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Research paper

Dynamic driveline torque estimation during whole gear shift for an automatic transmission

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ABSTRACT

This study proposes a novel method for estimation of driveline torque of wet type AT (Automatic transmission). The previous methods of torque estimation in the clutch-to-clutch shift mechanism is mainly applicable to the single gear shift. Thus, they require specific definitions of each gear shift and signal processing corresponding to the multi-gear shift. This study distinctly develops driveline torque estimator based on the whole transmission model, which is capable in applying on any conditional gear shift. This paper, also, incomparably investigates brake/clutch model including centrifugal force, describing physical behavior of real parts. In addition, the development of the method includes adaptive brake and clutch torque estimator in order to compensate variation factor during the shift. The estimation performance of the proposed estimator is evaluated both in simulations and experiments. The results demonstrate that the proposed methods can estimate the driveline torques effectively during the whole gear shift and well describes the typical clutch-to-clutch phenomena such as inter-locking.

1. Introduction

Automatic transmission (AT) bridges power from engine to drive wheel with the automatic shift strategies. It is capable in drawing immense torque increase and exceptional shift quality with the help of torque converter and multiple planetary gears. As a result, AT has been widely adopted in vehicle industries including passenger and commercial vehicles; however, various transmission types that lacks torque converter such as Dual Clutch Transmission (DCT) or Continuously Variable Transmission (CVT) has been introduced for fulfilling customers' expectation for vehicles to be compact and fuel efficient. In fact, as the powertrain downsizing has become one of the critical issues in order to maximize the vehicle performance, the mechanical structure of AT has been modified for compact size, resulting in satisfactory fuel efficiency and shift quality. As a result, the size issue of AT due to the existence of torque converter has been resolved from exchanging the complex and bulky one-way clutches to friction clutches and adopting newly introduced clutch-to-clutch shift. Such shift skim is similar to that of DCT except that torque converter is exploited for vast torque increase at the vehicle launching stage [1,2]. Since usage of torque converter is limited in the earlier shift stage, precise shift control strategy now became a critical factor in guaranteeing exceptional shift quality with minimization of shift impact. Among various control strategies, speed-based control [3,4] was widely adopted; however, the limitation of such control method yields difficulty in using speed feedback during torque phase [5]. Therefore, torque feedback control strategy alternatively has been adopted to acquire an

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extraordinary shift performance due to the simplicity of utilizing torque from engine to the wheel axle. Thus, torque-base control strategies, which are applicable to DCT, for improving shift quality has become the leading research area for vehicle transmission shift control [6–11].

The transmission size constraints and cost issues from implementing torque sensors to each clutch and drive shaft inevitably cause difficulty in applying torque-base control algorithm. In order to overcome such hampers, numerous researches have suggested drive shaft torque estimation methods without torque sensors [12–14]. Several estimation methods include the nonlinear sliding mode observers [15,16] and two different methods for estimating the drive shaft torque by employing the characteristics of the engine torque map and turbine torque map [17]. In fact, such methods fit for the estimation process of the drive shaft torque of Automated Manual Transmissions (AMTs) [18,19]. However, suggested torque estimation methods are unsuitable in applying for clutch-to-clutch shift since two clutches operates simultaneously in achieving a shift. Another research proposes the torque estimation methods for DCT driveline for the case of vehicle launch where only one clutch operates [20–23]. Some research, also, suggests the application of such estimation method for two clutches simultaneously operating in earlier launch phase from utilizing high-order sliding mode observer [24].

The clutch torque estimation for the clutch-to-clutch shift is more challenging than that of one-clutch engagement such as AMT due to the fact that both clutches concurrently operates, which makes the system over-actuated. The previous study analyzes the relation of speed and torque during clutch-to-clutch shift [25]. In fact, several recent researches for clutch-to-clutch shift have been proposed including torque estimation using unscented Kalman filters [26,27]: joint extended Kalman filter and dual extended Kalman filter [28], Takagi-Sugeno observer [29]. Such clutch-to-clutch shift method, however, overlook concurrent operation of clutches. In fact, other researchers suggest novel torque estimators from combining multiple observers in case of clutch to clutch concurrent gear shifts for DCT [30,31]; however, torque estimation method from combining multiple observer increases implementation complexity. To overcome this problem, other researches have suggested torque estimator using respective reduced order mode according to the shift phases (torque phase and inertia phase) for DCT with practical concerns [32,33]. In fact, other researches have suggested nonlinear sliding mode observer for AT according to the shift phases [34]. Although, this method handles the clutch-to-clutch shifts of AT with planetary gears, it's modelling is based on single shift like DCT.

The limitation of previously suggested torque estimation methods becomes apparent in the case of multiple gear shifts as they are mainly developed for single gear shift. The application of such methods to the real multi-step transmission requires additional formulations to calculate each gear ratio. Such work is more complex for AT than for DCT as AT uses many planetary gears together, while DCT uses only spur gears. Furthermore, additional signal processing is needed as the switching from one shift to other shift makes frequent jumps of estimators [31]. In order to overcome these issues, this research distinctly develops the whole transmission model for AT, which is capable in applying on any conditional gear shifts. This research, also, incomparably investigates brake/clutch model including centrifugal force, closely describing the physical behavior of real parts. In addition, the proposed method is also robust in torque estimation with the presence of parametric errors such as variation of the clutch parameters. In fact, with relatively simple implementation process, the estimation performance of shaft speed and clutch/brake torque are exceptional. The proposed state estimator is verified by applying to a specific tracked vehicle transmission; furthermore, such estimator is also capable in applying for other or simpler types of AT as well.

The rest of this paper is organized as follows: Section two introduces the transmission model of the six-speed tracked vehicle transmission and the design process of the torque estimator upon the model. Section three proposes the effectiveness of the state estimator, which is demonstrated via the simulation. Section four summarizes and discusses about the experiment method and result of the proposed estimator in depth. Section five, concludes the paper.

2. Dynamic torque estimation strategy

2.1. Transmission overview

The transmission studied in this paper is a wet type six-speed automatic transmission for tracked vehicles. Fig. 1 illustrates the clutch-pack which is consisted of two major parts. The first part consists three planetary gears (P4, PF, and PR) and two brakes (BF and BR) for controlling the driving direction of vehicle (forward and reverse). The second part composes three planetary gears (P1, P2 and P3), three brakes (B1, B2, B3), and two clutches (C1 and C2) for controlling the shift range from 1st to 6th gear. Table 1 shows the combination of engaged brakes and clutches in each gear for corresponding gear. Brake engagement in the first part and engagement of clutch/brakes in the second part realizes six-speed ranges for forward and reverse direction. For reverse direction, 4th, 5th and 6th gears are automatically restricted by transmission control unit (TCU) for driving safety.

2.2. Dynamic gear shift modeling

Since the gear shift operates only in the second part, the paper only investigates mathematical modeling of the second part. Fig. 2 illustrates the free-body diagram of the second part. Here T, I, R_r, F, ω, S and R mean torque, inertia, driving resistance, internal force or torque, speed, the radii of sun gear and ring gear respectively. The subscriptions i, o, r, c and s