Clutch Control Strategy of Driving Mode Transition for P2 Hybrid Electric Vehicle

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Abstract. Clutches are widely utilized for not only implementing gear shifting but also transmitting power in hybrid electric vehicles (HEVs). During the driving mode transition in a P2-structure HEV, the coordination of between power sources, such as engine and electric motor, is realized by a hybrid clutch. Therefore, it is of great significance to establish a control strategy for the hybrid clutch ensure drivability and driving comfort. In this study, a physical model of the hybrid clutch and other relevant components in the hybrid system is established in MATLAB/Simulink firstly. Then, a model-based coordinated control strategy is developed for the hybrid clutch during the driving mode transition. The hydraulic oil filling and torque transferring characteristics of the hybrid clutch are mainly considered in the control strategy. Finally, the proposed control strategy is validated by simulation and the results show that the quality of driving mode transition is obviously improved.

1. Introduction

As the energy shortage and environmental pollution problems are becoming increasingly serious, there is a worldwide trend for developing hybrid electric vehicles (HEVs) in the automotive industry. HEVs have multiple power sources and can be operated under variable conditions at different driving modes, such as electric motor driving mode, engine driving mode and hybrid driving mode. In a P2-structure HEV, shift clutches are utilized for gear shifting, while a hybrid clutch transmits power from engine or electric motor to the transmission. To ensure drivability and driving comfort during driving mode transition, the control of the hybrid clutch is necessary. Researches have been made to analyse the fluctuation in vehicle speed and engine torque during the connecting and disconnecting of hybrid clutch. There still exists some challenges in the control process of hybrid clutch, such as establishing specific control strategy for different phases in clutch fill process and reducing vehicle jerk during mode transition.

There are several studies that focus on this theme. Zhao Zhiguo proposed a robust control algorithm that resists external disturbance and model parameter fluctuation, which takes full advantage of fast and accurate torque (or speed) response of three electrical power sources and gets the clutch of DCT fully involved in the mode transition process [1]. In the study of Kumar Sushil, the control strategies for power flow management of a HEV were developed based on a supervisor controller which uses various torque and SOC checks to determine driving mode [2]. Su Yanzhao developed a dynamic coordinated control strategy (DCCS), including a staged engine torque feedforward and feedback estimation (ETFBC) and an active damping feedback compensation (ABDC) based on drive shaft torque estimation (DSTE) [3]. In the research of Schori Markus, the theory of hybrid optimal...
control was used to automatically calculate lookup tables for optimal gear shifts, optimal torque-split between motor/generator was designed to perform the accurate position tracking control, especially when the parameters uncertainties and external disturbance occurred in the clutch actuating mechanism [4]. In the study of Yang Chao, a novel robust hierarchical mode transition control method for a plug-in hybrid electric bus (PHEB) with pre-transmission parallel hybrid powertrain was presented, in which a hierarchical control structure including two robust controllers in both upper layer and lower layer was proposed based on the divided five stages of clutch control [5]. Lei Zhenzhen proposed the coordinated control strategy (including fuzzy logic control and PID control) of clutches to implement the mode transition and shifting simultaneously, which can solve the conflict between mode transition and DCT shifting in a HEV [6].

This study established a physical model of the hybrid clutch and other components in the hybrid system of a HEV in MATLAB/Simulink firstly. Then, a model-based coordinated control strategy is developed for the hybrid clutch during the driving mode transition. In the proposed control strategy, the hydraulic oil filling and torque transferring characteristics of the hybrid clutch are mainly considered. Finally, the control strategy is validated through simulation. The results show that the quality of driving mode transition is successfully improved.

2. Configuration of P2-structure HEV

As shown in Figure 1, the P2 structure of HEV in this study mainly consists of an engine, a hybrid clutch, an 8-speed automatic transmission (8AT), a dual mass flywheel (DMF) and an electric motor. The engine and electric motor are controlled by engine control unit (ECU) and motor control unit (MCU) respectively. The control of 8AT and the hybrid clutch is implemented in transmission control unit (TCU). The driving mode transition is realized by the coordination of ECU, MCU, TCU and hybrid control unit (HCU).

![Figure 1. Schematic of P2 structure.](image)

As presented in the schematic, the power generated from engine and electric motor can be transmitted to the drive shaft of HEV through the 8AT. The hybrid clutch is disconnected with the engine when electric motor driving mode is operated, which indicates the electric motor works as the power source. The hybrid clutch engages when there is a command signal that the transition to engine driving mode or hybrid driving mode need to be executed. During this process, the engagement of the hybrid clutch can be influenced by several factors, such as the characteristics of DMF, the ignition of the engine and the rotational speed of the electric motor.

3. Models and analysis of hybrid system

To achieve clutch control in the hybrid system, the models of the engine, the hybrid clutch, 8AT, DMF and the electric motor are developed and analysed.

3.1. Engine model
Considering the rigid-body motion of piston in the engine, the output torque of the engine \( (T_E) \) can be expressed as

\[
T_E = T_{Ep} - T_{Ef} - T_{Ei}
\]

where \( T_{Ep} \) is the cylinder pressure torque, \( T_{Ef} \) is the viscous friction torque, and \( T_{Ei} \) is the equivalent inertia torque.

### 3.2. Hybrid clutch model

A hyperbolic tangent function \((tanh)\) model is utilized in the modeling of the hybrid clutch. The maximum torque that can be transferred by the clutch, which is also named as the torque capacity of the clutch \((T_{C,cap})\), is determined by the control pressure of the clutch. The torque capacity is calculated by

\[
T_{C,cap} = \mu_s \cdot (P_{C,crl} - P_{C,kp}) \cdot A_p \cdot r_c \cdot z
\]

where \( \mu_s \) is the static friction coefficient, \( P_{C,crl} \) is control pressure of the clutch, \( P_{C,kp} \) is the kiss-point pressure of the clutch, \( A_p \) is the cross-section area of the piston, \( r_c \) is the equivalent radius of the friction plates, \( z \) is the number of friction pairs in the clutch.

When the slip between the two axes that connected by the clutch equals to zero, the clutch is in the state of rigid connection. In this state, the actual torque that transferred by the clutch \((T_C)\) is less than or equal to the \( T_{C,cap} \). However, if the slip is not eliminated, the actual torque \( T_C \) can be calculated by the \( tanh \) model, which can be expressed as

\[
T_C = \mu_d \cdot (P_{C,crl} - P_{C,kp}) \cdot A_p \cdot r_c \cdot z
\]

\[
\mu_d = \mu_s \cdot \tanh\left(\frac{\Delta \omega}{\Delta \omega_c}\right)
\]

where \( \mu_d \) is the dynamic friction coefficient, \( \Delta \omega \) is the rotation speed difference between the two axes, \( \alpha_c \) is an adjustable parameter, whose function is shown in Figure 2.

![Figure 2. Different tanh models.](image)

In the \( tanh \) models, the limitation for \( \Delta \omega \) is \( \Delta \omega \leq 5\,rpm \). The value of \( \mu_d \) is determined to be 0.106 when \( \Delta \omega \leq \Delta \omega_l \).

### 3.3. 8AT model

In this study, the input and output torque of 8AT can be calculated based on the kinematic and dynamic equations developed by the parameters and limitations in the transmission. The relationship between the input and output angular acceleration of the transmission \((\dot{\theta}_{in}^{'}, \dot{\theta}_{out}^{''})\) can be expressed as

\[
\dot{\theta}_{in}^{' \prime} = l_T \cdot \dot{\theta}_{out}^{''}
\]

where \( l_T \) is the total ratio of the transmission.
3.4. DMF model
The major function of DMF is to reduce the fluctuation of the engine torque and maintain the response speed of the engine output. A simplified model of DMF is developed as

\[ J_{D, pri} \ddot{\theta}_E + J_{D, sec} \ddot{\theta}_D = T_D - k_D \varphi_D - c_D (\dot{\theta}_E - \dot{\theta}_D) \]  
(6)

\[ J_{D, pri} \dot{\theta}_E + J_{D, sec} \dot{\theta}_D = -T_{C, Fr} + k_D \varphi_D + c_D (\dot{\theta}_E - \dot{\theta}_D) \]  
(7)

\[ \varphi_D = \theta_E - \theta_D \]  
(8)

where \( J_{D, pri} \) and \( J_{D, sec} \) are the inertia of primary and second mass, \( k_D \) is the torsional rigidity of the arc spring, \( c_D \) is the rotation damping coefficient, \( \theta_E \) and \( \theta_D \) are the rotation angle of the primary and second mass, \( \varphi_D \) is the displacement angle of DMF, \( T_{C, Fr} \) is the torque transferred to the front of hybrid clutch.

3.5. Electric motor model
In this study, the electric motor is directly controlled by MCU. The actual torque of electric motor can be expressed as

\[ T_M = \begin{cases} T_{M, cmd} & \text{if } |T_{M, cmd}| < T_{M, max}(n_M) \\ \text{sign}(T_{M, cmd}) T_{M, max}(n_M) & \text{if } |T_{M, cmd}| \geq T_{M, max}(n_M) \end{cases} \]  
(9)

where \( T_{M, cmd} \) is the command torque of electric motor, \( T_{M, max}(n_M) \) is the maximum torque when motor speed is \( n_M \).

4. Clutch control strategy
The dynamic control flowchart of clutch in this study can be illustrated as shown in Figure 3. The characteristics of torque-pressure transferring (T2P) and pressure-current transferring (P2C) are derived from the look-up tables stored in TCU. The clutch pressure is controlled by a direct proportional control valve.

![Figure 3. Control flowchart of clutch.](image)

During the mode transition, the engine is started and engaged into the powertrain through the engagement of the hybrid clutch. And the driving torque for the vehicle operation and the engine-start is provided by the electric motor. To describe oil filling and torque transferring characteristics of the clutch during mode transition, this study divides this process into six stages, as shown in Figure 4.

Stage 1: The mode transition starts and the command pressure of the hybrid clutch \( (P_{C, cmd}) \) is fixed at a high level to realize a fast-filling. Free displacement of clutch piston is diminished. A pulse of clutch torque \( (T_C) \) is produced due to the high-level pressure. The torque is used to start the engine by acting on the output shaft of the engine via DMF.

Stage 2: \( P_{C, ctri} \) is fixed at a low level to reach the kiss-point. The engine speed \( (n_E) \) is regulated actively due to the ignition. The torque produced by the engine is negative for the input shaft of 8AT and the vibration produced by ignition can be transmitted to the transmission via the clutch. In order to ensure the comfort, the clutch can be disconnected temporarily. This stage ends when \( n_E \) is larger than the electric motor speed \( (n_M) \). The torque that the engine transmits to the input shaft is mainly determined by the clutch pressure in this stage.

Stage 3: \( P_{C, ctri} \) increases to achieve the balance between the engine torque \( (T_E) \) and \( T_C \). The value of \( n_E \) keeps rising when the torque that transferred by clutch is smaller than \( T_E \). The peak of the engine speed is crucial for achieving high-quality control of the whole process.
Stage 4: The slip is eliminated via the control of clutch pressure. $P_{C,\text{ctrl}}$ is adjusted to adapt to the continuous changes in engine torque.

Stage 5: A rapid increase in $P_{C,\text{ctrl}}$ is executed to achieve the quick engagement of clutch. This stage ends until the pressure reaches the maximum and the clutch is locked.

Stage 6: The exchange of torque is realized between the engine and the electric motor. And the torque control strategy in the following phases can be implemented after this stage.

**Figure 4.** Schematic diagram of mode transition process.

### 5. Simulation results

The simulation results of the clutch control in this study are shown in Figure 5. In the simulation, the mode transition from the electric motor driving mode to the hybrid driving mode starts when the vehicle speed reaches the pre-set threshold value. According to the model of the hybrid clutch, the final compressed pressure of the clutch is 20bar.

Before the execution of the control strategy, the torque produced by the hybrid clutch does not properly match the output torque of the electric motor ($T_E$), as shown in Figure 5 (a). Meanwhile, a response delay in the actual pressure of the clutch ($P_C$) occurred in low-level filling process to reach the kiss-point pressure. Thus, this mismatching leads to the fluctuation in the input shaft torque of 8AT ($T_{in}$) and the flare of the engine speed $n_E$, which has a bad influence on the driving comfort. In the simulation, the speed flare of $n_E$ is over 300 rpm.

Due to the occurred jerk during the mode transition, the adjustment in the clutch control is executed in the next mode-transiting case based on the control strategy. The control pressure of the hybrid clutch $P_{C,\text{ctrl}}$ is adapted. As shown in in Figure 5 (b), the command value during the low-level filling process of the clutch increased. The torque exchange between the engine and the electric motor is
smooth and fast, which shortens the period of mode transition. Moreover, it is obvious that the fluctuation in \( n_E \) is diminished to an acceptable level.

The jerk is relieved after the adjustment and the performance of the control strategy is proved to be effective. The simulation results indicate that the quality of driving mode transition is obviously improved.

![Figure 5. Simulation results.](image)

6. Conclusions
This study focused on the clutch control problems that may occur during the driving mode transition for P2-HEV. The models of the hybrid clutch and other components in the hybrid system are established in MATLAB/Simulink. A model-based clutch control strategy is developed to achieve high-quality mode transitions in the hybrid system. In the proposed control scheme, the hydraulic oil filling and torque transferring characteristics of the hybrid clutch are mainly considered based on the previous jerks. The simulation results show that the quality of driving mode transition is successfully improved.

In the future work, the temperature of the hydraulic oil and the wear of the friction plates in the hybrid clutch will be considered in the design of clutch control strategy. Detailed adaptive methods will be used to achieve high-quality mode transitions when the driving mode changes frequently.

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