Study of the model-following control for electromechanical brake system

Zhengfeng Chen¹,*, Jiali Hou¹ and Guofeng Ren²

¹School of Mechanical and automotive Engineering, Liaocheng University, Liaocheng 252000, Shandong China
²Zhong Bus Holding Co., Ltd, Liaocheng 252000, Shandong China

*Corresponding author e-mail: chenzhengfeng_01@163.com

Abstract. X-by wire is one of the key technologies to realize vehicle intelligence. Electromechanical brake (EMB) is a form of wire brake. A one-fourth vehicle model based on electromechanical brake system was established and model-following controller was designed with the wheel angular acceleration as the state parameter. The simulation of the braking process on different roads at some speed demonstrates that the controller has a good feasibility and effectiveness. The brake actuator is built by the torque motor, deceleration mechanism and motion conversion mechanism. A bench experiment for the brake actuator was conducted. Clamping force of brake caliper can meet the braking requirements.

1. Introduction

At present, the automotive industry at home and abroad generally believes that low-carbon, intelligent, and networked are the main directions for the future development of automobiles. Low carbonization also includes electrification, new materials, etc. Among them, the development of intelligent network-linked vehicles has become a hot spot for global automotive technology development. Drive-by-wire [1] is one of the four core technologies to realize vehicle intelligence. It includes: brake, steer, throttle and suspension-by-wire, etc. There are two forms of brake-by-wire, electrohydraulic brake system (EHB) and electromechanical brake system (EMB), among which electromechanical brake is the best way to achieve automatic driving. The braking system control based on the slip ratio is the main method that currently studied. [3] studied sliding mode control. [4] studied fuzzy-sliding mode control in plug-in hybrid electric vehicles. [5] studied fuzzy control based on one-fourth vehicle model. [6] designed and studied the actuator of EMB.

2. Methods

This paper proposes a model-following control (MFC) method for EMB, aimed at braking deceleration as a control target. The method is applied to system state prediction control, can maintain the stability and reduce the uncertainty of the system, enhance the control accuracy of the system.

2.1. The one-fourth vehicle model

The EMB control algorithms are studied by using a one-fourth vehicle model. In this model, air
resistance, wheel rolling resistance, wheel's vertical load applied by inertia force in longitudinal, and interference and influence on the braking system caused by uneven road surface aren’t accounted.

The dynamic equation of the one-fourth vehicle can be expressed as follows:\[7\]:

\[ J_{\omega} \dot{\omega} = F_x r - T_b \]
\[ m v_x = -F_x \]

where \( J \) is the moment of inertia of the wheel; \( \omega \) is the rotate speed of the wheel; \( r \) is the wheel rolling radius; \( T_b \) denote the braking torque of the wheel; \( m \) is the one-fourth vehicle mass; \( v \) is the longitudinal speed of the vehicle; \( F_x \) denote the longitudinal brake tire force of the wheel.

2.2. Tyre-road Contact Forces

Tyre-road contact force is the root cause of vehicle braking. The key to build a vehicle model and performing dynamic simulations is to select a tyre model that is practical and easy to be used. In several tyre models used commonly, A "Magic Formula" tyre model which is proposed by Pacejka, fitting tire experimental data with a combination of trigonometric functions, is used\[8\].

2.3. Actuator Model

The floating caliper disc brake of a domestic ordinary passenger car is selected as the goal. Figure 1 shows the structural principle diagram of the modified electromechanical brake actuator. Table 1 gives the main parameters of the selected components of the brake actuator.

\[ T_h = k^* I_k - T_m \]
\[ k^* = 9.55 \times 2\pi K_e i \eta_i \eta_p k_p / p_h \]

where \( k^* \) is the total coefficient of the brake actuator; \( T_m \) is the resistance torque; \( k_p \) is the brake factor of the brakes; \( N_m \) is the return spring force of the brake mechanism; \( K_e \) is the counter-electromotive force of the motor, which value is the counter-electromotive force at unit speed; \( i \) is the ratio of the planetary gear deceleration device; \( \eta_i \) is the transmission efficiency of the planetary gear deceleration device; \( \eta_s \) is the transmission efficiency of the ball screw; \( p_h \) is the thread lead of screw, formula derivation in reference[9].

| Tab.1 The main parameters of actuator |
|--------------------------------------|
| Physical meaning | Numerical value |
| Brake disc outside diameter | 256mm |
| Working radius | 106mm |
| Brake gap | 0.3mm |
| Continuous stall torque | 8.7Nm |
| Planetary gear deceleration device ratio | 5 |
| Thread lead of screw | 6mm |
2.4. Design of MFC Controller

Model Following Control (MFC) was proposed by Japanese scholars Hideo Sado and Shin-ichiro Sakai et al in 1996[10][11]. For the one-fourth model studied, the basic principle is that, when the wheel is normally attached, the inertia moment acting on the wheel with the weight of the single wheel plus the moment of inertia of the wheel as the equivalent moment of inertia, i.e., the standard model. During the braking process, when the wheel is locked, the angular acceleration of the wheel output deviates from the angular acceleration output by the standard model. The control system sends a command correction deviation to the motor so that the slip rate is always controlled in the optimum state. The selection value is 0.2. Figure 2 shows the control system schematic. The model following controller is showed in the dashed box.

The slip ratio is given by the following set of equations.

\[ s = \frac{v - r \omega}{v} \]  \hspace{1cm} (4)

where \( v \) is the speed of vehicle; \( r \) is the radius of tyre; \( \omega \) is the rotate speed of the braking tyre.

Taking a derivative of Eq. (4), we can give

\[ \dot{v} = \frac{r \omega}{1 - s} \]  \hspace{1cm} (5)

Substitutes Eq. (5) into Eq. (2) and then add Eq.(1) into, we can get

\[ \left( J + mr^2 \right) \frac{1}{1 - s} \dot{\omega} = -T_b \]  \hspace{1cm} (6)

The part of Eq. (6) in brackets can be described as

\[ J = J_w + mr^2 \frac{1}{1 - s} \]

when the slip ratio equals to zero, the front equation can be described as

\[ J_{\text{mod:}0} = J_w + mr^2 \]

That is called the standard model.

3. Results

Based on the MATLAB/Simulink software, a one-fourth simulation model of the vehicle was set up. The feasibility of the designed model following controller was verified, and the simulation results were obtained and analyzed. Table 2 gives the main parameters of simulation.

| Tab.2 The main parameters |
|---------------------------|
| Physical meaning | Numerical value |
| One-fourth mass | 300kg |
| Rolling radius | 0.25m |
| Inertia moment | 1.2 kg·m^2 |
| Initial speed | 30(or 20) m·s^{-1} |
| Gravity acceleration | 9.8 m·s^{-2} |
| Target slip ratio | 20% |

The initial vehicle speed was defined as 30 m/s on the dry asphalt road and wet asphalt road, and
defined as 20m/s on the snow. The results of simulation are showed below.

Figure 3-5 show the curve of simulation for speed, slip ratio and brake distance on the dry asphalt road.

Figure 6-8 show the curve of simulation for speed, slip ratio and brake distance on the wet asphalt road.

Figure 9-11 show the curve of simulation for speed, slip ratio and brake distance on the snow.

![Speed curve (initial speed 30m/s)](image)

**fig.3** Speed curve (initial speed 30m/s)

![Slip curve (initial speed 30m/s)](image)

**fig.4** Slip curve (initial speed 30m/s)

![Braking distance curve (initial speed 30m/s)](image)

**fig.5** Braking distance curve (initial speed 30m/s)

![Speed curve (initial speed 30m/s)](image)

**fig.6** Speed curve (initial speed 30m/s)

![Slip curve (initial speed 30m/s)](image)

**fig.7** Slip curve (initial speed 30m/s)

![Braking distance curve (initial speed 30m/s)](image)

**fig.8** Braking distance curve (initial speed 30m/s)
According to the above simulation, it can be seen that the model following controller can meet the braking requirements of different roads. However, there are differences in the control on different road condition. The fluctuations in the speed and slip ratio of dry asphalt is the smallest, followed by wet asphalt and the largest in snow. Because the initial speed of 20m/s is slightly higher than that of snow, the fluctuation will decrease as the initial speed decreases. In addition, fluctuations will be further weakened through subsequent studies or adding other links.

4. Experiments

A brake actuator experimental bench was built, which is composed of a torque motor, deceleration device, and a motion conversion device. Clamping force bench experiment was finished during brake. Figure 12 shows the laboratory bench of EMB actuator.
The control curve of the torque motor current from the controller is introduced into the test bench software, and the clamping force curve under three working conditions is obtained through the pressure sensor. Figure 13-15 show the curve of clamping force. Through calculations, the clamping force can meet braking requirements.

5. Discussion

Using Pacejka's "magic formula" tire model as the basis to calculate the tire-road contact force, a one-fourth vehicle dynamics model for the electromechanical braking system was established. A model following controller was designed, which takes the wheel angular acceleration as the state variable and the best slip ratio as the control target. The simulation was finished on three kinds of roads and the ideal braking effect was achieved. Finally, a bench test of the brake caliper clamping force was performed on the brake actuator to further verify the practicality of the controller.

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