論文の内容の要旨

論文題目 Body Slip Angle Estimation for Stability Control of Electric Vehicle

(電気自動車の安定性制御のための車体すべり角推定に関する研究)

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（本文）

This thesis presents the algorithmic solutions of the nonlinear vehicle lateral dynamic control problem based on state observer, which has been validated both in a simulation environment and real-time. Different vehicle body slip angle (β) estimation methodologies are proposed and checked in the study, by combining the model-based estimation with adaptive mechanisms to form the adaptive nonlinear observers.

It has been commonly recognized that electric vehicles (EVs) are inherently more suitable to realize active safety stability control over conventional Internal Combustion engine Vehicles (ICVs). In EVs, the motor torque can be measured and controlled accurately; and in-wheel motors can be installed in each EVs' rear and front tires. Based on these structural merits, vehicle motion can be stabilized by additional yaw moment generated as a result of the difference in tire driving or braking forces between the right and left side of the vehicle, which is so called 'Direct Yaw-moment Control' (DYC). By applying Model Matching Control, the yaw moment optimal decision can be derived from the deviations of the state feedback compensator of body slip angle β and yaw rate γ from their desired values. Since sensors for the direct measurement of β are very expensive, the construction of an observer for its estimation is desirable.

Generally, such observer is based on the state equations derived from the vehicle dynamics. However, the implementation of these techniques is still difficult since the vehicle dynamics are highly nonlinear, especially for β. The main nonlinearity of vehicle dynamics comes from the tire force saturation imposed by the limits of tire adherence, which makes β response change considerably if the vehicle is cornering much more than usual. In other words, the model structure or model parameters should vary according to the different operating regimes for a more practical controller design. In addition, the nonlinear nature of vehicle dynamics is further complicated by the influence of the characteristics of whole chassis elements (tires, suspensions and steering system). It is hard to determine the physical model parameters theoretically.

In chapter 1 of the thesis, the basic principles and research situations of state observer-based stability control systems are described. Then the development and motion control studies of in-wheel-motored vehicles are introduced. In chapter 2, the vehicle lateral dynamics are represented by introducing tire and vehicle models with different complexity. The discussion of vehicle lateral dynamics is initiated by explaining fundamental concepts and introducing linear tire and vehicle models, which provide a basic idea of what states and parameters of a vehicle are important for vehicle dynamics control. The identification methods for the key parameters for the observer purpose are described. The analysis is also extended to the nonlinear handling characteristics according to the vehicle dynamic models. In chapter 3, the basic ideas of state observer theories are introduced, including the linear, nonlinear and fuzzy observers. The algorithms of recursive Kalman Filter equations and the algorithms of recursive least-squares (RLS) for parameter identifications and adaptive observer design are also explained. In chapter 4, different methodologies are applied for body slip angle observation, including the observer with nonlinear tire model, the hybrid observer based on fuzzy logic modeling and the adaptive observer by combining the kinematic estimations. The performance of the different methodologies and sensitivity on the modeling error are checked under the qualitative analysis and evaluated by simulations quantitatively. In chapter 5, the experiments of proposed observers are conducted in the In-Wheel-Motor electric vehicle "UOT Electric March II". The configuration of experimental systems in the test EV is introduced and the experimental results are shown. In chapter 6, the estimated vehicle states are used in the DYC system to modify a vehicle's handling characteristics through a full state feedback controller, which implies applicability of the proposed observers to a practical vehicle controller.

Based on the studies, the algorithmic solutions of vehicle state observer considering the nonlinear vehicle lateral dynamics are presented and evaluated.

The conventional linear observer (based on linear 2-DOF vehicle model) for body slip angle estimation can not eliminate the estimated $\beta$ error as expectation especially when vehicle in limit condition, in which the observation of $\beta$ is vital for vehicle stability control. So the author has been trying to improve it by combining with the kinematic estimation (integration estimation) and on-line cornering stiffness identification (Figure 1). Kalman Filter theory is adopted for the fusion of the information from model-based estimation and the kinematic estimation, by determining the Kalman Filter feedback matrix L related to the tuning of covariance matrices of process (vehicle model) noise and measurement noise. The influence of sensor bias on the integration results can be minimized, by resetting the integration value when getting to the steady states by the model-based observer. On the other hand, the body slip angle estimated through the kinematic approach during transient maneuvers is used to correct tire cornering stiffness in order to take into account changes in tires' properties. Some improvement has been shown in the experimental results, but still with some error for the delay of tire cornering stiffness identification algorithm. Further work will be on the improvement of on line RLS algorithm to make higher responsibility of cornering stiffness identification.

The robustness over tire cornering stiffness error is the main advantage of the proposed nonlinear observer over the linear ones, although a relative simplified form of function is adopted to describe the nonlinear tire characteristics. The simulation results also show the estimate $\beta$ values are more sensitive to the road surface friction coefficient $\mu$ errors, which confirm the importance of $\mu$ identification to ensure the observer's accuracy. However, compared with linear observer, the nonlinear functions in the nonlinear observer are realized in the ECU as long mathematical sums. This over-complication is unnecessary, especially in the region where the tire characteristic is linear. Another problem in such observer is the fixed form of functions applied in the nonlinear tire model, which weakens the ability of modeling adaptation and makes the modeling of vehicle dynamics can not consider the real conditions including the characteristics of whole vehicle chassis.

The study on hybrid observer pays the main attention to an algorithmic solution of the nonlinear vehicle dynamic control problem, as well as the real-time control aspect. In the first step of the hybrid observer design, to deal with the difficulties associated with nonlinearity modeling, as well as to make use of the linear observer advantages such as simplicity in the design and implementation, the nonlinear vehicle dynamics are represented by Takagi-Sugeno (T-S) fuzzy models. These modeling techniques are considered appropriate for on-line control system design (linear 2-DOF vehicle model). In the next step, a fuzzy-based modeling approach is used to get a hybrid-like vehicle model which is calculated as a weighted sum of the outputs of two local linear models. For practical applications, parameter identification is conducted experimentally. An adaptation mechanism of the fuzzy membership functions has been included to make the model fit different running conditions and road friction changes. The membership functions of the weighting factors are chosen to be dependent on lateral acceleration and road friction coefficient. The two local observers are based on local linear tire models, which inherently leads to a relatively simple design, have been combined into a single overall observer by means of fuzzy rules (Figure 2). Furthermore, the nonlinear global system results show high $\beta$ estimation capabilities and good adaptation to changing road friction.

A series of simulations are performed to evaluate the effectiveness of the proposed $\beta$ observer when incorporated into a DYC-based control scheme. The estimated vehicle states are applied as feedback signals to a stability controller, which virtually modifies a vehicle's handling characteristics. We have shown that the designed controller rely critically on the estimated value of $\beta$ and further research and effort will be devoted into the implementation of a full dynamic stability control of the electric vehicle "UOT MARCH II".

The future work will also focus on the theoretical analysis of the stability and convergence of proposed observers. In addition, based on the analysis, the adaptive laws will also be improved and verified.