The Design and Simulation of An Adaptive Maglev Control Algorithm Based on Oscillation Observation

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magnetic levitation control, Kalman filter, lead-compensation network, adaptive algorithm, design and simulation

Abstract

This paper studies an adaptive maglev control algorithm based on oscillation observation about the magnetic levitation control problem of maglev vehicles. The structure of the adaptive controller was presented, and the detail design of its adjustable digital-lead-compensation network and general Kalman filter was given. The applied controller stucture was discussed based on simulation and analysis.

1. Introduction

This paper researches the magnetic levitation control problem of maglev vehicles. The system, a quite complex and unstable one, consists of a group of electro-magnets, levitation bogies, aero-springs and guideway. The levitation controller is used to stabilize the system after mechanical structure is confirmed. It is one of maglev kernel techniques. New algorithm researching is a hot point in this area. Former maglev controller is based on analog circuits, mainly including 2 kinds. One is lead-compensation network based on PID controller, the other is state feedback controller based on state observation. With the progress of technology, levitation controller is designed by digital circuits now. The digital controller uses MCU or DSP as control platform. It is easy to realize varies new algorithms by software. Under this condition, the key problem of maglev controller designs has transformed from circuit designs to algorithm and software designs. This paper studies an adaptive maglev control algorithm based on oscillation observation. In essence it is still a digital-lead-compensation network, but whose center frequency can be adjusted by control effect so as to provide the biggest phase compensation in proper frequency. According to tiny oscillation of closed-loop control effects, a general Kalman filter is designed to observe its frequency, which is used as the center frequency of lead-compensation network to adjust the levitation controller. This paper also discusses some applied controller structures based on simulation and analysis.

2. The Model of Maglev System and the Structure of an Adaptive Levitation Controller Based on a General Kalman Filter

Take consider of the single electro-magnet levitation system. The model of the levitation system is[1]:

$$F_m = \frac{\mu_0 N^2 A I^2}{4\delta^2} \tag{1}$$

$$m\ddot{y} = mg - F_m + F_y \tag{2}$$

$$u = RI + \frac{\mu_0 N^2 A}{2\delta}\dot{I} - \frac{\mu_0 N^2 AI}{2\delta^2}\dot{\delta} \tag{3}$$

Where:

μ_0 : magnetic conductance constant in vacuum;

g : constant of gravity;

m : mass of levitated objects;

A : effective area of the electro-magnet;

N : number of winding of the electro-magnet;

R : resistance of the electro-magnet-winding;

u : control voltage;

I : current in the electro-magnet-winding;

δ : gap between the electro-magnet and the guideway;

y : displacement of the electro-magnet in the inertial space;

F_m : electro-magnetic force;

F_y : disturbing force.

Equation (1) is the relationship of the electro-magnetic force with structure parameters, gap and current; Equation (2) is Newton's dynamics equation about mechanism movement of levitated objects. Equation (3) is the relationship of current with voltage in an electro-magnet.

The negative gap feedback and lead-compensation network controller can be described as follows:

$$u(s) = K_P \cdot \frac{1+\alpha\tau s}{1+\tau s}[\delta_0 - \delta(s)], \quad \alpha > 1 \tag{4}$$

Where:

s : Laplace operator

τ : parameter to design center frequency of lead-compensation network

K_P : magnitude of controller

We use a general Kalman filter to observe the tiny oscillation of the gap, and then revise the controller according to it. Figure 1 shows the block diagram of the adaptive controller. Gap between the magnet and the guideway is measured by a gap sensor. The actual output is compared with the given value to form a control signal by passing through a lead-compensation network. A PWM Power Amplifier is used to drive the electro-magnet. The current of electro-magnet is fed back to power amplifier to improve adjustment speed. The general Kalman filter is used to observe the output signal and calculate the oscillation parameter, which can revise the parameters of lead-compensation network.

The design details of the adjustable lead-compensation network and the general Kalman filter is given below.

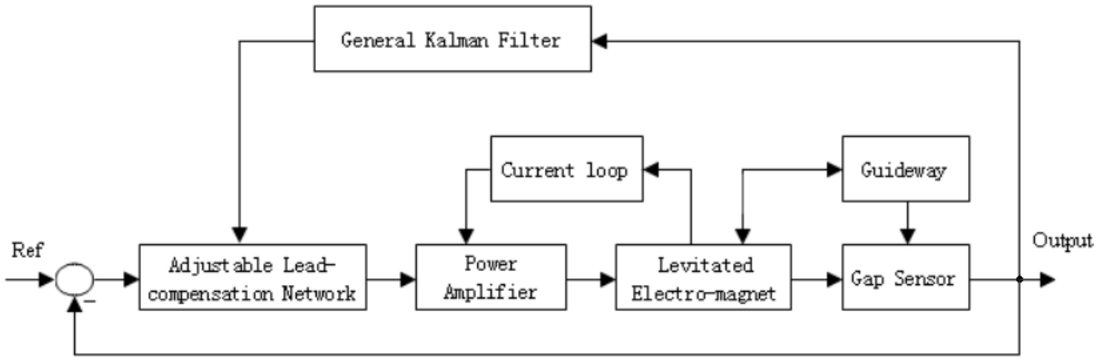

Figure 1: Block diagram of an adaptive controller based on oscillation observation

3. Adjustable Digital-Lead-Compensation Network Design

General formula of an analog lead-compensation network is: $\frac{1+\alpha\tau s}{1+\tau s}$, $\alpha > 1$. We have the biggest lead phase φ_m in the center frequency $\omega_0 = \frac{1}{\sqrt{\alpha\tau}}$, Where $\sin\varphi_m = \frac{\alpha-1}{\alpha+1}$. In general, lets $\alpha = 15$, the biggest lead phase will be 61°.

An inertial component $\frac{1}{1+Ts}$ is connected in series with lead-compensation network to keep high frequency noise within limits. Supposing the phase loss of this component in center frequency is 5°, that is $\tan^{-1}(T\omega_0) = 5°$, and we have $T = \tan 5° / \omega_0$.

Now, the transfer function of lead-compensation network is as follows,

$$H(s) = \frac{1+\alpha\tau s}{1+\tau s} * \frac{1}{1+Ts} = \frac{1+\alpha\tau s}{T\tau s^2 + (T+\tau)s + 1} \quad (5)$$

We transform the analog system to a digital one by bilinear method. Lets

$$s = \frac{2}{T_c} * \frac{1-z^{-1}}{1+z^{-1}}, \quad c_0 = \frac{2}{T_c} \quad (6)$$

Where T_c is the control period.

Substituting (6) into (5), we have

$$H(z) = \frac{(1+c_0\alpha\tau) + 2z^{-1} + (1-c_0\alpha\tau)z^{-2}}{[T\tau c_0^2 + (T+\tau)c_0 + 1] + 2(1-T\tau c_0^2)z^{-1} + [T\tau c_0^2 - (T+\tau)c_0 + 1]z^{-2}} \quad (7)$$

This formula can be realized by following difference equation

$$y(n) = \sum_{i=0}^{2} a_i * x(n-i) + \sum_{j=1}^{2} b_j * y(n-j) \quad (8)$$

Where:

$$b_0 = T\tau c_0^2 + (T+\tau)c_0 + 1$$

$$a_0 = \frac{1+c_0\alpha\tau}{b_0}, \quad a_1 = \frac{2}{b_0}, \quad a_2 = \frac{1-c_0\alpha\tau}{b_0} \tag{9}$$

$$b_1 = \frac{2T\tau c_0^2 - 2}{b_0}, \quad b_2 = \frac{(T+\tau)c_0 - T\tau c_0^2 - 1}{b_0}$$

By equation (9) we get all parameters of an adjustable digital-lead-compensation network from a given center frequency.

For example, given $\omega_0 = 2\pi f_0 = 20\pi(rad/s)$, $T_c = 1.92ms$, the transfer function of the analog filter is $\frac{0.06164s+1}{5.722\times10^{-6}s^2 + 0.0055018s + 1}$. According to equation (9), we get the coefficients of the digital network as follows.

$$a_0 = 5.0394, \quad a_1 = 0.1546, \quad a_2 = -4.8848$$
$$b_1 = 0.8051, \quad b_2 = -0.1142$$

4. Observing Oscillation Frequency by General Kalman Filter

To be simple, we assume the signal is of sine wave. The measure equation is

$$z(t) = A\sin\varphi + v(t) \tag{10}$$

Where:

$$\varphi = \omega t + \varphi_0 \tag{11}$$

and $v(t)$ is the measuring noise.

Using a general Kalman filter, we can observe parameters of this nonlinear system. Take notes as:

$X = [A \quad \omega \quad \varphi]^T$: state variable-vector,
Δt : sampling period,
Z_{k+1} : observing sequence,
Q_k : variance matrix of noise in state equation,
R_{k+1} : variance matrix of noise in measure equation.

The state transfer matrix will be:

$$\phi_{k+1/k} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & \Delta t & 1 \end{bmatrix}$$

The recursive algorithm of general Kalman filter to obtain $\hat{X}_{k+1/k+1}$, $P_{k+1/k+1}$ is as follows[4].

(1) Input initial value: $\hat{X}_{0/0}$、$P_{0/0}$、$k=0$;

(2) $\hat{X}_{k+1/k} = \phi_{k+1/k}\hat{X}_{k/k}$;

(3) $P_{k+1/k} = \phi_{k+1/k}P_{k/k}\phi_{k+1/k}{}^{T} + Q_k$;

(4) $H_{k+1} = \left[\sin\hat{\varphi}_{k+1/k},\quad 0,\quad \hat{A}_{k+1/k}\cos\hat{\varphi}_{k+1/k}\right]$;

(5) $K_{k+1} = P_{k+1/k}H_{K+1}{}^{T}\left[H_{k+1}P_{k+1/k}H_{k+1}{}^{T} + R_{k+1}\right]^{-1}$;

(6) $\hat{X}_{k+1/k+1} = \hat{X}_{k+1/k} + K_{k+1}\left[Z_{k+1} - \hat{A}_{k+1/k}\sin\hat{\varphi}_{k+1/k}\right]$;

(7) $P_{k+1/k+1} = \left[I - K_{k+1}H_{k+1}\right]P_{k+1/k}$;

(8) $k+1 \rightarrow k$, return to (2).

5. Simulation of Maglev Controller

The block diagram of the adaptive algorithm shows in figure 2. When simulating, we take the parameters as: N=320, A=0.84m×0.028m, m=750kg, R=0.5Ω, δ0=10mm, δ(0)=20mm.

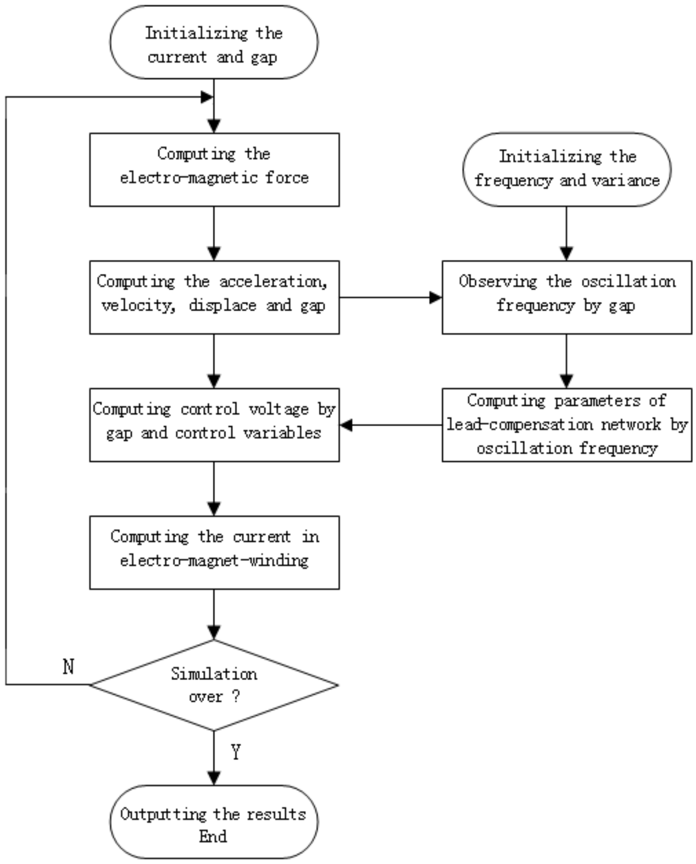

Figure 2: Simulation block of the adaptive controller

Figure 3 and figure 4 show the simulation results, and some descriptions are given with the figures. Based on simulation results, we can choose controller structure from the follows.

(1) Two one-order lead-compensation networks together with a current loop. The parameters of the current loop and one one-order network are fixed, the other network, however, is adjusted by the results of the general Kalman filter.

(2) One one-order lead-compensation network, an acceleration loop, together with a current loop. The parameters of the current loop and the acceleration loop are fixed; the lead-compensation network is adjusted by the results of the general Kalman filter.

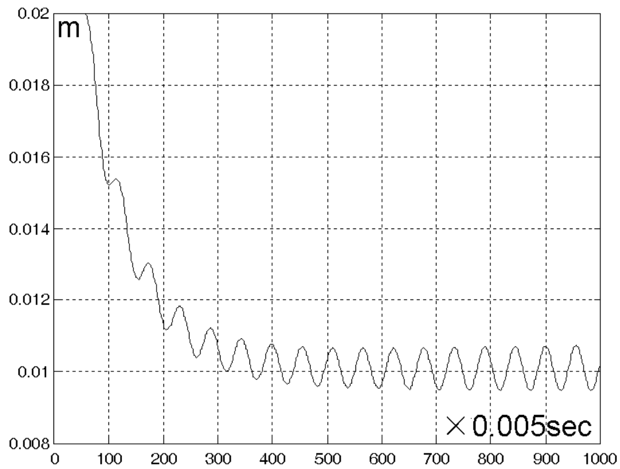

Figure 3: Effect of one-order lead-compensation network with current loop controller

Description of Figure 3: One one-order lead-compensation network cannot stabilize the system. But if a current loop is enhanced, the system can gradually change from large-scale non-linear oscillation to marginally stable and even asymptotically stable. In figure 3, system is Lyapunov stable under proper current loop gain. And the system will be asymptotically stable as the current loop is strengthened.

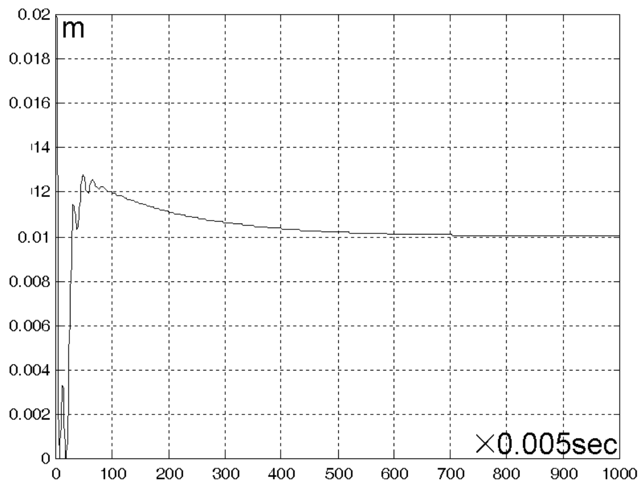

Figure 4: Simulation of controller with two one-order lead-compensation networks, and their center frequencies are 10Hz and 4Hz

Description of Figure 4: The system can be only marginally stable with one one-order lead-compensation network. But with another one-order lead-compensation network, the system will be stabilized easily. If center frequency of the first network is 10Hz, the system will be stabilized with the center frequency of the second network changing from 4Hz to 20Hz. They surely have different effects. If center frequency is too low, high-frequency noises cannot be held back and a high-frequency oscillation will occur. Then, we have to and will adjust the center frequency of lead-compensation network according to the output of the general Kalman filter.

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