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Estimation of Vehicle Sideslip Angle Based on Feedback Observer

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***Abstract*—Vehicle sideslip angle is a significant parameter for vehicle stability control. Based on the 2-DOF vehicle dynamic model, a feedback observer is built with the correction item. The estimation accuracy of the sideslip angle is improved by adjusting the feedback gain of the feedback term in the feedback observer. At the same time, the computational burden is reduced by using the three-map of tire lateral force based on the magic formula (MF) model. The simulation results show that the feedback gain plays an important role in improving accuracy of sideslip angle estimation. The estimation method can be applied to the vehicle stability control system.**

Keywords—sideslip angle estimation; three-map of tire lateral force; feedback observer; observer gain

I. INTRODUCTION

The vehicle stability control enables the vehicle to have good handling stability and active safety, which is an efficient way to reduce vehicle accidents [1, 2]. In the stability control algorithm, sideslip angle and yaw rate are important indexes to represent vehicle stability and are the main control variables [3]. However, unlike yaw rate, sideslip angle cannot be measured directly in production vehicles because of accuracy and cost issues.

In the literature, there have been many efforts to estimate sideslip angle. Reference [4, 5] use simple linear tire model to provide the required tire force to estimate sideslip angle. Unfortunately, because of the particular shape of the tire lateral force characteristics, the tire slip angles, and consequently also the vehicle slip angle, may increase quite rapidly without corresponding increase in lateral forces in nonlinear range. Therefore, the estimation accuracy of sideslip angle will be inevitably affected by using a linear tire model. Bevly et al. used GPS velocity information in conjunction with inertial measurement units (IMUs) to obtain sideslip angle [6]. Unlike indirect measurement of sideslip angle using lateral acceleration or yaw rate, direct measurement of sideslip angle via optical or GPS sensors are associated with problems of cost，and reliability. In addition, Zhang developed a side slip angle observer by adopting filter method. Huang developed a neural network algorithm and Shi proposed a Fuzzy logic method, which can estimate sideslip angle more accurately[7, 8]. Milanese et al. set up a nonlinear estimator and tested it for several steering maneuvers [9]. These estimation methods are based on the nonlinear estimation model. The model has many dimensions and the nonlinear estimation algorithm is complex, which would be limited in the application of the actual control system.

In this paper, in order to improve real-time , a feedback observer is proposed to estimate the sideslip angle based on a 2-DOF vehicle model. In the design procedure, we consider the nonlinear behavior of tire force between tire and road and obtain tire lateral force by using a three-map to reduce the computational burden. Finally, simulation experiments demonstrate the effectiveness of the proposed feedback observer.

II. VEHICLE DYNAMICS MODEL

A. Vehicle Modele

To estimate sideslip angle, the vehicle model used is a 2-DOF vehicle model which can accurately reflect the lateral characteristics with smaller computing load. The 2-DOF vehicle model is illustrated in Fig. 1. Assuming pure lateral slip and constant longitudinal speed, the lateral and yaw dynamics can be expressed as:

$$\begin{aligned} F_{yf} + F_{yr} &= m\left(\dot{v} + u \cdot r\right) \\ aF_{yf} - bF_{yr} &= I_z \cdot \dot{r} \end{aligned} , \tag{1}$$

where m is the mass of the vehicle; a and b are the distances from the front axle and rear axle to the vehicle gravity center, respectively, I_z is the vehicle inertia about the vertical axis, u is the longitudinal velocity, v is the lateral velocity, F_{yf} and F_{yr} are the lateral tire forces, r is the yaw rate of the vehicle and δ is the front wheel steering angle. By using simple kinematics, we can write α_f and α_r, the slip angle β of front and rear tires, in terms of u, v, and r:

$$a_f = b + \frac{ar}{u} - d,\ a_r = b - \frac{br}{u}. \tag{2}$$

where αf and αr are sideslip angle of front wheel and rear wheel.

B. Tire Model

The magic formula (MF) model is adopted in this study [10], which is expressed as:

$$Y(x)=D\sin\left(C\arctan\left(Bx-E\left(Bx-\arctan\left(Bx\right)\right)\right)\right)+S_V, \quad (3)$$

with $x = X + S_h$,

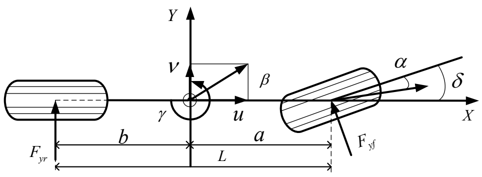


FIGURE I. 2-DOF VEHICLE DYNAMICS MODEL

where Y(x) is the lateral force F_y; and X is the slip angle, C, D, B and E are derived from experiments.

$$\begin{cases} C = A_0; \\ D = A_1 \cdot F_z^2 + A_2 \cdot F_z; \\ B = \dfrac{A_3 \cdot \sin\left(\arctan\left(F_z / A_4\right) \cdot 2\right)}{CD}; \\ E = A_6 \cdot F_z + A_7; \\ S_n = A_9 \cdot F_z + A_{10}; \\ S_V = A_{12} \cdot F_z + A_3; \end{cases}$$

where F_z is the vertical load of tire. The parameters of A_0—A_{13} obtained by fitting the experimental data. And F_y is a function of F_z, as shown in Fig. 2 .

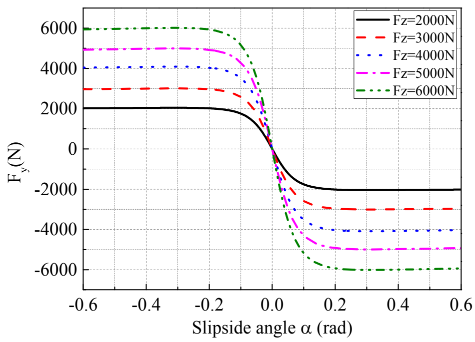


FIGURE II. LATERAL FORCE

The tire lateral force map is established as a three-dimensional look-up table which is a function of the friction coefficient and slip angle, as shown in Fig. 3.

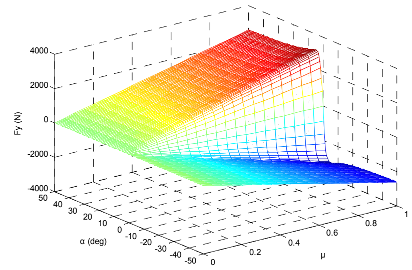


FIGURE III. THREE-MAP OF TIRE LATERAL FORCE

III. ESTIMATION OF VEHICLE SIDESLIP ANGLE

In order to analyze the estimation of sideslip angle and considering the existing on-board sensors, this paper makes the following assumptions: lateral acceleration of vehicle a_y, yaw rate r and friction coefficient μ are known. The estimation scheme based on feedback observer proposed is shown as Fig. 4.

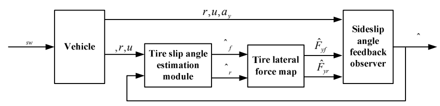


FIGURE IV. ESTIMATION SCHEME BASED ON FEEDBACK OBSERVER

Prior to beginning estimation, the steering wheel angle δ_{sw} is excitation input and the initial β_0 sideslip angle are set to zero (i.e. the vehicle is driving straight). Front and rear tire slip angle can be obtained through the tire slip angle. Front and rear lateral force can be obtained through the three-map of tire lateral force according to front and rear tire slip angle. And with the measured vehicle state information , the feedback observer can estimate sideslip angle.

A. Feedback Observer Design

From the geometric relation of Fig. 1, the sideslip angle is obtained as follows:

$$b = \frac{v}{u} \quad (4)$$

To update estimate of slip angle, we can derive the feedforward term of the update equation by taking the (1) and (4):

$$\dot{b} = \frac{1}{m \cdot u}\left(F_{yf} + F_{yr}\right) - r . \quad (5)$$

The lateral acceleration of the vehicle can be directly measured by the sensor. Therefore, the lateral acceleration is used as an observed output of the system:

$$y = a_y$$

On the basis of (2), (3) and (5), the dynamic equations of vehicle body are expressed as state space equation as follows:

$$\dot{\beta} = f(\beta), y = g(\beta)$$

Since the sideslip angle cannot be measured directly, a feedback observer is designed:

$$\dot{\hat{\beta}} = f(\hat{\beta}) + K(y - \hat{y}), \quad (6)$$

where K is an observer gain.

At the same time, the lateral force of the vehicle is calculated by lateral acceleration. Taking the difference between the measured lateral acceleration and the estimated value of vehicle lateral force as the correction term, the feedback observer of sideslip angle β is designed as follows:

$$\dot{\hat{\beta}} = \frac{1}{m \cdot u}\left(\hat{F}_{yf} + \hat{F}_{yr}\right) - r + K\left(m \cdot a_y - \hat{F}_{yf} - \hat{F}_{yr}\right) \quad (7)$$

where $\hat{F}_{yf}, \hat{F}_{yr}$ can be obtained through the three-map of tire lateral force according to front and rear tire slip angle. $\hat{\alpha}_f, \hat{\alpha}_r$, $\hat{\alpha}_f, \hat{\alpha}_r$ are calculated as follows:

$$\hat{\alpha}_f = \hat{\beta} + \frac{ar}{u} - \delta, \hat{\alpha}_r = \hat{\beta} - \frac{br}{u}$$

IV. SIMULATION AND DISCUSSION OF RESULTS

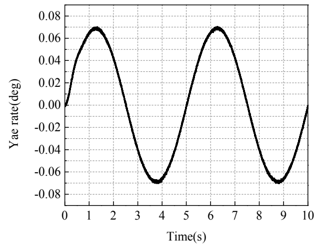
In order to verify the proposed estimation methods Simulations are conducted on the basis of Carsim and Matlab/Simulink. CarSim is a special software for the simulation of vehicle dynamics, which is widely used in modern vehicle control system.

In order to render the responses of CarSim model to be similar to that of real vehicle, white noise is added to the original model outputs. The parameters of the simulation vehicle model are shown in Table I.

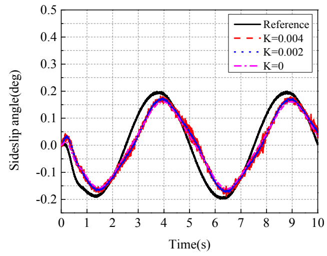
TABLE I. MAIN PARAMETERS OF CARSIM VEHICLE MODEL

Symbol	*Quantity*	*Value*	*units*
I_z	Moment of vehicle inertia	2031.4	kg.m2
a	Chassis length of front	1.04	m
b	Chassis length of rear	1.56	m
m	Vehicle mass	1111	kg
	Size of tire	185/65R15	

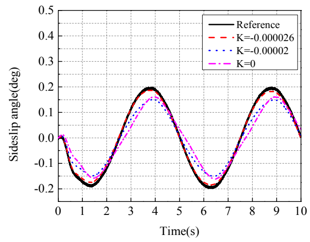
The vehicle speed is 120 km/h, and the adhesion coefficient μ is 0.85 in this simulation. In order to evaluate the performance of the proposed feedback observer, the simulation under different observer gains is conducted through sinusoidal input and step input test maneuver. Fig. 5 and Fig. 6 present observer results for the two tests.



(a) yaw rate

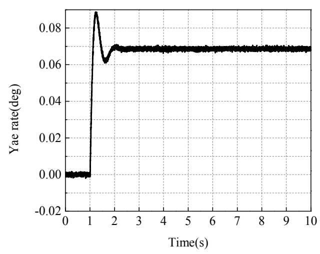


(b) sideslip angle (*K* is nonnegative)

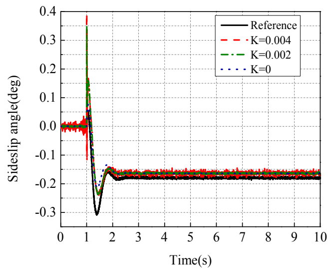


(c) sideslip angle (*K* is nonpositive)

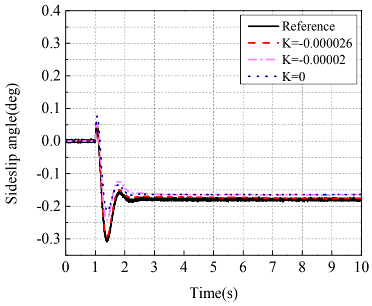
FIGURE V. SIMULATION RESULTS OF SINUSOIDAL INPUT



(a) yaw rate



(b) sideslip angle (*K* is nonnegative)



(c) sideslip angle (K is nonpositive)

FIGURE VI. SIMULATION RESULTS OF STEP INPUT

In the sinusoidal test (Fig. 5), estimation results are relatively satisfactory when observer gain K=-2.6E-05, nevertheless significant differences appear between sideslip angle estimations and measurement (normalised mean errors of 12% for K=0.002 and 10% for K=0.004). The estimated values ripple is eliminated when K is non positive as shown in Fig. 5(c).

The test results of step test are shown in Fig. 6. From Fig. 6(b) and Fig. 6(c), it can be seen that when observer gain

K=-2.6E-05, the estimated sideslip angle matches the reference more accurately. And ripples still exists at the beginning of the step when K=0.002 and K=0.004(Fig. 6(c)).

It can be seen that for each tests, the estimated values show good coherences with the outputs from CarSim when K=-2.6E-05. The estimated values show more and more coherences with the outputs from CarSim with the change of observer gain from -2.0E-05 to -2.6E-05. Indeed, only the appropriate observer gain will make correction for interference error and improve the estimation accuracy of the observer.

V. CONCLUSIONS

This paper focuses on improving the estimation accuracy of sideslip angle by designing a feedback observer. Based on a 2-DOF vehicle model, a feedback observer is built with the correction item, which adopts the three-map of tire lateral force to improve estimation accuracy of feedback observer and reduce the computational burden. Simulation results show the feedback observer has higher estimation accuracy and the calculation is simple. Therefore, the estimation method of sideslip angle proposed in this paper will find wider applications in vehicle stability control.

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