Mechanical Systems and Signal Processing 101 (2018) 377–388

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Estimation of longitudinal force, lateral vehicle speed and yaw rate for four-wheel independent driven electric vehicles

Te Chen [a], Xing Xu [a,b,*], Long Chen [a,b], Haobing Jiang [a], Yingfeng Cai [a,b], Yong Li [a,b]

[a] School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang 212013, China
[b] Automotive Engineering Research Institute, Jiangsu University, Zhenjiang 212013, China

ARTICLE INFO

Article history:
Received 14 March 2017
Received in revised form 27 June 2017
Accepted 24 August 2017

Keywords:
Longitudinal force
Lateral vehicle speed
Yaw rate
High-order Sliding Mode Observer (HSMO)
Electric vehicle

ABSTRACT

Accurate estimation of longitudinal force, lateral vehicle speed and yaw rate is of great significance to torque allocation and stability control for four-wheel independent driven electric vehicle (4WID-EVs). A fusion method is proposed to estimate the longitudinal force, lateral vehicle speed and yaw rate for 4WID-EVs. The electric driving wheel model (EDWM) is introduced into the longitudinal force estimation, the longitudinal force observer (LFO) is designed firstly based on the adaptive high-order sliding mode observer (HSMO), and the convergence of LFO is analyzed and proved. Based on the estimated longitudinal force, an estimation strategy is then presented in which the strong tracking filter (STF) is used to estimate lateral vehicle speed and yaw rate simultaneously. Finally, co-simulation via Carsim and Matlab/Simulink is carried out to demonstrate the effectiveness of the proposed method. The performance of LFO in practice is verified by the experiment on chassis dynamometer bench.

1. Introduction

To avoid accidents and increase vehicle safety, many active safety systems, such as anti-lock braking system and electronic stabilizing program, have been widely used in automotive industry [1–3]. Especially, own to the controllability of accurate and independent torque, four-wheel independent driven electric vehicles (4WID-EVs) have been testified effective in enhancing the performance of torque flexibility [4] and vehicle stability [5,6]. The advantages of 4WID-EVs propose novel train of thought for vehicle active safety [7], stability control [8,9] and energy-saving torque allocation [10]. These control systems or strategies require real-time and accurate vehicle state information, such as longitudinal force [11], lateral vehicle speed and yaw rate, as crucial part of the control logic. Hence, the security and performance of these systems directly depend on the accurate acquisition of vehicle state. Considering the cost and difficulty of vehicle states measurement, the design of model-based vehicle states observer is essential to achieve the estimations by low-cost sensors.

Several studies have been conducted concerning the estimation of longitudinal force, lateral vehicle speed and yaw rate. In general, these estimation approaches used in existing literatures can be categorized as Kalman-filter-based method [12–16], nonlinear-observer-based method [17–21], optimal estimation method [22–26], and fusion estimation method [14,16,27–30]. Boada proposed a novel observer based on Kalman filters to estimate the sideslip angle [14]. Baffet presented an adaptive tire-force model that takes variations of road friction into account, and studied the convergence of the

* Corresponding author at: School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang 212013, China.
E-mail address: xuxing@mail.ujs.edu.cn (X. Xu).

http://dx.doi.org/10.1016/j.ymssp.2017.08.041
0888-3270/

sliding-mode observer which was used to estimate the tire-road forces [18]. Damrongrit developed a real-time method to estimate the slip angle for vehicle stability control by utilizing the algorithm combination of model-based estimation and kinematics-based estimation [24]. Li proposed a hybrid estimation strategy in which the adaptive weight fusion algorithm is adopted to estimate the vehicle sideslip angle [30].

However, most prior approaches of vehicle state estimation are designed for traditional internal combustion engine vehicle. There are few results on the state estimation for electric vehicles, especially for 4WID-EVs. In 4WID-EVs, the electric driving wheel composed of in-wheel motor and tire is not only an actuator of vehicle's control system, but also a relatively independent control unit and information unit. Thus, by utilizing the dynamic characteristics of electric driving wheels low-cost and easy-to-get sensors, such as the current, speed and bus voltage of in-wheel motor, can be used to estimate the vehicle state. And the advantage of 4WID-EVs in observer design can be further explored. Seldom works have taken this concept into account. Hori calculated the longitudinal forces by integrating the rotational dynamics differential equation of driving wheel, but the noise is integrated at the same time [31]. Wang obtained the torque of in-wheel motor via multiplying the in-wheel motor current by the gain that was calibrated with experimental data [32].

In this paper, a novel fusion method to estimate the longitudinal force, lateral vehicle speed and yaw rate for 4WID-EVs is proposed. The electric driving wheel model is introduced into the longitudinal force estimation and the nonlinear coordinate transformation of EDWM is implemented based on analysis of exact linearization conditions. The transformed system of EDWM is extended to estimate the unknown input, and the longitudinal force observer (LFO) is proposed based on the design of adaptive high-order sliding mode observer (HSMO), which presents a novel thinking of the longitudinal force estimation for 4WID-EVs. The stability of the coordinate transformation system and adaptive HSMO are proved. Combining the LFO with the strong tracking filtering (STF) algorithm, a vehicle state estimation method is proposed to estimate lateral vehicle speed and yaw rate in which the pre-estimated longitudinal forces are used.

The rest of this paper is organized as follows. The vehicle dynamic model is presented is Section 2. The LFO is designed in Section 3. The STF-based estimation of lateral vehicle speed and yaw rate is described in Section 4. The simulation results are provided in Section 5, followed by the conclusive remarks.

2. Vehicle dynamic model

2.1. 3-DOF vehicle model

A schematic diagram of the 3-DOF vehicle model in the longitudinal, lateral, and yaw directions is shown in Fig. 1. An origin of dynamic coordinate system *xoy* fixed on the vehicle coincides with the vehicle gravity center, the *x* axis is the longitudinal axis of the vehicle (the forward direction is positive), the *y* axis is the lateral axis of the vehicle (the right-to-left direction is positive). The pitch, roll, vertical motions and the suspension system of the vehicle are ignored. It is assumed that the mechanical properties of each tire are the same. The serial numbers 1, 2, 3, and 4 of the wheels are respectively corresponding to the front left, the right front, the rear left and the right rear wheel. The dynamic equations of the 3-DOF vehicle model can be expressed as

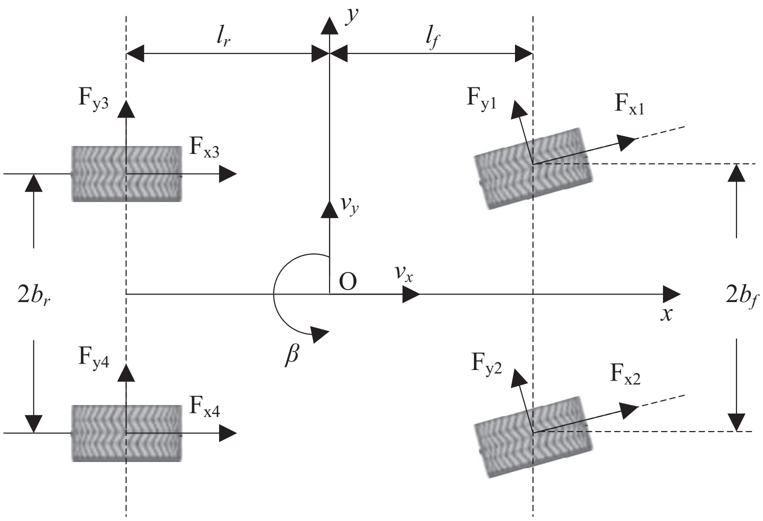

Fig. 1. 3-DOF vehicle model.