Design and Simulation of Fuzzy-Sliding Mode Anti-lock Braking System Capable of Identification of Different Surfaces of Road

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ABSTRACT
Anti-Lock Braking System has been designed to improve the effects of the braking process and retain the ability of steering vehicle. But ABS could not be effective in inadequate condition of the road. Coefficient of friction between tires and road is a non-linear function and a ratio of the slip, thus it is different for different surface of the road. In this study, the longitudinal friction coefficient between tires and the road is considered near the maximum value. Stimulations have been conducted in 1/4 car model by MATLAB. The results demonstrated that ABS with identifying system of road surface compared with previous generation of ABS system has better performance and recommended controller could maintain the slip in optimal value so that the vehicle could stop without slipping.

KEYWORDS: ABS, Sliding, Mode Control, Fuzzy Control.

1. INTRODUCTION
Different surface of roads has bad influences on vehicle stability and causes long brake. Vehicle stability and control are significant features that ABS has it. Because the driver have not precision control on oil pressure of tires and have not enough information about the road, he press the brake pedal hardly that leads to more pressure than the friction between tires and the road. This event not only couldn’t stop the vehicle, but also leads to lock of tire and loss of the lateral stability and controllability of the vehicle [1].

The friction and slip curve coefficient of tires for different surfaces has been shown in Figure 1. As you see, different surfaces of roads have different friction coefficient, so the ABS that has not surface identifying capability, will not have suitable performance. On the other hand, designing an ideal tire sliding controller is not easy since the brake system is non-linear and uncertain and causes many complications in designing. The performance of anti-lock brake system severely depends on road condition parameter which changes over a wide range [2], [6]. Therefore, a good controller is a good option for this issue. Sliding mode controllers have been widely reviewed because of its effect on nonlinear systems.

In many studies, suitable friction has been considered a constant value or in a certain interval but in this study considering road and speed changing by fuzzy controller, we present the best slip ratio for different situation which maintain the slip ratio in its optimum value and the vehicle stop in minimum distance without slipping.

So far, different types of ABS have been presented including adaptive fuzzy control [4], neural fuzzy [2], PID-fuzzy.

![Fig. 1. Coefficient of road friction versus wheel slip ratio [3]](image)
2. SYSTEM DYNAMICS

2.1. Vehicle model

Mathematical model for controller designing has been created based on rotational dynamics of a tire and longitudinal dynamics of vehicle. Thus, according to Newton’s second law and [7], [8] references, it is given:

\[ \dot{\omega}_\omega(t) = \frac{1}{J_\omega} \left[ -T_b(t) - B_\omega \omega(t) + R_\omega F_v(t) \right] \]  

(1)

Where \( J_\omega \) is the rotation inertia of the wheel, \( \omega(t) \) is the angular velocity of the wheel, \( T_b \) is the braking torque, \( R_\omega \) is the radius of the wheel, \( F_v \) is friction between the wheel and the road surface, \( B_\omega \) is the viscous friction of the wheel.

The slip rate is defined as following:

\[ \lambda_i(t) = \frac{\omega(t) - \omega_v(t)}{\omega_v(t)} \]  

(2)

Which \( \lambda \) is slip rate and usually is presented in percent and 100% slip rate means complete tire lock and 0% means no tire lock. Also \( \omega_v(t) = \frac{V(t)}{R_\omega} \) and \( V_v \) is speed forward and the quotation on longitudinal direction is:

\[ V_v = \frac{1}{M_p} \left[ 4F_t + B_v V_v(t) + F_\theta(\theta) \right] \]  

(3)

Where \( M_p \) is the mass of the vehicle; \( B_v \) is the vehicle viscous friction, \( F_\theta \) and \( F_t \) is defined as follow:

\[ F_\theta(\theta) = M_p \ g \ \sin(\theta) \]  

(4)

\[ F_t(t) = \mu(\lambda) \frac{M_p \ g}{4} \ \cos(\theta) \]  

(5)

Where \(-g\) is the gravitational acceleration constant, \( \theta \) is the angle of inclination of the road, and \( \mu(\lambda) \) is a function of friction that represent viscosity coefficient between road surface and tires.

2.2. Bruck Hard wheel friction model

The goal of ABS system is to maintain the operating spot of each tire near the peak of \( \mu-\lambda \) curve. Maximum friction occurs in this spot and optimum slip ratio also has been limited. In this paper, the below formula had been used as tire friction model that had been presented by Bruck Hard which friction coefficient between tires and road has been given based on a function of tires slip and vehicle velocity.

\[ \mu(\lambda, \nu) = (C_1 \left( 1 - e^{-\lambda C_2} \right) - C_3 \lambda) e^{-C_4 \lambda \nu} \]  

(6)

The parameters of this equation are:

C1: maximum value of friction curve, C2: friction shape, C3: friction curve difference between maximum value and the value at \( \lambda = 1 \), C4: wetness characteristic value and is in the range of 0.02 - 0.04m/s.

Table 1 shows the parameter of friction parameter in different condition of road.

<table>
<thead>
<tr>
<th>Road Condition</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( C_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry asphalt</td>
<td>1.2801</td>
<td>23.99</td>
<td>0.52</td>
</tr>
<tr>
<td>Wet asphalt</td>
<td>0.857</td>
<td>33.822</td>
<td>0.347</td>
</tr>
<tr>
<td>Snowy</td>
<td>0.1946</td>
<td>94.129</td>
<td>0.0646</td>
</tr>
</tbody>
</table>

3. SLIDING MODE CONTROL

Sliding Mode control has been accepted as the best procedure of control. The objective of Sliding Mode design is adjusting \( \lambda \) sliding coefficient over \( \lambda_d \) reference value.

Deriving equation 1 and 2, we have:

\[ \dot{\lambda} = \frac{(1-\lambda) \omega_v - \omega_v}{\omega_v} \]  

(7)

\[ \dot{\lambda} = \frac{\omega_v}{\omega_v} + \frac{\omega_v}{\omega_v} + \frac{\omega_v}{\omega_v} + \frac{\omega_v}{\omega_v} \]  

(8)

Now for designing sling mode control we have to obtain the equation. The equation of sliding surface for this system is as follow:

\[ s = \lambda - \lambda_d \]  

(9)

The control law could be presented in general case as follow:

\[ u = u_{\text{eq}} - k \text{sgn}(s) \]  

(10)

\( u_{\text{eq}} \) is input of control to system, \( K \) is slip use coefficient and \( \text{sgn}(s) \) is the mark function.

In ABS system, brake torque is \( T_b \) which is formed from two parts: equivalent torque control \( T_{b, \text{eq}} \) and switching torque control \( t_{b,r,b} \) which the first part makes \( (\lambda_d, \dot{\lambda}_d) \) States of the system to move along the sliding surface. It is determined from tires dynamics and sliding coefficient. Part two of the control is the assurance of attaining state route system to optimum sliding surface which its value is determined by \(-\) and stability condition analytically.

So in following we calculate the value of \( t_{b, \text{eq}} \) and \( t_{b, r, b} \).

Control equivalent is determined from \( \dot{s} = 0 \). In most study, \( \lambda_d \) is assumed constant. So \( \dot{\lambda}_d \) is zero but we
should keep in mind that \( \lambda_d \) is changed by velocity and different condition of road surface so we have:

\[ \dot{s} = \dot{\lambda} - \dot{\lambda}_d = 0 \]  

(11)

Using equations (7) and (8) we have:

\[ t_{b,eq} = \omega_v J_\omega (\lambda - 1) - B_\omega \omega_v + T_t + \omega_v J_\omega \dot{\lambda}_d \]  

(12)

For determining the control advantage, switching and Lyapunov function is selected then, the derivation is obtained less than zero or negative value of \( -\eta |s| \) in order to have stability condition.

\[ V(x) = \frac{1}{2} s^2 \]  

(13)

\[ \dot{V}_x = s \dot{s} \leq -\eta |s| \]  

(14)

Using equations (8), (11) and (14) we have:

\[ s \dot{s} = s \dot{\lambda} - s \dot{\lambda}_d \leq -\eta |s| \]

\[ \Rightarrow K \omega_v J_\omega |s| \geq \eta |s| \]  

(15)

\[ K \geq \omega_v J_\omega \eta \]  

(16)

As the result, substituting (12), (16), we got brake torque in (17)

\[ t_b = t_{b,eq} - K \text{sgn}(s) \]  

(17)

\[ t_b = \omega_v J_\omega (\lambda - 1) - B_\omega \omega_v + T_t + \omega_v J_\omega \dot{\lambda}_d - \omega_v J_\omega \eta - \text{sgn}(s) \]  

(18)

4. IDENTIFYING ROAD SURFACE

According to friction model, the friction coefficient between tires and road is depended on velocity and road condition which defining sliding coefficient. According to Figure 1, optimum sliding coefficient value is different in different road surface. So the objective of this paper is identifying road and determining optimum sliding coefficient in fuzzy logic procedure.

In this controller we use Mamdani fuzzy model for fuzzy conclusion. We also used multiplication and addition operator for fuzzy sharing and congregate respectively and used the mean center as non-fuzzy factor. We consider two input sliding coefficient and friction coefficient and the output of friction coefficient is considered optimum. The fuzzy system operates in such a way that makes a decision in the optimum friction coefficient range according to momentary friction and sliding coefficient.

The input and output - membership functions of this controller are as follow:

![Membership Function Plots](a)

![Membership Function Plots](b)

![Membership Function Plots](c)

**Fig. 2.** Membership functions of fuzzy road detector  
(a) First input: Adhesion coefficient, (b) Second input: Slip ratio, (c) Output: Maximum Slip ratio

Table 2 shows the rules table for the fuzzy system.
Table 2. RULE TABLE OF FUZZY DETECTOR

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$\mu$</th>
<th>$S$</th>
<th>$M$</th>
<th>$L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td></td>
<td>Wet</td>
<td>Wet</td>
<td>Wet</td>
</tr>
<tr>
<td>M1</td>
<td></td>
<td>Snow</td>
<td>Wet</td>
<td>Dry</td>
</tr>
<tr>
<td>L1</td>
<td></td>
<td>Snow</td>
<td>Wet</td>
<td>Dry</td>
</tr>
</tbody>
</table>

5. SIMULATION RESULTS
For simulations, the parameters of the ABS used in this study are $M_v = 4 \times 342$ kg, $B_v = 6$ Ns, $I_{wv} = 1.13$ Nm$s^2$, $R_w = 0.33$ m, $B_w = 4$ Ns, and $g = 9.8$ m/s$^2$.

The results of stimulation sliding mode controller without identifying road surface is showed in Figure 4. It is seen that the tractive forces for different road conditions are maximized near $\lambda = 20\%$, so the slip command $\lambda_c$ is chosen as 0.2. Moreover, a reference model is chosen as

$$\lambda_d(t) = -10\lambda_d(t) + 10\lambda_c(t)$$

(19)

And, the maximum braking torque is limited at 1200 N-m.

In Figure 4, we have the stimulation results by fuzzy controller when the fuzzy controller identifies road surface.

The stimulation had been done for dry, wet and snowy asphalt. The road surface changes from dry asphalt to wet after 1 second and then changes from wet to snowy asphalt after 1 second.

Fig. 3. (a) ABS response and Reference slip, (b) brake torque, - (c) Vehicle and wheel speed during the braking maneuvering in wet, snowy and dry condition
6. CONCLUSION

In this paper, the integral sliding mode controller is presented for vibration troubleshooting. The fuzzy logic is also presented for identifying road surface. Comparing the stimulation results we found that the fuzzy system determined the optimum sliding coefficient as optimum route for controller. We also found that the control tire sliding and stopping distance is decreased.

REFERENCES


