Research and analysis of steering-by-wire system stability

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Abstract—In this paper, the basic structure of steer-by-wire system is firstly introduced, and the steering stability of steer-by-wire system is summarized by means of stability control method and variable angle transmission ratio method. Finally, the unstudied direction of steer-by-wire system at this stage is summarized, and the intelligent steer-by-wire system is prospected, which provides basic information and ideas for the study of steering stability of steer-by-wire system.

1. Introduction
At present, China is in a high-speed development stage. Due to the rapid development, to a certain extent, the demand for energy will be large. In particular, oil resources, as non-renewable resources, have been in a state of tension, and China has a high degree of dependence on foreign oil. The rapid development of new energy vehicles eased the demand for oil in China. The emergence of new energy vehicles is also crucial for environmental protection. In the 5G era, in line with the concept of “intelligence, safety, energy saving and environmental protection” large domestic and foreign automobile enterprises and major scientific research institutions have invested cutting-edge technologies such as artificial intelligence in the new energy automobile industry, which has greatly promoted the related technology industries such as intelligent driving vehicles. In terms of the current automobile steering development situation, the traditional steering structure has been unable to meet the needs of intelligent vehicle electronic control technology.

In the process of continuous development, linear steering technology will be on the main stage of the times. Steering-By-Wire System realizes the decoupling between manual steering and vehicle response by replacing the traditional mechanical connection with electrical signal transmission. Due to the cancellation of the mechanical connection between the steering actuator and the steering wheel, the design freedom of each transmission ratio of the steering system is strengthened, and it is convenient to combine the vehicle state parameters with the optimized control algorithm, which can provide more steering maneuverability for drivers. Operating stability can be seen as two interrelated parts, and it is also a key indicator to measure vehicle driving performance.

2. Modeling of Steering Structure and Dynamics
Front wheel steer-by-wire system and distributed steer-by-wire system are the two parts of steer-by-wire research. According to the traditional front wheel mechanical steering, mechanical hydraulic power steering system, electronic hydraulic power steering system and electronic power steering system, the linear steering system is developed slowly, which is mainly composed of steering wheel and steering column integration part, steering actuator and front wheel integration part and main controller. In addition, fault tolerant system, power system segment and other auxiliary systems are also indispensable to the steer-by-wire system, as shown in Figure 1.
The distributed steer-by-wire system has the characteristics of high mobility, which can meet the needs of complex urban road conditions, such as moving in a narrow space and parking on the side, which greatly improves the maneuverability of drivers. In the research field, the actuator of distributed steer-by-wire system can be divided into two different technical forms. One is the independent steering of front and rear wheels. Two steering actuators are placed on the front and rear axles of the steer-by-wire chassis to drive the wheels on both sides to rotate at the same time. The other is a four-wheel independent steering, each wheel has a steering actuator, which can independently drive each wheel of the wire-controlled chassis to rotate. Four-wheel distributed steer-by-wire can make four-wheel independent steering, independent positive and negative driving, and the steering angle of the wheel can be ±90°. It can realize the omni-directional displacement function, and has eight driving modes. As shown in Figure 2, it has high controllable degrees of freedom, strong trajectory tracking ability, and can improve the comprehensive performance of the human-vehicle system by high-precision control, combined with the driver’s driving intention and characteristic identification algorithm, which greatly improves the handling stability and active safety of the vehicle. In the four-wheel distributed steer-by-wire configuration, the dynamic response of planar motion can be improved, especially in the lateral direction. It is not difficult to see that the four-wheel distributed steer-by-wire has stronger stability.

2.1. Steering wheel assembly modeling
The steering wheel assembly can receive the driver’s steering instructions and transfer the road feel. Its structure mainly includes steering wheel, road feel motor and reducer, angle and torque sensor. The torque input by the driver through the steering wheel is the driving torque, which is used to overcome the various resistance torques and friction torques existing in the steering wheel assembly. The dynamic model is established as follows:

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Figure 1. Structure diagram of steer-by-wire system
The steering wheel to torque sensor model:

\[ T_{sw} = J_{sw} \dot{\theta}_{sw} + B_m \dot{\theta}_m + T_{mw} + T_f \]  
\[ T_{mw} = K_c \left( \theta_{sw} - \theta_m / g_m \right) \]  

In the formula, \( T_{sw} \) - the driver’s torque; \( \theta_{sw} \) - steering wheel angle. \( \theta_m \) - Road induction motor angle. \( g_m \) - Reduction ratio of road induction motor reducer. \( T_{mw} \) - torque value of torque sensor. \( T_f \) - Equivalent friction torque of steering wheel assembly.

Torque sensor to road induction motor part model:

\[ T_m = J_m \ddot{\theta}_m + B_m \dot{\theta}_m + \frac{T_{mw}}{g_m} \]  

2.2. Modeling of steering execution assembly

The steering execution assembly is mainly composed of gear rack mechanism, steering component and steering execution motor. The torque provided by the steering motor has two directions. As shown in Figure 3, One is consumed by the inherent rotational inertia and damping of the motor, and the other is transmitted to the gear and rack mechanism through the steering gear to drive the wheel steering through the deceleration and torque increase of the deceleration mechanism.
Steering motor model, According to the torque balance, the dynamic equation can be obtained as follows:

\[ T_{fm} = J_{fm} \ddot{\theta}_{fm} + B_{fm} \dot{\theta}_{fm} + \frac{T_p}{g_m} \]  \hspace{1cm} (4)

\[ T_p = K_p \left( \frac{\theta_{fm}}{g_{fm}} - x_r / r_p \right) \]  \hspace{1cm} (5)

- \( T_{fm} \) - Steering motor electromagnetic torque.
- \( \theta_{fm} \) - Steering motor angle.
- \( T_p \) - Equivalent to the steering resistance distance on the steering gear.

3. Stability control of steer-by-wire system

There are two research methods for the steer-by-wire system. One is the stability control method, that is, based on the reference model, through tracking the driver input parameters and vehicle running state, combined with the control algorithm, the ideal yaw rate, centroid sideslip angle and other technical parameters are calculated. The stability controller is designed with the ideal front wheel angle as the main parameter, and then the angle is allocated. The required torque is transmitted to the actuator through the steering motor to complete the tracking of the front wheel angle, as shown in Figure 4. The second is the variable transmission ratio control method, that is, the ideal front wheel angle is obtained by calculating the driver’s front wheel angle and the system transmission ratio, and then the steering motor is controlled by designing the angle tracker to track the ideal front wheel angle.

3.1. Linear steering stability control technology

Literature [2] the integral terminal sliding mode control theory is used to optimize the upper controller. The actual yaw rate of the vehicle is infinitely close to the expected yaw rate, and the corrected angle is output. Robust adaptive sliding mode control algorithm is used for the lower controller to ensure that the desired front wheel angle is almost the same as the normal front wheel angle. This paper studies the phenomenon of sideslip and tail flick of steer-by-wire.

Literature [3] the fuzzy control method is used to control the angle of front wheel and rear wheel, and the error rate of yaw rate is used as an important parameter to reduce the overshoot of yaw rate and sideslip angle of centroid, so that the vehicle has strong stability.

3.2. Linear steering variable transmission ratio control technology

Most of the studies on the control of steer-by-wire variable-angle transmission ratio in China and abroad have realized the handling stability and safety adaptability of steer-by-wire vehicles the structure and control algorithm.
3.2.1. Variable Angle Transmission Ratio Control with Constant Steering Gain

Literature [4] adopted different design schemes in the middle-speed section and the high-speed section. In the middle-low speed section, the transmission ratio was designed under the design condition of constant steady-state yaw rate gain. Then the fuzzy control optimization transmission ratio scheme is used in high speed section. The experimental results show that the transmission ratio designed in this paper can improve the tracking effect and stability of the vehicle in the trajectory. Literature [5] Because it is a four-wheel independent steering, the variable transmission ratio control of front and rear wheel steering is studied respectively. In the study of variable transmission ratio control of front wheel steering, the constant transmission ratio strategy is used according to different speed ranges. In the middle speed range, the variable transmission ratio is determined by the constant yaw angular velocity gain method. In the high speed range, the variable transmission ratio is determined by limiting the lateral acceleration gain. In the study of variable transmission ratio control of rear wheel additional steering, the control method is low speed additional rear wheel reverse angle and high speed additional rear wheel co-direction angle. Literature [6] The Car Sim real vehicle model is used to simulate the vehicle stability, and the constant gain method is used to study the middle and low speed sections. Taking the vehicle handling stability evaluation index as the research factor, the genetic algorithm is combined with it to design the ideal transmission ratio. In the middle and high speed range, the ideal steering ratio is designed by combining the yaw rate gain with the lateral acceleration gain.

3.2.2. Variable Angle Transmission Ratio Control of Other Technologies

Literature [7] Based on the analysis of the influence of vehicle speed and road adhesion coefficient on the transient steering characteristics of the vehicle, the variable angle transmission ratio of the SBW system under different road adhesion coefficients is designed based on the steady-state yaw angular velocity gain. The simulation experiments are carried out under the conditions of double shift line test and steady-state rotation test. Considering the nonlinearity and time-delay time-varying of vehicle system, an active steering control method based on linear time-varying model predictive control (LTV-
MPC) is proposed. On the basis of considering the vehicle yaw, lateral and roll stability in three directions, the yaw angular velocity \( \omega_r \), the sideslip angle \( \beta \) and the rollover index RI are selected as the control objectives. A model predictive switching controller including four control modes is designed to greatly reduce the risk index of vehicle rollover.

4. Conclusion

With the combination of line control chassis and artificial intelligence, as an important component of line control chassis, line control steering will also consider intelligence, networking and personalization. On the premise of meeting the above objectives, ensuring the safety and stability of steer-by-wire must be the primary goal of scientific researchers. As far as current research is concerned, most literatures only improve vehicle handling stability by optimizing the stability control of steer-by-wire system and changing the control strategy of steer-by-wire variable angle transmission ratio. It is not difficult to find that most researchers only consider the control factor of vehicle parameters, and do not take into account the driver parameters and road parameters, temperature and humidity, manufacturing costs and other aspects of the stability factors, such as the driver’s driving state and driving habits and other human factors and road conditions, weather conditions. Drivers are the direct participants in the process of vehicle driving and steering. Therefore, in future research, complex unstable factors such as driver characteristics should be taken into account, and more stable and accurate control algorithms for safety and stability should be designed to enhance the human-vehicle trust bond.

Under the background of the development of vehicle line control, the fault-tolerant ability and actuator fault-tolerant ability of vehicle control system are still facing great challenges. The application of line control steering technology in mass vehicles is still unable to popularize. However, with the rapid development of automotive electronics technology and the strong support of national policies, the advantages of line control steering in active steering, variable angle transmission ratio and lateral dynamic control will be expanded, and the problems of handling stability, safety and economic cost will be solved. It will follow the trend of the times and combine with intelligent connected vehicles. So steer-by-wire technology will take a place in future vehicle development.

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