ARTICLE IN PRESS

Mechanical Systems and Signal Processing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Time-varying delays compensation algorithm for powertrain active damping of an electrified vehicle equipped with an axle motor during regenerative braking

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ARTICLE INFO

Article history:
Received 9 June 2015
Received in revised form
14 September 2015
Accepted 5 October 2015

Keywords:
Electrified powertrain
Time-varying delays compensation
Active damping
Regenerative braking
Cooperative control

ABSTRACT

The flexibility of the electrified powertrain system elicits a negative effect upon the cooperative control performance between regenerative and hydraulic braking and the active damping control performance. Meanwhile, the connections among sensors, controllers, and actuators are realized via network communication, i.e., controller area network (CAN), that introduces time-varying delays and deteriorates the control performances of the closed-loop control systems. As such, the goal of this paper is to develop a control algorithm to cope with all these challenges. To this end, the models of the stochastic network induced time-varying delays, based on a real in-vehicle network topology and on a flexible electrified powertrain, were firstly built. In order to further enhance the control performances of active damping and cooperative control of regenerative and hydraulic braking, the time-varying delays compensation algorithm for the electrified powertrain active damping during regenerative braking was developed based on a predictive scheme. The augmented system is constructed and the H_∞ performance is analyzed. Based on this analysis, the control gains are derived by solving a nonlinear minimization problem. The simulations and hardware-in-loop (HIL) tests were carried out to validate the effectiveness of the developed algorithm. The test results show that the active damping and cooperative control performances are enhanced significantly.

1. Introduction

Various types of electrified vehicles have been recognized as an important solution to the energy crisis and environmental pollution issues [1–3]. As the key features of electrified vehicles, the regenerative braking, which is capable of improving the energy economy effectively, has become an active topic of research and development among researchers and automakers worldwide [4–6]. Most manufactured electrified vehicles, including Toyota Prius, Nissan Leaf, and Tesla Model S, are equipped

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http://dx.doi.org/10.1016/j.ymssp.2015.10.008
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with axle motors. During regenerative braking process, the torque of the motor is transmitted to the wheel by the transmission path via a gear box, driving shaft, and half-shaft. Compared to the internal combustion engine (ICE) powertrains, electrified powertrains are prone to suffer from torsional oscillations owing to a number of reasons. Structurally, the electrified powertrains are poorly damped owing to the absences of crankshaft torsional vibration dampers and clutches [7]. On the other hand, in regard to the vibration excitation sources, the electric motors are characterized by fast dynamics where the driveline oscillation is easily generated. The number of vibration excitation sources is increased, owing to the hydraulic pressure and regenerative braking torque modulation during regenerative braking. Torsional oscillations in electrified powertrains will invariably result in driving discomfort and accelerated fatigue of the mechanical components [8].

Given the importance of powertrain torsional oscillations, a number of control algorithms have been adopted for active damping of the powertrain. For gear shift process, an active control strategy for manipulating both ICE and electric motor output torque via a proportional–integral-derivative (PID) controller was developed and implemented in [9]. The simulation results show that the powertrain vibrations are better suppressed by electric motor than ICE due to the short delay of the output torque. In [10], a sliding mode based control strategy was designed to enhance the speed regulation control capability during gear shifting operation for an electric vehicle. The simulation and experiment results show the proposed control algorithm can reduce the expense time of the synchronization phase during the gear shifting process. For the hybrid electric vehicle (HEV), the elimination of torque ripples in the ICE can be achieved by control the output torque of the electric motor. An LPV control strategy for torque ripple reduction in Hybrid Electric Vehicles was designed in [11], the control law is based on a dynamic-output feedback controller for a permanent magnet synchronous motor which is used to compensate for the diesel engine ripples resulting from the propulsion of the hybrid powertrain. In [12], a coordinated control strategy between ICE and electric motor was proposed to suppress the driveline vibration caused by the disturbances from the wheel torque. Another aspect of powertrain active damping control is to suppress vibration during the tip-in and tip-out conditions. A controller combines state feedback with a tyre reaction tracking loop by using pole placement method was introduced in [7], both resonance frequency of the drivetrain and the low frequency oscillations from the tyre are well damped. In [13,14], a Kalman filter was designed to observe the torque of the half-shaft to improve the control performance of traction control. Additionally, a feedback compensator was proposed using the pole placement method and PID control. The simulation and experiment results show that the active damping control algorithm improve the overall control performance when the motor torque changes rapidly. In [15], a feed-forward and feedback control scheme was proposed to address the shaking vibration issues for electric vehicles to support their quick and smooth acceleration response. Driving test results have confirmed that with the developed control strategy, the acceleration performance is improved from that of conventional vehicles with an ICE. The present authors have proposed two active damping algorithms during the regenerative braking and the normal deceleration process, the powertrain vibration induced by stiffness of the half shaft and gear backlash were both suppressed, whereby the braking comfort and regeneration efficiency are both improved [16,17].

However, all the control solutions listed above assume that the sensors, controllers and actuators are directly connected, which is not realistic. The control signals from the controllers and the measurements from the sensors are exchanged via a communication network, i.e., the controller area network (CAN). Because of the limited bandwidth, time-varying delays occur and may deteriorate the control performance, and even destabilize the closed-loop system [18–20]. Meanwhile, electric components, such as the electric motor, battery and corresponding control systems are added in electrified vehicles, and the number and frequency of messages exchanged via the communication network increase significantly. Thus, the effects of time-varying delays upon control performance become more critical for electrified vehicles than those of ICE vehicles [21–23]. Recently, the authors in [22,23] discussed the active damping control for powertrain considering the network induced delays. In [22], a robust energy-to-peak controller was proposed for the Integrated motor-transmission powertrain system to address the oscillation damping problem and also attenuate the external disturbance. In [23], a Lyapunov based predictive controller was designed for the powertrain model with time-varying delays, polytopic uncertainty and hard constraints to cope with the oscillation problem, the control algorithm was testified in a hardware-in-loop (HIL) test bench during tip-in conditions. However, all the discussions were conducted under driving conditions, the control algorithm under braking conditions were not investigated.

Compared with the driving conditions, the time-varying delays bring up additional challenges in regard to the design of the active damping control algorithm during regenerative braking, where not only the active damping performances of the electrified powertrain need to be considered, but also the cooperative control performances of regenerative and hydraulic braking. The active damping performance determines the driving comfort, while the cooperative control performance ensures how well the braking intentions of the driver are tracked. The time-varying delays elicit negative influences in both control performances, especially in the cases where the braking intentions of the drivers change rapidly.

Different from the existing publications, in this article, we aim to develop the time-varying delays compensation algorithm for electrified powertrain active damping during regenerative braking. The compensation algorithm is in a predictive scheme which is motivated by Liu et al. [24,25]. The nonlinear electrified powertrain, hydraulic brake, vehicle dynamics and tyre are modeled. The time-varying delay free system is obtained with stochastic parameters by constructing the augmented system. The H_∞ performance is analyzed and the control gains are derived by solving a nonlinear optimization problem. Simulations and hardware-in-loop (HIL) tests of the developed control algorithm during different normal braking processes were carried out. The main differences and contributions of this work are three-fold: (1) the time-varying delays compensation algorithm for electrified powertrain active damping is designed under regenerative braking conditions; (2) the