Mechanical Systems and Signal Processing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

ELSEVIER

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Review

Estimation of torque transmitted by clutch during shifting process for dry dual clutch transmission

Zhiguo Zhao [a,*], Lu He [a], Yunyun Yang [a], Chaochun Wu [a], Xueyan Li [a], J. Karl Hedrick [b]

[a] School of Automotive Studies, Tongji University, Shanghai 201804, China
[b] Department of Mechanical Engineering, University of California, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form
1 December 2015
Accepted 19 December 2015

Keywords:
Dual clutch transmission
Shifting process control
Estimation of torque transmitted by clutch
Unscented Kalman filter
Real vehicle test

ABSTRACT

The key toward realizing no-impact gear shifting for dual clutch transmission (DCT) lies in the coordination control between the engine and dual clutches, as well as the accurate closed-loop control of torque transmitted by each clutch and the output torque of the engine. However, the implementation and control precision of closed-loop control are completely dependent on the effective measurement or estimation of the instant transmission torque of the clutch. This study analyzes the DCT shifting process, and builds a three-dimensional (3D) clutch model and mathematical model of a DCT vehicle powertrain system. The torque transmitted by a twin clutch during the upshifting process is estimated by applying the unscented Kalman filter (UKF) algorithm. Then, the torque estimation algorithm is verified using a DCT prototype vehicle installed with a torque sensor on the drive half-shaft. The experimental results show that the designed UKF torque estimation algorithm can estimate the transmission torques of two clutches in real time; further, it can be directly used for DCT shift control and improving the shifting quality.

Contents

* Corresponding author at: School of Automotive Studies, Tongji University, Shanghai 201804, China. Tel.: +86 13044686469.
E-mail address: zhiguozhao@tongji.edu.cn (Z. Zhao).

http://dx.doi.org/10.1016/j.ymssp.2015.12.027
0888-3270/

1. Introduction

The most obvious advantage dual clutch transmission (DCT) has over automated mechanical transmission (AMT) is that it can realize power gear shifting with a shorter shifting time. To completely illustrate the advantage of DCT for a control system, first, a torque coordination control strategy should be proposed with respect to the indexes for evaluating shifting quality, which includes jerk intensity, friction work and shifting time. Second, a clutch actuator should be precisely controlled to attain the target torque. As for the designed control strategy, two clutches simultaneously transmit the engine output torque during the torque phase; the transmission ratio is uncertain. If the control of the two clutches does not coordinate well, the power cycle is affected, and thus deteriorating the shifting quality. As for the close-loop control, when the clutch transmits torque, the friction coefficient varies with the rotational speed difference between the driven plate and driving plate; it is also influenced by factors such as temperature and wear, which results in a difference between the actual transmitted torque calculated by the model and the demand torque of the clutch. The key to improve the shifting quality of DCT vehicles is to accurately estimate the clutch-transmitted torque in real time during the running process of vehicles, and constantly adjust the clutch actuator according to the difference between the estimated torque and the demand torque, to realize precise control of the clutch torque.

Some studies on estimating the output torque and clutch-transmitted torque have been conducted based on the equivalent linear model of a transmission system. Pettersson [1] and Nielsen [2] estimated the output torque of a vehicle drive shaft by considering the flexibility of the drive shaft. Kono et al. [10] designed a linear controller based on $H\infty$ control for the clutch slipping system. Baumanna et al. [3] considered the engine rotation speed, wheel speed, and torsional angular displacement of a drive shaft as state variables. They built a driveline linear system model using the difference between the engine speed and transmission output shaft speed as outputs, and designed a Luenberger observer to estimate the output torque of a drive shaft by applying the pole assignment method. However, considering the nonlinear characteristic of the real driveline system and the applicable scope of the linear model, the established model cannot accurately estimate the torque. Yi et al. [4] designed a self-adaptive sliding mode observer based on the measured angular velocity for automatic transmission (AT). The torque transmitted by a turbine was estimated and validation experiments were conducted. However, considering the differences in the structure and principle between AT and DCT, this method is not applicable to vehicles equipped with DCT. Yao [11], Kim [12], and Wu [13] conducted research on the estimation of clutch-transmitted torque, but the interaction process of the torque transmitted by two clutches was not taken into consideration, and they only focused on the launching process with a single clutch. This method is similar to the clutch torque estimation in AMT. Kulkarni [15] and Zhang [19] calculated the clutch transmitted torque by using the angle stiffness value based on the analytical model, and then the clutch torque was used for the analysis as well as the optimization of the shift control. Goetz [16] considered the uncertainty of the clutch transmitted torque during the shifting process, and he presented a clutch friction coefficient model that was dependent on the sliding speed across the clutch and was represented by a higher-order polynomial as a function of the sliding speed. Ahlawat [18] builded a clutch model that was modeled as a hybrid system containing two discrete states, a slip state and a locked state, and the fuel economy of the vehicle was simulated on the basis of the clutch model. Oh et al. [5] estimated the clutch-transmitted torque in DCT during the shifting process based on the designed observer. However, in this method, the estimation precision depends mainly on the sensor accuracy and model parameters; moreover, the angle stiffness value of each part of the transmission system is difficult to obtain.

In this study, a three-dimensional (3D) clutch model and a co-simulation simulation platform of a DCT vehicle is built and the transmission torque of twin clutches during the shifting process is estimated by applying the unscented Kalman filter (UKF) algorithm, by considering the nonlinear characteristics of the driveline system of DCT vehicles and the complexity of clutch torque estimation. The rest of the article is organized as follows. Section 2 presents a simplified shifting dynamic model of a five-speed dry DCT, and the shifting dynamic model includes models of the sliding friction phase and in-gear stable operation phase. In addition, the clutch and its actuator model is established here. Section 3 briefly introduces the control strategy of DCT vehicles during the shifting process. Section 4 proposes the co-simulation between Matlab/Simulink and the Adams software platform, and some analyses are conducted based on the simulation results. Section 5 introduces the UKF algorithm in detail. Section 6 presents an analysis of the related simulation results. Section 7 discusses an actual vehicle test, and the torque sensor is installed on the half-shaft of the DCT vehicle. Finally, the clutch torque estimation algorithm is validated based on the vehicle.

Please cite this article as: Z. Zhao, et al., Estimation of torque transmitted by clutch during shifting process for dry dual clutch transmission, Mech. Syst. Signal Process. (2016), http://dx.doi.org/10.1016/j.ymssp.2015.12.027