Design on Adaptive Fuzzy Observer of Vehicle Side Slip Angle

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Abstract

A novel observer structure for vehicle side slip angle (β) estimation is proposed, in which a local approximation of the nonlinear tire model is adopted. Fuzzy logic approach is adopted to combine the local observer models so as to deal with the nonlinear nature of vehicle dynamics. The derivation of observer's state equations and the estimation mechanism is developed. By choosing the membership functions of weighting factors to be dependent on tire slip angle, tire vertical load and road friction coefficient, the proposed observer is adaptive to different running conditions and road friction changing. The effectiveness is verified by simulation studies.

Key words: Vehicle side slip angle, observer, fuzzy logic, vehicle stability control

1. Introduction

Body slip angle (β) is an important value for vehicle stability control such as direct yaw-moment control (DYC) and four wheel steering (4WS). However, as sensors to measure β value are very expensive, it needs to estimate β from only variables measurable [1] [2] [3]. The most difficult for β estimation is the non-linear nature of vehicle dynamics. The main nonlinearity comes from the tire force saturation decided by tire vertical load and road friction, which makes vehicle characteristics change greatly as vehicle cornering in nonlinear area compared with that in linear area. So the effective observers must consider tire nonlinearity and must be adaptive to road friction changing [1] [3]. This gives the great challenge to the design of β observer.

There are many researches about vehicle body slip angle estimation, on linear observers or on nonlinear observers. As for linear observers design, vehicle and tire dynamics are linearized and fixed model parameters are adopted, which can not always get accurate results in different running situations for the highly nonlinear characteristics of vehicle dynamics [4]. In the nonlinear observers, the tires characteristics are described as nonlinear functions and with more parameters, which can get more accurate results in different running situations compared with linear observers. However, the nonlinear observers have the disadvantages of implementing complication and theoretical immaturity [5] [6].

Since the problem of linear observer is that the fixed model parameters are used which can not adaptive to the changing running situations. To make use of linear observer's advantages of simple design and implement, as well as overcome the above problem, local approximation of the nonlinear tire model and fuzzy logic method is introduced in this paper to construct a novel observer structure. The proposed observer is a combination of local linear observers with fuzzy logic. The local observers can be designed as simple as the linear observer, as well the combination calculation results can solve the nonlinear problem of β estimation.

In the first step for the observer design, The derivation of observer's states equations is developed, based on vehicle dynamics analysis and local approximation of nonlinear tire model. In the next step, fuzzy logic is introduced to get a fuzzy tire model which is calculated as a weighted sum of the outputs of two local linear models, one for tire slip angle is small and the other for the large. To be adaptive to different running conditions and road friction changing, the membership functions of weighting factors to combine the two local models are chosen to be dependent on slip angle value, vertical load and road friction coefficient. Then, the adaptive fuzzy observer mechanism is developed, which is a combination of two local observers based on local linear tire models. Each local observer is designed as a linear observer. The nature of linear local models makes it easy to design. Furthermore, the nonlinear global fuzzy observer results show high estimation capabilities and good adaptation to road friction changing. This is verified by simulation studies.

2. Vehicle dynamics and observer state equations

The observer is based on vehicle dynamics model shown as figure 1. The dynamics of vehicle is described by two-freedom vehicle model as following equations:

$$\begin{cases} ma_y = F_{xf}\sin\delta_f + F_{yf}\cos\delta_f + F_{yr} \\ I_z\dot{\gamma} = l_f F_{xf}\sin\delta_f + l_f F_{yf}\cos\delta_f - l_r F_{yr} + N \end{cases} \quad (1)$$

where a_y denotes vehicle lateral acceleration, γ is yaw rate, δ_f is steering angle of front wheel, N is direct yaw moment, m is mass of vehicle, I_z is yaw inertia moment, l_f is distance between mass center and front axle, l_r is distance between mass center and rear axle, F_{xf} is longitudinal forces of front tires, F_{yf} and F_{yr} are lateral forces of front and rear tires.

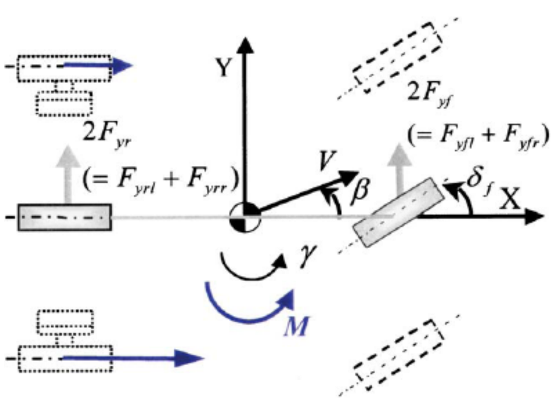


Fig.1 Two-freedom vehicle model

Taking vehicle slip angle β and yaw rate γ as state variables, and considering that the kinematics relationship is as $a_y = v(\dot{\beta}+\gamma)$ and that δ_f value is relatively small in the vehicle's high speed situations, vehicle's states equations are derived as:

$$\begin{cases} \dot{\hat{\beta}} = \frac{1}{mv}(F_{yf}+F_{yr}) - \hat{\gamma} \\ \dot{\hat{\gamma}} = \frac{1}{I_z}(l_f F_{yf} - l_r F_{yr} + N) \end{cases} \quad (2)$$

For the nonlinearity of tire lateral force characteristics, (2) are the state equations with nonlinear form. However, the nonlinear observer's design and application are relatively much difficult [5]. So this paper tries applying linear observer design method to solve the nonlinear problem. To do this, the observer model is changed into the form of an equivalent linear two freedom model by adopting the value of tire cornering power C_p, which is defined as:

$$c_p = \frac{F_y}{\alpha} \quad (3)$$

Where F_y is the tire lateral force and slip angle α is the tire slip angle at its operating point.

By adopting tire cornering power C_p, the nonlinear vehicle dynamic state equations (2) can be described as an equivalent linear state equation (4):

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \quad (4)$$

In which,

$$\mathbf{A} = \begin{bmatrix} \frac{-(C_{fl}+C_{fr}+C_{rr}+C_{rl})}{mv} & \frac{-l_f(C_{fl}+C_{fr})+l_r(C_{rl}+C_{rr})}{mv^2} - 1 \\ \frac{-l_f(C_{fl}+C_{fr})+l_r(C_{rl}+C_{rr})}{I_z} & \frac{-l_f^2(C_{fl}+C_{fr})-l_r^2(C_{rl}+C_{rr})}{I_z v} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \frac{C_{fl}+C_{fr}}{mv} & 0 \\ \frac{l_f(C_{fl}+C_{fr})}{I_z} & \frac{1}{I_z} \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} \beta \\ \gamma \end{bmatrix}, \quad \mathbf{u} = \begin{bmatrix} \delta_f \\ N \end{bmatrix}$$

Where, $C_{fl} \sim C_{rr}$ are the cornering power values of tires.

Based on state equations (4), a full order linear observer can be developed as reference [4]. Figure 2 shows the structure of the linear observer.

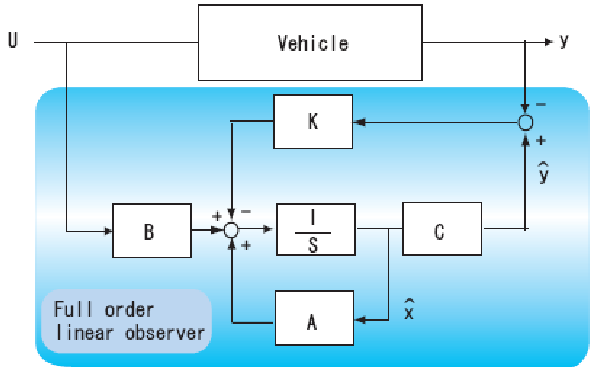


Fig.2 Structure of full order linear observer

Vehicle lateral acceleration a_y and yaw rate γ are 2 measurable variables in vehicle and are chosen as output variables of the observer. The estimate of β is computed as predicted value from states equation corrected by output feedback as (5).

$$\begin{aligned}\dot{\hat{\mathbf{x}}} &= \mathbf{A}\hat{\mathbf{x}} + \mathbf{B}\mathbf{u} - \mathbf{K}(\hat{\mathbf{y}} - \mathbf{y}) \\ \hat{\mathbf{y}} &= \mathbf{C}\hat{\mathbf{x}} + \mathbf{D}\mathbf{u}\end{aligned} \tag{5}$$

$$\mathbf{y} = \begin{bmatrix} \gamma \\ a_y \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} 0 & 1 \\ va_{11} & v(a_{12}+1) \end{bmatrix}, \quad \mathbf{D} = \begin{bmatrix} 0 & 0 \\ vb_{11} & 0 \end{bmatrix}$$

$\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ are the estimation values of $\mathbf{x}$ and $\mathbf{y}$ respectively. $\mathbf{K}$ is the feedback matrix of observer.

3. Fuzzy modeling of tire side force

In the above vehicle dynamics analysis, the tire model is linearized with only one parameter as the cornering power C_p. In the general analysis, C_p is defined as the value for tire slip angle is zero, that is:

$$C_{\mathrm{p}} = \left.\frac{\partial F_{\mathrm{y}}}{\partial \alpha}\right|_{\alpha=0} \tag{6}$$

With C_p defined as (6), equation (4) is only valid to represent the vehicle dynamics for the vehicle's normal running situations where the tire slip angles are small. However, for the vehicle stability control which works almost at the limitation of vehicle dynamics, equation (4) is no longer valid for the tire slip angles are relative larger. That is to say that the linear state equation is not adapted to the nonlinear running situations. For the same reason, the linear observer of figure 2 is not fit for β estimation at the limitation of vehicle dynamics. Therefore, in some researches, nonlinear tire models are applied for the observer design [5] [6].

One nonlinear tire model commonly applied is as (7):

$$F_y = k_x \frac{2}{\pi} \mu F_z \tan^{-1}\left(\frac{1}{2F_z\mu} \pi C_p \alpha\right) \tag{7}$$

Where F_z is tire vertical load, μ is road friction coefficient, k_x is the influence coefficient of tire longitudinal force.

Compared with linear tire model, this nonlinear model can describe the saturation characteristics of tire lateral force as tire slip angle gets large, which is reflect by the influence of tire vertical load and road friction. Theoretically, with the use of such nonlinear tire model in observer design, higher accurate results can be got. However, problems of nonlinear observer's designing complications and implementing difficulties are brought, which have not solved satisfactorily yet [5] [6].

Therefore, for the observer design, a novel modeling method for tire lateral force characteristics is adopted in this paper. Compared with linear model, operations of tire are divided as small slip region and large slip region for the proposed tire model. Figure 3 is the tire lateral force characteristics of large friction road and small friction road calculated according to (7). By application of fuzzy modeling logic, the tire operating points are considered as linguistic variables with two fuzzy sets: with tire slip angle is small and is large. The new structure of tire model includes two sub linear tire models which works as local models for they are with different cornering power (C_p) values respectively for small slip angle section and large slip angle section.

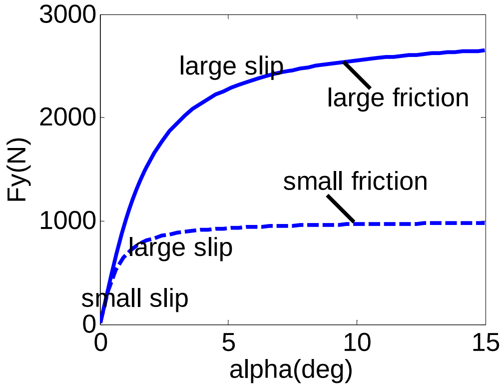


Fig. 3 Tire side force – slip angle characteristics

For the small slip local model, C_p has largest value C_{p1}. By contrast, for the large slip local model, C_p has quite smaller value C_{p2}. For the middle section of slip angle region, the C_p value should be between the above values. The whole nonlinear tire side force is described by combining the two models with fuzzy logic according to a membership function for tire slip. By appropriate choosing the membership function, the calculation of tire side force for different tire slip angle value can be done. In this paper, a straight line function is chosen for simplification as figure 2.

Tire side force is calculated as:

$$F_y(\alpha) = c_{p1}\alpha \cdot w_1(\alpha) + c_{p2}\alpha \cdot w_2(\alpha) \quad (8)$$

where $w_1(\alpha)$ and $w_2(\alpha)$ are the membership functions for small slip model and large slip model respectively, which is the functions of tire slip angle. For simplification, straight line function is chose for the membership function design (shown as figure 4). The formulation $w_1(\alpha)$ and $w_2(\alpha)$ are as follows:

$$w_1(\alpha) = \begin{cases} 1 - \dfrac{1}{\alpha_w}\alpha & |\alpha| \le \alpha_w \\ 0 & |\alpha| > \alpha_w \end{cases} \quad (9)$$

$$w_2(\alpha) = \begin{cases} \dfrac{1}{\alpha_w}\alpha & |\alpha| \le \alpha_w \\ 1 & |\alpha| > \alpha_w \end{cases} \quad (10)$$

where the coefficient α_w describes the value of tire slip angle value when the tire force is saturation.

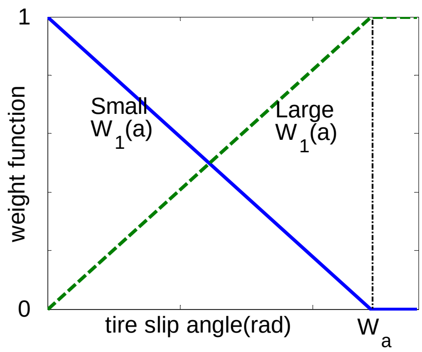


Fig.4 Membership functions for tire slip angle

According to (7), there are 3 basic parameters in the tire model: tire cornering power C_p, tire vertical load F_z and road friction coefficient μ. C_p is the characteristic of tire and is consistent generally. The value of μF_z determines the saturation value of tire lateral force in nonlinear running region. μF_z is uncertain and may change largely with the change of vehicle running situations and road conditions. The fuzzy tire modelling must be adaptive to such changes. In this paper, the observer adaptive design is dependent on the choice of α_w value. α_w is set to have a linear relationship with μF_z as follows:

$$\alpha_w = k_\mu \mu F_z \tag{11}$$

where k_μ is the adaptation coefficient.

4. Adaptive fuzzy observer design

The adaptive fuzzy observer is a combination of linear observer design and fuzzy modeling method described above. The proposed observer structure is as figure 5.

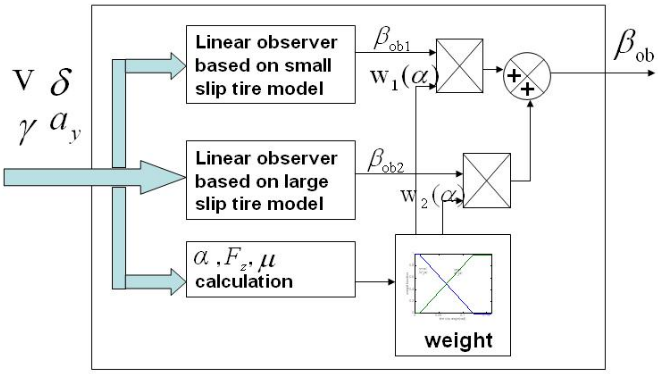


Fig.5 Structure of hybrid linear observer

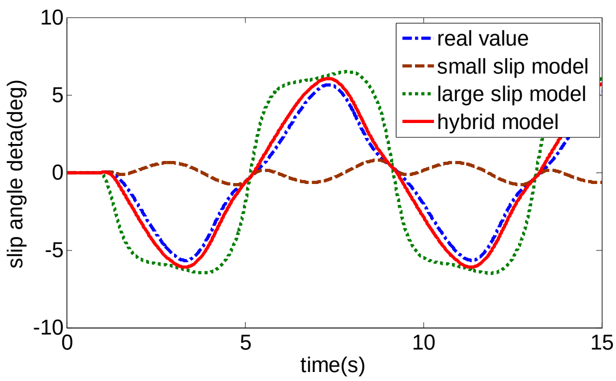
In the observer, there are two sub-observers respectively based on the above two local linear tire models. By introducing the fuzzy tire model described above, the final value is the weight addition of the two linear observer results according to the fuzzy tire model's membership functions. The linear observer design methods can be applied to these sub-observers referring to previous studies [4]. The advantages of linear observe as simple designing, fast running is kept and nonlinear problem can be solved.

5. Simulation studies

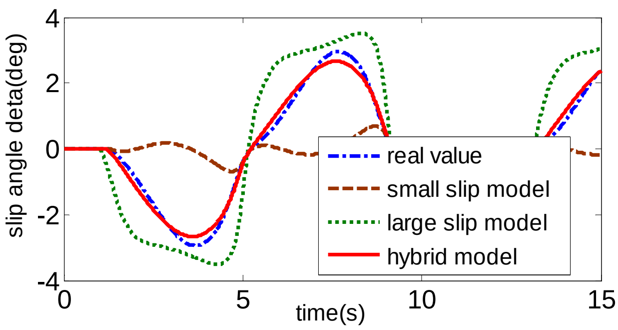
The simulation is conducted based on a four-wheel vehicle model and nonlinear tire model. The running situation is set with a sinusoid steering angle input to simulate consecutive lane change. The amplitude of input steering angle is large enough to make the tire span linear and nonlinear working region.

The simulation results in different road friction conditions are as figure 6. Both the two sub-observer results can not fit the real value well for the whole running situations, for they are based on local linear model with fixed parameter describing a little segment of tire characteristics. Comparatively, the hybrid observer results can always follow the real ones well and have satisfying ability to adapt with different road friction conditions.

In addition, compared with nonlinear observer, the calculating speed is quiet higher. Since the nonlinear observer is based on nonlinear tire model, at each controlling step, all the four tires forces must be calculated according to the update tires load values and slip angle values. Updating the tires cornering power value is also a time-consuming work for the controller. According to the simulation results, the hybrid observer's running time is only about one eighth of the nonlinear observer's.



a) Large road friction situation ($\mu = 0.85$)



b) Small road friction situation ($\mu = 0.4$)

Fig.6 Simulation results of hybrid observer

6. Conclusions

In this paper, a novel vehicle slip angle observer is proposed with the method of fuzzy logic. The key point of the observer is the fuzzy tire model which can describe the nonlinearity of tire lateral force characteristics. An adaptive observer is applied based on such fuzzy tire model. For the local models of the observer are still linear ones, the linear observer design methods can be implemented. Therefore, the complication of nonlinear observer problem is avoided and the running time is greatly shortened. The simulation results verify the effectiveness of the proposed observer and its adaptation with road friction conditions.

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