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Research on Vehicle Stability Control Algorithm for Direct Yaw Moment Control

Hongyu Zheng+ and Changfu Zong

State Key Laboratory of Automobile Dynamics Simulation, Jilin University

Changchun, China

Abstract—A vehicle will usually become unstable while it is turned on a low friction road or in high speeds because the lateral force of the tire reaches the physical limit. A direct yaw moment control (DYC) can control vehicle motion by a yaw moment which is actively generated by transversally distributed tire longitudinal forces, and has become one of the most promising means of chassis control for the improvement of vehicle active safety. The best advantage of the DYC is to greatly improve vehicle handling and stability, and DYC shows the expected robustness when vehicle parameters change, such as tyre cornering stiffness and vehicle mass, even with external disturbances.

In this paper, a driver-vehicle closed-loop model of 9 DOFs was built. Two control strategies of DYC were proposed, including forward control and single neural cell PID control. The two control methods were compared by simulation based on the vehicle model. The results show that the single neural cell PID control algorithm was more effective on improving the vehicle handling and stability.

Keywords-vehicle engineering; vehicle stability control ; direct yaw moment control; vehicle dynamic model

1. Introduction

In recent years, with the development of electronic technologies and control theories, vehicle handling and stability have become more and more important for safety of drivers. Traditional vehicle may be controlled easily in normal situations but easily lose stabilization in limited situations, often exhibiting oversteer or understeer, even spin out [1]. ABS and ASR are kinds of active control systems that control slip rate to improve safety, but it often need to utilization ratio of longitude and not provide enough safety in some special situations of lane change, steering under braking, J-turn, etc [2].

Based on ABS/ASR, DYC is studied in order to reduce driver burden, and to improve stability and safety greatly [3]. According to driver’s handling and vehicle movement state, the DYC controller can compute how to distribute four wheel cylinder braking pressure to generate a yaw moment to avoid changing steering excessively or insufficiently [4]. The DYC system is divided into some categories: sensors, ECU and actuators. Sensors include steering angle sensor, yaw rate sensor, brake pressure sensor, vehicle body accelerometer and so on. Actuators include hydraulic actuator and throttle actuator. Stability is easily lost when a vehicle is steered abruptly in high vehicle speed because of the effect of lateral load force of the tyre. According to information from the sensors, the ECU can compute ideal motion state according to a 2-DOFs model and compare actual motion with ideal motion to compute how to adjust wheel brake pressure, thus improving vehicle motion stability [5].

+ Corresponding author.
E-mail address: zhy_jlu@163.com

2. Driver-vehicle Closed-loop Model

A driver-vehicle closed-loop model is often needed to evaluate vehicle control strategy and algorithm. In this paper, a 9 DOFs vehicle model and driver model were built to make the driver-vehicle closed-loop model.

2.1. Driver-Vehicle Closed-loop Model

The driver has an important influence on the characteristic of the driver-vehicle closed-loop system which can be seen to have three parts: driver preview, driver control and driver prediction of vehicle motion as fig.1. f is an ideal path.

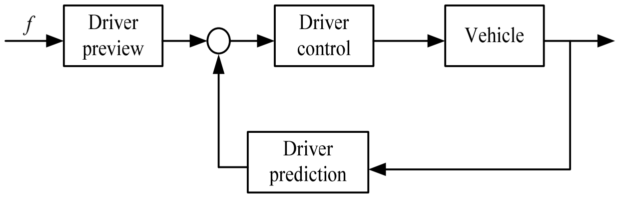

Fig.1. driver-vehicle closed-loop model

A driver model which is called optimal preview acceleration model is used to perform the driver-vehicle closed-loop simulation [6].

2.2. Vehicle Dynamic Model

The vehicle model is a 9 DOFs dynamic model including longitudinal, lateral, yaw, pitch, roll and four wheels rotation. The mathematic equations of the model are as follows.

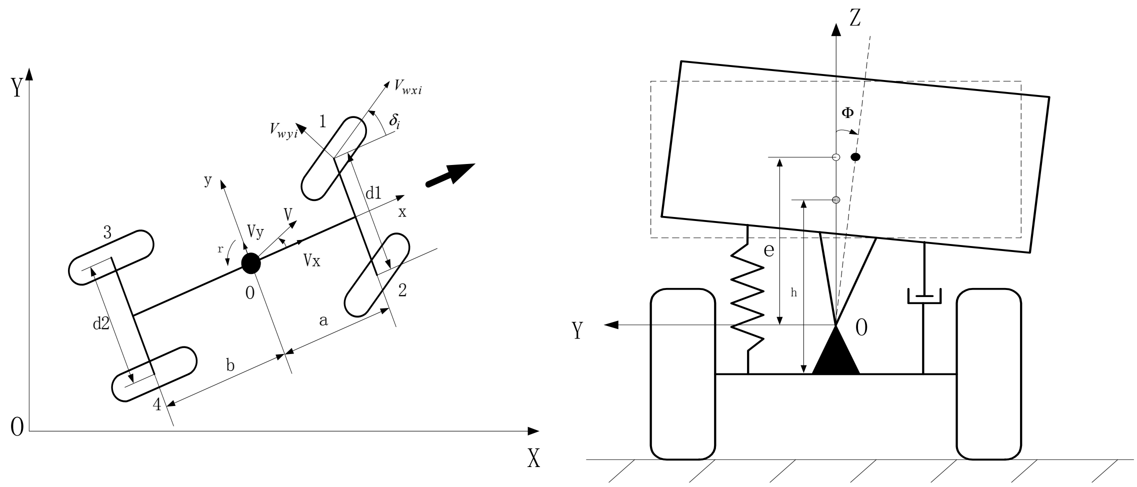

Fig.2. Schematic of 9 DOF vehicle model

The equation of longitudinal force:

$$\sum F_x = M\left(\dot{V}_x - \gamma V_y\right) + M_s e\dot{q} = \sum_{i=1}^{4}\left(F_{xi}\cos(\delta_i) - F_{yi}\sin(\delta_i)\right) + F_x' \tag{1}$$

The equation of lateral force:

$$\sum F_y = M\left(\dot{V}_y + \gamma V_x\right) - M_s e\dot{p} = \sum_{i=1}^{4}\left(F_{xi}\sin(\delta_i) + F_{yi}\cos(\delta_i)\right) + F_y' \tag{2}$$

The equation of roll moment:

$$I_{xs}\dot{p} + I_{zxs}\dot{\gamma} + I_{yxs}\dot{q} - M_s e(\dot{V}_y + \gamma V_x) = M_s g e\varphi - K_\varphi \varphi - C_p p + \sum_{i=1}^{4} M_{xi} + M_x' \tag{3}$$

The equation of pitch moment:

$$I_{ys}\dot{q}+I_{xys}\dot{p}+I_{zxs}\dot{\gamma}-M_s e(\dot{V}_x+\gamma V_y)=M_s g e\theta-K_\theta\theta-C_q q+\sum_{i=1}^{4}M_{yi}+M_y' \tag{4}$$

The equation of yaw moment:

$$I_z\dot{\gamma}+I_{xzs}\dot{p}+I_{yzs}\dot{q}=\sum_{i=1}^{4}F_{xi}R_{xi}+\sum_{i=1}^{4}F_{yi}R_{yi}+\sum_{i=1}^{4}M_{zi}+M_z' \tag{5}$$

Where *Mz* is sprung mass, *e* is height of mass center, *a* is distance from center of mass to front axis, *b* is distance from center of mass to back axis, β is slip angle, ϕ is the sprung mass roll angle, *P* is roll angular velocity of mass center, θ is pitch angle, *q* is pitch angular velocity, k_θ is pitch stiffness, C_q is pitch damper, C_ϕ is roll damper, F_{xi}', F_{yi}', M_{xi}, M_{yi}, M_{zi} are six directions of tyre force, F_x', F_y', M_x', M_y', M_z' are the sums of resistances from different directions.

2.3. Tire model

The tire model adopts the united tire model proposed by Professor Guo Konghui [7]. According to united tire model UniTire, F_x is longitudinal force, F_y is lateral force, M_z is aligning moment. They can be described by E index:

$$\begin{cases} F_x=u_xF_z(1-\exp(-\phi-E_1\phi^2-(E_1^2+\frac{1}{12})\phi^3))\cdot \phi_x/\phi \\ F_y=u_yF_z(1-\exp(-\phi-E_1\phi^2-(E_1^2+\frac{1}{12})\phi^3))\cdot \phi_y/\phi \\ M_z=F_y(D_x+X_b)-F_xY_b \end{cases} \tag{5}$$

$$D_x=(D_{x0}+D_e)\exp(-D_1\phi-D_2\varphi^2)-D_e \tag{6}$$

$$a_1=\tan^{-1}[\frac{V\cdot\sin\beta+a\cdot r}{V\cdot\cos\beta-\frac{d_f}{2}\cdot r}]-\delta \tag{7}$$

$$a_2=\tan^{-1}[\frac{V\cdot\sin\beta+a\cdot r}{V\cdot\cos\beta-\frac{d_f}{2}\cdot r}]-\delta \tag{8}$$

$$a_3=\tan^{-1}[\frac{V\cdot\sin\beta+b\cdot r}{V\cdot\cos\beta-\frac{d_r}{2}\cdot r}]-\delta \tag{9}$$

$$a_4=\tan^{-1}[\frac{V\cdot\sin\beta+b\cdot r}{V\cdot\cos\beta-\frac{d_r}{2}\cdot r}]-\delta \tag{10}$$

where u_x, u_y are longitudinal and lateral friction coefficients between tire and road surfaces. ϕ_x, ϕ_y and ϕ_z are slips of longitudinal, lateral and total. D_x is tire drag, E_1, E_2, u_x, u_y, D_{x0}, D_e, D_1, D_1 belong to functions of F_z. F_z is the vertical load which can be calculated from experiment. a_i is wheel sideslip angle.

3. Control Algorithm of DYC

The effect of DYC is to improve vehicle handling and stability in the linear and non-linear regions of the tyre. Two kinds of control algorithms are being used, including forward control and single neural cell PID control.

3.1. Select Control Variable of DYC

According to driver's handling and vehicle movement state, the DYC controller can get vehicle movement state and compute an ideal vehicle state. Then it compares actual vehicle movement state with ideal vehicle movement to compute an error by controller and calculates a yaw moment to renew vehicle stability. The yaw moment is distributed to four wheels to transform wheel cylinder pressure. The ECU generates PWM signals to control solenoid valves to adjust wheel cylinder pressure that control vehicle stability.

There are two kinds of control variable of DYC, including yaw rate and slip angle. When slip angle is near to zero, yaw rate may be described to steering of vehicle, so vehicle stability is performed by yaw rate and steering wheel angle gain when slip angle is smaller. But DYC does not use yaw rate and steering wheel angle gain to perform vehicle stability when slip angle is bigger. On this condition, it is difficult to renew stability. From 2 DOFs linear model it can be seen that the ratio of steady state slip angle gain and yaw rate gain is increased when aligning torque is reduced. Therefore, DYC does not only select yaw rate as the control variable because it cannot control big slip angle when real tyre characteristic become worse, so slip angle is also be selected as the control variable of DYC.

3.2. Forward Controller

In controller, Front wheel steering angle is the input parameter and slip angle is the control variable. Figure 3 is the control diagram schematic of the DYC control system.

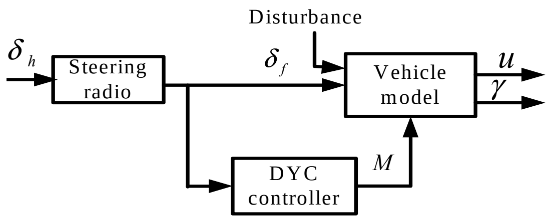

Fig.3. Feedforward control block diagram

Equations of 2 DOFs linear model for vehicle:

$$[mu+\frac{1}{u}(ak_1-bk_2)]\gamma+[mus+(k_1+k_2)]\beta=k_1\delta_f \tag{11}$$

$$[Is+\frac{1}{u}(a^2k_1+b^2k_2)]\gamma+(ak_1-bk_2)\beta=k_1a\delta_f+M \tag{13}$$

where u is vehicle speed, δ_f is front wheel steering angle, a is distance from center of mass to front axis, b is distance from center of mass to back axis, r is yaw rate, k_1 is cornering stiffness of front axis, k_r is cornering stiffness of back axis, I is moment of inertia.

$$M=\frac{d_f}{2}(F_{x2}-F_{x1})+\frac{d_r}{2}(F_{x4}-F_{x3}) \tag{14}$$

where M is output yaw moment of DYC controller. When $\beta=0$, equation 12 and 13 can transform to equation 15 and 16:

$$[mu+\frac{1}{u}(ak_1-bk_2)]\gamma=k_1\delta_f \tag{15}$$

$$[Is+\frac{1}{u}(a^2k_1+b^2k_2)]\gamma = 2ak_1\delta_f + M \tag{16}$$

The DYC control target can be described as:

$$\frac{M(s)}{\delta_f(s)} = G_M(s) = \frac{(a+b)bk_1k_2 - mu^2ak_1}{u^2m+ak_1-bk_2} + \frac{Iuk_1}{u^2m+ak_1-bk_2}s \tag{17}$$

3.3. Single Neural Cell PID Controller

The neural cell PID controller is modified and combined by neural network algorithm and traditional PID algorithm. Figure 4 is the single neural cell PID control diagram:

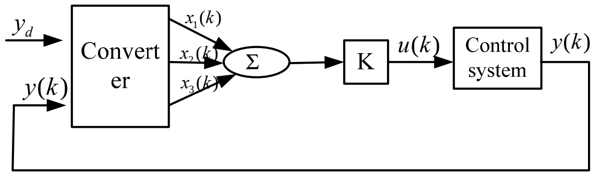

Fig.4. Single neuron PID control diagram

The control algorithm of single neural cell PID controller is:

$$u(k) = u(k-1) + k\sum_{i=1}^{3} w_i'(k)x_i(k) \tag{18}$$

$$w_i' = w_i(k) / \sum_{i=1}^{3}|w_i(k)| \tag{19}$$

$$\begin{aligned} w_1(k) &= w_1(k-1) + \eta_I z(k)u(k)x_1(k) \\ w_2(k) &= w_2(k-1) + \eta_P z(k)u(k)x_2(k) \\ w_3(k) &= w_3(k-1) + \eta_D z(k)u(k)x_3(k) \end{aligned} \tag{20}$$

$$\begin{aligned} x_1(k) &= e(k) \\ x_2(k) &= e(k) - e(k-1) \\ x_3(k) &= \Delta^2 e(k) = e(k) - 2e(k-1) + e(k-2) \end{aligned} \tag{21}$$

where η_P, η_I, η_D are the learning rates of integral, proportion and differential. K is proportional coefficient of neural cell.

4. Simulation and analysis

Matlab/Simulink software was used to simulate vehicle dynamic model and control algorithm in ISO 3888-1(passenger cars—Test track for a severe lane change manoeuvre—part 1: Double—lane change). The simulation experiments include that vehicle speed is 60 km/h and road friction coefficient is 0.2. The simulation verified and compared forward control and single neural cell PID control algorithm to improve vehicle handling and stability.

Figure 5 is shows DYC control. From the figure it can be seen that vehicle may keep stability when it begins the lane change, but when vehicle returns to the lane, it loses stability and the driver can’t control the vehicle because the slip angle becomes larger and makes the yaw moment smaller. Figure 6 shows forward control of DYC and figure 7 shows single neural cell control of DYC. The beginning of the lane change is the same as no DYC control. When the vehicle returns to the lane, the DYC controller changes wheel pressure and control yaw moment to keep the vehicle stability.

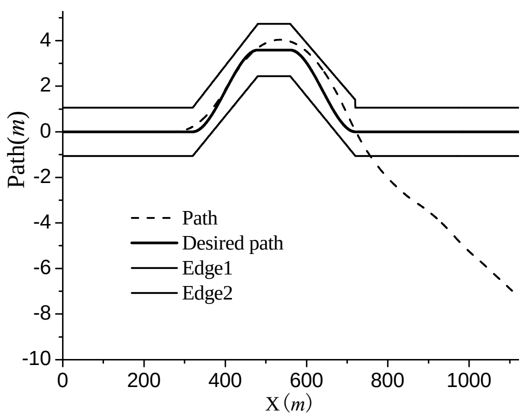

Fig.5. No DYC control

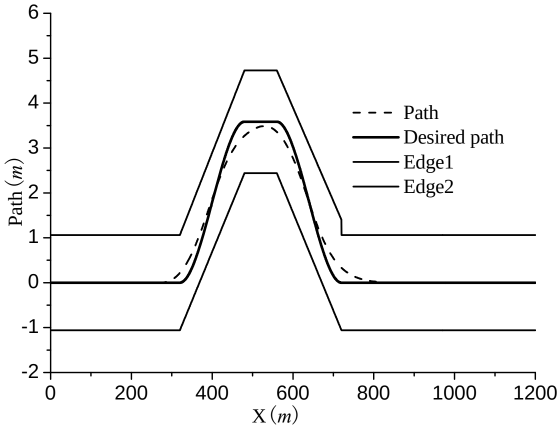

Fig.6. Feedforward control

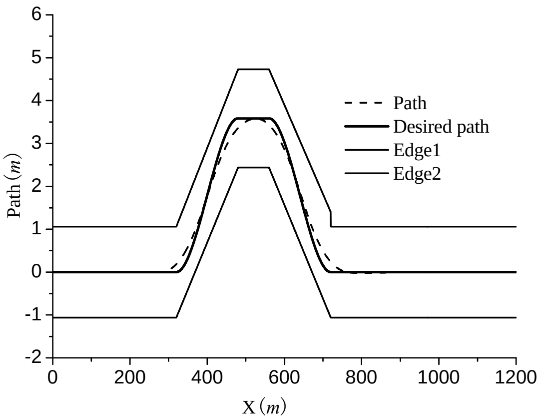

Fig.7 Single neural cell PID control

Figures 6 and 7 show that the vehicle with the single neural cell PID control algorithm follows the path more precisely than the vehicle with the forward control.

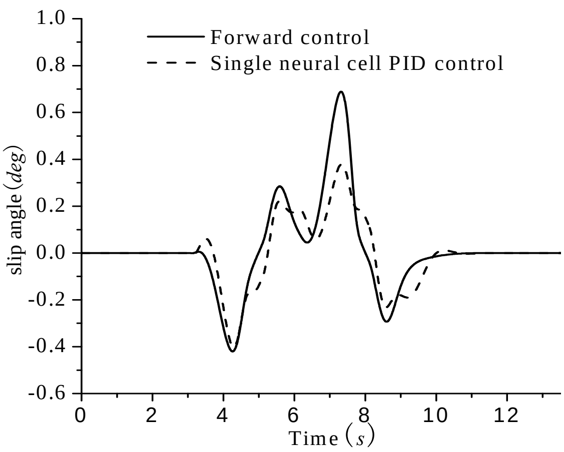

Fig.8. Time history of slip angle

Figure 8 is the time history of slip angle. It shows that slip angle is smaller by comparing single neural cell PID control with forward control. Therefore, single neural cell PID control of DYC may be better for improving vehicle handling and stability.

5. Conclusion

A driver-vehicle closed-loop system model was built for this study. Forward control and single neural cell PID control algorithms for DYC were studied base on the driver-vehicle model for controlling slip angle. Matlab/Simulink was used to simulate the vehicle dynamic model and control algorithm with a severe lane change manoeuvre on low road friction. The simulation results show that vehicle stability can’t be kept if there is no DYC control and the control effect of single neural cell PID control is better than forward control.

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