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Speed synchronization control for integrated automotive motor–transmission powertrain system with random delays

Xiaoyuan Zhu [a,b], Hui Zhang [a,*], Zongde Fang [b]

[a] Merchant Marine College, Shanghai Maritime University, Shanghai 201306, China
[b] School of Mechanical Engineering, Northwestern Polytechnical University, Xi'an 710072, Shaanxi, China

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ABSTRACT

This paper presents a robust speed synchronization controller design for an integrated motor–transmission powertrain system in which the driving motor and multi-gearbox are directly coupled. As the controller area network (CAN) is commonly used in the vehicle powertrain system, the possible network-induced random delays in both feedback and forward channel are considered and modeled by using two Markov chains in the controller design process. For the application perspective, the control law adopted here is a generalized proportional–integral (PI) control. By employing the system-augmentation technique, a delay-free stochastic closed-loop system is obtained and the generalized PI controller design problem is converted to a static output feedback (SOF) controller design problem. Since there are external disturbances involved in the closed-loop system, the energy-to-peak performance is considered to guarantee the robustness of the controller. And the controlled output is chosen as the speed synchronization error. To further improve the transient response of the closed-loop system, the pole placement is also employed in the energy-to-peak performance based speed synchronization control. The mode-dependent control gains are obtained by using an iterative linear matrix inequality (LMI) algorithm. Simulation results show the effectiveness of the proposed control approach.

1. Introduction

Integrated motor–transmission powertrain system is a good choice for electric commercial vehicles due to its potential in energy efficiency improvement and drivability keeping [1,2]. With the coordination control between driving motor and transmission, the clutch can be removed while the motor and transmission are directly coupled [3,4]. It can simplify the powertrain system's structure a lot and also reduce manufacturing cost. Furthermore, the motor size can be also reduced due to the use of transmission [5]. For different types of transmissions that adopted in current vehicle powertrain system, there are mainly continuously variable transmission (CVT), automatic transmission (AT), dual clutch transmission (DCT) and automated manual transmission (AMT) [3]. Considering the transmission efficiency, installation space requirement and also the cost, AMT is regarded as the ideal transmission type for integrated motor–transmission powertrain system, e.g., clutchless AMT system [6,7]. Actually, it has already been used in some pure electric buses [2,4].

* Corresponding author. Tel.: +1 614 886 3583.
E-mail address: huizhang285@gmail.com (H. Zhang).

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The shifting quality is one of the significant considerations in the shifting control for transmission system, which is usually determined by torque hole, shifting impact and the shifting time [3]. The torque hole is caused by the interruption of the driving torque when the transmission gears are disengaged. It can deteriorate the drive comfort and should be shortened as much as possible during the shifting process. For the conventional AMT system, an electronically controlled clutch is usually required to smooth the gear change process and also ensure the shifting quality. As the driving motor and transmission are direct coupled in the integrated motor–transmission powertrain system, more requirements are placed on the motor control. According to different operating modes of driving motor, there will be torque reduction phase, speed regulation phase and torque resume phase for the driving motor in the shifting process [2]. The speed regulation control can be seen as an additional requirement in the shifting control of the integrated motor–transmission powertrain system due to the absence of clutch. By speed control of the driving motor, the synchronization between the motor and transmission can be guaranteed. It can also help shorten the torque hole as well as the entire shifting duration. Besides, with good speed synchronization performance, the shifting impact during gear engagement can be also mitigated. Thus, compared with conventional AMT system, the speed synchronization control plays a critical role in the shifting process of integrated motor–transmission powertrain system, which can largely affect the shifting quality. Meanwhile, the synchronization control in the shifting process of integrated motor–transmission powertrain system is also challenging and demanding due to the elimination of damping components. According to some experimental studies of integrated motor–transmission powertrain system, e.g., clutchless AMT system, the duration of the speed synchronization process usually takes nearly half of the entire shifting time [7]. For the speed synchronization control of the driving motor in the integrated motor–transmission powertrain system, the conventional PID control is commonly used [8]. However, tuning of the PID control gains is time-consuming and there is no analytic solution for calculating the PID control gains. Besides, conventional PID controller is also usually lack of robustness. As the steady state speed synchronization error should be stabilized in an acceptable range to ensure smooth gear engagement, the sliding mode control is also adopted to enhance the speed regulation control capability [2,3]. However, additional boundary layer is usually required to deal with the chattering problem and the transient performance of the control system can't be easily ensured.

As the controller area network (CAN) is commonly required in the shift control of integrated motor–transmission system to do the coordination work between the motor control unit (MCU) and transmission control unit (TCU), the integrated motor–transmission system should be molded as a networked control system (NCS) [9]. Due to the bandwidth limitation and increasing usage of electric control units (ECUs), network-induced delays are easy to appear [10,11]. These undesired random delays can degrade or even destabilize the control system [12,13], which haven't been fully considered in the shifting control of powertrain system. To model the network-induced delays, there are generally two approaches. The first one is the deterministic method where the time-varying delays are only assumed to be bounded [14]. The other one is the stochastic method which assumes that the time-varying delays also follow certain probability distributions such as Markov chain [15]. To deal with the network-induced delays modeled by different approaches, the controller designs can be mode-independent and mode-dependent [16,17]. The mode-independent controller is usually designed for the delays modeled by deterministic approach. The sensor to controller (S–C) and controller to actuator (C–A) delays can be merged together to form a general time-delayed system [18]. While the mode-dependent controller is usually developed for delays modeled by stochastic approach in which the control gains will be varied with random time-varying delays [19]. The mode-dependent controller can be further divided into one-mode-dependent controller that depend on either S–C or C–A delays and two-mode-dependent controller depending on both S–C and C–A delays. Since integrated mode-dependent controller design can incorporate more statistic information of the network-induced random delays, generally, the obtained result would be less conservative [20].

In this paper, a robust speed synchronization control is proposed for integrated motor–transmission system in the presence of networked-induced random delays. The main contributions of this paper lie in the following aspects:

(1) Energy-to-peak performance based control is adopted to ensure the robustness of the speed synchronization controller for integrated motor–transmission powertrain system. Pole placement is applied to further improve the transient performance of the speed synchronization control system.
(2) The possible network-induced delays are considered in the speed synchronization controller design process. And the stochastic method is adopted to model the S–C and C–A delays by using two homogenous Markov chains.
(3) The controller is designed to be mode-dependent. Iterative linear matrix inequality (LMI) algorithm is adopted to obtain the optimal feedback control gains.

The paper is organized as follows. In Section 2, problem formulation along with system modeling is introduced. Section 3 presents the energy-to-peak performance based speed synchronization controller design. In Section 4, simulation results are presented to evaluate the effectiveness of the proposed controller. Concluding remarks are summarized in Section 5.

2. Problem formulation

A typical integrated motor–transmission powertrain system used in electric vehicles is shown as Fig. 1. Controller area network (CAN) is adopted to exchange the measurements from different sensors and control signals from various controllers such as MCU and TCU. The driving motor and transmission are directly coupled without clutch in the integrated motor–transmission

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