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Reliable fuzzy H_∞ control for active suspension of in-wheel motor driven electric vehicles with dynamic damping

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ABSTRACT

A fault-tolerant fuzzy H_∞ control design approach for active suspension of in-wheel motor driven electric vehicles in the presence of sprung mass variation, actuator faults and control input constraints is proposed. The controller is designed based on the quarter-car active suspension model with a dynamic-damping-in-wheel-motor-driven-system, in which the suspended motor is operated as a dynamic absorber. The Takagi-Sugeno (T-S) fuzzy model is used to model this suspension with possible sprung mass variation. The parallel-distributed compensation (PDC) scheme is deployed to derive a fault-tolerant fuzzy controller for the T-S fuzzy suspension model. In order to reduce the motor wear caused by the dynamic force transmitted to the in-wheel motor, the dynamic force is taken as an additional controlled output besides the traditional optimization objectives such as sprung mass acceleration, suspension deflection and actuator saturation. The H_∞ performance of the proposed controller is derived as linear matrix inequalities (LMIs) comprising three equality constraints which are solved efficiently by means of MATLAB LMI Toolbox. The proposed controller is applied to an electric vehicle suspension and its effectiveness is demonstrated through computer simulation.

1. Introduction

Electric vehicles (EVs) provide advantages over the Internal Combustion Engine (ICE) vehicles in terms of energy efficiency and environmental friendliness and are regarded as one of the solutions to decreasing the global CO_2 emission. Propulsion configurations of electric vehicles can be classified as centralized motor driven layout or in-wheel motor driven layout depending on the vehicle's architecture. The configuration, in which the motors are installed in the wheels (referred to as In-Wheel Motors (IWM)), has attracted an increasing research interest in recent years because of the benefits of IWMs [1]. In addition to the simplicity and efficiency, in-wheel motors could generate fast and precise torque which has no adverse effect on the driveshaft stiffness. In-wheel motors also have the capability of enhancing the performance of traction control systems (TCS), anti-lock brake systems (ABS), and electronic stability control systems (ESC) [2]. However, the development of IWMs has introduced new technological challenges. Installing the motors in the wheel can result in an increase in the unsprung mass, which greatly deteriorates the suspension ride comfort performance and road holding ability. Furthermore, the wear of the motor bearing is a problem that should be addressed in the active control of IWM EVs [3]. The motor bearing in vehicles with unsprung mass can easily wear because of heavy loads and the small gap between the motor rotor and the stator. Since the ride comfort and passenger safety are increasingly becoming critical criteria in vehicle suspension design, the influence of IWM on these criteria should be examined and addressed.

In order to decrease the tyre contact force fluctuation of an EV, Bridgestone developed the so-called dynamic-damping-in-wheel-

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motor-driven-system [4], which suspends shaftless direct-drive motors and isolates them from the unsprung mass. The motor was designed as a vibration absorber that could offset the road vibration input. The system is shown to have the potential to improve ride quality and road-holding performance. Tyre contact force fluctuations in conventional EVs and IMW EVs with dynamic damping are compared in [5]. Although it is shown that such structures can efficiently increase the road holding performance, active suspension control should be deployed to improve vehicle ride quality. Sun et al. [1,6] investigated the dynamic effect of an in-wheel Switched Reluctance Motor (SRM) on a vehicle in terms of vibration and noise issues, and proposed corresponding control methodology to improve the EV performance. A filtered-X least mean square controller was proposed for active suspension to suppress the vibration caused by SRM vertical force in [7]. Wang and Jing [3] proposed a finite-frequency state feedback H_∞ controller for active suspension of IWM EVs, and demonstrated that the deployment of a dynamic vibration absorber would significantly reduce the force applied to the in-wheel motor bearing. Jing and Wang [8] proposed a robust H_∞ fault-tolerant controller for active suspension of IWM EVs to decrease the motor vibration and to reduce the dynamic load applied to the in-wheel motor bearing.

In an active suspension design, a fully controlled suspension system improves the vehicle ride comfort, handling stability and safety. However, performance requirements, such as ride comfort, road-holding stability, and suspension deflection, are often conflicting design requirements. Different control methods such as fuzzy control [9,10], Linear Quadratic Regulator (LQR)/Linear Quadratic Gaussian (LQG) [11], neural network method [12], linear optimal control [13–15], robust H_∞ control [16–18] and adaptive control [19–21] are proposed to deal with the trade-off between these conflicting expectations. Brezas and Smith [13] proposed a clipped-optimal control algorithm which could optimize the vehicle ride and handling behaviour for semi-active vehicle suspension. In [14], optimal control for active suspension with sinusoidal disturbance based on a modified quadratic performance index was investigated. In [15], an optimal fuzzy-PID control strategy based on an improved cultural algorithm was proposed for active suspension to suppress the vertical vibration acceleration of the quarter vehicle. In [22], a skyhook adaptive neuro active force controller consisting of four feedback control loops for active suspension was proposed and validated theoretically and experimentally. A strategy utilizing neural network and backstepping techniques for semi-active suspension systems was investigated in [23], and the neural network was used to estimate the control voltage input to the magnetorheological damper. In [24], Variational Feedback Controllers (VFC) was proposed for feedback control of a nonlinear suspension system. In [25], a fixed order non-fragile dynamic output feedback controller for a suspension system with model uncertainty and nonlinear dynamics was proposed based on the convex optimization and LMI approach. In [20], an adaptive robust control based H_∞ control strategy was designed for full vehicle active suspension systems with electrohydraulic actuators in which the proposed controller could deal with actuator parametric uncertainties and uncertain actuator nonlinearities. A saturated adaptive robust control (ARC) strategy [21] and adaptive backstepping control strategy [19] were proposed for active suspension with parameter uncertainties and nonlinearities. According to the literature, the robust H_∞ control strategy can deal with complexities such as sprung mass uncertainty, damper time delay and time constant uncertainty [20,24–26].

In vehicle suspension control methods used to improve vehicle performance, it is assumed that all the control components of the systems are in an ideal working condition. In practice, unknown faults in components such as sensor and actuator failures can deteriorate the dynamic behaviour of the suspension. Fault-tolerant control (FTC) method which deals with possible actuator failure has attracted attentions in recent years. Generally speaking, the FTC method can be divided into two types: passive FTC and active FTC. The controller of passive FTC is fixed while active FTC could detect the faults and compensate the effect of faults in real time. A robust finite frequency passive fault-tolerant static-output-feedback H_∞ controller was designed for structure systems in [17]. In this work, the actuator faults were described by a polytopic model. A passive fault-tolerant robust LQR-based H_∞ controller was proposed for four-wheel independently actuated electric vehicle using Linear Parameter-Varying (LPV) control method in [27]. FTC based on virtual sensor and virtual actuator for nonlinear system were studied in [28,29] considering both actuator and sensor faults. Adaptive sliding mode control of Markov jump nonlinear systems in the presence of actuator faults was studied in [30]. The problem of fault detection in active suspension has been researched intensively in recent years. In [31], a robust optimal sliding mode controller was proposed to deal with actuator faults and to ensure the overall stability of the full vehicle suspension system. In [32], a fault tolerant control method was proposed for the electromagnetic suspension system subject to failure of the sensors and actuators. The problem of fault detection filters for an active suspension in a finite-frequency domain was dealt with based on the generalized Kalman-Yakubovich-Popov (KYP) lemma in [33]. Robust fault-tolerant H_∞ control for full-car active suspension with finite-frequency constraint was investigated in [3], where the controller was designed to reduce the heave, pitch and roll motions. Kong et al. [34] proposed a robust non-fragile H_∞/L_2-L_∞ static output feedback controller for vehicle active suspension considering actuator time-delays and the controller gain variations. In [35,36], the non-fragile H_∞ controller was proposed for the half-vehicle suspension systems in the presence of actuator uncertainty and failure.

The vehicle sprung mass varies with respect to the loading conditions such as the payload and the number of vehicle occupants. Model uncertainty, such as suspension sprung and unsprung mass variations should be taken into consideration in the design of active suspensions. The active control performance of a vehicle suspension is affected if the sprung mass variation is not considered. A Takagi-Sugeno (T-S) fuzzy approach can be applied to handle the uncertainties as the T–S fuzzy model is very effective in representing complex nonlinear systems. Du and Zhang [9] presented a fuzzy H_∞ static output feedback controller design approach for vehicle electrohydraulic active suspensions based on T–S fuzzy modelling techniques. A mode-dependent and fuzzy-basis-dependent T-S fuzzy filter was designed for discrete-time T-S fuzzy systems using multiple packet dropouts in a network environment [37]. The fuzzy tracking control problem for uncertain nonlinear networked system based on type-2 T-S fuzzy mode was studied in [38]. The studies addressing model uncertainty, unknown actuator dead zone and control constraints, using some adaptive controllers such as adaptive fuzzy controller and adaptive neural controller for uncertain non-strict-feedback stochastic nonlinear systems were presented in [39,40]. In [41], a sampled-data H_∞ control for an active suspension system with model