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Optimal control of the gear shifting process for shift smoothness in dual-clutch transmissions

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ABSTRACT

The control of the transmission system in vehicles is significant for the driving comfort. In order to design a controller for smooth shifting and comfortable driving, a dynamic model of a dual-clutch transmission is presented in this paper. A finite-time linear quadratic regulator is proposed for the optimal control of the two friction clutches in the torque phase for the upshift process. An integral linear quadratic regulator is introduced to regulate the relative speed difference between the engine and the slipping clutch under the optimization of the input torque during the inertia phase. The control objective focuses on smoothing the upshift process so as to improve the driving comfort. Considering the available sensors in vehicles for feedback control, an observer design is presented to track the immeasurable variables. Simulation results show that the jerk can be reduced both in the torque phase and inertia phase, indicating good shift performance. Furthermore, compared with conventional controllers for the upshift process, the proposed control method can reduce shift jerk and improve shift quality.

1. Introduction

The transmission system is a key component in automobiles, transferring power from the engine to the wheels to fulfill the propulsion demand for the normal daily driving. With the requirement of good shift quality and energy saving, many new types of transmission systems and relevant technologies have been developed and studied further, such as automated manual transmissions (AMTs), the automatic transmissions (ATs), continuous variable transmissions (CVTs), and dual-clutch transmissions (DCTs) [1]. DCTs which can be regarded as two manual transmissions with clutch-to-clutch shifting have received considerable attention. Because of their high transmission efficiency and good shift quality when controlled reasonably, they are regarded as a promising developing tendency for transmissions in the near future [2].

Smooth and fast shift control can be accomplished through continuous power transfer between the input and output of the transmission by the precise pressure and position control of the clutches. Various shift control strategies have been proposed for the gear shift in ATs and AMTs [3]. A model predictive control strategy with the sliding mode observer considering modeling uncertainties and resistance torque estimation for AMTs has been proposed in [4,5] based on tracking predetermined clutch position trajectories which are represented by a first-order exponential function. In order to improve the shift quality, an offline linear quadratic optimization method has been developed in [6] for the clutch slip control in an electric vehicle equipped with a manual transmission. A robust two degree of freedom controller with speed reference

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tracking during the inertia phase has been proposed in [7] to improve the shift quality. A nonlinear dynamic model of a wet clutch system has been developed in [8] together with a sliding mode controller for the clutch shift control under the desired pressure trajectories. A backstepping method guaranteeing input-to-state stability has been presented in [9] to track the clutch speed slip based on a third-order polynomial function. It can be seen that most of these methods require an optimal reference trajectory tracking of clutch pressure and position for clutch friction torque control.

In DCT control the whole shift process is divided into the torque phase and the inertia phase due to the special structure. In the torque phase the power from the engine is transferred from the engaged clutch to the on-coming clutch. When the formerly engaged clutch is open, it comes to the inertia phase where the on-coming clutch is synchronized under the new gear ratio. Feedback control and logic control for the power-on upshift and power-off downshift have been proposed in [10–13] to achieve good shift performance of DCTs. The dynamic response of DCTs during shift has been studied in [14–16]. In a recently published paper [17] a method for fast clutch engagement and smooth clutch control through tracking the demanded torque has been devised. This paper, however, only considers the smooth engagement during the inertia phase without addressing the torque phase where timing sequence and overlap friction for engaging and disengaging the two clutches have great effect on the shift quality. Recently a torque-based logic control method of DCTs for power-on and power-off shift transient strategies has been introduced in [18] for electric vehicles. In summary, a holistic optimal control strategy without predetermined reference tracking for the smooth shift process including both of the torque and inertia phase is not available yet.

Optimal control methods have been considered in several papers for powertrain control. The linear quadratic optimal regulator has been successfully applied on vehicle driveline systems in [19,20]. In order to deal with powertrain oscillations, active damping control methods based on the infinite-time LQR have been studied and applied for traditional vehicles in [21,22]. A finite-time LQR controller has been proposed in [23] to follow the power demand in a hybrid powertrain. An infinite-time LQR has also been applied in shift control of DCTs in [24]. However, the shift time cannot be defined in this method and the shift smoothness is not considered.

Throughout the literature, the shift control strategy can be divided into two levels: an upper-level control for torque trajectory generation and a lower-level control of the clutch actuation system to follow the desired torque accurately. A major limitation of the previously published papers is that most work focuses on the lower-level control of the nonlinear clutch systems. There has been little research reported on the upper-level control. During the torque phase two different gear pairs may engage at the same time under improper control of the two clutches. In this condition not only the power cannot be transferred smoothly from the current gear ratio to the coming gear ratio, causing drastic oscillation, but also a great friction power loss could generate considerable heat, decreasing the clutch longevity. Therefore the optimal control of torque trajectories in DCTs is of vital importance for the transmission system operation during shifting and needs to be studied further.

This paper proposes a new control method to get optimized trajectories for the clutch torque and input shaft torque to achieve a fast and smooth shift in DCTs. A finite-horizon LQR is proposed for the mutual engaging and disengaging control during the torque phase to obtain a proper friction torque for the two clutches. An LQR-based integral controller with fixed final cost is presented to generate the optimized input torque and relative speed difference during the inertia phase. Furthermore, in order to deal with unmeasured variables for feedback control, an observer is introduced to track all variables with the speed sensors commonly available in vehicles. The proposed control strategy is compared with two other methods to demonstrate its capabilities to smoothen the gear shift. Three major contributions are added to the existing literatures. First, the friction torque and input torque are optimized for overall shift smoothness and fast engagement during the upshift process. In the developed method the shift time can be defined through a terminal cost for the fast clutch engagement. Second, an observer is designed for online control application with speed sensors which are commonly available in vehicles. Third, comparisons between different controllers for DCT shift control are given.

The paper is organized as follows. In Section 2 the dynamic model of a DCT is introduced. The control methods for the torque phase and the inertia phase are discussed in Section 3. The observer design is presented in Section 4. In Section 5 simulation comparisons between the developed controllers and conventional controllers are provided. Conclusions are finally given in Section 6.

2. Powertrain system and problem statement

The power-on upshift process of DCTs is usually divided into two phases: the torque phase and the inertia phase. During the torque phase, one clutch is disengaging and the other clutch is engaging. The gear ratio of the transmission keeps unchanged with the current value. The engine power is transferred from the disengaging clutch to the engaging clutch. During the shift process, two different gear pairs determining two gear ratios may be engaged at the same time. Therefore the time sequence of the disengagement and engagement and the overlap slipping between the two clutches have great effect on the shift comfort and the shift time. During the inertia phase, the disengaging clutch is supposed to be totally open and the engine speed is controlled together with the relative slipping speed of the engaging clutch for synchronization, decreasing the vehicle jerk and synchronization time. Since the power can be delivered through two clutches during the whole shift process, there is no power interruption between the engine and the wheel without speed decrease, which is a major advantage of DCTs, compared to other kinds of transmission systems. Therefore the acceleration time and fuel consumption for