Modeling and Simulation of an Electric Clutch Actuator

Hanqi Yue, Bin Wang, Lijiao Yu, Bingzhao Gao and Hong Chen

Abstract For the development of an electric clutch actuator adopting DC motor and ball screw, a simulation model of the whole actuator system is set up using MATLAB/Simulink. At the same time, this chapter also gives a detailed introduction to the identification of the parameters. In the selection of motor parameters, the friction and spring parameters, lookup tables are used. By lookup tables, the model can get accurate data, and the simulation time can be reduced significantly.

Keywords Clutch actuator · DC motor · Ball screw · Modeling · Simulation

1 Introduction

Automatic clutch system is not only an important part of AMT [1, 2] and DCT, it is also widely used in hybrid electric vehicles to implement the operations of gear shifting and mode-switching. Usually, automatic clutch is actuated by electro-hydraulic, electro-pneumatic, or electro-mechanical systems. The electro-hydraulic (pneumatic) actuator contains a relatively complex system, including pump, tank and valves, etc. References [3, 4] introduced the design and simulation of this kind of

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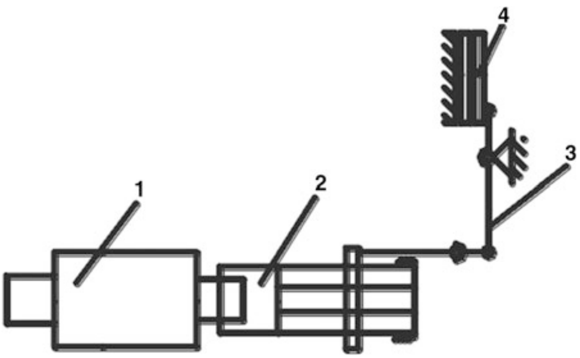


Fig. 1 Structure of automatic clutch actuator, *1* DC motor *2* Ball screw *3* Release lever *3* Clutch plate

actuators. Electro-mechanical actuator always adopts DC motor as the power source and worm-wheel or screw-nut as the speed reduction mechanism [5]. However, the transmission efficiency of worm-wheel and screw-nut is low (maybe less than 50 %), which affects the response speed of the actuator and consequently the dynamic performance of the vehicle is limited. Our Electro-mechanical actuator adopts ball screw as the speed reduction mechanism. Although ball screw is more expensive than sliding screw, the characteristics of ball screw include high transmission efficiency, short response time, long service time.

This chapter first introduces the structure and working process of this automatic clutch. Part 2 describes the model establishment. In Part 3 we compare the simulation results and the actual operation of the automatic clutch actuator.

2 Structure and Working Process of Automatic Clutch Actuator

This automatic clutch actuator mainly consists of DC motor, ball screw, load. There is no other gear set. The rotational motion of the DC motor is transformed into linear motion by the ball screw, and then the clutch lever is pushed (clutch disengaged) or released (clutch engaged). A potential meter is installed on the nut to measure the position of the clutch lever. DC motor is driven by an H-bridge circuit, which consists of 4 MOSFETs, and PWM control is used to modulate the motor current (Fig. 1).

3 Mathematic Model of Automatic Clutch Actuator

3.1 DC Motor

In order to meet the demands of clutch, DC motor must have following characteristics

- Forward rotation and reverse rotation are realizable for this DC motor.
- The motor can stop when taking up load.
- Making sure the clutch can engage smoothly.
- Short response time.

Mathematical model for DC motor
Voltage balance equation:

$$v_a + L_a \frac{di_a}{dt} = v_m - v_b \tag{1}$$

$$v_b = k_v \frac{d\theta_m}{dt} \tag{2}$$

Torque balance equation:

$$T_m = k_t \, i_a \tag{3}$$

$$T_m' = T_m - T_{mf} - J_m \frac{d^2\theta_m}{dt^2} \tag{4}$$

where

v_a Voltage-reduction of motor resistance(V), motor resistance is not constant, it changes with voltage on it. Considering non-ideal switching characteristics of semiconductor components, when the frequency of PMW is fixed, electric resistance of armatures circuits will change with duty-ratio. We can measure the value of current and voltage, and then we can simulate the change of voltage with current by lookup tables, as shown in Fig. 2.
i_a Armature current (A)
L_a Total inductance of the armature circuit 5×10^{-4} H (inspecting device parameters)
v_m Armature voltage (V)
v_b Back-EMF (V)
k_v Back-EMF coefficient 40.5×10^{-3} V/rad/s (inspecting device parameters)
θ_m Motor rotary angle (rad)
T_m' Motor output torque (N.m)
T_{mf} Loss of motor torque due to friction 0.01 N.m (measuring)
J_m Motor inertia 1×10^{-4} kg m2 (measuring)

Considering H—bridge driver links:

$$\bar{v}_m = v_{bat} \, u \tag{5}$$

$\bar{v}_m$ The average value of v_m in a control cycle (V)
v_{bat} Car battery voltage (12 V)
u PWM duty-ratio

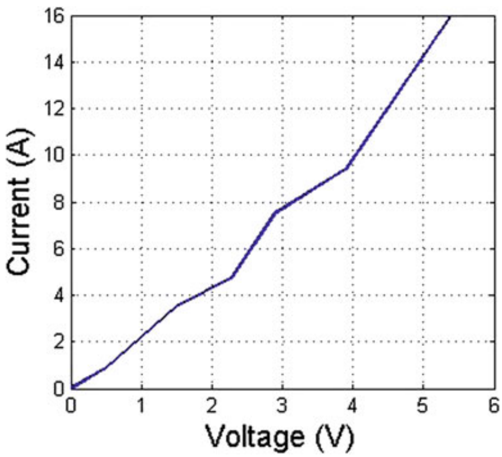


Fig. 2 Relationship between current and voltage of motor driving circuit

From equations (1.1) $\sim$ (1.5)

$$T'_m = k_t\, i_a - T_{mf} - J_m \frac{d^2\theta_m}{dt^2} \tag{6}$$

where

$$\frac{di_a}{dt} = \frac{\bar{v}_m - v_b - v_a}{L_a} \tag{7}$$

3.2 Ball Screw

Ball screw consists of two parts, nut and screw.

The requirements of ball screw.

- High transmission efficiency, smooth transmission, high sensitivity.
- Sufficient stiffness.
- Long service life.

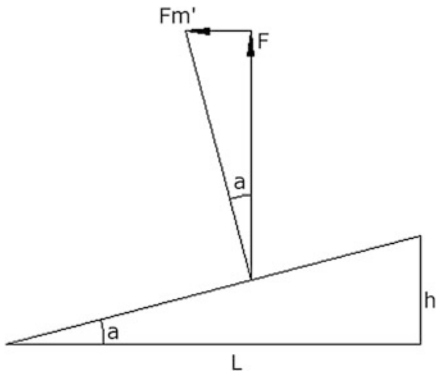
From Fig. 3, we have force balance equation of ball screw

$$\tan a = \frac{F'_m}{F_l} = \frac{h}{L} \tag{8}$$

$$L = D\,\pi \tag{9}$$

$$F'_m = \frac{T'_m}{\frac{D}{2}} \tag{10}$$

Fig. 3 Force analysis



We have

$$F_l = \frac{2\pi}{h} \cdot T'_m \tag{1.11}$$

F_l	Force on nut (N)
L	Circumference of the screw (m)
D	Diameter of the screw 0.016 m (inspecting device parameters)
h	Screw lead 5×10^{-3} m(inspecting device parameters)
Model input	motor output torque T'_m (N.m)
Model output	displacement of rod x (m)

$$T'_m \frac{2\pi}{h} = m\frac{d^2x}{dt^2} + F + f \tag{12}$$

m	Mass of the nut and rod (0.75 kg)
F	Spring force (N)
f	Frictional force (N)

3.3 Modeling of Frictional Force

Friction is caused by rotation of ball screw and sliding of lead rail. Due to the direction of rod movement changes in a circle, the direction of friction force changes too. When the rod keeps motionless, friction is static friction and when the rod moves forward or moves backward, the friction is sliding friction. The maximum static friction is a little bigger than sliding friction. Figure 4 shows the changes of frictional force with velocity.

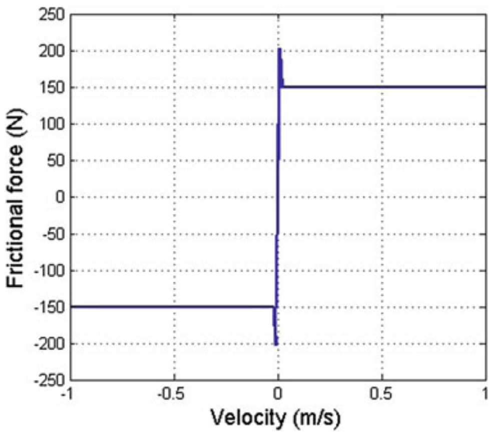


Fig. 4 Friction force

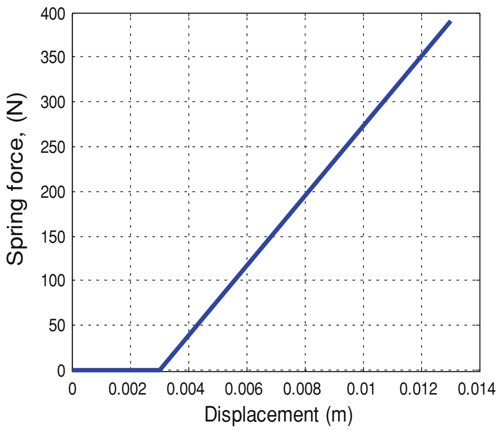


Fig. 5 Spring force

3.4 Modeling of Spring Force

We use a spring to simulate the resistance force that the clutch needs to overcome in real separation, giving no consideration to the mass of the spring. Because of the clearance of the clutch, the rod will move first to cross the clearance and promote the spring, overcoming the pressure of the spring and pressing the clutch plate of the clutch tightly. Given that the clearance is 3 mm, the change of the spring force F with the change of rod displacement is shown in Fig. 5.

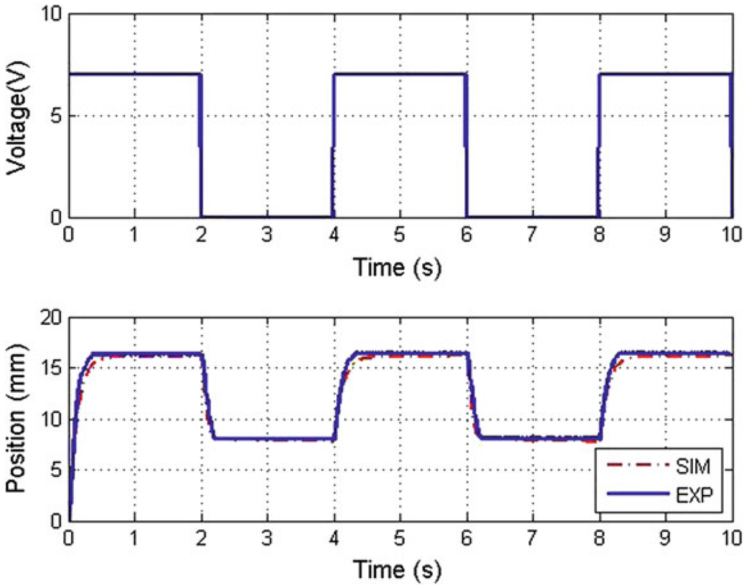


Fig. 6 Comparison between simulation and experiment, voltage of 7v

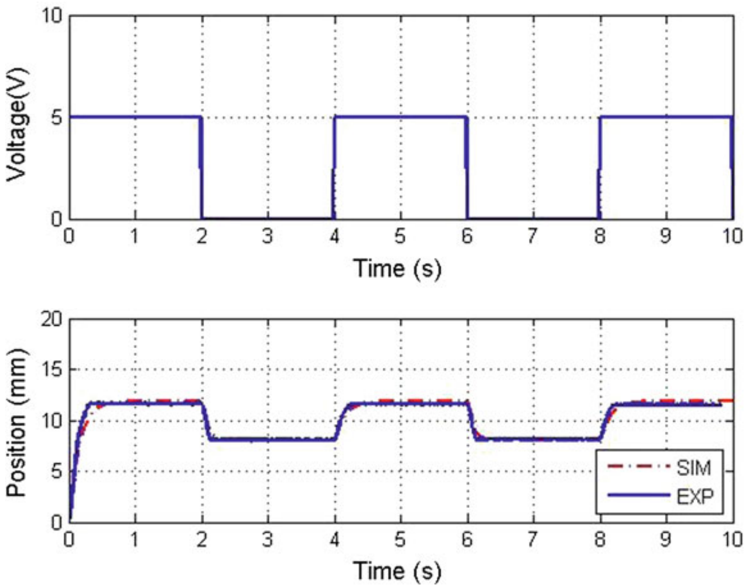


Fig. 7 Comparison between simulation and experiment, voltage of 5v

4 Simulation

We set input signal as square-wave, with period of 4 s. By changing the amplitude of duty-ratio, different v_{bat} can be simulated. The actual operation and simulation results are given in Figs. 6 and 7.

Through the figures we can see that the simulation model has good enough performance. When voltage is applied to the motor, the clutch responses quickly. In 0.4 s, the rod reaches its maximum displacement and remains motionless. When voltage becomes zero, the rod returns because of spring force. But it can not go back to the original position under the impact of friction force. In general there is no large difference between simulation results and the actual operation of the automatic clutch actuator. Comparing with actual movement distance of the rod, the simulation results only have error of about 4 %.

5 Conclusion

By using ball screw, we designed simpler automatic clutch actuator with higher efficiency. The simulation model is constructed. The simulation model has accurate enough precision, and it can be used for model-based control development.

At the stage of product development, modeling and simulation by MATLAB/simulink help a lot shorten product development cycles, reduce development costs. We can design our product flexibly and get optimization design easily.

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