Mechanical Systems and Signal Processing 101 (2018) 389–404

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Decoupling control of steering and driving system for in-wheel-motor-drive electric vehicle

Han Zhang, Wanzhong Zhao *

College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, No. 29, Yudao Street, Nanjing 210016, China

A R T I C L E   I N F O

Article history:
Received 29 April 2017
Received in revised form 21 August 2017
Accepted 24 August 2017

Keywords:
Electric vehicle
Decoupling control
Nonlinear control
μ-Synthesis

A B S T R A C T

To improve the maneuverability and stability of in-wheel-motor-drive electric vehicle, a control strategy based on nonlinear decoupling control method is proposed in this paper, realizing the coordinated control of the steering and driving system. At first, the nonlinear models of the in-wheel-motor-drive electric vehicle and its sub-system are constructed. Then the inverse system decoupling theory is applied to decompose the nonlinear system into several independent subsystems, which makes it possible to realize the coordinated control of each subsystem. Next, the μ-Synthesis theory is applied to eliminate the influence of model uncertainty, improving the stability, robustness and tracking performance of in-wheel-motor-drive electric vehicle. Simulation and experiment results and numerical analyses, based on the electric vehicle actuated by in-wheel-motors, prove that the proposed control method is effective to accomplish the decoupling control of the steering and driving system in both simulation and real practice.

1. Introduction

The electric vehicles have been promoted to solve the energy and environmental problems caused by the traditional vehicle, and great progress in the electric vehicle has been made because the electric power has variety of advantages, such as low-cost, renewable, zero discharge, and wide source et al. [1–5]. Comparing with the traditional electric vehicles, the in-wheel-motor-drive electric vehicle studied in this paper has more merits [6–8]. Firstly, the application of wheel hub motor in electric vehicle can improve the efficiency of motor-drive. Secondly, the transmission mode determines that the gearbox, clutch, transmission shaft and other transmission devices can be eliminated, saving the energy consuming on the transmission mechanism and reducing the costs of raw materials and processing required for the production process. At last, the chassis is easy to integrate and control to achieve better comprehensive performance.

Besides the advantages discussed above, the in-wheel-motor-drive electric vehicle is more able to show the advantages of the current motor drive technology by applying the chassis control strategies and optimization measures, because the in-wheel motor can be controlled through the ECU independently by X-by-wire technology, more easily obtaining a flexible response to various types of traffic and making the car run in the best condition [9–11]. Several prior researches have been done by using advanced control strategies to improve the stability and the maneuverability of the in-wheel-motor-drive electric vehicle. Based on the direct yaw-moment control, control method for four-wheel-drive electric vehicle is proposed in paper [12], giving the optimized wheel force distribution as well as the coordination control of the hydraulic braking and

* Corresponding author.
E-mail address: zhaowanzhong@126.com (W. Zhao).

http://dx.doi.org/10.1016/j.ymssp.2017.08.042
0888-3270/

the motor torque, which improves the stability of the four-wheel-drive electric vehicle effectively. In order to manipulate the vehicle driving speed and orientation, the adaptive functional approximation control scheme is first employed by Shinh-Jer Huang [13] to design the speed controller of each wheel for integrating with the Ackermann–Jeantand model-based electronic differential and the experimental results show that the induced electronic differential model successfully assisted the vehicle turning control and trajectory following control operations. The author of [14] presents a layered vehicle dynamics control system, which is composed of an adaptive optimal control allocation method using neural networks for optimal distribution of tire forces and the sliding mode yaw moment observer for robust control of yaw dynamics to solve the stability control problem. The driving-mode switching problem is also studied by Xin in paper [15,16], where a control strategy with a switched drive mode is proposed based on two vehicle velocity estimation algorithms and a vehicle velocity smoothing algorithm is proposed to eliminate the adverse effect in the conversion between the two modes.

All the studies above have achieved great accomplishments in the field of stability control of the in-wheel-motor-drive electric vehicle. But there still some problems remain to be solved. The first one is that four wheel torque differences will produce additional yaw moment, which will generate an adverse effect on the stability for the reason that it will affect the drivers' steering attention. Velocity changing is a common condition while steering, and it makes the whole vehicle a nonlinear coupling system, which means there will be certain limitations to the traditional linear control algorithms. Furthermore, the uncertainty of some vehicle parameters will also influence the performance of the control strategy.

Based on the previous studies, the inverse system decoupling control method [17,18] is proposed in this paper to solve the nonlinear coupling problem of the steering and driving system. The inverse system is connected in series before the original system to form a pseudo linear composite system, realizing the linearization and decoupling of the steering and driving system. Taking into account the presence of model uncertainty, external disturbances and sensors' noise in the in-wheel-motor-drive electric vehicle, the control strategy should ensure strong robustness. The feedback controller designed by μ-Synthesis [19–21] is presented to ensure robustness, tracking performance and disturbance attenuation.

The paper is organized as follows. The structure of four-wheel-drive electric vehicle is introduced and the models of which are built in Section 2. In Section 3, the nonlinear control method by inverse system decoupling is developed. The feedback controller designed by μ-Synthesis is presented in Section 4. The simulations are implemented and experiments are conducted in Section 5. Finally, the paper is concluded in Section 6.

2. Modeling for the in-wheel-motor-drive electric vehicle

Taking into account the complexity of vehicle dynamic behavior in reality, priority of the vehicle stability research, controller development feasibility, and the necessity of control effect verification, models of the in-wheel-motor-drive electric vehicle are built as follows.

Fig. 1 shows the 3-degree-of-freedom vehicle model. In the figure, a is the distance from centroid to front axle; b is the distance from centroid to rear axle; β is the side-slip angle of the vehicle; γ is the yaw rate of the vehicle; v_x is the longitude velocity of the vehicle; δ is the front wheel steering angle; α_f, α_r tire slip angle of front tire and rear tire, respectively; X represents the longitudinal direction; Y represents the lateral direction.

To analyze the dynamic characteristics of the system, vehicle dynamics model with three degrees of freedom is built as

$$\begin{cases} \dot{\beta} = \frac{k_f+k_r}{mv_x}\beta + \left(\frac{ak_f-bk_r}{mv_x^2} - 1\right)\gamma - \frac{k_f}{mv_x}\delta + d_{r1} \\ \dot{\gamma} = \frac{ak_f-bk_r}{I_z}\beta + \frac{a^2k_f+b^2k_r}{I_z v_x}\gamma - \frac{ak_f}{I_z}\delta + \frac{M_z}{I_z} + d_{r2} \\ \dot{v}_x = \beta\gamma v_x - \frac{k_f}{m}(\beta + \frac{a}{v_x}\gamma)\delta + \frac{1}{m}\sum F_x + d_{r3} \end{cases} \tag{1}$$

$$a_y = \frac{ak_f - bk_r}{mv_x}\gamma + \frac{k_f + k_r}{m}\beta - \frac{k_f}{m}\delta \tag{2}$$

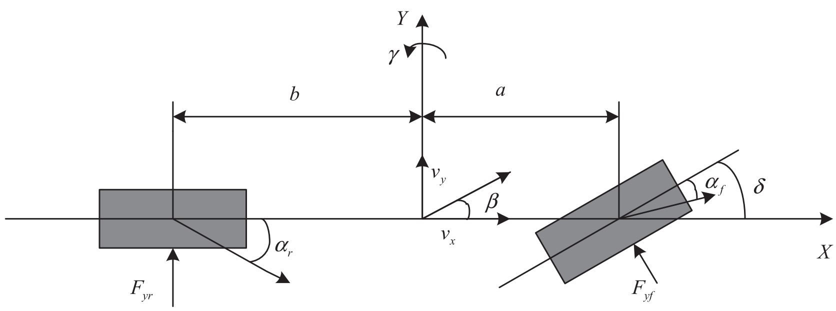

Fig. 1. The 3-degree-of-freedom vehicle model.