Braking Stability Control Algorithm for Vehicle Based on Fuzzy Logic

Hongyu Zheng, Yuchao Chen and Changfu Zong

Abstract A stability control strategy for vehicle electronic hydraulic brake system (EHB) related to active safety was developed for vehicle. A nonlinear electronic-hydraulic brake system mathematical model was built through analyzing the effects of the composing modules and linking pipelines of the EHB system on the performance. The vehicle stability control algorithm was simulated using software CarSim and MATLAB/Simulink under typical conditions. The results showed that control strategy can effectively control vehicle motion and meet the requirements of design.

Keywords Vehicle engineering · Electronic hydraulic brake system · Active safety · Fuzzy control · Stability

1 Introduction

In recent years, with the development of electronic technologies and control theories, vehicle handling and stability has become more and more important for drivers. EHB (Electronic Hydraulic Braking) system is a new type of vehicle active control braking systems, which replaced the mechanical connection between brake pedal and brake wheel cylinder by wire and the driver's braking

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behaviour is transmitted to the ECU (Electronic Control Unit) in the form of electronic signal, then ECU identify the driver's braking intention by collecting others vehicle sensors signals, making out the optimal cylinder brake pressure by controlling the solenoid valve to regulate cylinder pressure [1]. EHB can significantly improve the braking performance and vehicle handling and stability, while providing a variety of support functions, sharing information with other vehicle control systems to provide the development of the vehicle chassis integrating and realize the ultimate intelligent vehicle control system [2].

Based on the EHB system basic structure and working principle, this paper built mathematical model by EHB system and studied the stability control algorithm to improve vehicle stability. A nonlinear electronic hydraulic brake system mathematical model was built by software Matlab/Simulink through analyzing the effects of the composing modules and linking pipelines of the EHB system on the performance. Based on fuzzy logic, the vehicle stability control algorithm was simulated using software CarSim and MATLAB/Simulink under typical conditions.

2 Basic Structure of EHB System

EHB system can be broken with an electrical "joystick" completely independent of the traditional brake pedal. The signals of brake pedal sensor and wheel velocity sensor were transmitted to the ECU and integrated steering angle sensor, yaw rate sensor and lateral acceleration sensor etc. by CAN bus. According to signals, ECU can know about brake intention of driver and vehicle states to control the switching of the solenoid valve to regulate the wheel brake cylinder pressure which improved vehicle stability [3]. EHB system divided into some categories: brake pedal system, wheel, brake actuators, sensors, ECU, power source and assist systems [4] (Fig. 1).

Brake pedal system include brake pedal, pedal stroke sensor, pedal speed sensor. Pedal stroke and velocity sensors can measure signals transmit it to ECU. According to signals, ECU can know about brake intention of driver through the arithmetic in the ECU. Wheel and brake actuators are controlled by the signals of ECU to provide brake pressure with vehicle. Compared to traditional brake system, EHB has added to four brake pedal stroke sensors, brake velocity sensors and so on. The sensors consist of two kinds: the first sensor is used to know about intention of driver, for example brake pedal stroke sensors. The second is used to know about the drive state of vehicle, for example wheel sensors and yaw rate sensor. The sensors and ECU are integrative with CAN bus to communicate with other ECUs [5]. ECU is the most important in the EHB. It can get all signals come from sensors and actuators and estimate to how to control brake actuators.

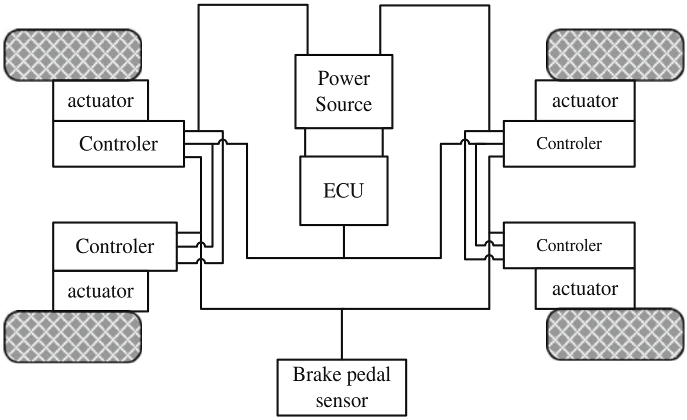


Fig. 1 Base structure of EHB system

3 Hydraulic System Mathematical Model of EHB

Hydraulic brake system model is consists of hydraulic unit, high speed on–off valve, hydraulic pipelines, wheel cylinders and so on [6].

3.1 Hydraulic Unit

From deal gas state equations can be seen

$$p_A V_A^n = p_1 V_1^n = p_2 V_2^n = \text{constant} \tag{1}$$

where V_1, V_2 are max and min pressure volume of gas. Where system pressure need be kept or leakage compensation by accumulator, $n = 1$, where need compensate a great deal of oil liquid, $n = 1.4$.

3.2 High Speed On-Off Valve Model

The flow equation of hydraulic valve port

$$Q = C_d A \sqrt{\frac{2|p_2 - p_1|}{\rho}} \tag{2}$$

where Q is liquid flow rate, C_d is flow coefficients, A is flow area, P_1, P_2 are fluid unsteady flow. High speed on–off valve is controlled by PWM signal with traffic have an approximately linear relationship as

$$A = A_0 I_{PWM} \tag{3}$$

where A_0 is the biggest opening state of valve port, I_{PWM} is the distribute coefficient of PWM signal and its range between 0 and 1.

3.3 Brake Wheel Cylinders System Model

The flux continuum equation of wheel cylinders as

$$Q_w = \frac{V_w}{K_w}\frac{dP_w}{dt} \tag{4}$$

where V_w is volume of wheel cylinders, P_w is pressure of wheel cylinders, K_w is representative volume modulus of elastic of wheel cylinders.

$$\frac{1}{K_w} = \frac{1}{K_l} + \frac{A_w^2}{k_{brake}V_w} \tag{5}$$

where is K_w stiffness of brake, K_l is modulus of elasticity of brake fluid, k_{brake} is synthetically stiffness that include distortion of wheel cylinders and compressive stress.

3.4 Brake Model

According to mechanism of friction, brake torque of wheel can be described to *Tb* as

$$T_b = GN_b \tag{6}$$

$$N_b = P_w A_w \tag{7}$$

where G is a constant factor about material, structure and temperature of brake, can be determined by experiment, N_b is piston thrust of wheel cylinders, P_w is pressure of wheel cylinders, A_w is piston area of wheel cylinders.

4 Stability Control Algorithm Based on EHB

Based on vehicle stability control theory, a stability control algorithm was established combined with structural characteristics of EHB hydraulic system. Reference to vehicle linear model with two degree of freedom (2DOF), an additional vehicle yaw torque was designed to comparing vehicle actual states with ideal states which were computed by two degree of freedom [7].

4.1 Computing Ideal States by Two Degree of Freedom Model

Equations of 2 DOFs linear model for vehicle as

$$\begin{cases} mV_x(\dot{\beta} + r) = -\left(K_f + K_r\right)\beta + \dfrac{bK_r - aK_f}{V_x} \cdot r + K_f\delta \\ I_z\dot{r} = (bK_r - aK_f)\beta - \dfrac{a^2K_f + b^2K_r}{V_x} \cdot r + aK_f\delta \end{cases} \tag{8}$$

where m is vehicle mass, V_x is vehicle speed, β is sideslip angle, r is yaw rate, k_f is cornering stiffness of front axis, k_r is cornering stiffness of back axis, a is distance from center of mass to front axis, b is distance from center of mass to back axis, δ is front wheel steering angle, I_z is moment of inertia to Z axis.

$$r_N = \frac{V_x \cdot \delta}{l \cdot (1 + KV_x^2)} \tag{9}$$

$$K = \frac{m(bK_r - aK_f)}{K_f K_r l^2} \tag{10}$$

where r_N is ideal yaw rate, l is the distance of between front and back axis, K is stability factor. If actual yaw rate great than r_N to a threshold value, it must be controlled by brake torque for wheel. This may use fuzzy logic control algorithm to control EHB system.

$$r_N = \min\left\{\left|\frac{V_x}{l(1 + KV_x^2)} \cdot \delta\right|, \left|\frac{\mu \cdot g}{V_x}\right|\right\} \cdot \mathrm{sgn}(\delta) \tag{11}$$

$$\Delta r = r - r_N \tag{12}$$

where μ is road friction coefficient, Δr is the difference of actual yaw rate and ideal yaw rate. In order to avoid error too small to adjust frequently, so this need set a threshold value as

$$|\Delta r| \le |cr_N| \tag{13}$$

where c is a threshold value and positive number.

According to driver' handling and vehicle movement state, ECU can get vehicle movement state and compute an ideal vehicle movement state. Compare actual vehicle movement state with ideal vehicle movement state to compute an error and introduction to ECU, ECU calculates a yaw moment to renew vehicle stability. The yaw moment is distributed to four wheels to transform wheel cylinder pressure. According to wheel cylinder pressure of sensor measured and vehicle needed, ECU generates PWM signals to control solenoid valves to adjust wheel cylinder pressure that control vehicle stability.

Table 1 Inference table of the fuzzy controller

Δr M_r $\Delta\dot{r}$	Very low	Low	Medium	High	Very high
Very low	Very	Very	Very low	Low	Medium
Low	Very	Very	Low	High	High
Medium	Very	Low	Medium	High	Very high
High	Low	Low	Medium	Very high	Very high
Very high	Low	Low	High	Very high	Very high

4.2 Stability Control Algorithm

This paper chose fuzzy control method to control brake torque for wheel. Firstly, the process to be controlled is difficult to mathematical model and the driving environment is complex and strongly nonlinear. The fuzzy logic methods deal with these difficulties by allowing the fuzzy rules. The input variable of fuzzy control algorithm is Δr and Δr's derivative and output variable is Mr to additional yaw torque of vehicle. The fuzzy controller is defined by 25 rules Table 1.

4.3 Brake Force Distribution of Yaw Moment

EHB system can adjust wheel cylinder pressure all four wheel but different brake distribution can attain different yaw moment. As usual, adjust wheel cylinder pressure of one of diagonal wheels can control vehicle stability and the other doesn't have obvious effect. Brake Force Distribution Table 2.

The relation of wheel braking force with yaw rate can be described as

$$\begin{cases} F_f\left(\cos\delta\dfrac{d}{2}+\sin\delta\cdot a\right)=M_r \\ F_r\dfrac{d}{2}=M_r \end{cases} \tag{14}$$

where F_f is front wheel braking force, F_r is rear wheel braking force, d is distance from front axis to back axis.

5 Simulation Result

It use software Matlab/Simulink to built mathematical model of the EHB system and vehicle dynamic model was simulated using software CarSim.

Table 2 Brake force distribution methods

Frong wheel steering angle	Difference of yaw rate	Brake force distribution
Left turn	$\Delta r > c\Delta r_{\mathrm{N}}$	Right front wheel braking
	$\Delta r < -c\Delta r_{\mathrm{N}}$	Left rear wheel braking
	$-c\Delta r_N \leq \Delta r \leq c\Delta r_N$	No braking
Right turn	$\Delta r > c\Delta r_N$	Left front wheel braking
	$\Delta r < -c\Delta r_N$	Right rear wheel braking
	$-c\Delta r_{\mathrm{N}} \leq \Delta r \leq c\Delta r_N$	No braking
No turn	$\Delta r > c\Delta r_N$	Right front wheel braking
	$\Delta r < -c\Delta r_N$	Left rear wheel braking
	$-c\Delta r_N \leq \Delta r \leq c\Delta r_N$	No braking

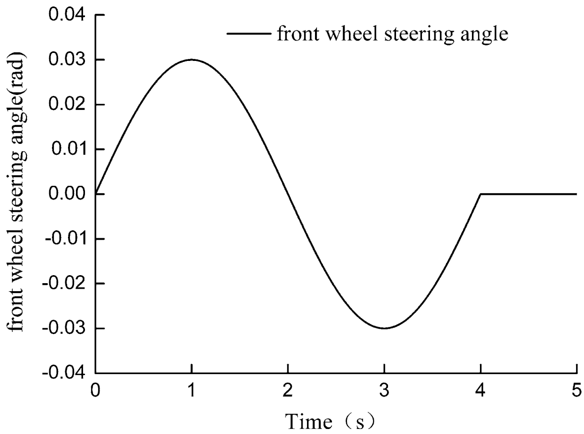


Fig. 2 Input of front wheel steering angle

5.1 *μ-Low Condition*

Simulation experiments include that vehicle speed is 80 km/s, road friction coefficient is 0.3, front wheel steering angle is a sinusoid. Figure 2 is front steering angle, period is 4 s and amplitude is 0.03 rad, Fig. 3 is yaw rate and Fig. 4 is vehicle running path.

From the simulation show that yaw rate can't track ideal yaw rate of non vehicle stability control. Vehicle stability control algorithm can make yaw rate track ideal yaw rate based on fuzzy control logic and the path was more precisely than the vehicle with no control.

Fig. 3 Yaw rate

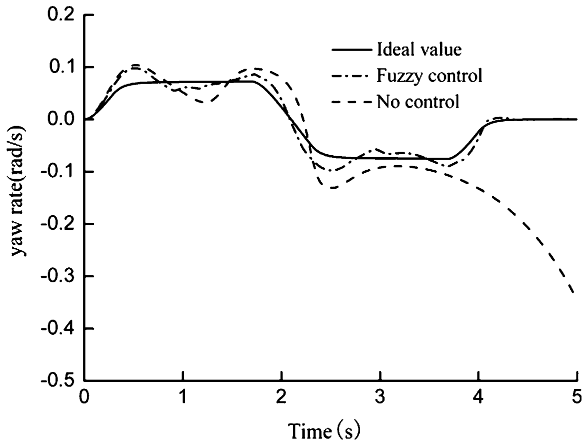
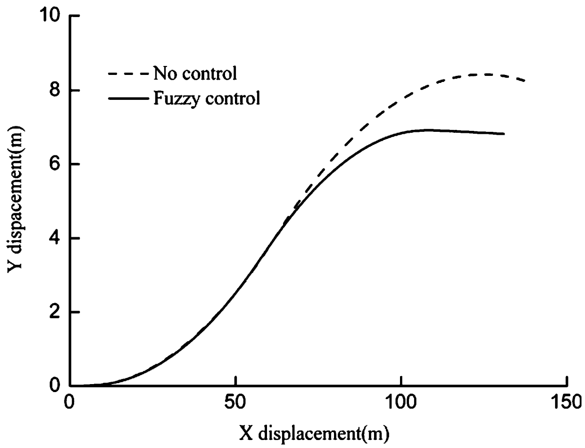


Fig. 4 Vehicle running path



5.2 Double Change Condition

Double change condition refers to the ISO/TR 3888-1 [8]. The simulation experiments include that vehicle speed is 100 km/h and road friction coefficient is 0.4.

Figure 5 is front steering angle, Fig. 6 is yaw rate and Fig. 7 is vehicle running path.

In the simulation result that yaw rate can't track ideal yaw rate of non vehicle stability control and vehicle lost stability. Based on fuzzy control logic, vehicle stability control can make yaw rate track ideal yaw rate and the path was more precisely than the vehicle with no control.

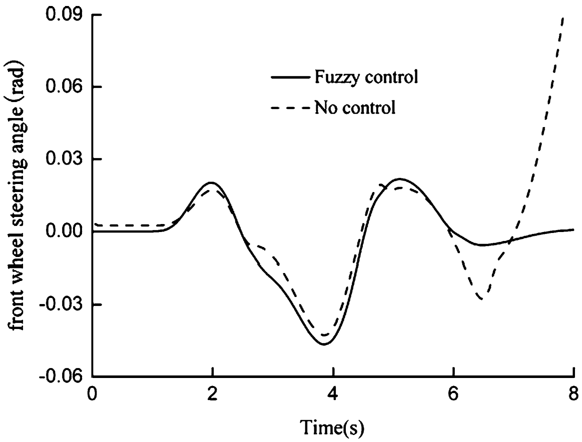


Fig. 5 Front wheel steering angle

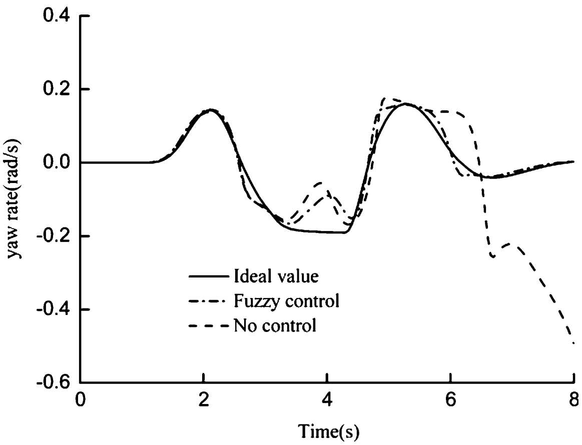


Fig. 6 Yaw rate

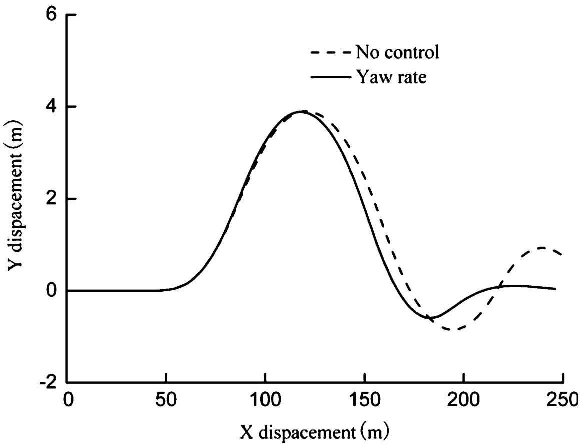


Fig. 7 Vehicle running path

6 Conclusion

The mathematical models were built of EHB system by Matlab/Simulink and vehicle dynamic models by CarSim, it provides platform for theoretical study and product development of vehicle system, and besides, the research on the stability control algorithm of EHB system based on fuzzy control logic. The computer simulation test results show that vehicle stability can't be kept if there is no stability control and the control effect of fuzzy control logic improved the vehicle stability.

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