Study on modeling of vehicle dynamic stability and control technique

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Abstract: In order to solve the problem of enhancing the vehicle driving stability and safety, which has been the hot question researched by scientific and engineering in the vehicle industry, the new control method was investigated. After the analysis of tire moving characteristics and the vehicle stress analysis, the tire model based on the extension pacejka magic formula which combined longitudinal motion and lateral motion was developed and a nonlinear vehicle dynamical stability model with seven freedoms was made. A new model reference adaptive control project which made the slip angle and yaw rate of vehicle body as the output and feedback variable in adjusting the torque of vehicle body to control the vehicle stability was designed. A simulation model was also built in Matlab/Simulink to evaluate this control project. It was made up of many mathematical subsystem models mainly including the tire model module, the yaw moment calculation module, the center of mass parameter calculation module, tire parameter calculation module of multiple and so forth. The severe lane change simulation result shows that this vehicle model and the model reference adaptive control method have an excellent performance.

Key words: vehicle dynamic stability and control; vehicle dynamics modeling; model reference adaptive control

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0 Overview

When the car runs in the high-speed steering, the adhesion between the car tires and the ground will exceed the attachment limit, and the car is very easy to lose control resulting in the generation of the vehicle body sideslip accidents. These models which have higher body center of gravity just like the SUV and light truck (LT) is easily to cause the car to roll and slide when the car lost control. Although the auto body can absorb the energy generated by the impact, as well as modern standard airbags can significantly improve the passive safety of motor vehicles in a traffic accident, but such passive safety technology only works in a car accident after, and can not completely avoid the loss of personnel and property. When the car is driving on the less road adhesion conditions, like snow or ice road, the driving safety is more difficult to ensure. The vehicle dynamic stability control system (VSC) which uses board computer as the core can make a real-time monitoring the operating status of the car and calculate the vehicle steady-state analysis. The VSC can issue control signals to adjust the engine running status to adjust the load points and adhesion characteristics between tires and road surface, thus the car can stable driving in the desired trajectory and the car skidding accidents can be reduced effectively.

In U. S. A, the SAE defines that the VSC system consists of the sensors, electronic control units and actuators. The VSC system must have the functions follows: detecting vehicle speed and yaw slip rate and car steering wheel angle, using the computer closed-loop control of vehicle under steer or over steer, adjusting the brakes to fix the yaw torque when the car is running. Many domestic and foreign scholars have conducted researches which mostly are based on the multi-body dynamics software [1-4]. Most of those studies are based on the linear two degree of freedom vehicle which is just a

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simple car physics model.

This paper established a vehicle model with seven degree of freedom, developed a model reference adaptive control strategy after anglicizing the automobile tire model and steering characteristics, and made a simulation to illustrate control effect.

1 Vehicle Dynamics Modeling

Vehicle dynamics is a modern development research on automotive systems emerging disciplines, including flexibility of the tires and damping elements studies and other knowledge. Those components are not an ideal linear system and the control strategies are more complex when study its control. The modern car tires are a typical viscosity structure with the obvious nonlinear characteristics and it has complex structures with special materials. Because the interaction between the tire surface and the road is complex, the tire mechanical properties will obviously affect the vehicle dynamics.

At present the Fiala tire model, UA tire model, Hui Guo tire model and H. B. Pacejka tire model (magic formula) is the extensive tire model [5-6]. The magic formula tire model which has been widely used in vehicle dynamics studies has high simulation accuracy with a simple expression.

The general expression of magic formula is follows:

$$Y = y + S_v \tag{1}$$

$$y = D \cdot \sin(C \cdot \mathrm{arctg}(B \cdot x - E(B \cdot x - \mathrm{arctg}(B \cdot x)))) \tag{2}$$

$$x = X + S_h \tag{3}$$

Where: Y represents the lateral force, longitudinal force or aligning torque; X represents the slip angle α or slip ratio s; D is the peak factor which indicates the maximum of the curve; B is the stiffness factor; E is the curvature factor of the curve which represents the shape of the curve near the maximum value; C is the curve shape factor which represents the lateral force, longitudinal force or self-aligning torque; S_h is the curve horizontally drift; S is the vertically.

All the parameters here are related with the load except the curve shape factor C.

Actually when the vehicle is moving, the lateral forces and longitudinal forces playing on the tire have composite relationship called longitudinal slip-cornering characteristics.

In the paper, a extension magic formula was defined to study which can more meet the moving characteristics of the tire [7-9].

The general tires sliding rate characteristics is:

$$s = \sqrt{s_x^2 + s_y^2} \tag{4}$$

The forces acting on the tire can be synergized from the vertical and horizontal. It was calculated by formula (1), and then the lateral force (or lateral force) is:

$$F_i = -\frac{s_i}{s} F(s),\ i = x, y \tag{5}$$

Here, s_x is the longitudinal slip and the lateral slip rate can be gotten by follows $s_y = -\tan\alpha = -v_y/v_x$.

Then the tire longitudinal slip and lateral slip side relationship can meet the characteristics called "tire-road friction ellipse".

Suppose ignoring the tire rolling resistance and car drag, just considering the vertical, horizontal and the yaw around the vehicle inertia axis, a four-wheel vehicle model can be established as well as taking into account the wheel rotates shown in figure 1. It defines that the front wheel is steering wheel and the rear wheels do not have the steering ability. The model ignoring the vehicle steering system uses the front wheel rotation angle as the car steering input. In study, suppose the vehicle just move on the parallel ground ignoring the vehicle suspension system and the pitch around the y-axis and roll angle around the x-axis is zero.

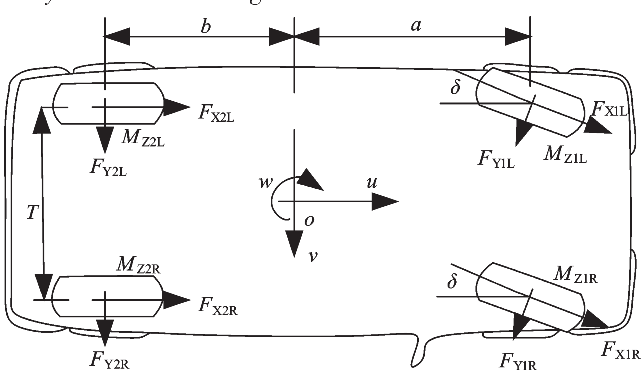


Figure 1 Schematic Vehicle with Seven Freedoms

Then a car model having the seven degrees of freedom vehicle model can be gotten which has a lateral movement, vertical movement, yaw movement and four wheels independence movement front and rear. According to Newtonian mechanics system, its motion equation was expressed as follows:

$$\sum F_x: m(\dot{u}-wv)=(F_{X1L}+F_{X1R})\cos\delta-(F_{Y1L}+F_{Y1R})\sin\delta+F_{X2L}+F_{X2R} \quad (6)$$

$$\sum F_y: m(\dot{v}+wu)=(F_{X1L}+F_{X1R})\sin\delta-(F_{Y1L}+F_{Y1R})\cos\delta+F_{X2L}+F_{X2R} \quad (7)$$

$$\sum M_z: I_z\dot{w}=[(F_{X1L}-F_{X1R})\cos\delta+(F_{Y1L}-F_{Y1R})\sin\delta]T/2+[(F_{X1L}+F_{X1R})\sin\delta+(F_{Y1L}+F_{Y1R})\cos\delta]a+(F_{X2L}-F_{X2R})T/2-(F_{Y2L}+F_{X2R})b+M_{Z1L}+M_{Z1R}+M_{Z2L}+M_{Z2R} \quad (8)$$

where: $M_{1L}=I_{zw}\dot{w}_{1L}+r_wF_{X1L}$; $M_{1R}=I_{zw}\dot{w}_{1R}+r_wF_{X1R}$; $M_{2L}=I_{zw}\dot{w}_{21L}+r_wF_{X2L}$; $M_{2R}=I_{zw}\dot{w}_{2L}+r_wF_{X2R}$.

m is the total mass of the car; v is the sliding speed of car quality heart; r is the yaw angular velocity heart of car quality heart; a is distance between quality heart and the front axle of vehicle; b is value between quality heart and the rear axle of vehicle; F_{Y1L} and F_{Y1R} is lateral tire force around the front axle; F_{Y2L} and F_{Y2R} is lateral tire force around the rear axle; M_{Z1L} , M_{Z1R} , M_{Z2L} and M_{Z2L} is self-aligning torque corresponding to the four wheels; u is the longitudinal velocity; δ is the front wheel steering angle; F_{X1L} and F_{X1L} is the vertical tire force of front axle; F_{X2L} and F_{X2L} is the vertical tire force of front axle; I is the moment of inertia of the wheel; R_w is the wheel radius; β is the slip angle of car mass center; w_{1L} is the angular velocity of front axle; w_{1R} is the angular velocity of rear axle; T is the wheel tread; M_{1L} 、M_{1R} 、M_{2L} and M_{2R} is the braking torque playing on the four wheel.

This vehicle model with seven degrees of freedom is ideal vehicle analytical models which can be easily analyzing the factors affect on the car steady state. However, this model is a nonlinear time-varying system with complex relationships between the parameters because of mutual coupling affects on each other. The system output response has a relationship not only with the system structure parameters but also the input variables and their initial value. Therefore, it is more difficult to analysis control theory using traditional method. In this paper, the Matlab software was selected as modeling and simulation tools to study. The paper built many functional modules in Matlab/Simulink to analyze the vehicle dynamical stability which mainly include the tire model module, the yaw moment calculation module, the center of mass parameter calculation module, tire parameter calculation module of multiple and so forth. The tire model using the extended magic formula which can reflecting the tire longitudinal force, lateral force and longitudinal wheel speed, wheel load, slip angle, rotation speed and other parameters linkages ignores the radial deformation of automobile tires, camber, and other factors.

Equation (6), (7) and (8) constitute a set of ör equations which build the vehicle mass center parameters calculation module, shown in figure 2. In figure 2 (a), there are many integrators following micro-component in the equation which output are the car heart parameter calculation module´s output is, that is, centroid horizontal speed u_car, centroid lateral speed v_car and quality of the heart declination w_car side. The module´s input variables were calculated by the other modules of the simulation system. Figure 2(b) is the centroid parameter calculation module package shape which calculates the centroid parameters.

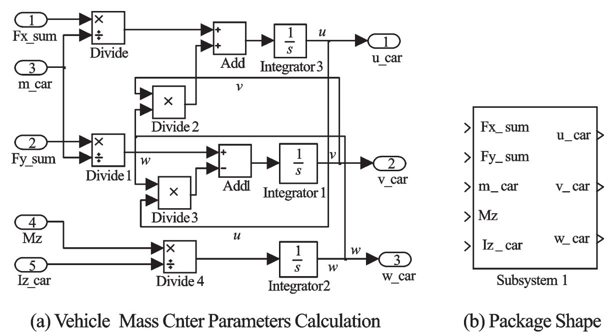


Figure 2 Block of Vehicle Centric Parameter Calculation

2 Vehicle Dynamic Stability Control

A reference model adaptive control structure, shown in figure 3, was designed to study vehicle dynamic stability control. The entire control system mainly

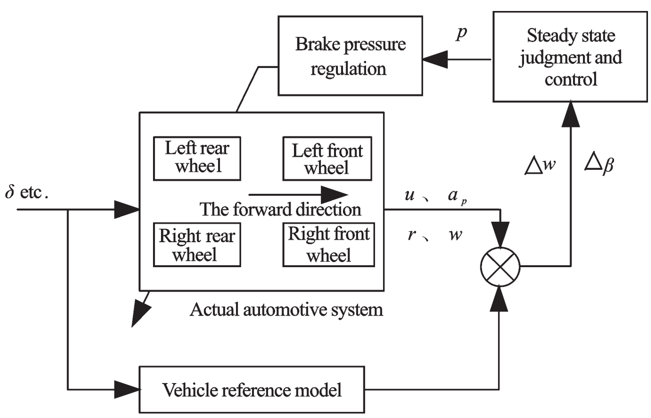


Figure 3 Diagram of Vehicle Stability Adaptive Control

consists of the actual automotive systems, automotive reference model, stability judgment and control, brake pressure regulation module. In the chosen input conditions the variable differences between actual automotive system and the vehicle reference model state was used to determine the actual running vehicle steady state [10-11]. The wheel braking forces p were constantly adjusted to change the yaw moment in order to keep the car running on a stable track.

In study yaw rate w and the side slip angle β were used as the control variable and the vehicle reference model real-time outputs were used to estimate the car's actual trajectory. The paper chooses a linear two degrees of freedom vehicle model as reference model and uses phase plane made by the yaw angle and sideslip angle as judgments to determine the steady state of the car. Shown in figure 4, the area close to zero is stability region; the others in first and third quadrants are unstable region; the areas in two and four quadrants are stability and quasi-stability region. The stability criterion using slip angle β was defined by following inequality approximately:

$$\left|\beta + B_1\dot{\beta}\right| \leq B_2 \tag{9}$$

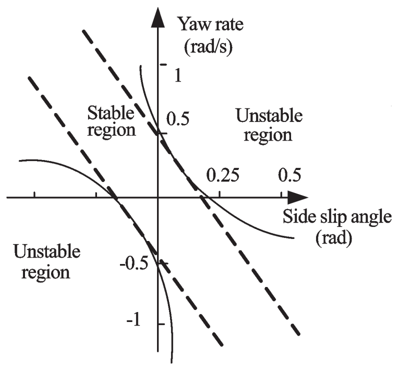


Figure 4　the Stability Rule of Yaw Angle

Where B_1 and B_2 is the constant coefficient. When the inequality holds, the car's driving state is stable, and when the inequality relationship is destroyed, and the car will lose kinetic stability.

According the stability criterion above Δw^+ was defined as the threshold limit of Δw and Δw^- was defined as the threshold limit. The yaw torque adjustment strategy is as follows:

While $\Delta w > \Delta w^+, \beta + B_1\beta > B_2, \delta > 0$, then a small step was used to increase the right front, left rear and right rear wheel braking force.

While $\Delta w > \Delta w^+, \beta + B_1\beta < -B_2, \delta > 0$, then a small step was used to increase the braking force of the right rear wheel and a large step was used to increase the right front wheel braking force.

While $\Delta w > \Delta w^+, \beta + B_1\beta > B_2, \delta < 0$, then a small step was used to increase the right front and right rear wheel braking force.

While $\Delta w > \Delta w^+, \beta + B_1\beta < -B_2, \delta < 0$, then a small step was used to increase left front wheel and right front wheel and right rear wheel braking force.

While $\Delta w^- < \Delta w < \Delta w^+, \beta + B_1\beta > B_2, \delta > 0$, then a small step was used to increase the left rear wheel braking force.

While $\Delta w^- < \Delta w < \Delta w^+, \beta + B_1\beta < -B_2, \delta > 0$, then a small step was used to increase the right front wheel braking force.

While $\Delta w^- < \Delta w < \Delta w^+, -B_2 < \beta + B_1\beta < B_2, \delta > 0$, then a large step was used to reduce the braking force of each wheel.

While $\Delta w^- < \Delta w < \Delta w^+, \beta + B_1\beta > B_2, \delta < 0$, then a small step was used to increase the braking force of left front wheel.

While $\Delta w^- < \Delta w < \Delta w^+, \beta + B_1\beta < -B_2, \delta > 0$, then a small step was used to increase the braking force of the right rear wheel.

While $\Delta w < \Delta w^-, \beta + B_1\beta > B_2, \delta > 0$, then a small step was used to increase the left front wheel and right rear and left rear wheel braking force.

While $\Delta w < \Delta w^-, \beta + B_1\beta < -B_2, \delta > 0$, then a small step was used to increase the left rear wheel and large step was used to increase the left front wheel braking force.

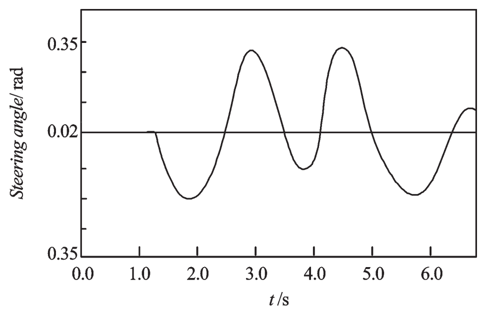
While $\Delta w < \Delta w^-, -B_2 \leq \beta + B_1\beta < B_2, \delta > 0$, then a small step was used to increase the left front wheel, left rear and right rear wheel braking force.

While $\Delta w < \Delta w^-, \beta + B_1\beta > B_2, \delta < 0$, then a small step was used to increase the left rear wheel braking force and the large step was used to increase in the left front brake force.

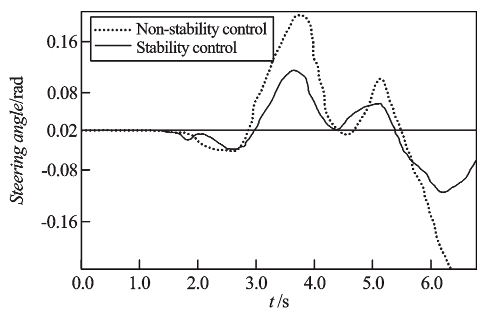
While $\Delta w < \Delta w^-, \beta + B_1\beta < -B_2, \delta < 0$, then a small step was used to increase the left front wheel, left rear and right rear wheel braking force.

3　Simulation and Analysis

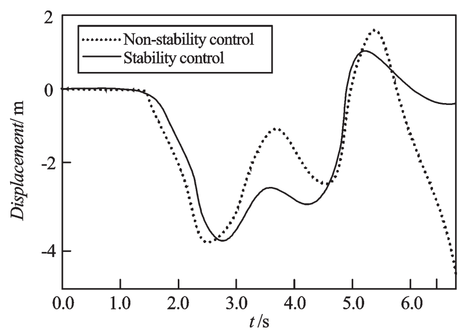
In order to facilitate the research in simulation the braking force was directly increased in the center of rotation wheel while the wheel needs to brake. And the car speed is 20 m/s, the B_1 is −1, the B_2 is 0.5, the road adhesion coefficient is 0.5. Excitation signal added on the front wheel to simulate the steering control signal when the vehicle avoiding obstacles traveling in bilinear track as shown in figure 5(a) shown. The car sideslip angle response is shown in figure 5(b) and the vehicle trajectory is shown in figure 5(c). It can be seen from the figure that the amplitude of car sideslip angle using the adaptive control VSC system have decreased significantly compared to generally car which do not use the VSC system. The trajectory curve of the car is kept within a small range with the adaptive control VSC system, but the other curve is not good enough. The amplitude of trajectory curve without VSC system increased continuously in the final simulation period which may be issued rollover accident when the car turns on a slip.



(a) the Front Wheel Steering Angle



(b) the Sideslip Angle Response



(c) Vehicle Trajectory

Figure 5　Simulation Results Diagram

4　Conclusions

Using model reference adaptive control technology is one of an effective method in VSC system. This research ignores many influencing factors, and the practical VSC system must consider the various situations when the car is running and combine the car models and variety of road. However, the simulation result above can give an important reference for design and research in actual VSC system.

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