

Differential Drive Assisted Steering Control for an In-wheel Motor Electric Vehicle

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ABSTRACT

For an electric vehicle driven by four in-wheel motors, the torque of each wheel can be controlled precisely and independently. A closed-loop control method of differential drive assisted steering (DDAS) has been proposed to improve vehicle steering properties based on those advantages. With consideration of acceleration requirement, a three dimensional characteristic curve that indicates the relation between torque and angle of the steering wheel at different vehicle speeds was designed as a basis of the control system. In order to deal with the saturation of motor's output torque under certain conditions, an anti-windup PI control algorithm was designed. Simulations and vehicle tests, including pivot steering test, lemniscate test and central steering test were carried out to verify the performance of the DDAS in steering portability and road feeling. Results showed that with the proposed DDAS, the reference steering wheel torque can be tracked satisfactorily, drivers' handling burdens were reduced efficiently and the vehicle steering performance was improved.

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INTRODUCTION

The vehicle steering system has gone through manual steering, hydraulic steering, electronic-hydraulic steering, electric power steering (EPS) and the latest steering-by-wire system (SBS) [1]. However, in order to realize EPS or SBS, one or more extra motors are required, which makes the steering system structure more complicated and expensive.

The distributed drive electric vehicle (DDEV), which is driven by four in-wheel motors, has advantages not only in environmental protection but also in dynamics control: Driving or braking torque on each wheel can be controlled independently, more quickly and more precisely. With those properties, unequal driving torque on each front wheel can be generated. As the existence of the kingpin lateral offset, the unequal moments to the kingpins will be produced. So there will be a surplus torque, which is called the differential assisted torque, can help the driver to steer without requirements for extra motors or mechanical structures [2,3].

In this paper, a closed-loop control method of differential drive assist steering (DDAS) was developed for a distributed drive electric vehicle to improve the vehicle steering properties. Simulations and experiments were conducted to verify the validity of the control strategy.

PRINCIPLE AND FEASIBILITY ANALYSIS

Principle of DDAS

For a distributed drive electric vehicle, the longitudinal force of each wheel can be controlled according to control requirements within a motor's capacity. Because of the existence of the kingpin lateral offset, the two unequal longitudinal forces produce unequal steering moments to each kingpin separately if the longitudinal forces on the left and right front wheels are different. The superposition of the unequal moments is a surplus steering moment which can be transmitted to the steering wheel at last and help the driver to make an anticipated steering angle (Figure 1).

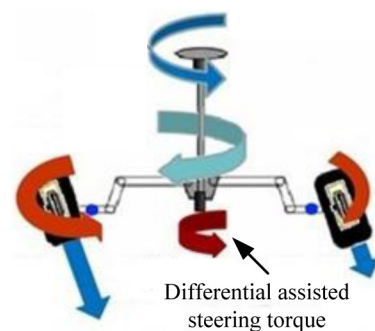


Figure 1. Schematic diagram of DDAS.

Feasibility Analysis of Structure

The effectiveness of the differential assisted steering is closely related to the layout form of the electrical motor in a distributed drive electric vehicle. In general, there are two kinds of layout forms: In-wheel motor layout (Figure 2) and wheel-side motor layout (Figure 3).

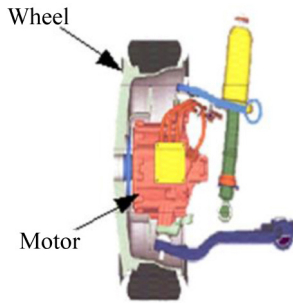


Figure 2. Layout form of an in-wheel motor EV.

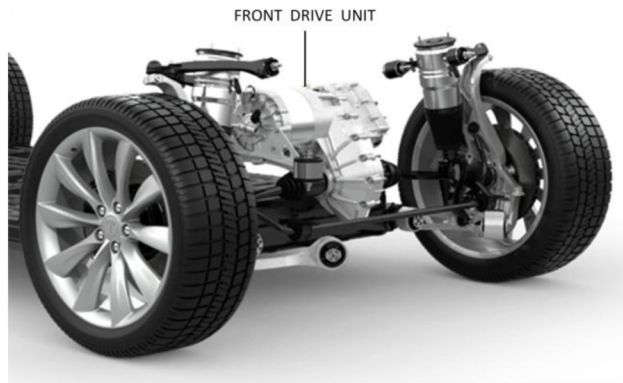


Figure 3. Layout form of a wheel-side motor EV (TESLA MODEL X).

In order to analyze the feasibility of the differential assisted steering with the in-wheel motor drive form, the force analysis of the steering wheel and the steering knuckle is necessary (Figure 4). Regard the front wheel, in-wheel motor and steering knuckle as a part-system in the whole system consisting of the front wheel the steering system and the road. The driving torque generated by the in-wheel motor is T . Since the stator is linked to the steering knuckle and the rotor is linked to the rim, the driving torque is an internal force of the part-system and can be ignored in the force analysis of the whole system. The external force applied to the system is the longitudinal force F_x acting on point A. Acting forces between knuckle and the lower and upper swing arm of suspension are F'_{x1} and F'_{x2} respectively and the force locations are their junction points C and D. Since the application points of F'_{x1} and F'_{x2} are on the kingpin axes, there is no other torques besides T_{st} which is generated by the longitudinal force between tire and ground. Hence, it is structurally feasible to realize the differential assisted steering on in-wheel motor drive electric vehicles. T_{st} can be described as Equation (1).

$$T_{st} = F_x \cdot r_\sigma \cdot \cos \alpha = T \cdot \frac{r_\sigma}{r_w} \cdot \cos \alpha \quad (1)$$

where, r_σ is the kingpin offset, α is the kingpin inclination angle and r_w is the wheel rolling radius

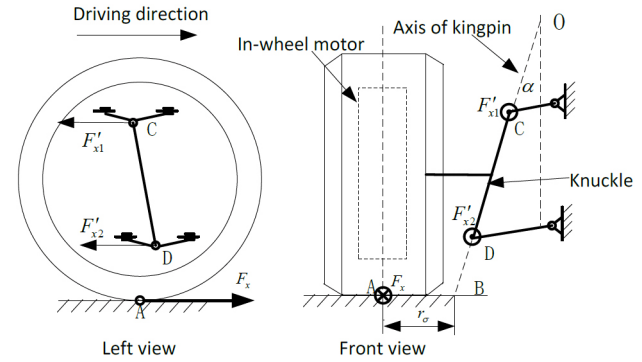


Figure 4. Force analysis of in-wheel motor drive vehicles.

As to a wheel-side motor drive vehicle, the most different point from an in-wheel motor drive vehicle is that the wheel-side motor is fixed on the vehicle chassis. The output torque of the motor, T is an external torque as to the system formed with the front wheel and the steering knuckle. The force analysis of wheel-side motor drive vehicles is shown in Figure 5.

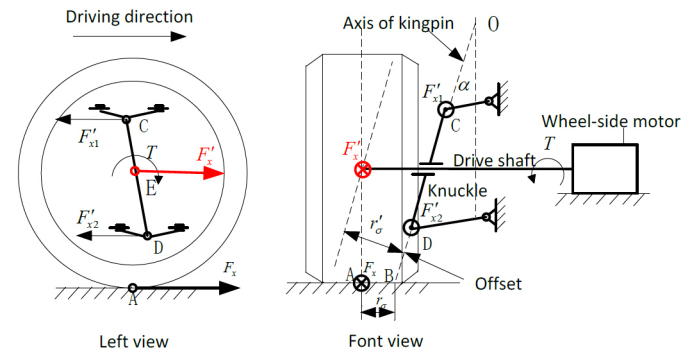


Figure 5. Force analysis of wheel-side motor drive vehicles.

Regard the front wheel and the steering knuckle as a whole system. The output torque of the wheel-side motor is T , which is an external torque for the system; in addition, the longitudinal force F_x is also an external force and acts on point A; F'_{x1} and F'_{x2} , acting forces between knuckle and the lower and upper swing arm of suspension, are also external forces and the force locations are points C and D respectively, the junction points between the knuckle and the lower and upper swing arm of suspension. Since the points C and D are on the kingpin axis, there is no torque acting on the kingpin. The longitudinal force F_x and the motor output torque T are equivalent to the acting force F'_x whose force location is point E, the center of the wheel. So that the arm of the acting torque to the kingpin is not the kingpin offset r_σ but the distance from the wheel center to the kingpin axis r'_σ . And the actual torque to kingpin is T'_{st} . It indicates that it is also structurally feasible to realize the differential assisted steering on wheel-side drive electric vehicles. T'_{st} can be described as Equation(2).

$$T'_{st} = F'_x \cdot r'_\sigma = T \cdot \frac{r'_\sigma}{r_w}$$

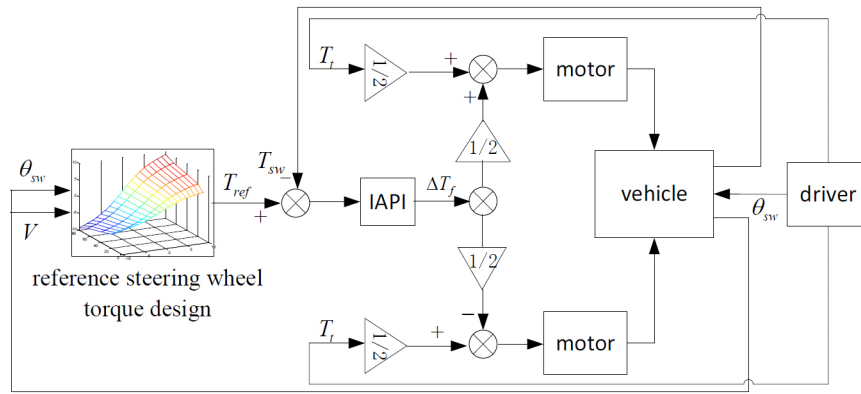


Figure 6. Control strategy frame.

In this paper, the DDEV is driven by four in-wheel motors.

CONTROL STRATEGY

A closed-loop control strategy of the DDAS is developed on the basis of research on optimal driver handling torque to steering wheel. And the steering wheel torque is the control object as it is easy to measure. The control system consists of a reference steering wheel torque (T_{ref}) design module, and an integral anti-windup variable PI (I-API) control module. The whole control frame is shown in Figure 6. To make the process of designing DDAS brief, we assume the tire-road friction coefficient is 1.0 and constant. The differential assisted torque ΔT_f is allocated to the left and right front in-wheel motors evenly; and the traction torque T_t required by the driver is distributed to four in-wheel motors evenly. In this paper, DDAS does not work in brake and reverse situations. The desired differential assisted steering torque can be obtained according to the difference value between the reference and actual steering wheel torque measured by a sensor.

Reference Steering Wheel Torque

Characteristic Analysis of the Steering Wheel Torque

Before confirming the reference steering wheel torque, the analysis of the steering wheel torque characteristic of the test vehicle is indispensable. In this paper, steering wheel angle ramp input maneuvers at a constant vehicle speed were conducted to analysis the relation among steering wheel torque, lateral acceleration and vehicle speed. The maneuvers were set as follows: Speeded up the vehicle to a certain speed (10km/h, 20km/h, ...) from static state with linear acceleration and kept the speed constant. Then made the lateral acceleration reach about 0.8g by steering gradually and recorded angles and torques of the steering wheel. The simulation results are shown in Figure 7.

As shown in Figure 7, at a constant vehicle speed, the change rule of the steering wheel torque along with the lateral acceleration is similar. When the lateral acceleration increases, the steering wheel torque rises firstly, and then decreases. With the increase of vehicle speed, the peak value of the steering wheel torque $T_{max}(V)$ becomes smaller.

In the process of designing the closed-loop steering wheel torque control algorithm, the steering wheel torque characteristic must be taken into consideration.

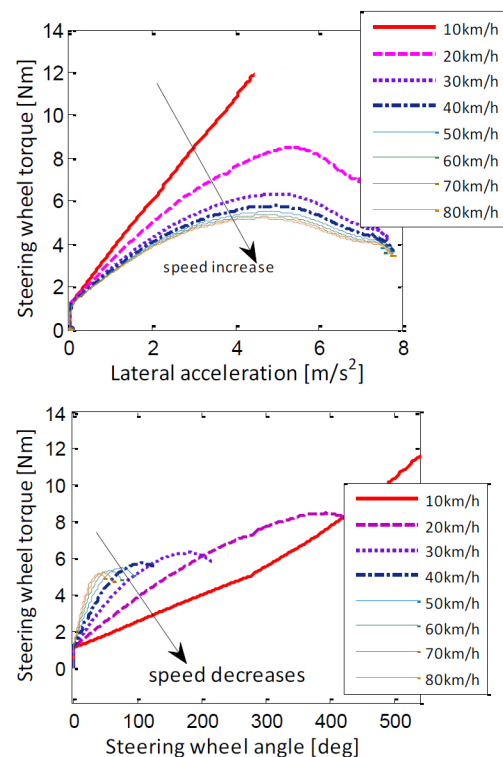


Figure 7. Relation among steering wheel torque, steering wheel angle and lateral acceleration at different vehicle speeds.

Design of the reference steering wheel torque

In this paper, the reference steering wheel torque is designed according to the steering wheel angle and vehicle speed. When vehicle speed and road adhesion condition are constant, the steering wheel torque is approximately proportional to the steering wheel angle. The relation between the reference steering wheel torque and vehicle speed is designed as Figure 8 by Wu [4].