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Dynamic coordinated control during mode transition process for a compound power-split hybrid electric vehicle

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ABSTRACT

The fuel economy of the hybrid electric vehicles (HEVs) can be effectively improved by the mode transition (MT). However, for a power-split powertrain whose power-split transmission is directly connected to the engine, the engine ripple torque (ERT), inconsistent dynamic characteristics (IDC) of engine and motors, model estimation inaccuracies (MEI), system parameter uncertainties (SPU) can cause jerk and vibration of transmission system during the MT process, which will reduce the driving comfort and the life of the drive parts. To tackle these problems, a dynamic coordinated control strategy (DCCS), including a staged engine torque feedforward and feedback estimation (ETFBC) and an active damping feedback compensation (ADBC) based on drive shaft torque estimation (DSTE), is proposed. And the effectiveness of this strategy is verified using a plant model. Firstly, the powertrain plant model is established, and the MT process and problems are analyzed. Secondly, considering the characteristics of the engine torque estimation (ETE) model before and after engine ignition, a motor torque compensation control based on the staged ERT estimation is developed. Then, considering the MEI, SPU and the load change, an ADBC based on a real-time nonlinear reduced-order robust observer of the DSTE is designed. Finally, the simulation results show that the proposed DCCS can effectively improve the driving comfort.

1. Introduction

As the energy crisis and environmental pollution problems become increasingly serious, the development of electric vehicles has become a focus of the automotive industry. The power-split hybrid electric vehicle (PS-HEV) has become one of the most promising schemes among various powertrain system configurations, and there have been a variety of such HEVs [1,2]. Examples of PS-HEV models include Toyota Prius, GM Cadillac and Geely Dili.

The PS-HEVs control the mode transition (MT) to reduce fuel consumption by means of its energy management control strategy. However, since the engine is directly connected to a power-split transmission by a torsional damper spring (TDS), during the MT process (especially with engine start/stop) between electric vehicle (EV) mode and HEV mode, the engine ripple torque (ERT) [3–6], inconsistent dynamic characteristics (IDC) of engine and motors [7,8] can directly cause jerk and

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vibration to the powertrain. Besides, the model estimation inaccuracies (MEI) (e.g. engine torque estimation (ETE) inaccuracies) and system parameter uncertainties (SPU) (e.g. stiffness and damping uncertainties of the TDS and drive shaft) can also lead to the jerk and vibration of the powertrain [9]. Therefore, in order to improve the driving comfort, research efforts have been put into analyzing system dynamic characteristics (SDC) using a powertrain dynamic simulation model (plant model) and studying dynamic coordinated control strategy (DCCS) during the MT process.

For the PS-HEVs, measures have been taken to suppress the jerk and vibration of the powertrain system. Such measures include establishing a simplified engine torque physical model (ETPM) [10,11], creating an ERT approximation function [12], and using an ETE method based on motor torque feedback values (MTBV) [13,14]. Then based on these measures, motor torque compensation control is used to improve the driving comfort. Most of these methods took into account the ERT, but only feedforward or feedback single ETE method was used and the characteristics of the ETE model before and after engine ignition, and the influence of MEI and SPU on the powertrain system were neglected. Zeng [15] limited the power source torque change rate to improve the driving comfort, but ignored the ERT. Zhuang [16] used the dynamic programming algorithm to optimize the appropriate torque and brake pressure, but this method is mainly adopted to provide guidance for the formulation of control strategy and can not be used for real-time control. Besides, to suppress the ripple torque that passes to the wheels, a motor active damping and weighted feedback filtering control method [17] and an active damping control method based on PID control [12] have been proposed. However, the MEI and SPU were neglected by these methods, so their robustness in practice is not satisfactory. Several control methods are proposed to cope with the jerk and vibration caused by the SPU, such as the method based on online parameter identification [9], the fuzzy adaptive sliding mode control [18], the H_∞ robust coordinated control method [19] and the $m\mu$ integrated robust control method [20,21]. However, these methods not only neglected the ERT but also mainly solve the coordinated control problem of clutch engagement process for a parallel HEV. In addition, these works did not establish a detailed plant model to analyze the SDC of a powertrain, and thus could hardly provide guidance for the development of DCCS.

For the PS-HEV considered in this paper, a simplified ETPM method can be used before engine ignition due to its simple structure and suitability for feedforward control. After ignition the engine speed becomes higher (greater than 800 rpm) [14] and the ERT has little effect on system jerk and vibration, the use of an ETE method based on the MTBV is simpler than the ETPM method, avoiding the effect of ignition and injection on the estimated model. Therefore, the staged ETE compensation control may become a choice. However, factors such as the MEI and SPU make it difficult to completely compensate the fluctuation torque, if only the ETE compensation control method is used. As a result, the uncompensated fluctuation torque will be transmitted to the wheels by the drive shaft and in turn jeopardize the driving comfort. To solve this problem, this paper designs a drive shaft torque (DST) observer with robust and real-time performance, and employs the motors to perform feedback compensation control for the drive shaft torque estimation (DSTE) (i.e. active damping feedback compensation control (ADBC)).

Therefore, different from the existing solutions, we aim to develop a DCCS including "a staged ETFBC and a DSTE-based ADBC" during the MT process, in order to suppress the jerk and vibration of the powertrain. This study shows the following three major contributions: (1) A detailed plant model, including the ERT model and the planetary dynamic model etc., is established to reflect the SDC with higher accuracy. (2) The characteristics of the ETE model before and after the engine ignition are taken into account, and the motor torque compensation control based on the ERT model feedforward estimation before engine ignition and the ERT estimation with motor feedback values after ignition is developed. (3) The MEI, SPU and load change are considered, and a DSTE-based ADBC is designed for all work modes, which presents good robustness and real-time performance.

The rest of this paper is organized as follows: In Section 2, the plant model is established, and then the MT process and problems are analyzed. In Section 3, the detailed DCCS is developed. In Section 4, the proposed DCCS is validated using the plant model. In Section 5, some concluding remarks are provided.

2. Powertrain dynamic modeling and analysis

In this paper, a compound PS-HEV based on the Ravigneaux planetary gear set (shown in Fig. 1) is investigated. This is a typical power-split HEV configuration, which will been applied on a *Changan* HEV. S_1 and P_f are the small sun gear and the front planetary gear, respectively. S_2 and P_r are the big sun gear and the rear planetary gear, respectively. C represents the sharing planetary carrier. R denotes the sharing ring gear, whose output torque drives the vehicle. The big motor 2 (MG2) is connected to the S_2 shaft. The small motor 1 (MG1) is connected to the S_1 shaft and it can be locked by the brake B_2. The engine is connected to the carrier shaft by the TDS and can be locked by the brake B_1.

2.1. Dynamic modeling

To ensure that the plant model is accurate enough to reflect the SDC and to verify the effectiveness of the strategy, a detailed plant model including engine, battery, motor, compound power-split transmission and brake, is established in the *MATLAB/Simulink* environment.