Modeling and simulation of the anti-lock braking system based on MATLAB/Simulink

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Abstract. The article illustrates basic operations and control features of ABS system. To Control the ABS Slip Ratio with Simulink, and create a single wheel ABS model according to the ABS principle. It produces Simulation curves, which verifies that the Auto ABS has good braking performance and direction of the manipulation.

1. Introduction
In an emergency, most drivers will immediately step on the brake pedal to death. When the car is braking, if the wheels lock and slip, the lateral adhesion between the wheels and the road will completely disappear: if only the front wheels (steering wheels) lock and slip while the rear wheels are still rolling, the car will lose its steering ability; If only the rear wheel locks and slips while the front wheel is still rolling, the car will also have a side-slip (tail-flick) phenomenon even if it receives a small lateral interference force. These are very easy to cause serious traffic accidents. In order to avoid traffic accidents caused by vehicle slip, it is necessary to develop an anti-lock braking system (ABS) that takes the slip rate as the target to control [1-2]. ABS is one of the main factors to improve the safety performance of automobiles. It is difficult to establish accurate mathematical models for the braking process of automobiles with high nonlinearity. With the rapid development of computer technology and software technology, simulation technology has become a research at home and abroad. It has been widely used in automobile research and development. This paper takes the car as the research object, establishes the ABS mathematical model, and uses the Matlab/Simulink simulation software to simulate the ABS.

2. The relationship between slip rate and adhesion coefficient during automobile braking
When a car is braking, as the braking intensity continues to increase, the components of wheel rolling will become less and less, and at the same time, the components of wheel sliding will become more and more. We use slip rate λ to describe the amount of slip component in the braking process. The definition of slip rate is:

\[ \lambda = \frac{v - \omega r}{v} \times 100\% \]

In the formula, v is the speed of the wheel center; r is the rolling radius of the wheel; \( \omega \) is the angular velocity of the wheel. In pure rolling, the vehicle speed \( v = \omega r \), slip rate \( \lambda = 0 \); in pure sliding, the wheel's angular velocity \( \omega = 0 \), slip rate \( \lambda = 100\% \); when the wheel slips and rolls, \( 0 < \lambda < 100 \% \). Therefore,
the size of the slip rate reflects the proportion of the slip component during the movement of the wheel. The greater the slip rate, the greater the slip component during the wheel movement.

According to the relationship curve between adhesion coefficient and slip rate during braking, when the value of wheel slip rate is controlled near the optimal slip rate of 20%, the car will be able to obtain the best braking performance while also having better directional stability.

The value of the adhesion coefficient mainly depends on the road material, the condition of the road surface, the structure of the tire, the tread pattern, the material, and the speed of the vehicle. Therefore, the relationship between adhesion coefficient and slip rate is different for different road surfaces.

3. Principles of automobile ABS
As an active safety device, automobile ABS can control the slip rate of the front and rear wheels of the car near the optimal slip rate by adjusting the brake pressure of the wheels, so that the car has good directional stability while obtaining the maximum ground braking force.

3.1. The basic structure of automobile ABS
ABS usually consists of wheel speed sensors, brake pressure adjustment devices, electronic control devices and ABS warning lights. In different ABS systems, the structure and working principle of the brake pressure adjustment devices are often different. The structure and control logic may also be different.

3.2. The control principle of automobile ABS
In a common ABS system, a speed sensor is installed on each wheel, and the signal about the speed of each wheel is input to the electronic control device (ECU). The electronic control device (ECU) monitors and judges the motion state of each wheel according to the signal input by each wheel speed sensor, and forms corresponding control commands. The brake pressure regulating device is mainly composed of a pressure regulating solenoid valve, an electric pump and an accumulator, etc., forming an independent whole, which is connected to the master brake cylinder and each wheel brake cylinder through a brake pipeline. The brake pressure adjusting device is controlled by the electronic control device (ECU) to adjust the brake pressure of each brake wheel cylinder.

4. Mathematical model of automobile ABS
The mathematical model of automobile braking system mainly includes automobile dynamics model, tire model and brake model.

4.1. Vehicle dynamics model
Since the establishment of a vehicle dynamics model is a complicated process, this article uses a single-wheel model to establish a vehicle dynamics model. The simplified single-wheel model is shown in Figure 1.
The dynamic equation of the vehicle can be obtained from the figure:

Vehicle motion equation:
\[
m \frac{dv}{dt} = -F
\]  
(1)

Wheel motion equation:
\[
I \frac{d\omega}{dt} = FR - Tb
\]  
(2)

Longitudinal friction of the vehicle:
\[
F = \mu N
\]  
(3)

In the formula, \( m \) is 1/4 vehicle mass (kg); \( F \) is ground braking force (N); \( R \) is wheel radius (m); \( I \) is wheel moment of inertia (kg•m²); \( Tb \) is braking torque (N•M); \( v \) is the vehicle speed (m/s); \( \omega \) is the wheel angular velocity (rad•s); \( N \) is the normal reaction force of the ground to the wheel (N); \( \mu \) is the ground friction coefficient.

4.2. Car tire model
The automobile tire model reflects the relationship between wheel and ground adhesion coefficient and slip rate. Commonly used tire models include bilinear models and magic formula models. However, due to the limitation of experimental conditions [6], this paper adopts a bilinear model to simplify the adhesion coefficient-slip rate curve into two straight lines. As shown in picture 2.

![Bilinear curve of adhesion coefficient-slip rate.](image)

The calculation formula is:
\[
\begin{align*}
\mu &= \frac{\mu_h \lambda}{\lambda_c} \quad \lambda < \lambda_c \\
\mu &= \frac{\mu_h - \mu_g \lambda_c}{1 - \lambda_c} - \frac{\mu_h - \mu_g}{1 - \lambda_c} \lambda \quad \lambda \geq \lambda_c
\end{align*}
\]  
(4)

In the formula, \( \mu \) is the longitudinal adhesion coefficient; \( \mu_h \) is the peak adhesion coefficient; \( \mu_g \) is the adhesion coefficient with a slip rate of 100%; \( \lambda_c \) is the best slip rate; \( \lambda \) is the slip rate.
4.3. Automobile brake model

The automobile brake model refers to the relationship model between the brake torque and the gas-hydraulic pressure of the brake system. When a car is braking, it must first overcome the spring return force in the brake and brake cylinder. Set this force as \( P_m \), then the corresponding braking torque can be expressed by the following formula:

\[
T_b = \begin{cases} 
0 & P < P_m \\
K_f (P - P_m) & P > P_m 
\end{cases}
\]

(5)

In the formula, \( T_b \) is the brake braking torque (N\( \cdot \)m); \( K_f \) is the brake braking coefficient (N\( \cdot \)m/kPa); \( P \) is the brake gas-hydraulic pressure (kPa); \( P_m \) is the gas required to overcome the spring return force Hydraulic pressure (kPa).

Due to the gap and friction of various mechanical parts in the brake, the brake hysteresis and other strong nonlinear dynamic characteristics are caused, which brings great difficulties to the brake modeling. In order to facilitate the study of control algorithms, this article assumes that the brake is an ideal component during the simulation, ignoring the impact of hysteresis. Therefore, the brake equation is:

\[
T_b = K_f P
\]

(6)

4.4. Simulink model of automobile ABS

Use Matlab/Simulink graphical modeling tools to establish a computer simulation model, and connect the established vehicle dynamics model, tire model and brake model into a closed-loop simulation system.

The wheel speed calculation sub-module includes brake model and control model. Taking pedal braking force as input, the controller controls the output brake braking torque according to the optimal slip rate and the actual slip rate, and finally outputs the wheel linear speed. The vehicle dynamics model takes the adhesion coefficient as input, and takes the body speed and braking distance as output. Finally, the linear wheel speed, vehicle speed and braking distance are input to the slip rate calculation module, and the actual slip rate is calculated. This simulation model also sets up an oscilloscope to observe the simulation curve and perform related analysis.

The automobile parameter model used in this article is shown in Table 1.

Table 1. Vehicle parameters of single-wheel model.

| Names and symbols                  | Names and symbols |
|-----------------------------------|-------------------|
| Vehicle curb weight M/kg          | 1500              |
| Initial braking speed \( v/(m/s) \) | 120               |
| Moment of inertia of wheel l/kg\(*m^2\) | 4.8               |
| Effective wheel radius R/m        | 0.4               |

5. Effective wheel radius R/m

According to the vehicle parameters for simulation, the best slip ratio is set to 0.2, the simulation graphics obtained are as follows:
Figure 3. Speed change curve of body and wheel.

Figure 4. Variation curve of slip rate.
Figure 5. Braking distance curve.

In order to facilitate the analysis, the braking process simulation without ABS is carried out, and the results are as follows:

Figure 6. Speed change curve of body and wheels (without ABS).
Figure 7. Slip rate change curve (without ABS).

Figure 8. Braking distance (without ABS).

6. Conclusions
According to the simulation results, when a car with ABS brakes at an initial speed of 120km/h, as the wheels are locked, the body speed is 5km/h, and the braking distance is 1200m. During the braking process, the slip rate can be controlled at around 0.2; when a car without ABS is braked at an initial speed of 120km/h, the wheels will lock up for 7 seconds after the start of braking. At this time, the body speed is 65km/h, and the vehicle is prone to sideslip and tail. The moving distance is 1400m.

It can be seen that ABS can effectively avoid the phenomenon of car lock and drag, thereby ensuring the stability and maneuverability of the driving direction when the car is braking, which is beneficial to driving safety.

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