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Research paper

Gear shift control of a dual-clutch transmission using optimal control allocation

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ABSTRACT

This study develops control strategies for the gear shift of dual-clutch transmissions (DCTs) using optimal control allocation. DCT powertrains require sophisticated control of two clutch actuators and the engine throttle to achieve good shift performances, i.e. smooth and fast gear shifts. In this paper, a new approach to the control strategies is implemented through interpreting the DCT powertrain as an over-actuated system that possesses actuator redundancy. The developed control structure is divided into two stages: the upper level control that governs the procedure to determine the most suitable torque trajectories of the clutches and engine, and the lower level control that manages the strategy for each actuator controller to track the given torque trajectories. The core of this study is the development of an effective upper level controller based on the optimal control allocation, to which previous studies have not paid adequate attention. A major advantage of this control approach is that the resulting shift performances can be easily and intuitively adjusted by tuning only one parameter. The effectiveness of the control scheme is demonstrated through various simulations using a high-fidelity DCT model implemented with a commercial software SimDriveline, and detailed discussions of the results are also provided.

1. Introduction

Recently, dual-clutch transmissions (DCTs) have garnered substantial attention in the global automotive industry because they have demonstrated significant improvements regarding both efficiency and ride quality of vehicles. During gear shifts, DCTs use two sets of clutches and transfer shafts to transmit the engine torque to the axle shaft without using torque converters, which can effectively nullify the drawbacks of other types of transmissions. In particular, such configurations enable the transmission systems to considerably reduce the torque discontinuities and interruptions, which are chronic problems in manual transmissions (MTs) and automated manual transmissions (AMTs); DCTs also result in significantly higher efficiency than conventional planetary-type automatic transmissions (ATs) do [1]. However, due to the absence of the smoothing effect of torque converters, DCT powertrains are more likely to cause awkward shift shocks during gear shifts, particularly when the clutch-to-clutch shift is performed fast [2]. Fast gear shifts are generally desired in order to minimize

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the loss of vehicle acceleration regardless of the transmission types. In addition, if the driver wants fast acceleration by pressing the accelerator pedal abruptly, the shift duration must be shortened accordingly [3]. In general, the conditions of comfortable and quick shifts conflict with each other and they are typically regarded as the two main objectives of gear shift controls (e.g. [4]).

The desired shift performances can only be attained when accompanied by precise torque transfer controls in vehicle drivelines. Various control strategies for gear shifts have been investigated for hydraulic ATs in [5–8]. Although the methodologies are similar to those for ATs, the lightly damped powertrains such as AMTs and DCTs need elaborate controls for the clutch(es) and engine throttle that focus more on ride quality improvement [3,9]. Shift control problems for AMTs have also been explored in numerous studies. Optimal linear quadratic clutch controllers were designed for dry AMTs considering several gear shifting performances in [10], and a clutch slip controller was developed to regulate the slip acceleration in [11]. In [12], a gear shift control strategy for an AMT was proposed through interpreting the gearshift process of AMTs as five phases considering its transient behaviors in each phase.

For DCT powertrains, however, gear shifts are realized through the handover of the torque delivered by the engine from one clutch to the other clutch, which further complicates the control problems. The DCT shifting process can be split into two phases: the torque phase where the torque is transferred from the engaged clutch to the on-coming clutch, and the inertia phase where the on-coming clutch with the new gear ratio is synchronized with the engine. In the torque phase, the cross shift control of the two clutches should be performed delicately in order to minimize the torque dip without causing an engine flare or clutch tie-up [7,13]. In the inertia phase, the synchronization control of the on-coming clutch accompanying the engine inertia control is crucial for comfortable ride quality and fast engagement. The engine throttle control is used to compensate the torque oscillations caused by the abrupt gear ratio change and the lag in the inertia torque [14,15]. Most literature on DCT shift control has adopted various methods of controlling torques or speeds in order to satisfy the pre-determined shift requirements in both phases [3,4,9,16,17]. The detailed control strategies of the clutch and engine speeds to meet the target torque requirement have been described in [3]. The gear shifts were divided into several phases and control strategies were proposed in each phase to ensure both fast and smooth clutch engagement based on the clutch slip and output torque information in [4]. A coordinated control algorithm for the engine and clutches to achieve the target average torque was proposed with detailed modeling of the hydraulic actuators in [9]. Since torque sensors are not available for production DCT powertrains, estimation methods for the torque states were developed in [18,19].

This paper proposes a new approach to the combined control of the clutches and engine throttle for a dry DCT gear shift considering the DCT driveline as an over-actuated system. A DCT has natural actuator redundancy because it has an additional clutch and shaft set compared with an AMT for the same transmission function. Previously, one of the clutches in a DCT or AT was controlled in an open-loop way so that it simply ramped up or down during the torque phase. There are several practical reasons for adopting this approach in these clutch-to-clutch shifts (see e.g. [7,16]), but the actuator redundancy problem must be addressed for more in-depth analysis of the shift processes. Here, the output shaft torque and the slip speed of the on-coming clutch are selected as the outputs to be controlled by the three actuators: the off-going clutch, the on-coming clutch, and the engine throttle. The control algorithm is divided into two levels: an upper level control that generates the desired torque values of each actuator considering the given shifting performances and a lower level control that forces on each actuator to follow the respective desired torque accurately.

A major shortcoming of previously published works is that there has been little research reported on the upper level control. Hence, this paper focuses on the development of a novel upper level controller that generates desired torque trajectories in real time for coordinated control of clutches and engine throttle using control allocation. Control allocation is a control technique for over-actuated systems that allocates the total control demand to the individual actuators [20,21]. Actuator redundancy can be found in various applications including the control of aerospace systems, marine vessels, and vehicles. Several control allocation approaches have been developed for vehicle motion control, such as vehicle yaw stabilization [22] and rollover prevention [23]. In this paper, the control allocator is designed to produce the optimized torque trajectories of two clutches and an engine after consideration of several actuator constraints. Using the proposed method, the desired torque trajectories can be designed to satisfy the shift requirements arbitrarily by tuning only one weighting factor between the two conflicting performances: fast shift and smooth shift. The resulting torque trajectories can be utilized as reference values for various shift control strategies, and they can also provide insights into the clutch-to-clutch shift process.

The remainder of this paper is organized as follows. In Section 2, DCT driveline and clutch actuator models are described. The DCT shift control structure consisting of the upper level and lower level controls is introduced, and detailed explanations of the developed control strategies are presented in Section 3. Next, in Section 4, the feasibility and effectiveness of the proposed control scheme are evaluated in simulations using a high-fidelity SimDriveline DCT model. A detailed discussion of the results is also presented. Finally, this study is concluded in Section 5.

2. System modeling

2.1. Driveline model

The basic configuration of the DCT is similar to that of an AMT, but the DCT is equipped with two sets of input and transfer shafts between the engine and the output shaft. The driveline model is composed of several angular speed dynamics