Soft Measurement of Intelligent Vehicle side-slip Angle Based on Extended Kalman Filter*

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Abstract-A soft measurement method based on extended Kalman filter is proposed for the measurement of Intelligent Vehicle CG Side-slip Angle. Firstly, the nonlinear dynamic state model of intelligent vehicle is established, the state equation of Side-slip Angle is determined, and the extended Kalman soft measurement method is used for analysis. Secondly, through the establishment of a real vehicle test system, the soft measurement method of Side-slip Angle is verified under two working conditions and different vehicle speeds on the actual road. The test results show that the extended Kalman soft measurement method is reliable and accurate. The extended Kalman soft measurement method can meet the requirements of the full vehicle control system, and it has a certain value of full vehicle application research.

1. INTRODUCTION (HEADING 1)
The stability and safety of automobile are the problems that the engineers constantly improve and optimize [1-2]. Ideally, during the operation of the vehicle, the vehicle can get timely, stable, and assumed feedback for various incentives given by the driver. But due to various error, this feedback is not timely and cannot achieve the ideal expectations. So how to monitor real-time status of the vehicle becomes the main problems of the present study [3-4].

The Vehicle Stability Control System (ESP) mainly adopts the CG Side-slip Angle to measure the real-time running state of vehicles [6]. The current methods for the measurement of CG Side-slip Angle include kalman filter method[7], state observer method [8], fuzzy logic method [9], neural network method [10], etc. In this paper, EKF algorithm based on Kalman filtering is adopted to realize the soft measurement of CG Side-slip Angle [11]. Through the actual road test, the method has high precision and can meet the practical application of intelligent vehicle.

2. NONLINEAR MODEL OF INTELLIGENT VEHICLE
In order to realize the soft measurement of the side-slip Angle of intelligent vehicle, a reliable vehicle dynamics model should be established first. Considering the accuracy of side deflection measurement and the requirements of algorithm solution, this paper establishes a two-degree-of-freedom nonlinear model for intelligent vehicles as shown in Figure 1. This model ignores the role of suspension. Tire force is directly transmitted through the front and rear wheels, and the mass of the whole vehicle is concentrated at the center of mass [12].
Figure 1. Nonlinear model of intelligent vehicle

The dynamic equation of the model can be expressed as follows:

\[
\begin{align*}
\dot{\beta} &= -\psi + \frac{F_f \cos \delta_f + F_r}{mv}, \\
\dot{\psi} &= \frac{1}{J}(l_f F_f \cos \delta_f - l_r F_r)
\end{align*}
\]

(1)

where \(\beta\) denotes the side-slip angle, \(\psi\) denotes the yaw angle, \(\dot{\psi}\) denotes the yaw angular velocity, \(\ddot{\psi}\) denotes the yaw angular acceleration, \(J\) denotes the moment of inertia of vehicle around the \(z\) axle, \(\delta_f\) denotes the angle of vehicle front wheel, \(m\) denotes the mass of the vehicle, \(v\) denotes the vehicle centroid speed. \(F_f\) and \(F_r\) denote the lateral forces of the front and rear axles of the vehicle respectively. \(l_f\) and \(l_r\) denote the distances from the center of mass to the front and rear axes respectively.

The tire model [13] as shown in (2) is adopted. The relationship between the lateral force and the side-slip angle of the tire is given by the model.

\[
F_f = c_1 \arctan(c_2 \alpha)
\]

(2)

where \(\alpha\) denotes the side-slip angle of the tire. \(F_f\) denotes the lateral force of the tire. \(c_1\) and \(c_2\) are the model parameter of the tire.

According to (2), the lateral side-slip angle and the lateral deflection force of the front axle are shown in (3).

\[
\begin{align*}
\alpha_f &= -\beta - (l_f / v)\psi \\
F_f &= \frac{J\dot{\psi} + ma_f l_f}{l}
\end{align*}
\]

(3)

The lateral side-slip angle and the lateral deflection force of the rear axle are shown in (4).

\[
\begin{align*}
\alpha_r &= -\beta + (l_r / v)\psi \\
F_r &= \frac{-J\dot{\psi} + ma_r l_r}{l}
\end{align*}
\]

(4)

After arranging above formula, The equation of state for \(x = [x' \ x]^T = [\beta \ \psi]^T\) can be obtained as follows:

\[
\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \dot{\beta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \frac{1}{mv} c_{r_1} \arctan \left( c_{r_2} (\delta - x_1 - \frac{l_r}{u} x_2) \cos \delta + c_{r_3} \arctan \left( c_{r_4} (-x_1 - \frac{l_r}{u} x_2) - x_2 \right) \right) \\ \frac{1}{J} (l_r c_{r_1} \arctan \left( c_{r_2} (\delta - x_1 - \frac{l_r}{u} x_2) \cos \delta - l_r c_{r_3} \arctan \left( c_{r_4} (-x_1 + \frac{l_r}{u} x_2) \right) \right) \end{bmatrix} \cdot \begin{bmatrix} \psi \\ \beta \end{bmatrix}.
\]

(5)
3. SOFT MEASUREMENT METHOD FOR THE SIDE-SLIP ANGLE OF INTELLIGENT VEHICLE

According to the established nonlinear state dynamics model, the state equation of the side-slip Angle of the center of mass is determined. Due to the advantages of extended Kalman filter in nonlinear system state estimation, this paper adopts EKF method to carry out soft measurement of intelligent vehicle side-slip Angle.

EKF algorithm is a minimum variance estimation method suitable for nonlinear systems. Based on linear Kalman filtering, this algorithm expands the nonlinear system around the state estimation value according to Taylor series and omits more than second-order terms, linearizes the nonlinear system, and then uses Kalman filtering to filter the linearized model [14].

The concrete implementation process of EKF algorithm is as follows.

The state equation and observation equation of the nonlinear system are shown in (6).

\[
\begin{align*}
\dot{x}_k &= f(x_{k-1}, u_{k-1}, w_{k-1}) \\
y_k &= g(x_k, v_k)
\end{align*}
\]

(6)

where \(x_k\) and \(x_{k-1}\) denote the state variables of the system \(k\) and \(k-1\) respectively. \(u_k\) and \(u_{k-1}\) denote the input variables of the system \(k\) and \(k-1\) respectively. \(y_k\) denotes the output variable of the \(k\) time system. \(v_k\) denotes the observation noise of the system at the time of the system. \(w_{k-1}\) denotes the process noise of the system at the \(k-1\) time. \(f(\cdot)\) denotes the state function of the system. \(g(\cdot)\) denotes the observation function of the system.

The specific process of EKF estimation mainly includes prediction and calibration.

3.1 Prediction process

The state prediction method can be described as follows:

\[
\hat{x}_{k|k-1} = f(\bar{x}_{k-1}, u_{k-1}, 0)
\]

(7)

where \(\bar{x}_{k}\) and \(\bar{x}_{k-1}\) denote the prior value and the current estimated value of the system state variable respectively.

The covariance matrix of the system error can be described as follows:

\[
P_{k|k-1} = P_{k-1|k-1} + AP_{k-1|k-1}A^T + Q_{k-1}
\]

(8)

where \(P_{k-1}\) and \(P_{k-1|k-1}\) are the prior value of the system error covariance matrix. \(A\) denotes the Jacobian matrix of the observation equation for the state variable. \(Q_{k-1}\) denotes the covariance matrix of system process noise.

3.2 The calibration process

The gain matrix \(K_k\) of EKF can be described as follows:

\[
K_k = P_{k|k-1}H_k^T(H_kP_{k|k-1}^T + R_k)^{-1}
\]

(9)

where \(H_k\) denotes the Jacobian matrix of the state equation for the state variable. \(R_k\) denotes the covariance matrix of noise measured by the system.

The EKF estimation equation can be described as follows:

\[
\hat{x}_k = \hat{x}_{k|k-1} + K_k[y_k - g(\bar{x}_k, u_k, 0)]
\]

(10)

where \(\hat{x}_k\) denotes the current estimate value of the system state variable.

EKF estimation error covariance update equation can be described as follows:

\[
P_k = (I - K_kH_k)P_{k|k-1}
\]

(11)

where \(P_k\) denotes the current value of the system error covariance matrix. \(I\) denotes the identity matrix.
According to the established two free nonlinear systems, the state method of the deflection Angle of the center of mass can be described as follows:

\[ \dot{x}(t) = f(x(t), u(t)) + w(t) \]  
(12)

The state vector \( x(t) = [\beta(t), \dot{\psi}, Ff, Fr]^T \), the input \( u(t) = \delta(t) \).

The measurement equation of the system can be described as follows:

\[ y_k = Hx_k + v_k \]  
(13)

The observed quantity is \( y = [\alpha_y, \dot{\psi}]^T, H = \begin{bmatrix} 0 & 0 & 1/m & 1/m \\ 0 & 1 & 0 & 0 \end{bmatrix} \).

After discretization of the continuous equation, it can be obtained as follows:

\[ x_{k+1} = x_k + f(x_k, u_k)dt \]  
(14)

where \( dt \) denotes the sampling period.

Initial state quantity \( x_0 = [0 \ 0 \ 0 \ 0]^T \).

4. VERIFICATION OF CG SIDE-SLIP ANGLE

4.1 The Testing System

A test system was constructed to verify the soft measurement method of centroid deflection Angle. The test system adopts the intelligent vehicle as shown in Figure 2. The main on-board sensors on the vehicle are: laser scanning radar, camera, wheel speed sensor, 3-axis gyro, 3-axis acceleration sensor, steering wheel Angle sensor, DGGPS.

![Figure 2. Test intelligent vehicle](image)

The test verification system is shown in Figure 3, which is composed of MicroAutoBox, VBox and computer. VBox can directly measure the side-slip Angle of the car body with a sampling frequency of 20Hz. The data of the vehicle-sensor and VBox are transmitted to MicroAutoBox through CAN trunk, and then stored and displayed by the computer.
In order to verify the effectiveness of the soft measurement method, the serviform condition that can simulate the serpentine continuous and the double-shift condition that can simulate the rapid return of vehicles to the original lane after overrunning are selected for the experiment. The test site is a dry, flat cement floor.

4.2 Test Results and Analysis

4.2.1 Double shift Condition: Under the double-shift condition, the actual road test was carried out at 60km/h and 100km/h respectively. The test results are shown in Figure 4-5. Figure 4 shows the test results at a speed of 60km/h, and Figure 5 shows the test results at a speed of 100km/h.
In Figure 4 and 5, the solid line is the actual measured value of the vehicle model, and the dotted line is the measured value of the operation according to the extended Kalman soft measurement method of intelligent vehicle side-slip Angle proposed in this paper. As can be seen from the figures, the dashed lines of the two speeds basically coincide with the solid lines except for the large side deviation Angle in the actual running process of the vehicle. The comparison of the two speeds shows that the error at 100km/h is smaller than that at 60km/h. This is also consistent with the actual vehicle conditions under the operating results. It shows that the soft measurement method of side-slip Angle proposed in this paper has good anti-interference ability and high precision, which can meet the application requirements of real cars and has application value.

4.2.2 Positioning Figures and Tables:

In the serpentine condition, the road test was carried out at 60km/h and 80km/h respectively, and the test results were shown in Figure 6-7. Figure 6 shows the test results at a speed of 60km/h, and Figure 7 shows the test results at a speed of 80km/h.

![Figure 6. the test results at a speed of 60(km/h)](image)

![Figure 7. the test results at a speed of 80(km/h)](image)

The serpentine condition challenges the limit of vehicle operation, from which we can get a good understanding of the actual running state of the vehicle. In Figure 5 and 6, the solid line is the actual measured value of the vehicle model, and the dotted line is the measured value of the extended Kalman soft measurement. As can be seen from the figures, the dashed lines of the two speeds basically coincide with the solid lines except for the large side deviation Angle in the actual running process of the vehicle. Among them, when the vehicle is about 7s at a speed of 60km/h, the side deflection error is the largest and the linear characteristic is insufficient. The vehicle has a high precision under the speed of 80km/h, and the solid line and the dotted line are basically consistent to meet the practical application requirements.
5. CONCLUSION
In this study, an extended Kalman filter soft measurement method for the CG side-slip Angle of intelligent vehicle is presented, which can realize the control stability of the vehicle in the actual running process. The nonlinear state dynamics model of intelligent vehicle is built to determine the state equation of side-slip Angle, and the EKF algorithm based on extended Kalman filter is used to explain the prediction and correction process of the state equation and measurement equation. Through the establishment of a full vehicle test system, and in the actual road under two conditions and different speeds of the soft measurement method of the side-slip Angle. The test results show that the method has good reliability and high precision, can meet the requirements of real vehicle application, and has high application research value.

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REFERENCES
[1] Dave Crolla, Yu Fan. Vehicle Dynamics and Control[M]. Beijing: Journal of China Communications Press,2003.
[2] Georg Rill, Abel Arrieta Castro. Road Vehicle Dynamics. 2020
[3] KIENCHEU, NIELSENL. Automotive Control System[M]. Berlin: Springer, 2000.
[4] PACEJKHB. Tyre and Vehicle Dynamics[M]. London: Buterworth Heinemann, 2002.
[5] Science- Applied Sciences; Reports Summarize Applied Sciences Research from Chinese Academy of Sciences (An Adaptive Target Tracking Algorithm Based on EKF for AUV with Unknown Non-Gaussian Process Noise) [J]. Science Letter,2020.
[6] Guo Hongyan, Chen Hong, Ding Haitao, Hu Yunfeng. Vehicle side-slip angle estimation based on Uni-Tire model[J]. Control Theory and Application,2010,27(09):1131-1139. (in Chinese)
[7] ArndtC, KaridasJ, BuschR. Estimatingnon-measuredvehiclestateswithanextendedlinearisedKalmanfilter[J]. Review of Automotive Engineering,2005,26(1):91-98.
[8] JoannyS, AliC. Virtual sensor: Applicationtovehiclesideslipangleandtransversalforces[J]. IEEE Transaction son Industrial Electronics,2004,51(2):278-289
[9] Shi Shuming, Henk Lupker, Paul Bremmer, Joost Zuurbier. Estimation of Vehicle Side Slip Angle Based on Fuzzy Logic [J]. Journal of Automotive Engineering,2005(04):426-430.(in Chinese)
[10] Grid Based Path Planning Using CNN & Artificial Potential Field Method[J].Haruyama Shigeyuki, Didik Nurhadiyanto, Kazuya Ushijima, Ken Kaminishi, Dai Heng Chen. Applied Mechanics and Materials,2013(392)
[11] Lin Fen, Zhao Youqun. ComparisonsofMethodsofEstimatingVehicle Side Slip Angl[J]. Journal of Nanjing University of Science and Technology( Natural Science),2009,33(01):122-126+131.
[12] Yoshiki Fukada. Slip-Angle Estimation for Vehicle Stability Control[J]. Vehicle System Dynamics,1999,32(4-5).
[13] Yuan Yifan, Liang Jun, LIU Changning, Chen Lei, WU Longwei, Chen Long, Jiang Haobin. Dynamic Model and Simulation of Driverless Vehicle Based on Neural Network Integrated PID Control [C]. Proceedings of the 2014 Annual Meeting of Chinese Society of Automotive Engineering,2014:360-366.
[14] Zhang Lu. Stability Control test and Control Algorithm of Vehicle adhesion Limit State [D]. Beijing: China Agricultural University,2016:70-73.