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On Levitation Controller Design for Maglev Vehicles Considering Different Track Curves

***Abstract**. The model of maglev vehicle varies when the vehicle is on different track curves, which will affect the suspension performance and limit the vehicle's speed passing curves. The problem of model change can be settled when the nonlinear control method applied to the levitation system, in the control method the accelerometer output and second derivative of gap are applied. The adverse effect brought by the track curve change can be eliminated and the maglev suspension performance is invariable. The validity of the method is proved through simulation results.*

Streszczenie** Model pojazdu pociągu maglev zmienia się dla różnych krzywizn toru, co może wpłynąć na działanie zawieszenia i ogranicza szybkość pojazdu na krzywiźnie drogi. Problemu zmiany modelu można uniknąć przez zastosowanie, do systemu lewitacjj, nieliniowej metody sterowania oraz wykorzystania , w metodzie sterowania, wyjściowych danych akceleratora i różniczki drugiego rzędu względem szczeliny. W ten sposób można wyeliminować niekorzystny efekt wniesiony przez zmianę krzywizny toru i ustabilizować działanie zawieszenia. Symulacja dowodzi słuszności zastosowanej metody.* ***O projektowaniu sterownika lewitacji pojazdu szybkiej kolei maglev przy uwzględnieniu różnych krzywizn toru

Keywords: Maglev control, Feedback linearization, Track curves, Accelerometer.
Słowa kluczowe: Sterowanie kolei maglev, Linearyzacja ze sprzężeniem zwrotnym, Krzywizna toru, Akcelerometr

1. Introduction

Maglev techniques are widely utilized in application, such as maglev vehicles, magnetic bearings, magnetic suspension balance systems, magnetically levitated anti-vibration systems and so on[1]. Maglev vehicle technique is attracting more and more interest and going through the research period into the application period because of its dominant advantages. Maglev system is nonlinear and unstable, so active control should be applied to stabilize it. Research of suspension arithmetic is an important matter to maglev researcher, the familiar arithmetic which is applied to maglev system includes PID control arithmetic [2,3,4], state feedback control arithmetic [5,6,7], nonlinear feedback control arithmetic [8,9], and so on. In the literatures mentioned above, most of them only introduced how to apply the arithmetic to control the system, but not involved how to obtain the feedback signal, and those research works are based on the linear track and didn't consider the variety of track curve. Actually, the model of maglev system varies when the rain is on different track, for the matter is not considered in the common arithmetic, when the track curve changed the common arithmetic can not assure the coherence of the system's performance. The experiment result showed when the vehicle runs on the ramp or in/out transition curve there exits strong impact, that changed the steady suspension gap, and the faster the vehicle's speed the more the change. The relation of the velocity and the smallest ramp radius is discussed in literature [10], but the way how to improve the vehicle velocity to pass the ramp is not mentioned. When the common arithmetic is applied to maglev vehicle, to reduce the change of steady suspension gap and avoid the maglev vehicle hitting the track the only thing we can do is to limit the velocity or increase the curve radius. Obviously, limiting the velocity will weaken the maglev vehicle's advantage of high speed, and increasing the curve radius will waken the maglev vehicle's advantage of better climbing ability. To solve the proposed problems, accelerometer output and second derivative of gap are obtained and applied to the feedback linearization control arithmetic in this article, the maglev vehicle's model is united by this way and the suspension performance is invariable.

2. Description of track

Maglev track curves are various, however, considering influence to suspension performance, there are three types of track curves: straight, transient curve and ramp. There are two cases of transient curves, namely, the segment BC and segment DE in Figure 1. In the next content we can find the model of suspension system is different when the vehicle is on different track curves. In order to facilitate the subsequent description of the content, different track curves characteristics are described in Figure 1.

As shown in Figure 1, the traveling direction of the vehicle is from point A to point F, AB segment is straight , BC segment is transient curve, CD segment is ramp, DE segment is another section of the transient curve, EF segment is the straight. Under normal circumstances, the transient curve is sine curve or swing curves. Because there isn't ultra-high problem, the transient curve can be circular curve. Considering the difficulty of vehicle passing the curve, the circular curve is the most severe, if the vehicle can pass through the circular curve then it can pass through the other type curves [10], so we select the circular curve to analyze problem, supposing the radius of the circular curve is r , the gradient is α_0 .

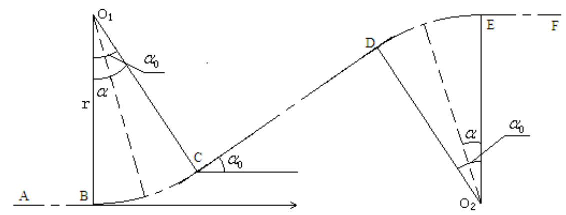

Fig..1. Sketch of track curve

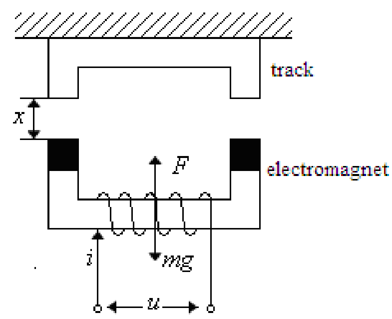

Fig.2. Single-point magnetic levitation system

3. Modelling

3.1 Model on straight AB or EF

A maglev vehicle is suspended more than one control point. For the decoupling function of the vehicle, each control point can be designed independently. Decoupling control is not the emphases in this article. In order to simplify the problem, we only analyze a single-point suspension system. Single-point suspension system generally includes compartments, secondary suspension system, suspension magnet and rail systems, etc. Under normal circumstances, in order to simplify the system, the track deformation impact on the system and the dynamic characteristics of the secondary suspension department are ignored. Not considering the impact of elastic rail and air spring system performance to the system performance, the single-point levitation system structure diagram is can be described in Figure 2 [11].

In Figure 2, x is levitation gap, F is electromagnetic force, mg is the gravity of the electromagnet, u is electromagnetic coil voltage, i is the coil current. When the vehicle is on the straight AB segment or EF segment shown in Figure 1， based on mechanical and electrical knowledge, the model of single-point levitation system in the orbital coordinate system is [11]:

(1) $$\begin{cases} \ddot{x} = g - ki^2/mx^2 \\ u = Ri + (2k/x)\dot{i} - (2ki/x^2)\dot{x} \end{cases}$$

In (1), R is the resistance of the electromagnet, k is the electromagnetic force coefficient, the first equation in (1) is the mechanical equation, the second equation in (1) is the electrical equation.

3.2 Model on transient curve BC

In Figure 1, when the vehicle is on the transient curve BC, the force to the magnet in the suspension direction includes magnetic force $-ki^2/x^2$, centrifugal force mV^2/r, the component of gravity in the levitation direction $mg\cos\alpha$, the electrical equation dose not change, so the single-point levitation system is :

(2) $$\begin{cases} \ddot{x} = g\cos\alpha + V^2/r - ki^2/mx^2 \\ u = Ri + (2k/x)\dot{i} - (2ki/x^2)\dot{x} \end{cases}$$)

In the expression (2), V is the velocity of the vehicle.

3.3 Model on ramp CD

In Figure 1, when the vehicle is on the ramp CD, the force to the magnet in the suspension direction includes magnetic force $-ki^2/x^2$ and the component of gravity in the levitation direction $mg\cos\alpha_0$, the electrical equation dose not change, so the single-point magnetic levitation system is :

(3) $$\begin{cases} \ddot{x} = g\cos\alpha_0 - ki^2/mx^2 \\ u = Ri + (2k/x)\dot{i} - (2ki/x^2)\dot{x} \end{cases}$$

3.4 Model on transient curve DE

In Figure 1, when the vehicle is on the transient curve DE, the force to the magnet in the suspension direction include magnetic force $-ki^2/x^2$, centrifugal force $-mV^2/r$, the component of gravity in the levitation direction $mg\cos\alpha$, the electrical equation dose not change, so the single-point magnetic levitation system is :

(4) $$\begin{cases} \ddot{x} = g\cos\alpha - V^2/r - ki^2/mx^2 \\ u = Ri + (2k/x)\dot{i} - (2ki/x^2)\dot{x} \end{cases}$$

From expressions (1), (2), (3), (4) we can find the model of the single-point levitation system is different when the vehicle is on different curves.

4. Control method

.1 Control law when the vehicle on different curves

4.1.1 The vehicle is on straight AB

When the vehicle is on the straight segment AB or EF, in order to meet the global stability of the system, nonlinear control method based on feedback linearization is adopted. Based on the theory of feedback linearization, to the model (1), after the following substitution of state variables and input, we can get the new model [12]:

(5) $$\begin{cases} z_1 = x \\ z_2 = \dot{x} \\ z_3 = g - ki^2/mx^2 \end{cases}$$

(6) $$u_1 = Ri - \frac{mx}{i}v$$

From the expression (1), (5) and (6), the model (1) is linearized and the linear model is:

(7) $$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} v$$

To the linear model (7), state feedback control method is adopted and the control law is as the following:

(8) $$v = k_1(z_1 - z_0) + k_2 z_2 + k_3 z_3$$

In expression (8), z_0 is steady suspension gap.

Substitute (5) to (8), substitute (7) to (6), we can get the final expression of control law:

(9) $$u_1 = Ri - \frac{mx}{i}\left(k_1(x - x_0) + k_2\dot{x}\right) - \frac{k_3 mx}{i}\left(g - \frac{ki^2}{mx^2}\right)$$

In the expression (9), x_0 is steady suspension gap.

4.1.2 The vehicle is on transient curve BC

When the vehicle is on the transient segment BC, using the same method as section 3.1.1, in order to linearize the model (2), the substitution of state variables and control law are as the following:

(10) $$\begin{cases} z_1 = x \\ z_2 = \dot{x} \\ z_3 = g\cos\alpha + V^2/r - ki^2/mx^2 \end{cases}$$

(11) $$u_2 = Ri - \frac{mx}{i}v$$

And the final control law is:

(12) $$u_2 = Ri - \frac{mx}{i}\left(k_1(x - x_0) + k_2\dot{x}\right) - \frac{mx}{i}k_3\left(g\cos\alpha + \frac{V^2}{r} - \frac{ki^2}{mx^2}\right)$$

4.1.3 The vehicle is on ramp CD

When the vehicle is on the ramp CD, using the same method as section 3.1.1, in order to linearize the model (3), the substitution of state variables and control law are as the following:

(13) $$\begin{cases} z_1 = x \\ z_2 = \dot{x} \\ z_3 = g\cos\alpha_0 - ki^2/mx^2 \end{cases}$$

(14) $$u_3 = Ri - \frac{mx}{i}v$$

And the final control law is:

(15) $$u_3 = Ri - \frac{mx}{i}\left(k_1\left(x - x_0\right) + k_2\dot{x}\right) - \frac{mx}{i}k_3\left(g\cos\alpha_0 - \frac{ki^2}{mx^2}\right)$$

4.1.4 The vehicle is on transient curve DE

When the vehicle is on the transient curve DE, using the same method as section 3.1.1, in order to linearize the model (4), the substitution of state variable and control law are as the following:

(16) $$\begin{cases} z_1 = x \\ z_2 = \dot{x} \\ z_3 = g\cos\alpha - V^2/r - ki^2/mx^2 \end{cases}$$

(17) $$u_4 = Ri - \frac{mx}{i}v$$

And the final control law is:

(18) $$u_4 = Ri - \frac{mx}{i}\left(k_1\left(x - x_0\right) + k_2\dot{x}\right) - \frac{mx}{i}k_3\left(g\cos\alpha - \frac{V^2}{r} - \frac{ki^2}{mx^2}\right)$$

From the final control law expressions (9), (12), (15) and (18) we can find that in order to linearize the system different control law should be applied when the vehicle is on different track curve. In fact, which type of track curve the vehicle is on is unknown, this condition greatly limits the use of nonlinear feedback control method in the magnetic levitation system, and reducing the usefulness of the above method. The key to solve the problem is how to get a unified control law while the vehicle is on different track curve. To solve this problem mentioned above, an accelerometer is installed on the electromagnet.

4.2 Output of Accelerometer

The accelerometer is installed on the electromagnet. Accelerometer's horizontal plane is parallel to the polar of electromagnet. The output of the accelerometer is the electromagnet's acceleration in the levitation direction. Here we describe the output of accelerometer when the vehicle is on different track curves.

4.2.1 The vehicle is on straight AB

When the vehicle is on straight segment AB, the accelerometer's output a includes the acceleration of the gravity g, the electromagnet's moving acceleration $\ddot{x}$ in the levitation direction, so the accelerometer's output is :

(19) $$a = g + \ddot{x}$$

4.2.2 The vehicle is on transient curve BC

When the vehicle is on transient curve BC, the accelerometer's output a includes the component of the gravity $g\cos\alpha$, the electromagnet's moving acceleration $\ddot{x}$ in the levitation direction and the centrifugal acceleration V^2/r, so the accelerometer's output is :

(20) $$a = g\cos\alpha + \ddot{x} + V^2/r$$

4.2.3 The vehicle is on ramp CD

When the vehicle is on ramp CD, the accelerometer's output a includes the component of the gravity $g\cos\alpha_0$ and the electromagnet's moving acceleration $\ddot{x}$ in the levitation direction, so the accelerometer's output is:

(21) $$a = g\cos\alpha_0 + \ddot{x}$$

4.2.4 The vehicle is on transient curve DE

When the vehicle is on transient curve DE, the accelerometer's output a includes the component of the gravity $g\cos\alpha$, the electromagnet's moving acceleration $\ddot{x}$ in the levitation direction and centrifugal acceleration $-V^2/r$, so the accelerometer's output is :

(22) $$a = g\cos\alpha + \ddot{x} - V^2/r$$

4.3 Unified form of control law

From section 4.1 we know the control law form is different when the vehicle is on different track curves, in order to unify the control law form, accelerometer is fixed on the electromagnet. The following content will show how to unify the control law expression when the vehicle is on different track curve.

4.3.1 The vehicle is on straight AB

When the vehicle is on the straight AB, from expression (19), we can get the following expression:

(23) $$g = a - \ddot{x}$$

Substitute (23) to (9), the control law is:

(24) $$u_1 = Ri - mx\left(k_1\left(x - x_0\right) + k_2\dot{x}\right)/i - mxk_3\left(a - \ddot{x} - \frac{ki^2}{mx^2}\right)\Big/i$$

4.3.2 The vehicle is on transient curve BC

When the vehicle is on the straight BC, from expression (20), we can get the following expression:

(25) $$g\cos\alpha + V^2/r = a - \ddot{x}$$

Substitute (25) to (12), the control law is:

(26) $$u_2 = Ri - mx\left(k_1\left(x - x_0\right) + k_2\dot{x}\right)/i - mxk_3\left(a - \ddot{x} - \frac{ki^2}{mx^2}\right)\Big/i$$

4.3.3 The vehicle is on ramp BC

When the vehicle is on the ramp CD, from expression (21), we can get the following expression:

(27) $$g\cos\alpha_0 = a - \ddot{x}$$

Substitute (27) to (15), the control law is:

(28) $$u_3 = Ri - mx\left(k_1\left(x - x_0\right) + k_2\dot{x}\right)/i - mxk_3\left(a - \ddot{x} - \frac{ki^2}{mx^2}\right)\Big/i$$

4.3.4 The vehicle is on transient curve DE

When the vehicle is on the transient curve DE, from expression (22), we can get the following expression:

(29) $$g\cos\alpha - V^2/r = a - \ddot{x}$$

Substitute (27) to (15), the control law is:

(30) $$u_3 = Ri - mx\left(k_1\left(x - x_0\right) + k_2\dot{x}\right)/i - mxk_3\left(a - \ddot{x} - \frac{ki^2}{mx^2}\right)\Big/i$$

Compare the control law expression (24), (26), (28) and (30), it shows that after the quadratic differential of gap and accelerometer's output are applied to feedback control method the control law forms are unified when the vehicle is on different track curves.

4.4 Design of feedback control coefficient

For the linearized system, poles placement method is used to design the state feedback coefficient. Supposing the performance of the system is designed as: overshoot is 5%, adjust time is $0.1s$. If considering a third-order system, there will be a lot of mathematical calculations, the control method is complex and its practicality can not be guaranteed. For the reason, the ideology of the dominant pole is applied [13]. First, two dominant poles of the system are designed to make the system performance meet the design requirements, and then the third pole is designed farer away from the imaginary axis than the dominant poles.

The dominant pole can be calculated in accordance with the above performance:

$s_1 = -20 + 42.925j$, $s_2 = -20 - 42.925j$

In order to make the overall system performance is mainly determined by the dominant poles, the third pole is designed farer away from the imaginary axis than the dominant poles. The third pole is designed as the following:

$$s_3 = -200$$

From the three poles designed before, the characteristic equation of the system is:

(31) $$s^3 + 280s^2 + 19357.712s + 671542 = 0$$

Appling feedback control method to the linearized system (7), substitute (8) to (7), the closed-loop system's characteristic equation is:

(32) $$s^3 - k_3 s^2 - k_2 s - k_1 = 0$$

In order to assure the system's performance meet the requirement, the coefficients in the expression (31) should be equal to the coefficients in the expression (32). Compare the expression (31) to the expression (32) the feedback control coefficients are:

$k_1 = -671542$, $k_2 = -19357.712$, $k_3 = -280$

5. Simulation results

Taking one magnetic levitation system as the object, the system parameters are as the following:

$k = 0.00545$, $m = 725$ kg, $x_0 = 0.012$ m, $R = 4.44\Omega$, $r = 500$ m, $V = 60$ m/s

The track curve parameters are as the following:

$\tan\alpha_0 = 0.07$ AB=30m，BC=30m, CD=30m，DE=30m，EF=30m

By the Simulink tools of MATLAB [14], the simulation result when the PID control method is applied to magnetic levitation system is shown in Figure 3, the simulation result when the textual control method is applied to magnetic levitation system is shown in Figure 4.

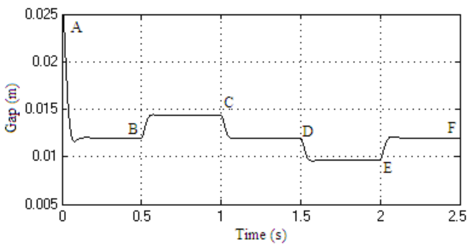

Fig.3. Simulation result of PID control method

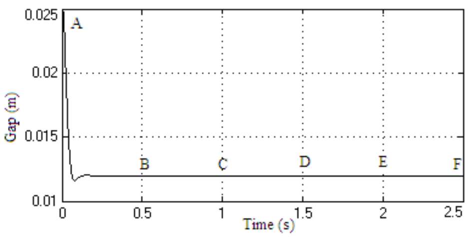

Fig.4. Simulation result of textual control method

In Figure 3 and Figure 4, points A, B, C, D, E, F are correspond to points A, B, C, D, E, F in Figure 1. The Figure 3 shows that the stable levitation gap changes when the vehicle is on different track curves if the PID control method is applied. The figure 4 shows that the stable levitation gap does not change when the vehicle is on different track curves if the control method proposed in this paper is applied. This character can enhance the security of the maglev vehicle.

From the first equation of the model on the straight segment model (1) and on the transition curve model (2) we can see, at the moment when the vehicle entering the transition curve, it is equivalent that there is force impact to the vehicle. The force impact is related to the vehicle running speed and the radius of the transient curve, the faster the speed and the greater the impact, the smaller the radius the greater the impact. When the value of the speed and radius satisfy certain conditions the vehicle will hit the track. In experiment, there were a number of cases that the vehicle hit track when traditional PID control method is applied, the following simulation result in Figure 5 demonstrates this phenomenon

When the PID control method is used, the control parameters are adopted as before. When V^2/r =20, the simulation result is shown in Figure 5:

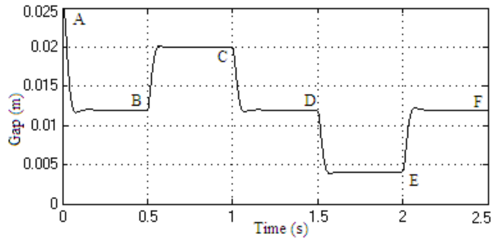

Fig.5. V^2/r=20，simulation result of PID control method

Under normal circumstances, when the vehicle landing on the track, the gap between the electromagnets and the track is about 20mm, from Figure 5 can be seen, the vehicle hit the track. From the simulation result we can see, when the vehicle entering the transition curve the vehicle hit the track if the vehicle speed and the radius of the transition curve meet certain conditions. (Note: to the PID control method, when the control parameter is different, the system resistance to external impact is different, so the conditions under which the vehicle hit the track when the vehicle entering the transient curve is different).

6.Conclusion

Maglev track curve's variety will change the mathematical model of suspension system and has adverse influence on the suspension performance. This paper presents the application of accelerometers and the second gap differential to nonlinear feedback control method to solve the problem of track curve's adversely effect to the suspension performance, eliminating the speed limit of vehicle in/out transient curve when the conventional suspension control algorithm is used, highlighting the maglev vehicle advantage of faster speed. There is some inspired effect for practical magnetic levitation control algorithm design in the paper.

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