# Soft Sensor Application in Vehicle Yaw Rate Measurement Based on KALMAN Filter and Vehicle Dynamics

Gao Zhenhai

*Abstract*—**The accurate measurement of vehicle yaw rate is vital for vehicle dynamics control, such as yaw control and traction control. Generally vehicle yaw rate is measured by gyro that will cost too much to be used commercially as an on-vehicle sensor. Based on soft sensor technique in inferential control theory, a novel method for the estimation of vehicle yaw rate is proposed. The estimation is based on Kalman filter and 2 degree-of-freedom vehicle dynamic model to realize the estimation of yaw rate of linear minimize mean square error. Results of simulation and experiment show an accurate and low-cost estimation of yaw rate is achieved and soft sensor estimation method is feasible in measurement of vehicle state.**

*Index Terms*—**estimation; kalman; soft sensor; vehicle yaw rate**

## I. INTRODUCTION

Recent years, vehicle active safety is the focus point and many systems are developed, such as anti-lock brake, traction control and yaw control that improve active safety by controlling some key vehicle state during running, for example tire slip and yaw rate. So the important precondition of realizing these control function is to on-line measure vehicle state accurately and effectively.

Hence the accurate measurement of vehicle state is the key to realize vehicle dynamic control. Generally vehicle state parameters are measured directly by on-vehicle sensors, such as tire rate sensor, accelerometer and steering angle sensor. But during running, some important state parameters are unable to measure by sensor or correlative measure sensors cost too much to install in mass produced vehicle. For example, yaw rate is an important element in vehicle dynamic control that influences the drivers' feeling for vehicle handling and stability. In general experiment, yaw rate is measured by gyro, but gyro will cost too much to use widely. So this information incompletion of vehicle state bring so many difficulties for realizing vehicle active safety control.

In order to solve the information incompletion in control process, inferential control theory was proposed by Brosillow.C.B in 1978 and with this theory, soft sensor has begun to use in many fields, especially in the monitoring and control of chemical plants. Based on indirect measurement way, soft sensor is a good method to inferring unmeasured parameter by measurable parameter, which can realize these difficultly-measured or unmeasured parameter on-line estimation with some easily-measured parameter and mathematical model can describe the relationship between these parameters [1]. Soft sensor is usually associated with hardware sensor, in which provides an estimation algorithm to realize on-line estimates of the unmeasured variables, model parameters and overcome measurement difficulty and delays. Compared with hardware sensor, soft sensor has many advantages such as low cost, workability, agility and universality. Now there are many soft sensor methods, such as filter technique and artificial neural networks.

In the research of advanced vehicle control, the on-line estimation of vehicle state, tire force and road friction coefficient, based on Kalman filter and vehicle dynamics have been given more and more attention. L.R.Ray has proposed an extended Kalman filter to estimate nonlinear vehicle state and tire force [2]. In this paper, a simple soft sensor method is implemented to measure yaw rate based on an Kalman filter and 2 degree-of-freedom vehicle dynamic model, which mainly uses the measurement of lateral acceleration, vehicle velocity and steering angle to estimate yaw rate. Here we assume vehicle speed is constant. Some field experiments are also made in which a high-precision gyro is installed in experiment vehicle to directly measure yaw rate and the comparison of experiment and estimation results shows good accuracy.

## II. TWO DEGREE-OF-FREEDOM VEHICLE DYNAMIC MODEL

In the research of vehicle handling and stability, the two degree-of-freedom vehicle model is used widely and figure 1 is the sketch map of this linear model. In Fig.1, $X_\alpha O_\alpha Y_\alpha$ is the inertial coordinate frame and $xoy$ is the vehicle-fixed coordinate frame. This model regards two front and rear tires as

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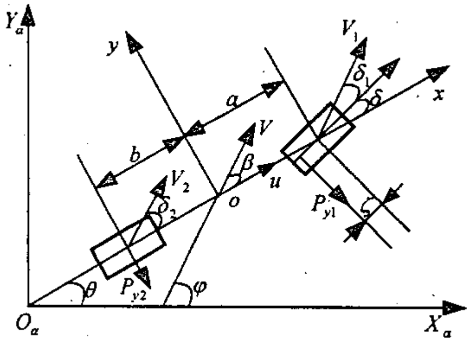

Fig.1 Two degree-of-freedom vehicle dynamic model

a single front and rear tire and neglect roll motion. Here two degree-of-freedom are yaw rate and side-slip angle of center of gravity. In this paper this model is used to establish process and measurement model of Kalman filter. The disturbances from lateral wind and sensor noise are also added and the noises from lateral wind are acted on front and rear tire respectively.

The process equation of vehicle dynamic model is the following:

$$[\dot{X}]=\begin{bmatrix}\dot{r}\\ \dot{\beta}\end{bmatrix}=[A]\begin{bmatrix}r\\ \beta\end{bmatrix}+[B]\delta_{sw}+[E]w \quad (1)$$

where:

$$A=\begin{bmatrix}-\dfrac{b^2\cdot K_2+a^2\cdot K_1}{I_z\cdot v} & \dfrac{b\cdot K_2-a\cdot K_1}{I_z}\\ \dfrac{K_2\cdot b-K_1\cdot a}{M\cdot v^2}-1 & -\dfrac{K_1+K_2}{M\cdot v}\end{bmatrix} \quad (2)$$

$$B=\begin{bmatrix}\dfrac{a\cdot K_1}{i\cdot I_z}\\ \dfrac{K_1}{i\cdot Mv}\end{bmatrix} \quad (3)$$

$$E=\begin{bmatrix}-\dfrac{a}{I_z} & -\dfrac{b}{I_z}\\ -\dfrac{1}{M\cdot v} & -\dfrac{1}{M\cdot v}\end{bmatrix} \quad (4)$$

The measurement equation of vehicle dynamic model is the following:

$$[Y]=[a_y]=[C]\begin{bmatrix}r\\ \beta\end{bmatrix}+[D]\delta_{sw}+[F]w+q \quad (5)$$

where

$$C=\begin{bmatrix}\dfrac{K_2\cdot b-K_1\cdot a}{M\cdot v} & -\dfrac{K_1+K_2}{M}\end{bmatrix} \quad (6)$$

$$D=\begin{bmatrix}\dfrac{K_1}{i\cdot M}\end{bmatrix} \quad (7)$$

$$F=\begin{bmatrix}\dfrac{-1}{M} & \dfrac{-1}{M}\end{bmatrix} \quad (8)$$

Where $M$ is vehicle's mass, $a$ is the distance from front tire to the center of gravity, $b$ is the distance from rear tire to the center of gravity, $K_1, K_2$ are the effective cornering stiffness of front and rear tire, $I_Z$ is the moment of inertia of the vehicle, $i$ is the ratio of steer system, $r$ is yaw rate, $\beta$ is side-slip angle of center of gravity, $\delta_{sw}$ is the angle input of steering wheel, $a_y$ is the lateral acceleration, $w=[w_1;w_2]$ are the process noise from lateral wind at front and rear tire, $q$ is the measurement sensor noise of lateral acceleration. Here $w_1 w_2, q$ are assumed to be independent of each other, white and with normal probability distributions.

## III. KALMAN FILTER

Kalman filter is a set of mathematical equations that provides an efficient recursive solution of the minimize mean square error by using a form of feedback control: the filter estimates the process state and then obtains feedback from noisy measurements [3].

These equations can be divided into two groups: time update equations and measurement update equation. The time update equations can be thought as predictor equations and project the current state estimate ahead in time, while the measurement update equations can be thought as corrector equations and adjust the projected estimate by an actual measurement at that time. Figure 2 shows the predictor-corrector algorithm of

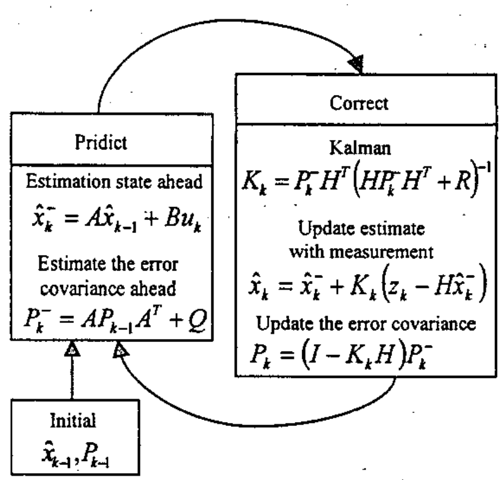

Fig.2 Kalman filter algorithm

Kalman filter [3]. Here the process and measurement equations are the following:

$$x_k=Ax_{k-1}+Bu_k+w_{k-1} \quad (9)$$

$$z_k = Hx_k + v_k \quad (10)$$

Where:

$$p(w) \sim N(0, Q) \quad (11)$$

$$p(v) \sim N(0, R) \quad (12)$$

$Q, R$ are the process noise covariance and measurement noise covariance.

## IV. SIMULATION AND EXPERIMENT

Based on two-degree-of-freedom vehicle model, we can get the system process and measurement equation, then with Kalman filter, the estimation of yaw rate can be made. Here we assume that the variance of noise from lateral wind is 100 and the variance of noise from measurement sensor is 0.01.

To verify the soft measurement method of yaw rate, some double-lane-change field experiments were made. In the experiments, a fifth-wheel trolley as speed sensor, angle sensor of steering wheel, and a high accurate gyro for measuring yaw rate were installed in experimental vehicle. In the experiment, vehicle speed is at 22m/s, and the shape of double-lane change is following the criterion of ISO/FDIS 3888 of China.

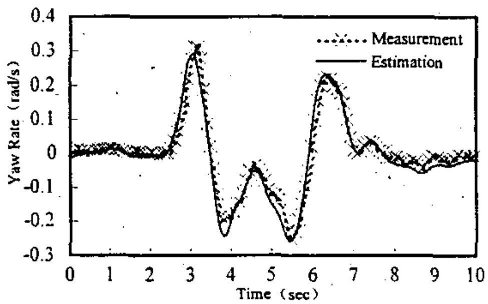


Fig.3 estimation and experiment results

Figure 3 is the result contrast of estimation and experiment of yaw rate. In experiment the time step is 0.002s. For the sake of looking clearly, the time step of the data in Fig.3 is 0.04s. From Fig.3, the estimate of yaw rate can follow the actual measurement very closely.

## V. CONCLUSION

Soft sensor of vehicle state is a good supplement to vehicle parameter measurement and can help solving the problem of control-key-information inadequacy. Because the costs of some on-vehicle sensors such as gyro are too high, soft sensor measurement of yaw rate can easily realize the estimation of minimize mean square error and only use some usual and low-cost on-vehicle sensor such as lateral acceleration, speed and angle of steering wheel. From the results of simulation and experiment, the estimation follows closely and shows good agreement with the actual measurement.

In this paper, we just use vehicle linear dynamic model of two degree-of-freedom. The next step vehicle nonlinear model of more degree-of-freedom will be adapted and the tire force will also be estimated with extended Kalman filter; while some other nonlinear filter, such as adaptive Kalman filter and unscented Kalman filter will also be used to improve the estimation accuracy.

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