CHARACTERITICS OF MODIFIED PD CONTROL OF ELECTROMAGNETIC SUSPENSION SYSTEM FOR NON-CONTACT STEEL PLATE CONVEYANCE

Dehong Xu, Xiao Sun and Wei Feng
The Department of Electrical Engineering
Zhejiang University, Hangzhou 310027, China
Fax:+86+571+7951625 Email: ee_office@ema.zju.edu.cn

ABSTRACT-Based on the linear model of electromagnetic suspension (EMS) system, it is able to be further simplified into a standard second-order model with a modified PD control. In this paper static and dynamic characteristics of EMS with modified PD control are investigated when suspended weight of steel plate changes. A experimental system has been built to verify static and dynamic characteristics of EMS system. Simulation and experiment results are both given.

1. INTRODUCTION

Electromagnetic suspension (EMS) system has been applied to Maglev train, magnetic bearing, induction heating furnace[1]. In steel plate processing industry, the application of a magnetic levitation to steel plate conveyance is also expected. The advantages of non-contacted conveyance of steel plates are perfect surface quality of steel plate and low noise , as shown in Fig.1.

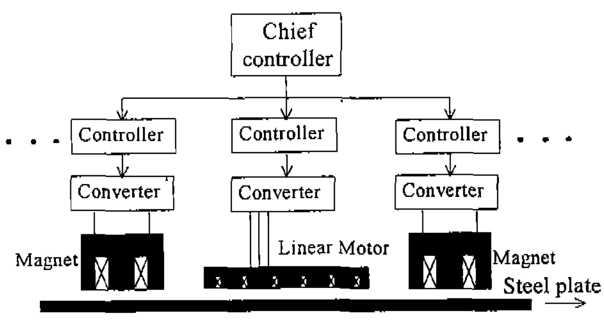


Fig.1 Non-contacted Conveyance of Steel Plates

Since steel plates have characteristics of beam which is easily excited by disturbance, it is hard to reach stable suspension. Vibration suppression of steel plate conveyance system with EMS has been investigated.[2][3] For practical application, it is necessary for the steel plate conveyance system with EMS to adapt to changes of weight which results from variation of thickness and size of suspended steel plates.

Modified PD control has been introduced to simplify steel plate conveyance system with EMS into a standard second-order model by predecessor. However characteristics of Modified PD control with changing of weight of suspended steel plates has not been investigated before. In this paper, the static and dynamic characteristics are studied when suspended weight varies. A experimental system is built to verify static and dynamic characteristics of EMS system for steel plate.

2. MODEL OF THE EMS SYSTEM WITH MODIFIED PD CONTROL

Generally, it is assumed that

- The distribution of the magnetic field in the airgap is uniform.
- The iron core of an electric magnet and a suspending steel plate are ideal magnetic conductor, i.e., the permeability of the iron core of the magnet and the steel plate are infinite.

Thus, a EMS system can be described by[4]:

$$\begin{cases} m\ddot{y}(t) = -F_m(y,i) + mg + f_d(t) & (1) \\ u(t) = R\cdot i(t) + \dfrac{\mu_0 AN^2}{2y(t)}\cdot \dot{i} - \dfrac{\mu_0 AN^2 i(t)}{2y(t)^2}\cdot \dot{y} & (2) \end{cases}$$

Where $F_m(y,i)=\frac{\mu_0 AN^2 i(t)^2}{4y(t)^2}$ is attractive force, mg is suspended weight, y is airgap length, f_d is disturbing force, A is area of magnet poles, N is the number of windings of the magnet coil, R is resistance of magnet coil and μ_0 is the permeability of air.

Through linearization and Laplace transform, we obtain:

$$\Delta Y(s)=\frac{-K_i/mL_0}{s^3+\frac{R}{L_0}s^2-\frac{RK_y}{L_0 m}}\Delta U(s)$$

$$+\frac{(s+R/L_0)/m}{s^3+\frac{R}{L_0}s^2-\frac{RK_y}{L_0 m}}\Delta f_d(s) \tag{3}$$

with

i_0: Current in the magnet coil when airgap is fixed in y_0

$$i_0=\frac{2y_0}{N}\sqrt{\frac{mg}{\mu_0 A}} \tag{4}$$

L_0: Inductance of magnet coil

$$L_0=\frac{\mu_0 AN^2}{2y_0} \tag{5}$$

K_i: Force-current factor

$$K_i=L_0 i_0/y_0 \tag{6}$$

K_y: Force-displacement factor

$$K_y=K_i i_0/y_0 \tag{7}$$

PD Control

Conventionally PD control is used to stabilize EMS. The controller can be described by:

$$\Delta u=K_p(\Delta y-\Delta y^*)+K_d(\Delta\dot{y}-\Delta\dot{y}^*)-K_c\Delta i \tag{8}$$

Where K_p, K_d are proportional and derivative factor of airgap error respectively and K_c is proportional factor of current error. Due to large inductance of magnet coil, a large negative current feedback is generally used to reduce the lag of the electromagnetic system. Since K_c is so large that minor loop of current control can be treated as a proportional factor of $1/K_c$. Therefore, the whole system can be simplified to be a second order transfer-function.

$$\frac{\Delta Y(s)}{\Delta Y^*(s)}=\frac{K_i(K_d s+K_p)/K_c m}{s^2+\frac{K_i}{K_c m}(K_d+K_i)s+\frac{1}{m}(\frac{K_p K_i}{K_c}-K_y)} \tag{9}$$

It can be observed that the closed loop system have a zero and is not a standard second-order system.

Modified PD Controller

If we modify the controller into:

$$\Delta u=K_p\Delta y-K_g\Delta y^*+K_d\Delta\dot{y}-K_c\Delta i \tag{10}$$

then the transfer-function of the closed loop system will changed into:

$$\frac{\Delta Y(s)}{\Delta Y^*(s)}=\frac{K_i K_g/K_c m}{s^2+\frac{K_i}{K_c m}(K_d+K_i)s+\frac{1}{m}(\frac{K_p K_i}{K_c}-K_y)} \tag{11}$$

which has the form of a standard second-order model as shown below.

$$H(s)=\frac{\omega_n^2}{s^2+2\xi\omega_n s+\omega_n^2} \tag{12}$$

Where ω_n is natural frequency and ξ is damping ratio. Since the characteristics of a standard second order model is decided by ξ and ω_n, K_p, K_d and K_g are chosen according to the requirement of ξ and ω_n.

3. EFFECTS OF SUSPENDED WEIGHT DEVIATION ON EMS CHARACTERISTICS

Parameters of EMS model studied are listed below.

Weight of steel plate: $mg=27.6N$

Number of coil in a Magnet: $N=251$

resistance of coil of a magnet: $R=0.5\ Ohm$

Sectional Area of a magnet pole: $A=1.76\times10^{-4}m^2$

Two modified PD controllers are investigated. One controller is got from the linearized EMS model with linearized operation point of airgap y_0=2mm. The PD controller is

$$\Delta u = 1248840\Delta y - 358766\Delta y^* + 8047\Delta \dot{y} - 1000\Delta i$$

Here it is named as 2mm controller. The other one is got from the linearized EMS model with linearized operation point of airgap y_0=5mm. :

$$\Delta u = 1786986\Delta y - 896906\Delta y^* + 20182\Delta \dot{y} - 1000\Delta i$$

Here it is called 5mm controller.

Effect of Suspended Weight on Static Characteristics

According to Equ.(4)~(7) and Equ.(11), the DC gain of the linearized model is:

$$K_0 = \frac{K_g}{K_p - \sqrt{\frac{4mg}{\mu_0 AN^2}} \cdot K_c} \quad (13)$$

It is shown that variation of suspended weight mg will cause changing of DC gain K_0. It results in static error in air gap.

According to linear control theory, steady-state error of air gap can be described by:

$$\Delta = (K_0 - 1)y^* . \quad (14)$$

Steady-state error is proportioned to setting air gap reference value when $K_0 - 1$ are constant.

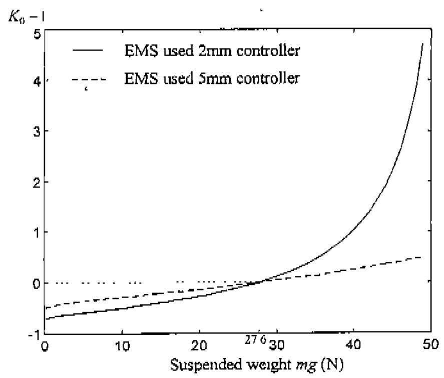


Fig.2 Relationship of $K_0 - 1$ with mg

Fig.2 is relationship between $K_0 - 1$ and mg. We can see that $K_0 - 1$ is equal to zero with designed weight mg=27.64N. If suspended weight is equal to designed value, steady-state airgap error is zero. Steady-state air gap error increases when deviation of suspended weight from designed weight increases. Increase of suspended weight from designed one will result in positive steady-state error while decrease of suspended weight from the designed one will result in negative steady-state error. Absolute value of steady-state error is proportioned to deviation from the designed weight.

Effect of Suspended Weight on Dynamic Characteristics

Here, ξ=0.707 and ω_n=62.8rad/s(f=10Hz) are selected to get good dynamic characteristics. With the standard second order model, it can be deducted that the settling time $t_s \approx \frac{4}{\xi\omega_n} \approx 70ms$ and overshoot $\sigma = e^{-\pi\xi/\sqrt{1-\xi^2}} = 4.5\%$. Based on Equ.(4)~(7) and (11), we obtain:

$$\omega_n = \sqrt{\frac{K_p K_i}{K_c m} - \frac{K_y}{m}}$$

$$\xi = \frac{(K_d + K_i)K_i}{2mK_c\omega_n} = \frac{K_i K_d}{2mK_c\omega_n} \quad (K_d >> K_i) \quad (15)$$

That means the change of suspended weight will also influence the dynamic characteristics of EMS system. Settling time t_s and overshoot σ vary when suspended weight varies. Fig.3 and Fig.4 are relationship of t_s, σ with suspended weight mg respectively.

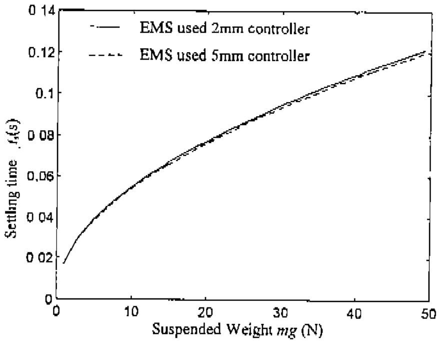


Fig.3 Relationship of *ts* with *mg*

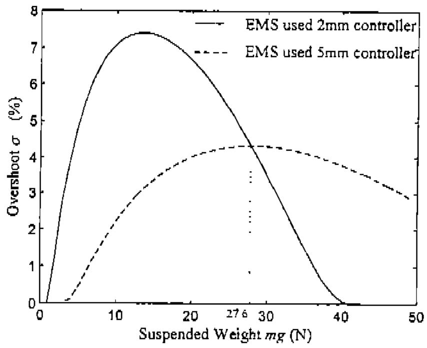


Fig.4 Relationship of σ with *mg*

From Fig. 3, we can see that settling time increases when suspended weight increases. From Fig.4 we can see that overshoot varies with change of suspended weight.

4. SIMULATION AND EXPERIMENT

Based on Equ.(1) and (2), a non-linear simulation model and an experimental EMS system(Shown in Fig.5) is used to verify characteristics of EMS with modified PD control. The parameters of both simulation and experiment are the same as parameters given in section 3. Two Modified PD controller .i.e. 2mm controller and 5mm controller, are investigated in both Simulation and experiment.

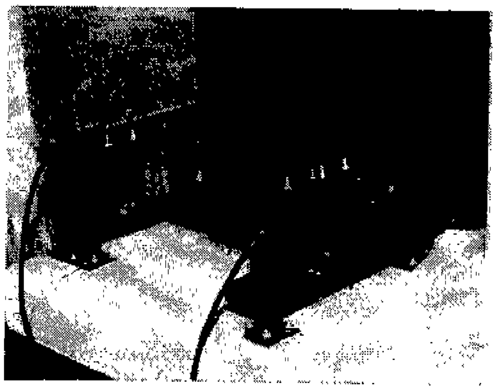


Fig.5 Photograph of Experimental EMS System

Static Characteristics

Suspended weight is changed from designed weight of 27.6N to 18.4N and 39.3N respectively in simulation and experimental.

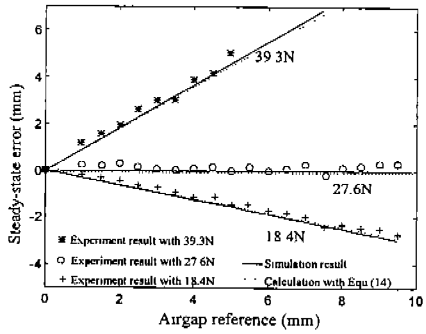


Fig.6 Steady-state error of EMS system with 2mm controller

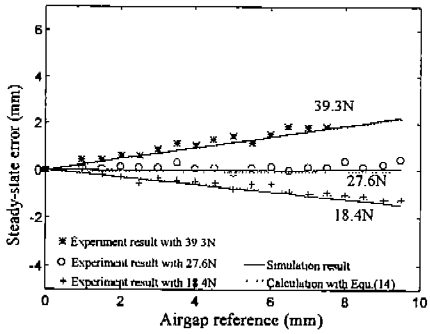
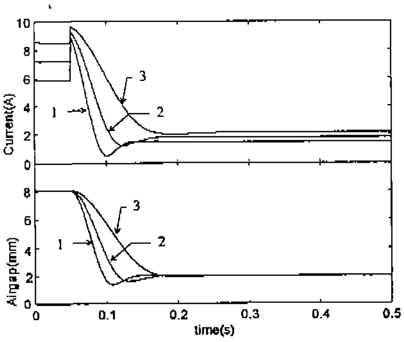


Fig.7 Steady-state error of EMS system with 5mm controller

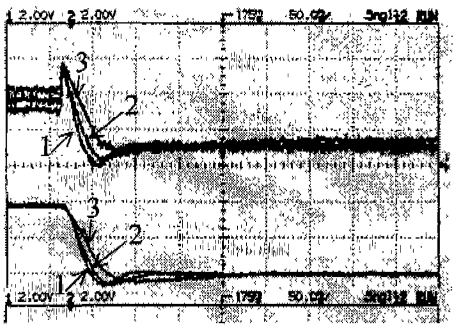
Fig.6 and Fig.7 show relationship between steady state error of air gap and steel plate weight when 2mm controller and 5mm controller are implemented respectively. They illustrate that steady state airgap error is zero when steel plate has the designed weight of 27.6N. For certain suspended weight other than designing value, steady-state error is proportioned to airgap reference. With certain airgap reference, steady-state error of airgap changes from zero to negative value when suspended weight is lowered from designing one to a lighter one. With certain airgap reference, steady-state error of airgap increase from zero to positive when suspended weight increase from designing one to a heavier one.

Dynamic characteristics

The dynamic characteristics of system with the change of suspended weight is also examined through both simulation and experiment. Fig.8 is dynamic response of EMS with 2mm controller when step signal inputs. Fig.8(a) is simulation results which has two group of waveforms. The upper one is waveforms of current in magnet, and the lower one is waveforms of airgap. In each group, waveform 1 is results with suspended weight of 18.4N, waveform 2 is results with suspended weight of 26.7N, waveform 3 is results with suspended weight of 39.4N. Fig.8(b) is experiment results corresponding to simulation results of Fig.8(a). Table 1 shows comparison of settling time and overshoot for different steel plates.



(a)Simulation



Time: 50ms/div Current:3.1A/div
Airgap:3mm/div

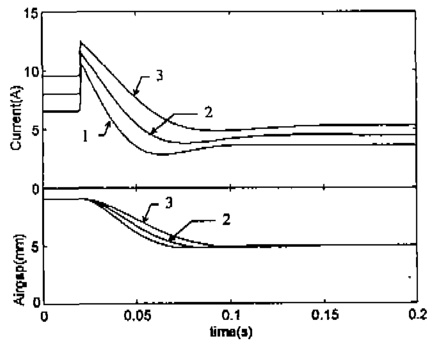
(b) Experiment

Fig.8 Simulation and experiment results of EMS system controlled by 2mm controller with different suspended weight

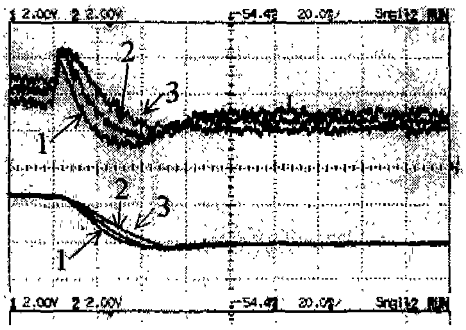
Table.1 statistic data of Fig.8

N	Suspend weight(N)	Simulation overshoot (%)	Simulation Settling time(s)	Experiment overshoot (%)	Experiment Settling time(s)
1	18.4	10.5	110	16.4	108
2	27.6	6.5	127	14.7	107
3	39.3	1.5	130	11.5	210

Fig.9 is the same with Fig.8 except 5mm controller is used. Table.2 shows comparison of settling time and overshoot for different steel plates.



(a) Simulation



Time: 20ms/div Current:3.1A/div
Airgap:3mm/div

(b) Experiment

Fig.9 Simulation and experiment results of EMS system controlled by 5mm controller with different suspended weight

Table2 Statistic data of Fig.9

	Simulation		Experiment	
Suspended weight(N)	overshoot (%)	Settling time(s)	overshoot (%)	Settling time(s)
18.4	6.0	109	9.1	64
27 6	6.1	114	9.6	68
39.6	5.3	129	7.0	84

Results mentioned above shows that settling time increases with increase of suspended weight. Overshoot varies with change of suspended weight.

5. CONCLUSION

In EMS system, steady-state error of airgap is proportioned to airgap reference when suspended weight is fixed. Increase of suspended weight from designed one will result in positive steady-state error, decrease of suspended weight from the designed one will result in negative steady-state error. Settling time increases when suspended weight increases. Overshoot varies when suspended weight changes.

6. REFERENCE

[1] B.V.Jayaeant, "Electromagnetic Suspension a Levitation", IEE PROC 1982, vol.129, no.8, pp.549~5 1992.

[2] D.Ebihara, H.Kawaguchi, Y.Muraguchi and e "Transportation Technique for Magnetically Levitat Thin Iron Plates", IEEE Trans. on Magnetics, vol.1 no.6, pp.2974~2976, 1993

[3] H.Hayashiya, N.Araki, J.e.Paddision, H.Ohsaki a E.Masada, "Magnetic Levitation of a Flexible Steel Pl With a Vibration Suppressing Magnet", IEEE Trans. Magnetics , vol.32, no.5, p5052~5054, 1996

[4] Jiang Hao * Lian Jisan, "The Dynamic Model a Control of Single-Magnet Suspension System", Journ of Southwest Jiaotong University of Chin 1992,(1):p59~67.