The Design of a Magnetic Levitation Controller Based on the Study of Coupling Vibration

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Abstract

Based on the model of magnetic levitation state feedback system, the paper analyzes the system stability, and finds out the condition of vibration and vibration frequency. In sequence the system is simulated to validate the analytical results. At last the essential causation of vibration is discussed and a new control algorithm of adjusting the real-time controller parameters is brought forward to eliminate the coupling vibration between the vehicle and guideway and to enhance the performance of levitation control.

1 Introduction

Maglev train is a new ground tracked vehicle that is levitated, guided, driven and braked by electromagnetism. The maglev system has a bright prospect because it will offer the advantages of lower noise and emissions and better ride quality, as well as potential energy savings and economic benefits, relative to conventional guideway systems[1-2]. The levitation control is one of the most key technologies in the system. All researchers are focusing on the coupling vibration between the vehicle and guideway in resent years, which is the content of this paper. Based on the model of magnetic levitation state feedback system, the paper analyzes the system stability, and finds out the condition of vibration and vibration frequency. In sequence the nonlinear system is simulated to validate the analytical results. At last the essential causation of vibration is discussed and a new control algorithm of adjusting the real-time controller parameters is brought forward to eliminate the coupling vibration between the vehicle and guideway and to enhance the performance of levitation.

2 Modeling the Levitation Control System

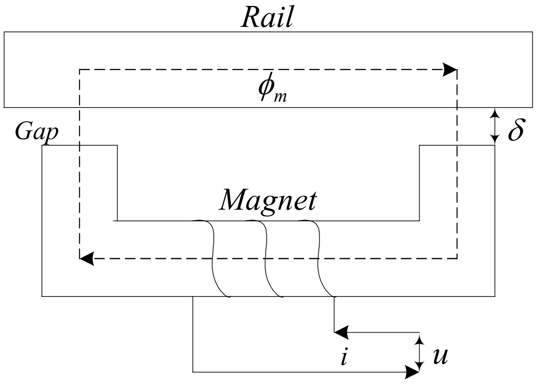


Fig.1 The model of levitation control system

The levitation control system is shown in fig.1, which is a nonlinear system. The one-order linear state-space equation is:

$$\dot{X} = A \cdot X + B \cdot v \tag{1}$$

$$\text{where } X = \begin{pmatrix} \Delta\delta \\ \dot{\delta} \\ \Delta i \end{pmatrix}, \quad A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{F_\delta}{M} & 0 & -\frac{F_i}{M} \\ 0 & \frac{i_0}{\delta_0} & -\frac{R}{L_0} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L_0} \end{bmatrix}, \quad v = \Delta u \tag{2}$$

$$F_\delta = \frac{\mu_0 A N^2}{2} \cdot \frac{i_0^2}{\delta_0^3}, \quad F_i = \frac{\mu_0 A N^2}{2} \cdot \frac{i_0}{\delta_0^2}, \quad L_0 = \frac{\mu_0 A N^2}{2\delta_0} \tag{3}$$

M is the mass of magnet and loads; δ is the gap between magnet and guideway; i is the current flowing in the coil; u is the voltage of coil; μ_0 is the free-space permeability; A is valid area of magnet; N is the circles of coil; R is the resistance of the coil; δ_0 is the given gap; and i_0 is the balance current and the relationship between it and mass is :

$$i_0 = \sqrt{\frac{4Mg\delta_0^2}{\mu_0 A N^2}} \tag{4}$$

3 The System Stability Analysis

3.1 The Linear System Stability Analysis

This paper employs a state-feedback controller hereby:

$$v = KX, \quad K = \begin{bmatrix} k_p & k_d & -k_i \end{bmatrix}, \tag{5}$$

Table 1. Routh Table

	First Column	Second Column
s^3	$a_0 = 1$	$a_2 = \frac{F_i i_0}{M\delta_r} + \frac{F_i k_i k_d}{ML_0} - \frac{F_\delta}{M}$
s^2	$a_1 = \frac{R+k_i}{L_0}$	$a_3 = \frac{F_i k_i k_p}{ML_0} - \frac{F_\delta (R+k_i)}{ML_0}$
s^1	$b = \frac{a_1 a_2 - a_0 a_3}{a_1} = \frac{F_i i_0}{M\delta_r} + \frac{F_0 k_i k_d}{ML_0} - \frac{F_i k_i k_p}{M(R+k_i)}$	
s^0	$c = \frac{F_i k_i k_p}{ML_0} - \frac{F_\delta (R+k_i)}{ML_0}$	

And the system state-space function is evolved into:

$$\dot{X} = (A + B \cdot K)X \tag{6}$$

The system characteristic polynomial is:

$$\lambda^3 + \frac{R+k_i}{L_0}\lambda^2 + \left(\frac{F_i i_0}{M\delta_r} + \frac{F_i k_i k_d}{ML_0} - \frac{F_\delta}{M}\right)\lambda + \left(\frac{F_i k_i k_p}{ML_0} - \frac{F_\delta (R+k_i)}{ML_0}\right) = 0 \tag{7}$$

Routh criterion is applied to solve the stable problem of linear system. The Routh table is given as Table 1 according to the equation (7).

According to Routh criterion[4], the following results are known:

(1) The system is stable when the first column of table 1 are greater than zero, i.e. the equation (7) satisfies.

$$\begin{cases} \frac{F_i i_0}{M\delta_r} + \frac{F_i k_i k_d}{ML_0} - \frac{F_i k_i k_p}{M(R+k_i)} > 0 \\ \frac{F_i k_i k_p}{ML_0} - \frac{F_\delta (R+k_i)}{ML_0} > 0 \end{cases} \tag{8}$$

Solve it and the stable region is expressed as inequality (9):

$$p < k_p < qk_d + p \tag{9}$$

Where p and q are constants, $p = \frac{i_0}{\delta_0} \cdot \frac{R+k_i}{k_i}$, $q = \frac{R+k_i}{L_0}$

(2) The system may vibrate when $c > 0$ and $b = 0$, i.e. equation (10) satisfies.

$$\begin{cases} \frac{F_i i_0}{M\delta_r} + \frac{F_i k_i k_d}{ML_0} - \frac{F_i k_i k_p}{M(R+k_i)} = 0 \\ \frac{F_i k_i k_p}{ML_0} - \frac{F_\delta (R+k_i)}{ML_0} > 0 \end{cases} \tag{10}$$

Solve it and the stable region is expressed as inequality (11):

$$p < k_p = qk_d + p \tag{11}$$

The vibration frequency is $f = \frac{1}{2\pi} \cdot \sqrt{\frac{a_3}{a_1}}$, i.e.,

$$f = \frac{1}{2\pi} \sqrt{\frac{F_i k_i k_p}{M(R + k_i)} - \frac{F_\delta}{M}} \tag{12}$$

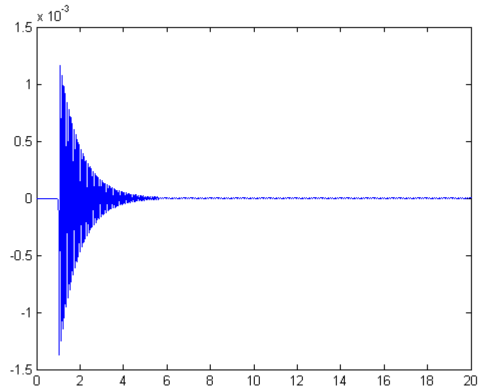
Lyapunov had proved that the solutions of a system would be asymptotically stable if the real of all eigenvalues of one-order approximate equation is less than zero [4]. That is, expression (9) is the stable region of nonlinear system. But the vibration condition and vibration frequency of the nonlinear system needs to be validated by simulation.

3.2 Nonlinear System Simulation

During the simulation the system parameters are set as below:

$A = 840 \times 28mm^2$, $N = 320$, $R = 0.5\Omega$, $\delta_0 = 10mm$, $M = 500kg$ and $k_i = 30$ [5].

$i_0 = 25.71A$, which is evaluated from expression (4).



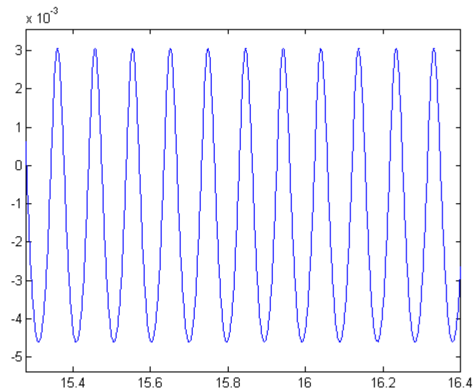


Fig.2(a) System is asymptotically stable when $k_d = 30$ Fig.2(b) System vibrates when $k_d = 26.73$

According to expressions (9), the system is stable when $2614 < k_p < 202k_d + 2614$.

When k_p equals to 8000 and k_d is set 20, 26.73, 30 in turn, the simulation results are given as figure 2. The vibration frequency is about $10.3Hz$ in figure 2(b), which is according to the result $10.22Hz$ from expression (12). The simulation results validate the analysis conclusions.

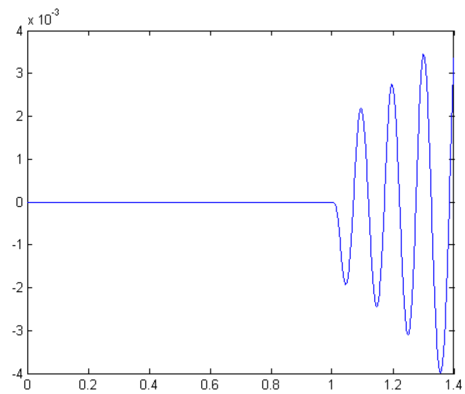


Fig.2(c) System diverges when $k_d = 20$

4 The Design of an Improved Magnetic Levitation Controller

The coupled vibration of vehicle and guideway often appears during the levitation test. The fact shows the vibration with a frequency and fixed amplitude is caused from the vehicle-guideway interaction. Equation (11) tells the vibration condition. Though k_p and k_d are designed parameters that can be known and modified, others parameters, such as (p, q) are unknown because of model errors and vary during running. If the varying parameters satisfy the equation (11), the vibration will occur.

A series of steps are applied to eliminate the vibration. The first step is to monitor the vibration and evaluate the levitation effect and the second is to destroy the equation (11) by two methods: magnifying k_d or reducing k_p. Magnifying k_d is applied before reducing k_p because the latter may cause k_p does not satisfy $k_p > p$. If the vibration disappears, the expected object achieves.

k_d represents the gain of velocity feedback and magnifying k_d means magnifying the damp of system. The velocity signal is developed from signal processing, which is accompanied with noises and loses phase because of filter. So magnifying k_d cannot guarantee to magnify the damp and eliminate the vibration.

In order to eliminate the vibration, two questions should be finished according to the analysis above. The first aspect is to make the velocity signal be closed to true velocity; the second one is to search best k_p and k_d under certain condition. For first aspect, the state observation in reference [6] is valid, which combines gap and acceleration into velocity signal. The second aspect is mainly discussed here.

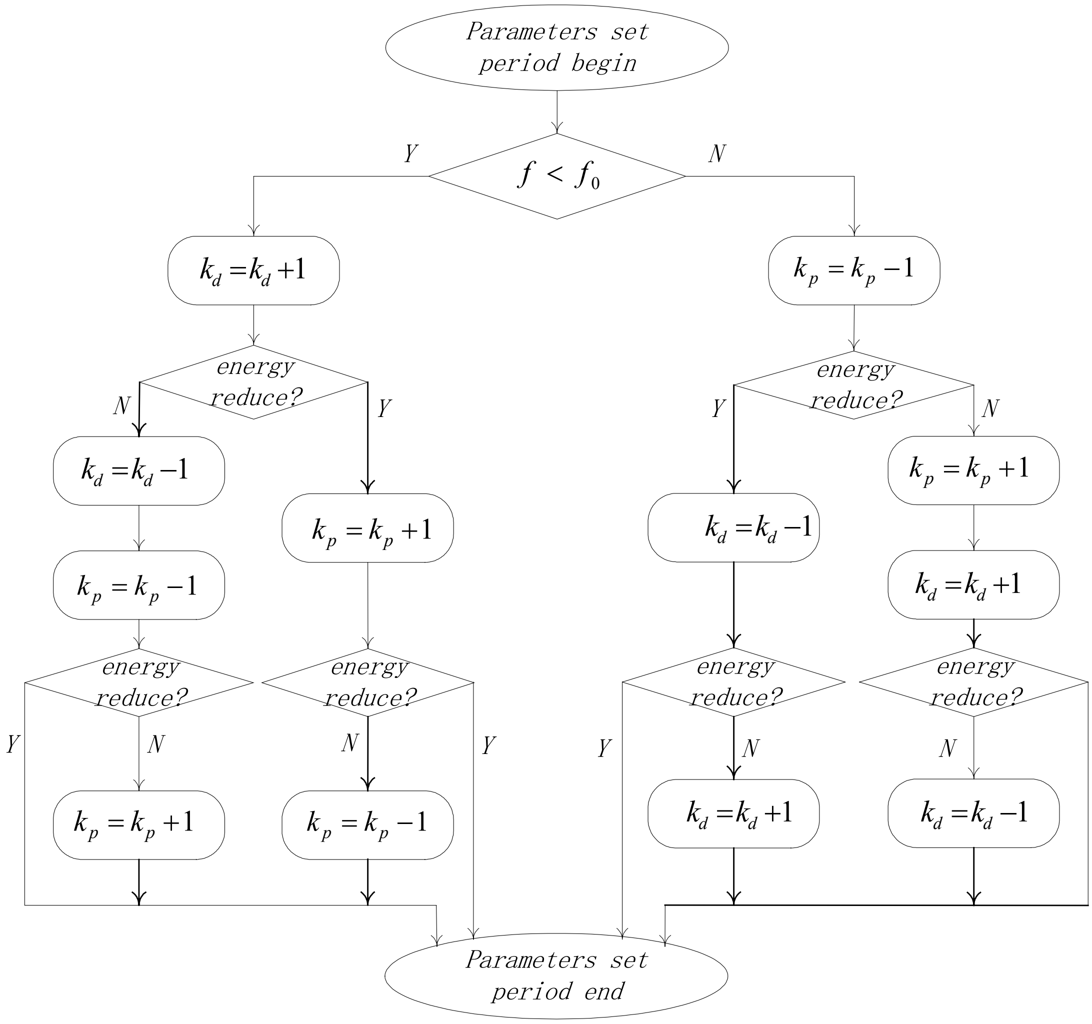


Fig.3 The improved controller design flow

In order to adjust the controller parameters, the levitation performance such as vibration frequency and energy herein is needed to evaluate firstly. According to equation (12), the vibration frequency may be judged by k_p. High vibration frequency means the value of k_p is large. The vibration energy is the function of frequency and amplitude and is used to evaluate the levitation performance. The more energy, the worse levitation performance is. Reference [7] provides a method to observe the vibration frequency and amplitude by Kalman filter. FFT may be a general method in most cases[8].

Basing on the calculation of vibration frequency and energy, this paper brings forward a new controller arithmetic shown in figure 3, where f_0 is the expected frequency. The controller adjusts the parameters during the period of parameters set, which is working in real-time and in parallel with control arithmetic.This controller can optimize the system energy and set system frequency as the expected one.

5 Conclusion

In conclusion, the paper calculates magnetic levitation system vibration condition and vibration frequency by theoretical analysis and simulation. Based on the analysis results, a new method is brought forward to minimize even eliminate the vibration by the observation of frequency and energy estimation.

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