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Optimal Control Design for Decoupling the Direct Drive Stability of Distributed Drive Electric Vehicles

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Abstract: As a new type of drive for electric vehicles, distributed drive has many advantages such as simple structure and easy control, and is one of the important development directions of new energy vehicles in the future. In the past decade, the research on the active safety control of distributed drive electric vehicles has become more and more mature. In this paper, we propose a decoupled optimal control strategy based on the drive torque for the vehicle run-off and motion coupling problems that exist during the straight-line driving of distributed-drive electric vehicles. The upper control logic layer is responsible for cross-swing motion control and drive anti-skid control. The middle control logic layer is responsible for secondary planning of the additional torque from the upper control layer, based on which the decoupled cross-swing motion control with wheel anti-skid is realised. The lower control logic layer is responsible for the optimal distribution of the drive torque for speed following control. The decoupled optimal control of drive torque proposed in this paper can achieve the optimal distribution of drive torque, avoiding vehicle deflection on the premise of ensuring vehicle speed, while preventing excessive wheel slip, realising the decoupled control of vehicle linear motion and enhancing the linear driving stability of the vehicle.

1. Introduction

Electric vehicles have received more attention in recent years as energy efficiency and emission reduction have become a public concern [1-2]. Compared to vehicles driven by internal combustion engines, electric vehicles allow a higher degree of freedom in the layout of the power source (i.e. the electric motor). The power source is mounted inside the wheels as a hub motor, i.e. a distributed drive electric vehicle [3]. Due to the elimination of the conventional drive train and the fact that the drive torque of each wheel can be controlled independently, distributed drive electric vehicles offer several advantages over conventional vehicles in terms of economy, comfort and safety [4]. At present, research on the stability control of distributed drive electric vehicles, such as drive brake anti-skid control, speed control and lateral control, is based on wheel torque adjustment to achieve its corresponding vehicle response stability requirements. This makes the distributed drive electric vehicle subject to other stability constraints when the drive is adjusted to a certain stability requirement. In the process of stability control, the excessive pursuit of a performance target may lead to an imbalance in the vehicle's other response stability, reducing the vehicle's driving stability and smoothness [5]. In the process of straight-line lateral control, if the driving force of any of the inner drive wheels exceeds the road adhesion, it is easy to cause wheel slip or even tailspin. In this case, the vehicle may fail to meet the transverse stability requirements even if transverse moment control is applied, as the effect of tyre slip is not considered in the drive force distribution during the control of the distributed drive electric vehicle. During the lateral control of the steering motion, there is also a lateral pitching motion, and the driving force of the wheels will be transferred to the body via the suspension to further aggravate the lateral pitching or pitching motion, resulting in the vehicle losing stability and overturning [6]. Therefore, the distributed drive electric vehicle is a complex and strongly coupled kinematic body, and a controller can be designed to solve the kinematic coupling and improve the spatial kinematic stability of this type of vehicle.

Distributed drive electric vehicle stability control is through changing the four-wheel drive force, as a typical over-drive system, in the stability control process must take into account its motion coupling characteristics, to avoid each vehicle stability target value constraints on each other, resulting in vehicle motion control instability. For the distributed drive electric vehicle strong coupling, non-linear characteristics, design an effective decoupling control method, for improving the driving stability of this type of vehicle has very important theoretical significance and engineering application value.

2. Analysis of vehicle stability in straight driving

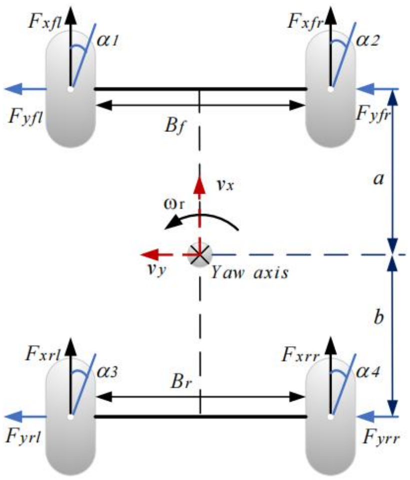

Figure 1: Mechanical analysis diagram of vehicle linear motion

As shown in Figure 1, in the process of driving a distributed drive electric vehicle in a straight line, assuming that the four-wheel drive torque distribution is uneven, when the driving force of the right driving wheel is greater than the driving force of the left driving wheel, the driving force of the left and right sides will produce a counterclockwise deflecting moment around the vehicle's center of mass axis. In order to maintain the vehicle balance, the left and right wheels are deflected sideways, the lateral force of the left and right wheels increases and a clockwise deflecting moment is generated around the vehicle's centre of mass axis. This process produces a significant transverse sway angle and wheel lateral deflection, causing the vehicle to deviate from a straight driving path. In addition, when the vehicle is driven on a smoother road surface, the driving force provided by the road surface is smaller due to the low ground adhesion coefficient, resulting in the wheel driving force being exceeded and the wheels appearing to slip and turn in an unstable region, when the lateral wheel force is applied, the wheels are very likely to slip sideways and the vehicle loses the ability to drive in a straight line and deviates from the straight line driving trajectory [7]. Therefore, the distributed drive electric vehicle straight line driving deviation cause for the left and right sides of the drive wheel drive torque distribution is not uniform, resulting in the vehicle produces obvious cross-swing angular speed and lateral speed, the vehicle do cross-swing movement, deviate from the straight line movement trajectory, especially when the wheel in the transition slip, the lateral force increase makes the wheel occur side slip, intensify the vehicle deviation degree.

According to the above linear driving stability analysis, to ensure the linear driving stability of distributed drive electric vehicles, three conditions must be met: (1) transverse pendulum stability (2) slip rate is in the safe region (3) speed follows the desired speed.

At present, most research on the linear driving stability of distributed drive electric vehicles only addresses one or two of these conditions. In contrast, the distributed drive electric vehicle, as a complex multi-coupled system, has transverse pendulum motion, wheel slip and wheel speed all regulated by the drive torque, making the distribution of drive wheel torque difficult. The control process must therefore consider the motion coupling problem and achieve an optimum distribution of the drive torque to the wheels.

Therefore, the angular velocity of the transverse pendulum at the vehicle's centre of mass and the wheel slip rate are selected as control variables to track the vehicle's desired velocity in real time and decouple the four-wheel drive torque for optimal control to suppress the vehicle's lateral motion, prevent wheel slip, avoid the vehicle deviating from its straight-line trajectory and improve the vehicle's straight-line driving stability.

3. Control system architecture design

The angular velocity of the cross-swing is one of the state response quantities that assesses the stability of the vehicle's cross-swing motion, and a small angular velocity of the cross-swing can ensure the lateral stability of the vehicle driving in a straight line. The wheel slip rate is a state response quantity describing the wheel motion of the vehicle, and maintaining a safe slip rate is the basis for ensuring the stability of wheel motion [8]. In this paper, the angular velocity of the transverse pendulum at the vehicle centre of mass and the wheel slip rate are selected as control variables to decouple the additional drive force control of vehicle transverse pendulum and wheel slip, and finally the optimal distribution of the drive force is carried out based on the following control of the desired vehicle speed. The structure of the decoupled optimal control strategy for the linear driving stability of the distributed drive electric vehicle proposed in this chapter is shown specifically in Figure 2.

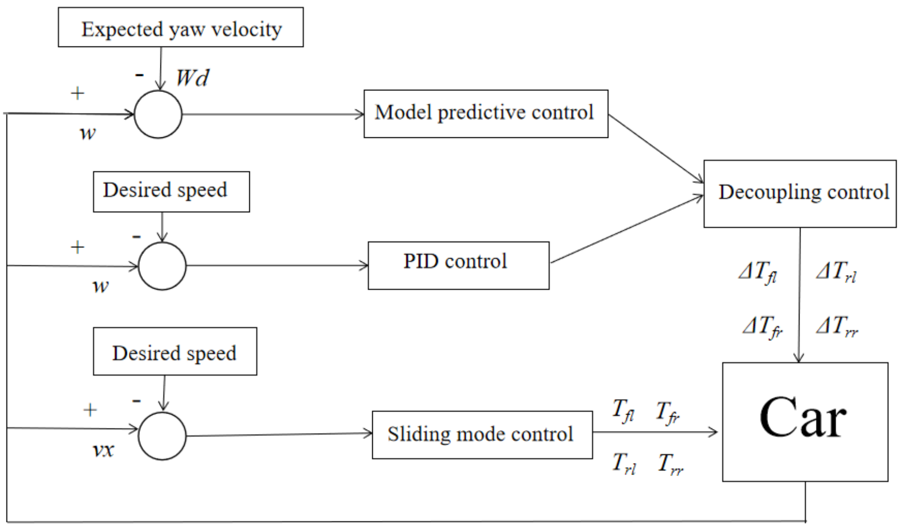

Figure 2: Control system flow chart

Firstly, a predictive traverse controller for the vehicle linear driving model is designed based on the difference between the desired traverse angular velocity ωd and the traverse angular velocity ω simulated by the joint Carsim/Simulnk model of the distributed drive electric vehicle, while a wheel slip rate PID controller based on the difference between the theoretical wheel speed and the actual wheel speed is designed, i.e. the upper level control. Secondly, the output values of the traverse controller and the output values of the slip rate controller obtained in real time from the upper control layer are decoupled for drive torque control to obtain the optimal drive torque increments ΔTfl, ΔTfr, ΔTrl and ΔTrr, which is the middle decoupling control. Finally, the vehicle speed sliding mode controller is designed to follow the desired vehicle speed, and the drive torque is planned twice based on the tyre longitudinal force utilisation rate to achieve the optimal distribution of the drive torque, completing the closed-loop control of the whole vehicle driving in a straight line, i.e. the lower level control.

4. Drive anti-skid controller design

From the above distributed drive, it can be seen that the linear driving stability analysis of electric vehicles. When the vehicle is on a flatter road surface, the resistance of the vehicle to lateral mobility is greatly reduced. If at this time the wheel appears to slip, under the action of side force, the wheel appears to slip, lose the linear driving ability. Therefore, this paper selects the wheel slip rate as the vehicle straight line driving stability control variable, and believes that when the wheel slip rate exceeds the optimal slip rate of the current road surface, the wheel will over-slip, which will most likely lead to wheel sideslip, and the vehicle will lose the straight line driving ability, then the drive wheel drive torque needs to be controlled to change the wheel speed, to ensure that the wheel slip rate is always in the safe range. The wheel slip rate formula is shown in Equation 1.

$$S_{ij} = \frac{w_{ij}r - v}{w_{ij}r} \tag{1}$$

The wheel slip rate is regulated by the wheel speed and is related to the angular speed of the wheel. The optimal wheel slip rate, S_{opt}, has a corresponding ideal angular speed of the wheel, w_{ref}.

$$w_{ref} = \frac{v}{r(1 - S_{pot})} \tag{2}$$

During the straight-line driving of a distributed drive electric vehicle, when the slip rate of a drive wheel exceeds the optimal slip rate of the road, i.e. the drive wheel speed is greater than the ideal speed, this drive wheel is in an excessive slip state, at this time PI control of the wheel speed is carried out based on the ideal wheel angular speed, and the additional drive torque ΔTsij for regulating the slip rate of the drive wheel is obtained.

$$\begin{cases} e_{ij} = w_{ref} - w_{ij} \\ \Delta T_{sij} = k_p e_{ij} + k_i \int e_{ij} d(t) \end{cases} \tag{3}$$

When the slip rate of the drive wheel does not exceed the optimal value of the current road slip rate, i.e. the actual speed of the drive wheel does not exceed the optimal value of the drive wheel speed, the drive wheel is in the stability zone and the additional drive torque $\Delta T_{sij} = 0$ for regulating the slip rate of the drive wheel.

5. Mid-level decoupling control

Both the vehicle traverse controller and the wheel slip rate control are based on the adjustment of the driving force and torque of the wheels, both of which affect the vehicle's straight-line driving stability. If the additional driving torque is not managed, it will cause motion coupling, resulting in the traverse angular speed and wheel slip rate not reaching the ideal state. Therefore, the drive torque from the traversing controller and wheel slip controller needs to be decoupled and the decoupling control method is as follows.

$$v = Bu \tag{4}$$

Where, $v = [\Delta M_Z, \Delta T]^T$, $u = [\Delta F_{xfl}, \Delta F_{xfr}, \Delta F_{xrl}, \Delta F_{xrr}]^T$, $B = \begin{pmatrix} -\frac{k_f B_f}{2}, \frac{k_f B_f}{2}, -\frac{k_r B_r}{2}, \frac{k_r B_r}{2} \\ r, r, r, r \end{pmatrix}$.

In practice, when assigning wheel drive torque, the threshold value of the torque available from the drive wheel hub motor, i.e. the torque constraint, needs to be taken into account.

$$T_{dmax}/r \le u_i \le T_{lmax}/r \tag{5}$$

Where Tdmax is the maximum braking torque that can be provided by the drive wheel hub motor and Tlmax is the maximum drive torque that can be provided by the drive wheel hub motor, i=1, 2,3, 4.

In the case of the torque constraint, the distribution of the driving torque becomes more complex and Equation 4 is difficult to solve. To ensure that the problem can be solved, Equation 4 is combined as

$$\Omega = \min_{u_{min} \le u \le u_{max}} \|w(Bu - v)\|_2^2 \tag{6}$$

Where Ω is the domain of feasible solutions and W is the weight of the control quantity, let $W = diag(w_1, w_2), w_1, w_2$ be the weight of the control vehicle traverse angular velocity and wheel slip rate. The quadratic programming function of Matlab/Simulink is used to solve for the additional drive forces ΔFxfl, ΔFxfr, ΔFxrl, ΔFxrr for each drive wheel and the additional drive moments ΔTfl, ΔTfr, ΔTrl, ΔTrr for each drive wheel to obtain Equation 7.

$$\begin{cases} \Delta T_{fl} = \Delta F_{xfl} r \\ \Delta T_{fr} = \Delta F_{xfr} r \\ \Delta T_{rl} = \Delta F_{xrl} r \\ \Delta T_{rr} = \Delta F_{xrr} r \end{cases} \tag{7}$$

The optimum decoupled additional torque is thus obtained and distributed to the individual drive wheels to complete the mid-level decoupling control.

6. Conclusion

This paper analyses the linear driving stability of distributed drive electric vehicles and proposes a decoupled optimal control strategy based on the driving torque according to the factors affecting linear driving stability. The strategy uses a hierarchical control, where the upper control layer is a model predictive control of the vehicle transverse angular velocity and wheel slip rate PID control, the middle control layer decouples the additional drive torque from the upper control layer, and the lower control layer is responsible for achieving the optimal torque distribution for the desired vehicle speed following, which can realise the decoupled control of vehicle linear motion and enhance the linear driving stability of the vehicle.

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