Study on ESP Control Principle of Light Off-road Vehicle Based on Brake / Drive Integrated Control

Wang Guoye¹, Zhang Juanli¹, Fen Yanli¹, Zhang Yanru²

¹Vehicle and Traffic Engineering Department
College of Engineering, China Agricultural University
Beijing, China

²Industrial Engineering Department, College of Mechanical and Automotive Engineering, Hefei University of Technology
Hefei, China

Abstract

Set up the dynamic model of light off-road vehicle, including body dynamics model, wheel model, engine model, and so on. For light off-road vehicle, project the ESP control principle based on the integrated control of brake and drive, the ASR engine control principle based on the PID control and the ASR differential brake intervention control principle. Based on the Matlab/Simulink, establish the dynamic simulation model of the ESP control system for the Beijing JEEP2500 light off-road vehicle. Using the simulation model, we respectively simulate and analyse the vehicle performance of low engine throttle opening control, ASR control and ESP control when the vehicle straight runs and turns on the bisectional road. The study results indicate that the proposed ESP control principle can obviously improve the comprehensive driving performances of light off-road vehicle, including the driving stability under different conditions.

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1. Introduction

In recent years, the off-road vehicles develop rapidly. As progress of technology and increase of security performance requirements, the driving stability and the security performance of off-road vehicles are paid more and more attention. Electronic Stability Program (ESP) has been proven to be one of the current key technologies to effectively solve the vehicle active safety. The structural characteristics of off-road vehicles have an adverse impact on driving stability, such as the body structure and the technical parameters of off-road vehicles vary greatly compared with cars, the higher chassis of off-road vehicles
leads to higher position of mass center, the off-road vehicles use four-wheel drive or rear-drive, the longitudinal position of mass center of off-road vehicles is closer to the center of body, and so on. The driving stability and security problems of off-road vehicles are severer, so the stability control system of off-road vehicles is set higher requirements. At present, the car ESP has been extensively researched and applied, but there are few studies on the off-road vehicles ESP.

The current ESP control principles have differential braking control, driving torque control and active steer control and so on\cite{1}\cite{2}. For the characteristics of light off-road vehicles, we project the ESP control principle based on the integrated control of brake and drive, set up the dynamic model of light off-road vehicle\cite{3}\cite{4}. Based on the Matlab/Simulink establish the dynamic simulation model of the ESP control system for the Beijing JEEP2500 light off-road vehicle. Using the simulation model, we respectively simulate and analyse the vehicle performance of low engine throttle opening control, ASR control and ESP control when the vehicle straight runs and turns on the bisectional road. The study results indicate that the dynamic model and the simulation model of light off-road vehicle are reasonable, and the proposed ESP control principle based on the integrated control of brake and drive can obviously improve the comprehensive driving performances of light off-road vehicle, including the driving stability under different conditions.

2. Dynamic Model of the Off-road Vehicle

2.1 Dynamic Model of the Whole Vehicle

The dynamics model of vehicles applies 7-DOF vehicle dynamic model, shown in Fig. 1. The 7-DOF includes: car body longitudinal movement, lateral movement, yaw movement and rotational movement that four wheels rotate around their axis.

xOy is the coordinate system of vehicle mass center, x is on the longitudinal direction of the vehicle, the positive direction is the vehicle running direction; y is on the lateral direction of the vehicle, the left is the positive direction. \( \delta_1 \) and \( \delta_2 \) are the steering angles of the inside and outside front wheels respectively, rad. \( \alpha_i \) (i=1,2,3,4) are slip angles of tires, rad; \( \beta \) is the slip angle of the mass center of the vehicle, rad; \( F_{xi} \) and \( F_{yi} \) (i=1,2,3,4) are the longitudinal braking forces and the lateral forces of tires, N.

![Figure 1. The off-road vehicle Dynamic Model](image)

The vehicle movement equations in coordinate system xOy are:

\[
\begin{align*}
F_x &= m(\ddot{x} - \dot{y}\omega_z) \\
F_y &= m(\ddot{y} + \dot{x}\omega_z) \\
M_z &= I_z\dot{\omega}_z
\end{align*}
\]  

(1)
where $F_x, F_y$ are the resultant forces of the mass center of the vehicle in coordinate system xOy, N; $M_z$ is the yaw resultant torque, N·m; $m$ is total mass of the vehicle, kg; $\dot{x}, \dot{y}$ are the acceleration in coordinate system xOy, m·s$^{-2}$; $\dot{x}, \dot{y}$ are the velocity in coordinate system xOy, m·s$^{-1}$; $\dot{\phi}_z$ is the vehicle yaw acceleration, rad·s$^{-2}$; $\phi_z$ is the vehicle yaw velocity, rad·s$^{-1}$; $I_z$ is the inertia of the vehicle yaw moment, kg·m$^2$.

The dynamic equations of the whole vehicle:

\[
\begin{align*}
\sum F_x &= F_{x1} \cdot \cos(\delta_1) - F_{y1} \cdot \sin(\delta_1) + F_{x2} \cdot \cos(\delta_2) \\
& - F_{y2} \cdot \sin(\delta_2) + F_{y3} + F_{y4} \\
\sum F_y &= F_{x1} \cdot \sin(\delta_1) + F_{y1} \cdot \cos(\delta_1) + F_{x2} \cdot \sin(\delta_2) \\
& + F_{y2} \cdot \cos(\delta_2) + F_{y3} + F_{y4} \\
\sum M &= [F_{x1} \cdot \sin(\delta_1) + F_{y1} \cdot \cos(\delta_1) + F_{x2} \cdot \sin(\delta_2) \\
& + F_{y2} \cdot \cos(\delta_2)] \cdot a - (F_{x3} + F_{y4}) \cdot b - [F_{x1} \cdot \cos(\delta_1) \\
& - F_{y1} \cdot \sin(\delta_1) - F_{x2} \cdot \cos(\delta_2) + F_{y2} \cdot \sin(\delta_2)] \cdot B_i / 2 \\
& -(F_{x3} - F_{y4}) \cdot B_i / 2 - M_{i1} - M_{i2} - M_{i3} - M_{i4}
\end{align*}
\]

where, $M_{i}$ (i=1,2,3,4) is the aligning torque of the wheels, N·m; the other parameters are the same as the above.

2.2 The Wheel Model

The dynamic analysis [2][3] of the vehicle tire is shown in Fig. 2. The torque balance equation of the wheel is:

\[
I_w \dot{\phi}_i = T_{qi} - F_{xi} R - T_{\mu i}
\]

where, $I_w$ is the rotational inertia of the wheel, kg·m$^2$; $F_{xi}$ (i=1,2,3,4) is the driving force of the wheel, N; $R$ is the wheel rolling radius, m; $T_{qi}$ (i=1,2,3,4) is the driving torque of the wheel, N·m; $T_{\mu i}$ is the braking torque of wheel, N·m.

2.3 The Engine Model [1]

The engine dynamic equation can be represented by:

\[
I_e \dot{\phi}_e = T_{\text{ind}} - T_{\text{load}} + T_f
\]

where, $T_{\text{ind}}$ is the indicated combustion torque, $T_{\text{load}}$ is the external load torque on the crankshaft, $T_f$ represents the pumping and friction losses in the engine and $I_e$ is the rotational inertia of the engine.

The load on the engine $T_{\text{load}}$ is typically provided by a torque converter which couples the engine to the transmission. The indicated torque $T_{\text{ind}}$ is generated by combustion.

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Figure 2. Dynamic Analysis for Driving Wheel
where, $H_u$ is the fuel energy constant, $\eta_i$ is the indicated thermal efficiency and accounts for the cooling and the exhaust system losses, and $\dot{m}_f$ represents the fuel mass flow rate into the cylinders. The fuel mass flow rate $\dot{m}_f$ is typically determined by a fuel injection control system which attempts to maintain a stoichiometric air-fuel ratio in the cylinders. If it is assumed that a stoichiometric air-fuel ratio is successfully maintained in the cylinders, then the fuel mass flow rate $\dot{m}_f$ is related to the outflow from the intake manifold into the cylinders of the engine.

3. The Control Principle of Vehicle Driving Stability

3.1 The ESP control

The off-road vehicle ESP control based on the integrated control of brake and drive uses the hierarchical control, as Fig. 3 shows. The upper controller is the state controller of car body, which uses the PID controller, the input of the controller is bias value $\Delta \beta$ between the ideal slip angle $\beta_0$ and the actual slip angle $\beta$ of the vehicle mass center, the output is the correction value $\Delta S$ to the best slip rate of wheels(for the ABS controlling to the non-driving wheel or for the ASR controlling to the driving wheel). The lower controller is including ABS controller to the non-driving wheel and the ASR controller to the driving wheel; the ABS controller uses the target slip rate obtained by the best slip rate of the non-driving wheel and its correction value to the braking control; the ASR controller uses the target slip rate obtained by the best slip rate of driving wheel and its correction value to the driving control. In order to achieve the desired steering performances, the ESP controller is the integrated control to the non-driving wheel and the driving wheel using the ABS controller and the ASR controller.

The ABS control to the non-driving wheel applies the general way of threshold control; The ASR control include the engine control and the brake intervention control. Driving on the uniform adhesive road, the ASR control is mainly through the engine control, supplemented by the brake intervention control; On the complex roads with the inconsistent adhesive condition, the ASR control is the opposite; The engine control uses the PID control, as Fig. 4 shows, the brake intervention control uses the differential brake control.

Proportional-integral-derivative control (referred to as PID control) is the method of using in the engineering widely because of the simple structure and the stable performance, also can be well used on the control system with the uncertain structure and the parameters of the control object. Dynamic performances of the off-road vehicle influenced by many factors in the running process, so it is difficult to establish the accuracy dynamic model of the running process, therefore the PID control can be well used in the ESP control of off-road vehicle.
3.2 The Engine Control

In order to maintain the larger driving force with the driving wheel, the engine control applies to control the angle of the throttle opening through the mean bias value based on the slip rate of the right and left driving wheel, therefore it can improve the vehicle performances on the complex roads.

The controlling strategy is shown in Fig. 4, the input of the engine PID controller is \((\Delta S_1 + \Delta S_2)/2\), \(\Delta S_1 = S_{c1} - S_1\), \(\Delta S_2 = S_{c2} - S_2\), where \(S_{c1}, S_{c2}\) is the target slip rate of the driving wheels respectively, \(S_1, S_2\) is the actual slip rate of the driving wheels respectively, the output is the angle of the engine throttle opening.

3.3 The Brake Intervention Control

As Fig. 4 shows, the brake intervention control uses the differential brake control, the input of the brake intervention control is \(\Delta S_1 - \Delta S_2\), which is the error of the bias value between the actual slip rate and the controlling slip rate of the driving wheels; the output by the quantization is the control signal of braking control valve with the driving wheels. The brake intervention control has its effects when \(\Delta S_1 - \Delta S_2\) exceeds the setting threshold value, the effect isn’t exist when \(\Delta S_1 - \Delta S_2\) is lower than the threshold value, then the ASR control only uses the engine control.

4. The ESP Control Performance Analysis

To fully verify the performance of the ESP control system, establish the dynamic simulation model of the ESP control system for the Beijing JEEP2500 light off-road vehicle based on the Matlab/Simulink. By the simulation model, we respectively simulate and analyse the vehicle performance in the three controls: low engine throttle opening control, ASR control and ESP control on two typical dangerous conditions: straight run and turn run on the bisectional road.

![The ASR controller of the driving wheel](image)

Figure 4. The ASR controller of the driving wheel

Use the trajectory and slip angle of vehicle mass center to measure the control effect of vehicle ESP system. Fig. 5 and Fig. 7 show the trajectories of vehicle mass center, where X-axis represents the horizontal displacement of vehicle mass center in the ground coordinate system, Y-axis represents the vertical displacement of vehicle mass center, all the units are meter. Fig. 6 and Fig. 8 show the change of slip angle of vehicle mass center, where X-axis represents the horizontal displacement of vehicle mass center, the unit is meter, and Y-axis represents the slip angle the horizontal displacement of vehicle mass center, the unit is degree. In Fig. 5, 6, 7, 8, the thin solid line is the vehicle performance curve of low engine throttle opening control; the thin dashed line is the vehicle performance curve of ASR control; the thick solid line is the vehicle performance curve of ESP control.
4.1 Straight Run on Bisectional Road

Set the steer angle of vehicle left-front wheel is 0.001°, close to the straight state; the initial vehicle velocity $v_0=10\text{km/h}$, the stop simulating vehicle velocity $v_t=60\text{km/h}$; bisectional road, the ground adhesion coefficient of two inside wheels is 0.1, the ground adhesion coefficient of two outside wheels is 0.9.

Fig. 5 shows the trajectories of vehicle mass center for straight running on the bisectional road, Fig. 6 shows the slip angle of vehicle mass center for straight running on the bisectional road. In the three control simulation tests, the maximum vertical displacement of vehicle mass center is 1.0441m and the slip angle of vehicle mass center remains at around 0° under the low engine throttle opening control, the vehicle runs close to a straight line; the maximum vertical displacement of vehicle mass center is 25.294m and the minimum slip angle of vehicle mass center is -0.321670° under ASR control; the maximum vertical displacement of vehicle mass center is 6.8818m and the minimum slip angle of vehicle mass center is -0.02797° under ESP control, stability control effect is better than ASR control. ASR control can make the driving forces on both sides of driving wheels achieve maximum to improve driving capacity, because the maximum driving forces on both sides of driving wheels differ greatly on the bisectional road, it influences the straight driving stability of vehicle. Under low engine throttle opening control, the role of the differential can make

![Figure 5. The trajectories of vehicle mass center for straight running on the bisectional road](image1)

![Figure 6. The slip angle of vehicle mass center for straight running on the bisectional road](image2)
sure the driving forces on both sides of driving wheels are nearly equal, the straight driving stability of vehicle is best in three control simulation tests, but the driving capacity are poor because the driving forces on both sides of driving wheels are smaller. ESP control can not only improve vehicle stability but also ensure the driving capacity, so ESP control can obviously improve the comprehensive driving performances of light off-road vehicle. The results of simulation tests are consistent with actual results.

4.2 Turn Run on Bisectional Road

Set the steer angle of vehicle left-front wheel is 5°; other parameters are same as above.

Fig. 7 shows the trajectories of vehicle mass center for turning on the bisectional road, Fig. 8 shows the slip angle of vehicle mass center for turning on the bisectional road. In the three control simulation tests when the tests ending, the maximum curvature radius of the trajectories of vehicle mass center is 32.275m under the low engine throttle opening control, shows under steering characteristic; the minimum curvature radius of the trajectories of vehicle mass center is 21.9825m under ASR control, shows over steering characteristic; it can be seen that, the curvature radius of the mass center trajectories under ESP control is smaller than under the low engine throttle opening control, larger than

![Figure 7. The trajectories of vehicle mass center for turning on the bisectional road](image1)

![Figure 8. The slip angle of vehicle mass center for turning on the bisectional road](image2)
under ASR control, and the mass center slip angle is smallest, the vehicle performance under ESP control is close to the neutral steering characteristics, the comprehensive driving performances of vehicle including the driving stability are improved obviously.

In Summary, under the low engine throttle opening control, the vehicle runs close to a straight line on the condition of straight run on the bisectional road, shows close to the neutral steering characteristics on the condition of turn run on the bisectional road, are consistent with actual results, so the dynamic model of light off-road vehicle is reasonable; on the two conditions of straight run and turn run on the bisectional road, the comprehensive driving performances of ESP control vehicle, especially driving stability, are improved obviously than ASR control vehicle.

5. Conclusions

Set up the dynamic model of light off-road vehicle. For light off-road vehicle, project the ESP control principle based on the integrated control of brake and drive, the ASR engine control principle based on the PID control and the ASR differential brake intervention control principle. Based on the Matlab/Simulink, establish the dynamic simulation model of the ESP control system for the Beijing JEEP2500 light off-road vehicle. Using the simulation model, we respectively simulate and analyse the vehicle performances of low engine throttle opening control, ASR control and ESP control when the vehicle straight run and turn run on the bisectional road. Finally we can draw the conclusions as follows:

1) Under the low engine throttle opening control, the vehicle runs close to a straight line on the condition of straight run on the bisectional road, and close to the neutral steering characteristics on the condition of turn run on the bisectional road, which are consistent with actual results, so the dynamic model of light off-road vehicle is reasonable. 2) On the condition of straight run on the bisectional road, the straight driving stability of ESP control vehicle is better than ASR control vehicle, ESP control can not only improve vehicle stability but also ensure the driving capacity. 3) On the condition of turn run on the bisectional road, the performance of ESP control vehicle is close to the neutral steering characteristics, the comprehensive driving performances of vehicle including the driving stability are improved obviously.

The study results indicate that the dynamic model and the simulation model of light off-road vehicle are reasonable, and the proposed ESP control principle based on the integrated control of brake and drive can obviously improve the comprehensive driving performances of light off-road vehicle, including the driving stability in different conditions.

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