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A current-differential-based method for improving dynamic characteristics of electromagnetic actuators*

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Abstract: This paper presents a new control strategy based on current differential feedback to accelerate the dynamic response of electromagnetic actuators, instead of traditional closed-loop control based on displacement feedback. The method mainly includes a differentiator, proportioner and signal synthesizer. Analysis and simulation on the step characteristics of an electromagnetic actuator were discussed, and all the results show that the approach can improve the actuator's step response greatly. Finally, the control method is applied to a real gravure system which verifies the control performance.

Key words: Electromagnetic actuator, Control method, Dynamic characteristics, Current differential
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INTRODUCTION

Electromagnetic actuators are widely used in industrial applications. With growing demands for fast response, the dynamic characteristics of electromagnetic actuators have been a focus of many research groups. There are lots of reports ranging from prototype design, parameter optimization to control strategy with the aim of improving the dynamic behaviors of electromagnetic actuators (Peterson *et al*., 2002; Darl, 2005; Mianzo and Peng, 2007; Cvetkovic *et al*., 2008). Position/Displacement-based closed-loop control method is generally adopted, which uses the displacement signal acquired by a sensor like LVDT/RVDT (Linear/Rotary Variable Displacement Transducer) as the feedback signal. However, there are some cases in which it is difficult to obtain the displacement, e.g., a valve actuator surrounded by high pressure fluid, or a gravure engraving actuator with a decimillimeter-level displacement (Clark *et al*., 2005; Fang *et al*., 2006). Although attempts of sensorless position estimation have been made on multiphase machines and solenoid actuators, the deviation between the estimated and the actual is somehow undeterminable (Huang *et al*., 2006; Rahman *et al*., 1995).

Therefore, we put forward a new approach based on differential current for enhancing the dynamic responses of the electromagnetic actuators. Here, we use an engraving actuator (Fig.1) as the test with an angular travel of 0.0064 rad and amplitude frequency response of 4 kHz (@−3 dB) (Zhang *et al*., 2006).

THEORECTICAL ANALYSIS

The motion of the armature is

$$M = J\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2} + B\frac{\mathrm{d}\theta}{\mathrm{d}t} + K\theta, \tag{1}$$

where M is the sum of the polarized and control

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magnetic torque, J the rotary inertia of the moving components, K the spring's stiffness, B the viscous damping coefficient, θ the angle of the armature.

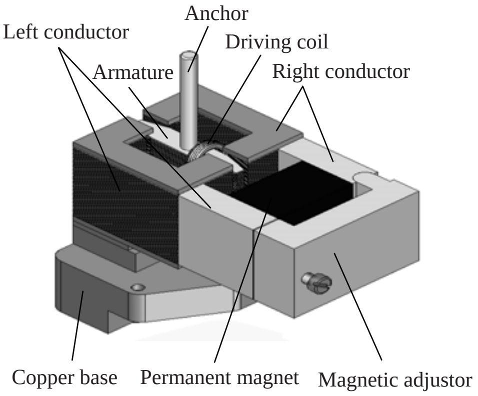


Fig.1 Structure of an electromagnetic actuator

The torque produced by the magnetic field is

$$M = \frac{\partial \lambda(\theta, i)}{\partial \theta} i; \tag{2}$$

for the electrical circuit,

$$V = \frac{\mathrm{d}\lambda}{\mathrm{d}t} + Ri, \tag{3}$$

where V is the applied voltage to the driving coil, λ the magnetic flux linkage, R the coil resistance, and i the driving current. The flux linkage λ is dependent on the current of the coil and the air gap distance. Eq.(2) can be expanded as

$$V = Ri + \left(L_{\mathrm{e}} + \frac{\partial \lambda}{\partial i}\right)\frac{\mathrm{d}i}{\mathrm{d}t} + \frac{\partial \lambda}{\partial \theta}\frac{\mathrm{d}\theta}{\mathrm{d}t}, \tag{4}$$

where an external inductance term L_{e} represents the flux linkage.

From Eqs.(3) and (4), we can obtain

$$\frac{\mathrm{d}i}{\mathrm{d}t} = \left(V - Ri - E(\theta, i)\frac{\mathrm{d}\theta}{\mathrm{d}t}\right) L(\theta, i)^{-1}, \tag{5}$$

where

$$E(\theta, i) = \frac{\partial \lambda(\theta, i)}{\partial \theta}, \tag{6}$$

$$L(\theta, i) = L_{\mathrm{e}} + \frac{\partial \lambda(\theta, i)}{\partial i}. \tag{7}$$

Based on the Eqs.(1)~(7) (Huang *et al*., 2005), it can be seen that $\frac{\mathrm{d}i}{\mathrm{d}t}$ is dependent on several factors including the armature speed, the armature position and the driving current. Therefore, if we directly use $\frac{\mathrm{d}i}{\mathrm{d}t}$ as the feedback signal, the control loop will involve more information of the armature movement with no more sensors needed.

MODELING AND DISCUSSION

Based on the assumptions above, we built a control loop (Fig.2). The driving current was acquired via a sampling resistance, and then through a differentiator and proportioner the differential current was added to the signal synthesizer to make up a closed loop control.

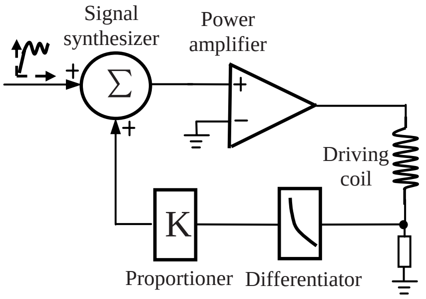


Fig.2 Schematic of new control method

Then based on Eqs.(1)~(4) and actuator parameters listed in Table 1, we carried out a simulation in MATLAB by regarding the electromagnetic actuator as a second-order system, assuming a step signal of the input 10 V, the damping ratio 0.8, the gain of the proportioner 15 and the time constant of the differentiator 0.01 ms. The simulation result is shown in Fig.3. It can be seen that the control method speeds up the step response while the rising time decreases from 0.28 to 0.12 ms. The reason lies in the feedback signal, the differential current, which varies greatly at the beginning and becomes stable afterwards.

Furthermore, we investigated the influence of the gain of the proportioner K and the time constant of the differentiator T on the dynamic response, respectively. The results indicate that a high value of *K* or *T* is more suitable; however, when the value of *K* or *T* is too high, there occurs overshoot and even vibration (Fig.4).

Table 1 Actuator parameters

Parameter	Value
Power supply (V)	24
Rated voltage (V)	10
Current (A)	0~15
Resistance (Ω)	1.5
Inductance (mH)	25~50
Coil turns	60

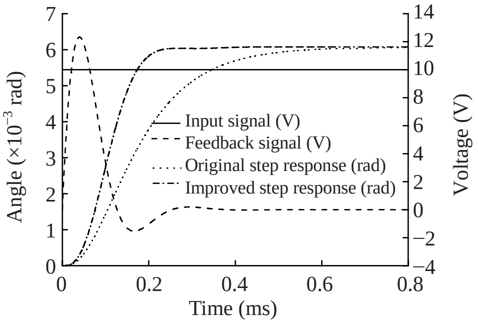
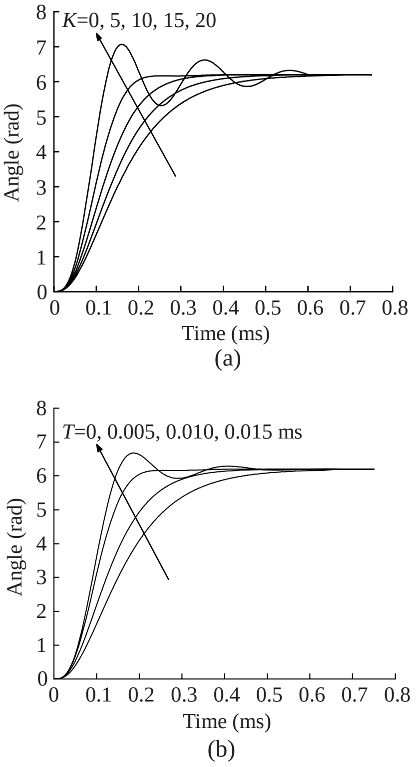


Fig.3 Simulated dynamic characteristics of the actuator



(a)

(b)

Fig.4 Simulation results of step response. (a) *T*=0.01 ms; (b) *K*=15

EXPERIMENT

The new control method is applied to control a real engraving actuator in a gravure printing system. Fig.5a and Fig.5b show the engraving results with and without the control strategy, respectively. While an input signal of the image density steps from 0 to 100%, Fig.5a indicates that the actuator becomes stable after engraving four cells of cells 1~5. While in Fig.5b, it goes stable after engraving only cell 1. Hence, the dynamic responses of the electromagnetic actuator are improved apparently.

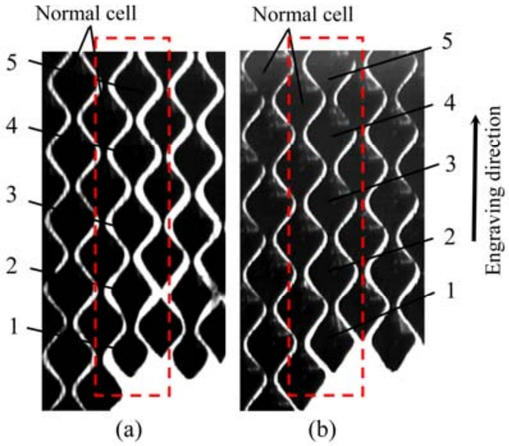


Fig.5 Application results (a) with and (b) without the control strategy (×400)

CONCLUSION

A new control method based on current differential feedback to accelerate the transient response of electromagnetic actuators is presented, mainly comprising differentiator and proportioner. The gain of the proportioner and the time constant of the differentiator are discussed. The theoretical analysis, simulation and application test results show that the method can greatly improve the actuator's dynamic characteristics with advantages of sensorless and easy fulfillment.

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