Control Engineering Practice 76 (2018) 155–166

Contents lists available at ScienceDirect

Control Engineering Practice

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

Optimization-based assessment of automatic transmission double-transition shift controls

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ARTICLE INFO

Keywords:
Automatic transmission
Double-transition shift
Control
Assessment
Optimization

ABSTRACT

In the new generation of torque converter automatic transmissions (ATs), characterized by a high number of gears, multi-step gear shifts may be executed frequently in order to improve the driving performance. They include double-transition shifts (DTSs), which require close coordination between multiple control inputs (e.g. torque capacities of four clutches and engine torque). The previously developed AT control trajectory optimization tool is utilized in this paper for the purpose of DTS control optimization including engine torque control. With the aim to gain insights into optimal control action and coordination, six different DTS control strategies are proposed and assessed. These strategies are incorporated into the optimization problem formulation through additional, shift phase-related constraints that the optimization algorithm needs to satisfy. In this way, control strategies with different degrees of complexity and applicability can be quantitatively assessed in terms of achievable shift performance. The proposed strategies have been examined on an example of characteristic DTS downshift of an advanced 10-speed AT. Based on the summarized optimization results obtained for different levels of clutch energy loss penalization, it has been found that the strategy characterized with quick release of the off-going clutches can provide an optimal compromise between shift comfort performance and energy loss reduction.

1. Introduction

A trend of accelerated increase of the number of forward gears of step gear automatic transmissions (ATs) has emerged recently due to the legislative and market pressure for CO_2 reduction and improved fuel economy (Dong, Liu, Tenberge, & Xu, 2017; Greiner & Grumbach, 2013). Increased number of gears (up to 10, nowadays), on the other hand, makes the development of AT control systems more challenging. Therefore, advanced shift methods are introduced in order to provide good drivability demanded by users. A typical example of an advanced shift method is a double-transition shift (DTS; in the literature also known as multi-element shift, four-element shift, dual clutch-to-clutch shift, and indirect shift), which requires close coordination of multiple (usually four) clutching elements and the transmission input torque (Kondo et al., 2007; Lee, Zhang, Jung, & Lee, 2014; Marano, Moorman, Whitton, & Williams, 2007). The DTSs relate to power-on downshifts that are executed when a brisk increase in the vehicle acceleration is demanded by the driver. It is of significant importance to perform these shifts directly and as fast as possible in order to reduce the transmission response delay with respect to driver's command.

There are two basic ways of performing the DTS downshifts. The first one is to combine two or more single-transition shifts (STSs), which should generally be avoided to prevent a long overall shift time, i.e. a poor shift feel (Marano et al., 2007). The second and more challenging way of performing a DTS includes simultaneous control of four active clutches in a single shift event. The underlying concept of DTS control has not yet been thoroughly explored and understood in the existing literature that includes only several publications dealing with DTS control. For example, the DTS control strategy from Marano et al. (2007) proposes to swiftly drop the off-going clutches, thus leaving the transmission momentarily in a "neutral" state. In Lee et al. (2014), the DTS shift process is divided into multiple phases, where each shift phase is defined with respect to the clutch elements synchronization events. Although these publications provide insight into practical methods of DTS control, they do not provide systematic analysis and evaluation of optimal control strategies with practical constraints included, which is the main objective of work presented in this paper.

In order to guide the control system design towards the best achievable system performance, different approaches of shift quality

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https://doi.org/10.1016/j.conengprac.2018.04.016
Received 1 June 2017; Received in revised form 24 April 2018; Accepted 28 April 2018

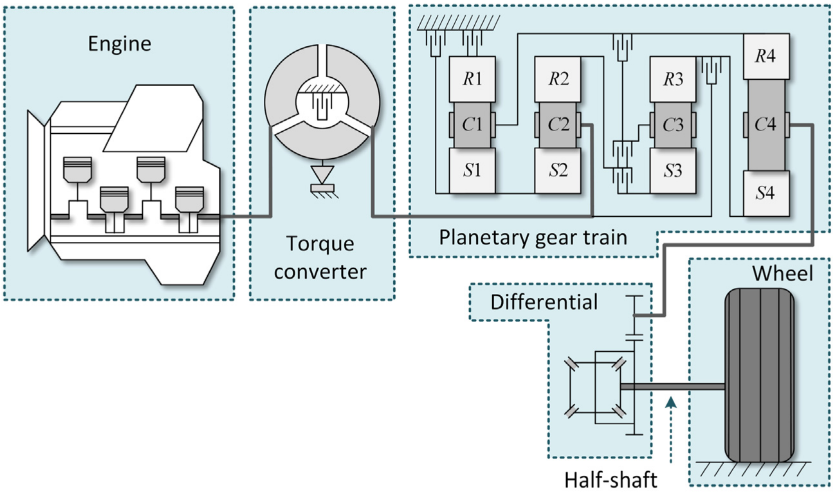

Fig. 1. Schematic representation of AT-based powertrain.

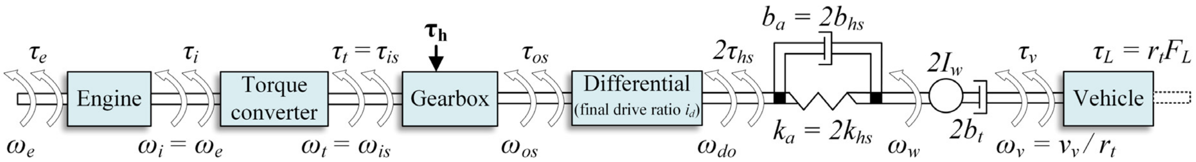

Fig. 2. Schematic illustration of powertrain structure.

optimization have been proposed in literature, such as those based on dynamic programming (DP) method (Haj-Fraj & Pfeiffer, 2001) and multi-objective genetic algorithm (Wurm & Bestle, 2015). Čorić, Ranogajec, Deur, Ivanović, and Tseng (2017) has proposed an off-line/open-loop AT control trajectory optimization approach, which is based on the pseudospectral collocation method, and can be regarded as a general approach readily adaptable to different shift control cases (e.g. STS, DTS, and change-of-mind shifts) with no prior knowledge of control trajectories required. Based on this optimization approach, a numerical tool has been developed and examined by employing it for optimization of a wide range of single- and multi-step STSs (Ranogajec, Deur, & Čorić, 2016) and optimization of hybrid dual clutch transmission shifts (Ranogajec & Deur, 2017b). This paper utilizes the optimization tool in investigating the demanding DTS control task and related performance, with the final aim to formulate practical and optimal shapes of engine and clutch control trajectories.

The paper contributes to the field of DTS control by: (i) proposing different DTS open-loop control strategies and related optimization problem formulations, (ii) conducting a quantitative assessment of these control strategies and giving related recommendations for feasible control system design, (iii) providing insights into optimal control action for each strategy based on the analysis of optimization results.

The remaining part of the paper is organized as follows. Section 2 outlines a control-oriented powertrain model used in the optimization study, whose central part relates to the 10-speed AT from (Goleski & Baldwin, 2013). The control trajectory optimization problem formulation is discussed in Section 3. Section 4 presents and discusses optimization results for a characteristic DTS power-on downshift, which are obtained by employing the general control strategy. Based on those results and identified possible control challenges, six pragmatic control strategies are defined through imposing additional shift phase-related constraints. Optimization results for different weighting factor calibrations are shown in Section 5. Section 6 presents Pareto frontier-based analysis of proposed control strategies including their assessment. The optimization-based analysis of DTS shift dynamics is conducted in Section 7 for each individual control strategy. Concluding remarks are presented in Section 8.

2. Mathematical model

The control-oriented powertrain model used in this study is based on first principles, and its foundation has been proved and also experimentally validated through many automotive control studies (see e.g. Bai, Maguire, & Peng, 2013; Deur, Asgari, Hrovat, & Kovač, 2006). The schematic diagram of the considered powertrain is shown in Fig. 1. Fig. 2 depicts the powertrain structure and outlines the key system variables and parameters used in the paper. The driveline is represented by an equivalent double-wheel model based on the assumption of equivalent power flow to the left and right wheels (Deur et al., 2006; Hrovat, Asgari, & Fodor, 2000).

2.1. Engine and torque converter model

The engine is modeled as a torque source element, where the engine torque τ_e is the external input set by the user. The dynamic equation describing the engine rotational dynamics is given by

$$I_{ei}\dot{\omega}_e = \left(\tau_e + \Delta\tau_{ec}\right) - \tau_i, \tag{1}$$

where τ_i is the impeller torque (i.e. the engine load torque), I_{ei} is the total moment of inertia of the engine and the torque converter impeller/pump. The term $\Delta\tau_{ec} \le 0$ represents the amount of engine torque reduction, which is implemented through the fast spark control or the fuel cut action (Marano, Moorman, Czoykowski, & Ghike, 2011), in order to improve the shift quality (see Čorić et al., 2017).

For the shifts considered in this paper the torque converter is locked by means of the lock-up clutch. The torque converter is by-passed in this way, i.e. the equation $\omega_{is} = \omega_i = \omega_e$ and $\tau_{is} = \tau_i = \tau_e + \Delta\tau_{ec}$ are valid, and the engine and impeller inertia I_{ei} is lumped to the turbine inertia (present within the inertia matrix $\mathbf{A}_{\mathbf{red}}$ in Eq. (2)).

2.2. Gearbox model

The 10-speed AT from Goleski and Baldwin (2013) is used as a generic example of an advanced transmission system. A schematic of