Analysis of Gap Time-Delay in Maglev Control System

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Abstract. In the maglev control system, signal filtering, A/D sampling and communication all bring time-delay to the gap signal, which will affect the performance of the levitation control. In order to analyze this effect, a single-degree-of-freedom maglev system model is established. The state feedback control method is used to control the maglev system, and the stability of the closed-loop system is analysed and he stable region of control parameters is studied. Gap time-delay is introduced into the closed-loop system model, and the influence of time-delay on the stability range of control parameters is analyzed. It is concluded that the gap time-delay will reduce the stability range of control parameters, the larger the time-delay of position signal is, the smaller the lower limit of the stability region of differential feedback coefficient is and the smaller the stability region is. The simulation results are used to verify the validity of the theoretical analysis.

1. Introduction

In recent years, with the rapid development of maglev train technology, maglev technology has attracted wide attention. At present, there are more or less problems in the maglev train system, which affect the stability of the train and even lead to the instability of the train suspension system in serious cases, thus weakening the competitiveness of maglev train in rail transit.

The magnetic levitation system itself is unstable, and it needs external control to maintain its stability. Common magnetic levitation control methods include pole placement method [1], PID control method [2], non-linear control method [3], robust control method [4], adaptive control method [5], variable structure control method [6]. For a specific control system, the time-delay may be caused by the signal filtering or the A/D sampling, or by the communication. Strictly speaking, time-delays are ubiquitous in control systems, only with different sizes [7]. In maglev train system, because the environment of suspension controller and suspension sensor is complex and the gap signal is greatly disturbed by external disturbance, it is necessary to filter the gap signal in feedback control to remove the noise signal caused by interference, which brings the time-delay of gap signal and affects the performance of the system. The influence of clearance time-delay on the system performance is analysed below, and corresponding measures are taken to ensure the excellent performance of the suspension control system.

2. Modeling of single degree of freedom maglev system

The single-degree-of-freedom maglev system is shown in figure 1. Mg is the weight of electromagnet , F_m represents the electromagnetic force produced by electromagnet, z_a is the vertical absolute displacement of electromagnet, z_m is the relative displacement of electromagnet, z_h is the track disturbance, i is the current of electromagnet coil, $v(t)$ is the voltage at both ends of the coil. The reference plane of the vertical displacement is the polar plane of the track, the downward direction is positive, the electromagnet is the rigid body, and the track is the elastic track. There is only vertical degree of freedom.

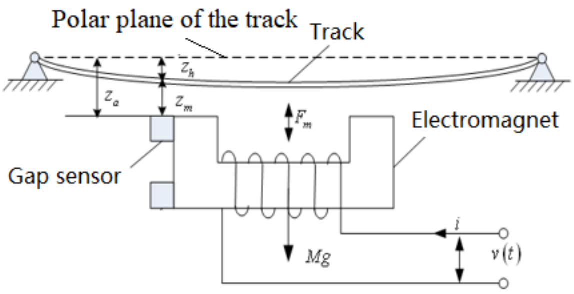

Figure 1. Structure of Single-degree-of-freedom Maglev System

The equations of system dynamics and electromagnetics are as follows [8]:

$$v = Ri + A_1 \frac{\dot{i} z_m - i\dot{z}_m}{2z_m^2} \tag{1}$$

$$M\ddot{z}_a = Mg - \frac{A_1 i^2}{4z_m^2} \tag{2}$$

$$z_a = z_m + z_h \tag{3}$$

In the upper forms, $A_1 = N^2\mu_0 S$, μ_0 is the vacuum permeability, N is the coil turns, S is the electromagnet pole area, R is the electromagnet resistance, the superscript ‘ represents the derivative of time.

In order to study the stability of the system in equilibrium position, the usual method is to ignore the influence of orbit disturbance. In this case, the definition is $z = z_m = z_a$,that (1) and (2) are deformed into:

$$v = Ri + A_1 \frac{\dot{i}z - i\dot{z}}{2z^2} \tag{4}$$

$$M\ddot{z} = Mg - \frac{A_1 i^2}{4z^2} \tag{5}$$

The expressions (4) and (5) are the system equations.

3. Stability analysis without gap time-delay

Maglev system is an unstable system. Active control is needed to make the system stable.

In this paper, a state feedback control method is used to analyze the stability of the system. In order to simplify the debugging process, the current loop can be controlled to improve the current response speed in the electromagnet. With the appropriate current loop control method, the voltage at both ends of the electromagnet and the current in the coil can be considered as equal in mathematics [9]. Then (5) the deformation is as follows:

$$M\ddot{z} = Mg - \frac{A_1 v^2}{4z^2} \tag{6}$$

In order to analyze the stability of the system, Taylor expansion near the equilibrium point is carried out.

$$M\Delta\ddot{z} = \frac{A_1 {v_0}^2}{2{z_0}^3}\Delta z - \frac{A_1 v_0}{2z^2}\Delta v \tag{7}$$

For ease of writing, remove the Δ in (7):

$$M * \ddot{z} = \frac{A_1 v_0^{\ 2}}{2 z_0^{\ 3}} z - \frac{A_1 v_0}{2 z^2} v \tag{8}$$

The state feedback control method is used to control the system. The forms of control are as follows:

$$v = k_p z + k_d \dot{z} \tag{9}$$

The closed-loop system equation is obtained by introducing (9) into (8):

$$M * \ddot{z} = \frac{A_1 v_0^{\ 2}}{2 z_0^{\ 3}} z - \frac{A_1 v_0}{2 z_0^{\ 2}} \left(k_p z + k_d \dot{z} \right) \tag{10}$$

The characteristic equation of the equation is as follows:

$$\lambda^2 + \frac{A_1 v_0 k_d}{2 M z^2} \lambda + \left(\frac{A_1 v_0 k_p}{2 M z_0^{\ 2}} - \frac{A_1 v_0^{\ 2}}{2 M z_0^{\ 3}} \right) = 0 \tag{11}$$

From the above formula, it can be concluded that the control parameter region which makes the system stable is:

$$k_d > 0 \, , k_p > \frac{v_0}{z_0} \tag{12}$$

The parameters of a magnetic levitation system are as follows: M=200kg; N=340; S=0.0742; A_1=0.0108; z_0=0.008; v_0=6.8161;

Under the above parameters, the stable region of the control parameters described by (12) is:

$$k_d > 0 \, , k_p > 852.0125 \tag{13}$$

4. Stability analysis with gap time-delay

In suspension control, the clearance signal is usually filtered, which brings time-delay to the clearance signal and affects the performance of the system. For the convenience of analysis, Laplace transform is applied to (10):

$$Z(s)s^2 + \frac{A_1 v_0 k_d}{2 M z_0^{\ 2}} Z(s) s + \left(\frac{A_1 v_0 k_p}{2 M z_0^{\ 2}} - \frac{A_1 v_0^{\ 2}}{2 M z_0^{\ 3}} \right) Z(s) = 0 \tag{14}$$

In the system, the transfer function of a pure time-delay is:

$$e^{\tau s} = 1 + \tau s + \frac{(\tau s)^2}{2!} + \frac{(\tau s)^3}{3!} + \cdots \tag{15}$$

Because τ is very small, the first two parts of the formula can be obtained:

$$e^{\tau s} \approx 1 + \tau s \tag{16}$$

and:

$$e^{-\tau s} \approx \frac{1}{1 + \tau s} \tag{17}$$

Considering the time-delay of gap signal, the closed-loop control system (14) is transformed into:

$$Z(s)s^3 + \left(\frac{1}{\tau} + \frac{A_1 v_0 k_d}{2 M z_0^{\ 2}} \right) Z(s) s^2 + \left(\frac{A_1 v_0 k_d}{2 M z_0^{\ 2} \tau} - \frac{A_1 v_0^{\ 2}}{2 M z_0^{\ 3}} \right) Z(s) s + \left(\frac{A_1 v_0}{2 M z_0^{\ 2} \tau} k_p - \frac{A_1 v_0^{\ 2}}{2 M z_0^{\ 3} \tau} \right) Z(s) = 0 \tag{18}$$

Thus, the characteristic equation of the system is:

$$\lambda^3 + \left(\frac{1}{\tau} + \frac{A_1 v_0 k_d}{2 M z_0^{\ 2}} \right) \lambda^2 + \left(\frac{A_1 v_0 k_d}{2 M z_0^{\ 2} \tau} - \frac{A_1 v_0^{\ 2}}{2 M z_0^{\ 3}} \right) \lambda + \left(\frac{A_1 v_0}{2 M z_0^{\ 2} \tau} k_p - \frac{A_1 v_0^{\ 2}}{2 M z_0^{\ 3} \tau} \right) = 0 \tag{19}$$

Lemma 1: The sufficient and necessary conditions for the roots of equation $\lambda^3 + a\lambda^2 + b\lambda + c = 0$ to contain negative real parts are as follows:

$$a > 0 \, , ab > c \, , c > 0 \tag{20}$$

Lemma 1 can be obtained by Routh-Hurwitz stability criterion [10].

By using lemma 1, the stable region of the control parameters in the system (19) can be obtained. Because of the complexity of the coefficients in (19), the stable region of the control parameters is calculated after the specific parameters of the magnetic levitation system in the second part are brought into the system. When the system parameters are brought into (16), the system deformation is as follows:

$$\lambda^3 + \left(\frac{1}{\tau} + 2.8755k_d\right)\lambda^2 + \left(\frac{2.8755}{\tau}k_d - 2450\right)\lambda + \left(\frac{2.8755}{\tau}k_p - \frac{2450}{\tau}\right) = 0 \qquad (21)$$

From lemma 1, the stability range of the control parameters is obtained as follows:

$$k_p > 852.0125 \qquad (22)$$

$$k_d > 426.0129\,\tau - \frac{0.1739}{\tau} + \frac{0.0035}{\tau} \cdot \sqrt{1.5006\times10^{10}\tau^4 + (28755k_p - 1.225\times10^7)\tau^2 + 2500} \qquad (23)$$

From the above formula, we can see that the stability range of differential feedback coefficient k_d decreases with the increase of gap time-delay, and also decreases with the increase of proportional feedback coefficient k_p.

5. Simulation verification

In the control of the system, assuming that the dynamic performance index of the target system is 10% overshoot and the adjustment time is 0.15 seconds, the control parameters without gap time-delay are obtained.

$$k_p = 3274,\ k_d = 45 \qquad (24)$$

Under the above control parameters, the clearance response under different gap time-delay can be obtained by using MATLAB simulation software [11]. The simulation results are shown in the following:

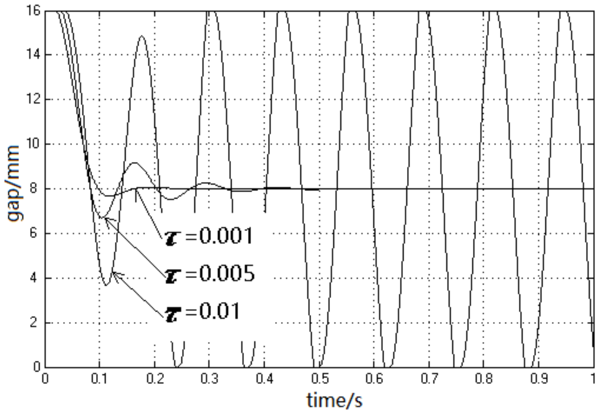

Figure 2. Gap response with the same control parameters and different time-delays

As can be seen from figure 2, when the control parameters remain unchanged, the performance of the system will deteriorate with the increase of time-delay, and the system will be unstable when it increases to 0.01 seconds.

In order to keep the suspension performance unchanged under the condition of clearance time-delay, the control parameters need to be adjusted.

When the gap time-delay is 0.005s, the control parameters are changed to keep the dynamic performance of the system unchanged.

$$k_p = 3474,\ k_d = 65 \qquad (25)$$

At this time, the gap response is shown in figure 3.

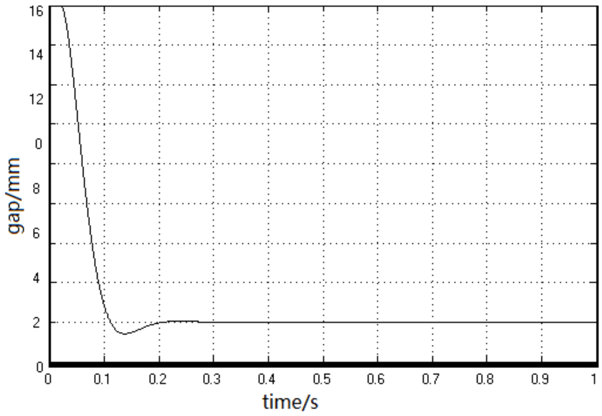

Figure 3. Gap response with time-delay of 0.005 seconds

When the gap time-delay is 0.01s, In order to keep the dynamic performance of the system unchanged, the control parameters are changed to:

$$k_p = 3674, k_d = 85 \tag{26}$$

At this time, the gap response is shown in the following figure:

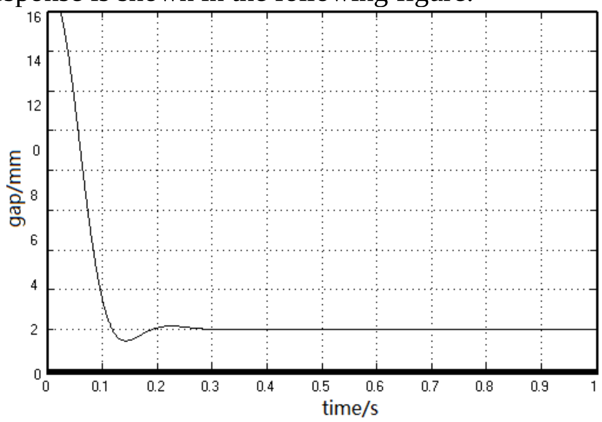

Figure 4. Gap response with time-delay of 0.01 seconds

From figure 3 and figure 4, it can be seen that the suspension performance of the system can be basically kept unchanged by changing the control parameters under the condition of gap tiem-delay. The change rule of the parameters is basically as follows: within the controllable range, the time-delay increases, and the control parameters should also increase.

6. Conclusion

In the design and debugging of the magnetic levitation control system, the filtering of the suspension gap will lead to the time-delay of the gap signal. In order to study the influence of gap time-delay on control performance, the stable region of control parameters is studied in this paper. The results show that the larger the time-delay of position signal is, the smaller the lower limit of the stability region of differential feedback coefficient is and the smaller the stability region is. If the control parameters remain unchanged, the system performance will deteriorate with the increase of time-delay, which will eventually lead to instability. In the case of gap time-delay, in order to keep the dynamic performance of the system unchanged, the proportional and differential feedback coefficients are increased. These conclusions provide a good reference for the debugging of control parameters in practical engineering.

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