acceleration being one of important parameters for easy movement has been considered and reaches to zero in the shortest time by choosing appropriate portion coefficients. One of advantages of this controller rather than previous presented methods is this that all possible errors of desirable air gap can be ruined when vast change or disorder accrued by choosing an integral controller. Also integral portion changes have been considered and it has been showed that correct choosing of integral portion can decrease the time necessary for steady state mode. Also correct choosing of integral portion helps to decrease system time reaching to stability mode. Also we can observe that energy consuming of system is acceptable and voltage and consuming current have been limited. In summary we can say that in this controller, most important parameters in movement can be controlled by optimal place finding of system poles and using integral controller and desirable air gap can be reached by choosing proper integral portion in case of any changes in system parameters.

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