

Actuator Fault Detection and Diagnosis of 4WID/4WIS Electric Vehicles

Chao Liu, Changfu Zong, Lei He, and Chunshan Li
State Key Lab of ASC, Jilin University

Minghui Liu
China FAW Group Corporation R&D Center

ABSTRACT

A fault detection and diagnosis (FDD) algorithm of 4WID/4WIS Electric Vehicles has been proposed in this study aiming to find the actuator faults. The 4WID/4WIS EV is one of the promising architectures for electric vehicle designs which is driven independently by four in-wheel motors and steered independently by four steering motors. The 4WID/4WIS EVs have many potential abilities in advanced vehicle control technologies, but diagnosis and accommodation of the actuator faults becomes a significant issue.

The proposed FDD approach is an important part of the active fault tolerant control (AFTC) algorithm. The main objective of the FDD approach is to monitor vehicle states, find the faulty driving motor and then feedback fault information to the controller which would adopt appropriate control laws to accommodate the post-fault vehicle control system.

The unique character of the proposed FDD approach is that it is a system-level method, namely it tries to locate the faulty motor and motor driver systems, while it does not need to identify which part of the motor and motor driver systems has a failure. The information about which motor and motor driver system is faulty is total enough for the fault tolerant control mechanism which is also on the system level.

The theoretical basis of the FDD method is the vehicle dynamics which demonstrate the relationship between the forces acted on the vehicle and the vehicle motions. The Analytical Redundancy Relations (ARR) method is applied to set up the residual generation equation. If a component fails in the motor and motor driver system, it causes the inconsistency in the vehicle dynamics relationship whose appearance is that the generated residuals are much larger than the thresholds. Based on this method, we can identify whether the motor and motor driver system is faulty or not. In order to obtain the residual generation equation, the magic formula tire model is adopted.

Several simulations have been conducted to verify the proposed FDD approach. The results have shown that once the driving motor fails, the FDD approach identifies the fault and transfer this information to the FTC controller.

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INTRODUCTION

Electric vehicles (EVs) have attracted many attentions of researchers and engineers duo to their potentials in energy saving and emission reduction. Four-wheel independently driven and steered (4WID/4WIS) electric vehicles are a new type of EVs. 4WID/4WIS electric vehicles have more controllable actuators than conventional EVs so 4WID/4WIS EVs could have improved handling and stability when advanced vehicle control technologies are employed.

However the fault detection and diagnosis of 4WID/4WIS EVs is of great importance which monitors vehicle states and provides fault information to fault tolerant controller.

Fault detection and diagnosis of EVs has aroused interest of many researchers. Dumont [1] employed analytical redundancy relations method to diagnose the actuator faults. Wang [2] proposed a diagnosis approach which does not need precise tire-road friction coefficient (TRFC) to diagnose the in-wheel motor faults. Chang [3] presented a fault detection filter to find the fault occurring in a two motor-driven EV.

Meskin [4] investigated fault detection and isolation (FDI) filters for over-actuated systems focusing residual relationships among multi-faults. However, there are not many researches in actuator fault detection and diagnosis of 4WID/4WIS EVs.

In this study we put forward a fault detection and diagnosis approach based on analytical redundancy relations (ARR). The proposed FDD approach is a system-level technique which is used to monitor the whole system not only some components. ARR is employed to generate residuals which represent the healthy conditions of actuators. From residuals to fault reasons, we set up a set of decision rules to identify which system has broken down.

This paper is organized as follows: the diagnosis-oriented vehicle model is introduced in section 2. Actuator fault diagnosis based on ARR is described in section 3. Simulation studies are presented in section 4 followed by conclusions in section 5.

DIAGNOSIS-ORIENTED VEHICLE MODEL

Vehicle Planar Motion Model

The 4WID/4WIS EV is driven by each driving motor and steered by each steering motor in every wheel corner. The motion control of the 4WID/4WIS EV mainly focuses on the vehicle planar motion, namely longitudinal, lateral and yaw movement, neglecting vehicle vertical, pitch or roll motion. The vehicle planar motion model can be formulated as follows [5]:

$$\begin{cases} m(\dot{V}_x - V_y r) = \sum F_x \\ m(\dot{V}_y + V_x r) = \sum F_y \\ I_z \dot{r} = \sum M_z \end{cases} \quad (1)$$

where m is the vehicle mass. V_x , V_y , r are respectively the longitudinal velocity, lateral velocity, and yaw rate of vehicle mass center. I_z is the vehicle inertia around z-axis of vehicle coordinate system. $\sum F_x$, $\sum F_y$, $\sum M_z$ are respectively the generalized force along the x-axis, y-axis and generalized moment around z-axis of vehicle coordinate system and they can be expressed by:

$$F_{xfl} + F_{xfr} + F_{xrl} + F_{xrr} = \sum F_x \quad (2)$$

$$F_{yfl} + F_{yfr} + F_{yrl} + F_{yrr} = \sum F_y \quad (3)$$

$$\frac{1}{2}(F_{xfl} - F_{xfr} + F_{xrl} - F_{xrr}) + a(F_{yfl} + F_{yfr}) - b(F_{yrl} + F_{yrr}) = \sum M_z \quad (4)$$

where fl , fr , rl , rr denote the front left wheel, the front right wheel, the rear left wheel and the rear right wheel of the vehicle independently; F_x , F_y , represent the longitudinal and lateral tire force

Driving System Model

Each driving motor supplies traction torque so that the vehicle can move forward. The relationship between the electric traction torque, resistance torques and the wheel rotation movement can be defined by the following wheel rotational dynamics:

$$\begin{cases} T_{de} - (T_{dL} + T_{dfl} + T_{dfe}) = J_d \cdot \dot{\omega} \\ T_{de} = K_{dm} \cdot i_d \\ T_{dL} = F_x \cdot r \\ T_{dfl} = F_f \cdot r \\ T_{dfe} = \mu_d \cdot \omega \end{cases} \quad (5)$$

where T_{de} is the output traction torque of a driving motor, K_{dm} is the torque coefficient of a driving motor, i_d is the driving motor current. T_{dL} is the load torque which generates the longitudinal force F_x , r is the wheel effective rotational radius. T_{dfl} is the tire rolling resistance moment, F_f is the equivalent tire rolling resistance. T_{dfe} is the friction torque in a driving motor, μ_d is the friction coefficient of a driving motor, ω is the wheel rotational speed which is also the rotational speed of the in-wheel motor rotor, J_d is the rotational inertia.

Tire Model

There are two tire forces in Formula (5): the tire rolling resistance F_f and the longitudinal tire force F_x . F_f can be calculated in the empirical formula as follows [6]:

$$F_f = F_z \cdot (\eta_0 + \eta_1 \cdot V_x^2) \quad (6)$$

where F_z is the vertical tire force, η_0 and η_1 are the coefficients, V_x is the longitudinal velocity.

Based on the Magic Formula [7], the longitudinal tire force F_x can be solved.

$$F_x = \left(D \sin \left(C \arctan \left(Bx - E \left(Bx - \arctan(Bx) \right) \right) \right) \right) + S_v \\ x = \kappa + S_h \quad (7)$$

where κ is tire slip. Coefficient D is the peak factor, C is the shape factor, B is the stiffness factor, and E is the curvature factor. S_h and S_v represent the horizontal shift and vertical shift.

ACTUATOR FAULT DIAGNOSIS BASED ON ARR

The objective of the fault detection and diagnosis (FDD) is to find the faulty actuator by comparing the actual system behavior and the estimated system behavior which is calculated based on a nominal system model. The general