A Study on ABS Slip Ratio Control of Vehicle using One Solenoid Valve

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ABSTRACT

Anti-lock Braking System (ABS) is a safety device for preventing wheel-locking in a sudden braking. It consists of hydraulic modulator, ECU and wheel speed sensors. The hydraulic modulators are classified into two types; sol-flow type and sol-sol type. In this paper, the hydraulic modulator is composed of one solenoid valve with 3way-2position. The braking friction force described by function of slip ratio can obtained maximum value if slip ratio can be maintained from 0.1 to 0.3. Consequently, slip ratio is controlled by PWM and SMC based on vehicle dynamics in the same way a two-level control scheme.

KEY WORDS

Anti-lock Braking System, Solenoid Valve, Slip Ratio, Pulse Width Modulation, Sliding Mode Control

NOMENCLATURE

A = the open area of valve
A_p = the area of braking pad
C_d = the discharge coefficient
C_a = the resistance coefficient of air
F_t = the braking friction force
F_a = the aerodynamic drag force
J = the moment of inertia of wheel
K_m = the effective bulk modulus
K_r = the constant gain
M = the entire vehicle mass
P_s = the supply braking pressure
P_r = the return braking pressure
p = the braking pressure
q = the fluid flow
r = the radius of tire
r_e = the effective radius of wheel
T = the time constant of valve
T_b = the braking torque
V = the total compressed volume
v = the linear velocity of vehicle
W = the weight of vehicle
x = the displacement of valve


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\[ \lambda = \text{the slip ratio of wheel} \]
\[ \mu = \text{the coefficient of friction between tire and road} \]
\[ \mu_p = \text{the coefficient of friction between brake pad and wheel} \]
\[ \rho = \text{the density of brake liquid} \]
\[ \rho_s = \text{the density of air} \]
\[ \omega = \text{the angular velocity of wheel} \]

1. INTRODUCTION

Automobile technique has been developed for satisfying a various demand of consumer since a development of internal combustion engine. Because vehicle is concerned for passenger life the most requirements on passenger car may be a good steering response and braking performance. Anti-lock Braking System (ABS) is a safety device in the passenger car for preventing wheel locking in a sudden braking. Then the maximum braking force can be obtained on braking. ABS is a commonly installed feature in vehicle at the present time. It was first developed in the 1950s for aircraft, but was too expensive for vehicle. The first ABS for vehicle appeared in the late 1960s. In the 1970s the real growth of ABS technology was made possible by integrated electronics and microcomputers.

The major parts of ABS are the hydraulic modulator, wheel speed sensor and ECU (Electronic Control Unit). On operating the brake system the friction force between the tire and the road surface is generated and the velocity of vehicle decrease slowly. The friction force that is the main braking force depends on the road condition and the value of the wheel slip ratio. As presented WI, the friction coefficient can be described function as wheel slip ratio.

The goal is to control slip ratio that is defined as the ratio of the linear velocity to the angular velocity. The hydraulic modulator in this paper is constructed using one solenoid valve with 3way-2position. The valve operates on the modulated signal due to PWM method and SMC based on the vehicle dynamics is applied on the braking torque. As presented in [1], a two-level control scheme is applied for controller design through computer simulation.

2. SYSTEM MODEL FOR SLIP RATIO CONTROL

2.1 Hydraulic Modulator Model

ABS consist of hydraulic modulator, ECU, wheel speed sensor. For the hydraulic modulator there are two types: sol-flow type using solenoid valve and flow control valve, sol-sol type using two solenoid valves. In this paper, a hydraulic modulator is composed of one solenoid valve with high responsibility shown in Fig.1.

![Fig. 1 System model](image)

The valve can be in two positions, closed or open. The pressure in the wheel cylinder increases if the valve is open and if the valve is closed the pressure decreases due to the fluid flow in the direction of the low-pressure accumulator. The movement of valve can be approximated to first order time delay and the open area can be considered as a constant gain as follows:

\[ \dot{x} = -\frac{1}{T} x + \frac{K_s}{T} i \]
\[ A = c_o \cdot x \] (1)

If the valve is open the fluid flow in for the wheel cylinder and the braking pressure increases. It can be modeled as follows [3];

\[ q = c_d A \sqrt{\frac{2}{\rho}} (P_s - p) \] (3)
\[ \dot{p} = \frac{K_m}{V} q \] (4)

If the valve is closed the fluid flow out for the wheel cylinder and the braking pressure decreases. It can be modeled as follows;

\[ q = c_d A \sqrt{\frac{2}{\rho}} (p - P_s) \] (5)
\[ \dot{p} = -\frac{K_m}{V} q \] (6)

2.2 Vehicle Dynamics

For vehicle motion on braking the model consist of linear dynamics and the rotational dynamics, neglecting lateral motion and yaw.

The linear dynamics and the rotational dynamics can be described by Newtonian equation of motion;
The braking friction force depends on the friction coefficient and the total weight of the vehicle and the aerodynamic drag force is modeled as follows:

\[ F_i = \mu(\lambda)W \]  

\[ F_a = \frac{1}{2} C_a \rho_a A_a v^2 \]  

The braking torque at the wheel is described as 

\[ T_b = C_b \mu_b r_e A_b \lambda \]  

And the slip ratio is defined as the ratio of the linear velocity to the angular velocity 

\[ \lambda = \frac{\nu - r \omega}{\nu} \]  

The friction coefficient between the tire and the road depends on the road condition and the value of the wheel slip ratio. According to a typical \( \mu-\lambda \) curve, a mathematical description is described by Peng and Tomizuka as follows:

\[ \mu(\lambda) = \frac{2 \mu_p \lambda_p \lambda}{A_2 + \lambda^2} \]  

where \( \mu_p \) and \( \lambda_p \) are the peak values at the \( \mu-\lambda \) curve.

3. SLIDING MODE CONTROLLER DESIGN

The vehicle dynamics described above eq.(7)-(13) is the 2nd order system

\[
\begin{align*}
\dot{x}_1 &= a_1 x_1 + a_2 x_2, \\
\dot{x}_2 &= a_3 x_1 + a_4 u
\end{align*}
\]

where \( X=[x_1, x_2]^T=[\nu, \omega]^T \), \( u \) is control input and

\[
\begin{align*}
a_1 &= -2 \mu \lambda W, \\
a_2 &= -\frac{1}{2} C_a \rho_a A_a, \\
a_3 &= \frac{2 \mu_p \lambda_p r}{J}, \\
a_4 &= \frac{1}{J}
\end{align*}
\]

and the error signal is defined as \( e = \lambda_d - \lambda \).

Since the system is of the 2nd order, the sliding surface is defined by the sliding variable to zero[2][6][7]

\[ S(\lambda, \dot{\lambda}) = \left( \frac{d}{dt} + \lambda \right)^{n-1} e = \dot{e} + \lambda e \]  

The control input \( u = u_o + \Delta u \) to make the system trajectory along the sliding surface and reached the original point. The control input can be

\[ u = k_r e + k_d \dot{e} + k \text{sat} \left( \frac{S}{\Phi} \right) \]  

4. SIMULATION RESULTS

For the purpose of simulation assumption is that; the initial velocity of vehicle is 80km/h, the road condition is wet. The parameters used in simulation are given in Table. 1.

The PWM method can modulated error signal using a carrier wave with a high frequency, a periodically tooth wave. The duty ratio is defined as the ratio of the time of switching ON state to the period of the carrier wave. The solenoid valve operates on the modulated error signal. And the control input generated SMC is added to braking torque. Fig. 2 and 3 show the results of the slip ratio and the braking torque that are the less variations and more stable in comparison with operating ON/OFF state. Fig. 4 show the velocity of vehicle and the angular velocity of wheel. The angular velocity of wheel is oscillated in large due to switching ON and OFF state. But, applied SMC on the braking torque the value of variation of angular velocity is small and the reduction ratio of vehicle velocity is large in comparison with operating

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>T</td>
<td>0.025 sec</td>
</tr>
<tr>
<td>K_s</td>
<td>0.015 cm</td>
</tr>
<tr>
<td>c_d</td>
<td>0.6</td>
</tr>
<tr>
<td>\rho</td>
<td>1070 kg/m^3</td>
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<tr>
<td>K_m</td>
<td>3232.5 bar</td>
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<td>\nu</td>
<td>50 cm^3</td>
</tr>
<tr>
<td>\mu_s</td>
<td>0.3</td>
</tr>
<tr>
<td>A_s</td>
<td>22.5 cm^2</td>
</tr>
<tr>
<td>P_s</td>
<td>150 bar</td>
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<tr>
<td>P_r</td>
<td>1 bar</td>
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<tr>
<td>M</td>
<td>1430 kg</td>
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<tr>
<td>J</td>
<td>2.8 kg \cdot m^2</td>
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<tr>
<td>r</td>
<td>0.28 m</td>
</tr>
<tr>
<td>C_o</td>
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<tr>
<td>\mu_b</td>
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<tr>
<td>A_o</td>
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<tr>
<td>\rho_a</td>
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</table>

Table. 1 Parameters for simulation
5. CONCLUSION

In this paper, a hydraulic modulator of ABS can be constructed using one solenoid valve, 3way-2position, which is operated on the modulated error signal due to PWM method. Sliding mode controller based on vehicle dynamics is appended to the braking torque. So, through computer simulation the work is carried out to control slip ratio.

For controlling slip ratio the variation of angular velocity can be decreased and the velocity can be reduced in a rapid time. Applied two-level control scheme as PWM and SMC the proposed hydraulic modulator can be applied on the vehicle against the established modulator of sol-sol type.

REFERENCE