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Displacement and force coupling control design for automotive active front steering system

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A B S T R A C T

A displacement and force coupling control design for active front steering (AFS) system of vehicle is proposed in this paper. In order to investigate the displacement and force characteristics of the AFS system of the vehicle, the models of AFS system, vehicle, tire as well as the driver model are introduced. Then, considering the nonlinear characteristics of the tire force and external disturbance, a robust yaw rate control method is designed by applying a steering motor to generate an active steering angle to adjust the yaw stability of the vehicle. Based on mixed H_2/H_∞ control, the system robustness and yaw rate tracking performance are enforced by H_∞ norm constraint and the control effort is captured through H_2 norm. In addition, based on the AFS system, a planetary gear set and an assist motor are both added to realize the road feeling control in this paper to dismiss the influence of extra steering angle through a compensating method. Evaluation of the overall system is accomplished by simulations and experiments under various driving condition. The simulation and experiment results show the proposed control system has excellent tracking performance and road feeling performance, which can improve the cornering stability and maneuverability of vehicle.

1. Introduction

The yaw motion of a vehicle can be disturbed under some critical situations, such as low tire-road friction and side-wind gust at high speed. It is difficult for a human driver to maintain yaw control for a vehicle under such dangerous situations. The active front steering (AFS) system, as an effective technology to assist driver in yaw motion control, has been studied for years [1–3], assisting driver in vehicle handing by automatically producing an extra steering angle to improve yaw stability, such that the vehicle can stay maneuverable in presence of the critical situations.

So far, there are two methods to realize active front steering [4]. One is called steer-by-wire (SBW) system [5], where the driver's steering commands are electrically transmitted to the steering actuators without any mechanical connection. The other method employs a steering motor and a gear set to the steering column, where the mechanical connection between steering hand wheel and front wheel still exists, and it has already been used in commercial vehicles successfully [6]. The second technique is applied in this paper.

A lot of researches on AFS control have been reported. Paper [7] proposed a vehicle lateral dynamics control through AFS/DYC (direct yaw-moment control) and robust gain-scheduling approach by considering the variation of the velocity, the nonlinear characteristics of the tire and the external disturbance. The control variables were the front wheel angle and

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the additional yaw moment. Although the simulations validated the effectiveness of the proposed control strategy, the output limit of the front wheel angle and the distribution of the yaw moment were not mentioned in the paper. A novel H-infinity controller via scenario optimization (H-infinity VSO) was presented in [8] for AFS control, of which the aim is to handle and stabilize vehicle under the uncertainty of parameter road adhesion coefficient μ. The variation of road adhesion coefficient μ leaded to the changing of the tire corning stiffness which was considered in the modeling. Simulation results showed indicated that in this manner a chance constrained problem was solved resulting in less conservativeness in stability and optimality, while the limit of the front wheel steering angle was not considered. The control methods developed in [9–12] involved more than one chassis system to insure the stability of the vehicle [9] came up with an LPV/H-infinity integrated vehicle dynamic control involving semi-active suspension, active steering and electromechanical braking systems to accomplish stability control under low slip, high slip and the emergency situation. The control strategy presented in [10–12] applying ESC and AFS, including two levels control: the upper level was to derive the control yaw moment needed to stabilize the lateral motion of a vehicle, and the lower level was to coordinate the braking of electronic stability control and the corrective steering obtained by active front steering to acquire the needed yaw moment. In [13], a robust method of direct lateral tire force control is presented for vehicle motion control via SBW. The control performance is verified through experiment, but the tire force is very hard to obtain through sensor or and costly to realize.

According to the literatures above, the parameters' uncertainty and states change are of great importance to the AFS control quality. And because the yaw moment is closely related to the tire lateral force, the nonlinear characteristics and saturation of the tire also must be considered. Besides, there are still some problems to be solved. Firstly, the anti-interferences performance is of great importance because the real driving condition could be very complicated; secondly, the tracking performance is also an important issue because under normal circumstances, the vehicle must comply with the driver's driving intentions; furthermore, the added equipments will influence the drivers' understanding of road conditions.

To improve the anti-interferences performance tracking performance of the AFS system, robust control has been considered. The H_∞ optimal control method is proposed by several researches for its disturbance rejection and robustness [14,15]. The H_∞ performance is introduced to realize the disturbance suppression by selecting the actuator forces as virtual inputs, and an adaptive robust control technology is further used to design controllers which help real force inputs track virtual ones. Although H_∞ optimal control is convenient to enforce robustness to model uncertainty and express frequency-domain specifications, it usually leads to an excessive control effort. Since AFS system controls vehicle stability by the lateral force of front tires, the control output should be constrained within lateral tire force saturation to avoid uncontrollable situation. Therefore, the mixed H_2/H_∞ control is adopted in this paper, not only to stabilize the yaw rate response in the presence of disturbance and uncertainty, but also reduce the control output of AFS.

Most of the studies on AFS control strategy are limited to the visual interaction between driver and vehicle without considering the haptic interaction. These may be a problem when applied to the commercial vehicles, because the system contains planetary gears, additional reactive torque caused by active steering will transfer to the driver directly through the mechanical connection, which could lead to oscillations of driver's handling [16]. Based on the AFS system applied before, a planetary gear set and an assist motor are both added to realize the road feeling control in this paper to dismiss the influence of extra steering angle through a compensating method. A driver model incorporating neuromuscular dynamics is introduced in [17,18] to get a better understanding of vehicle dynamic behavior through closed-loop driver-vehicle simulation.

The integrate control structure proposed in this paper is shown as Fig. 1.

The driver manipulates the hand wheel according to tracking error, inputting the hand wheel torque Td and hand wheel angle θ_{sw} to the steering system. The reference yaw rate can be calculated by θ_{sw} though reference model, and then the tracking error is obtained with the yaw rate feedback. Based on the yaw rate tracking error, the yaw rate controller calculate the needed control input θ_{r2}, the second ring gear angle of planetary gear set, which can be provided by the steering motor. Then the stability control of the vehicle is accomplished. Meanwhile, the torque compensator calculate the assist torque T_p by the steering column sensor torque T_s, the second ring gear angle θ_{r2} and the hand wheel angle, and then the T_p is generate by the assist motor to realize the torque compensation control. By this means, the force and displacement coupling control for AFS system is completed.

The rest of this paper is organized as follows. The system models of AFS, vehicle and driver are established in Section 2. The yaw rate controller based on mixed H_2/H_∞ control is given in Section 3. The steering torque compensator is designed in

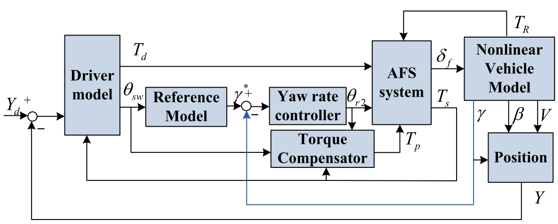

Fig. 1. The integrate control structure.