Research on Characteristics Analysis and Dynamic Coordination Control of the Hybrid Electric System Coupling Mechanism

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Abstract. As the key component of hybrid electric vehicles (HEV), the dynamic performance of the power coupling mechanism is found to have a significant effect on the power switching process for the whole vehicle. The research object is the double planetary gear coupling mechanism of hybrid electric vehicles. Through analysis of the relationship between each power source and the planetary gear, this paper obtained the characteristics of a dynamic coupling mechanism under non-steady state (such as engine starting). On the basis of this coupled system, a dynamic coordinated control method is proposed based on model predictive control under unsteady engine operating conditions. The results show that the dynamic coordinated control strategy can effectively reduce the impact of the whole vehicle mode switching, the dynamic coordinated control strategy is adopted, the mode switching process of the power coupling mechanism (engine starting conditions) works smoothly, reducing the total output torque shock, which is conducive to improving the vibration and noise level of the vehicles.

1. Introduction

It is known that the power coupling mechanism is a key component for coupling the hybrid vehicle engine and motor output power. In the dual-motor hybrid system, the motors MG1 and MG2 are used as the power source together with the engine, coupled through the input end connected to the planetary gear coupling mechanism, and finally transmitted to the vehicle part through the output end [1]. However, the power coupling mechanism must withstand the steady-state load of each power source input and the transient impact during the power switching process. The resulting vibration and noise directly affect ride comfort. Therefore, the vibration and noise of the power coupling mechanism is becoming more and more prominent for HEV[2].

The dynamic characteristics of the planetary gear system centered on the gear pair, impact, vibration and gear system noise laws during power transmission were studied [3]. The planetary gear train transmission process is affected by dynamic excitation such as time-varying stiffness excitation, error excitation and shock excitation [4-6], which makes the dynamic characteristics of the dual planetary-row dynamic coupling system complex and variable. Previous studies on the multi-mode dynamics of the compound planetary gear train including the entire drive train and structural system are rare. To explore the transient impact of the dynamic coupling mechanism influence on vehicle vibration and noise characteristics during the mode switching process. The mode switching process...
was selected as the research condition. The stability of the dynamic characteristics was studied during the mode switching of the coupling mechanism. And on the basis of the coupling mechanism, a dynamic coordinated control strategy was adopted to verify the feasibility of the control strategy[7].

2. Dynamic Analysis of Planetary Hybrid System

The planetary hybrid power coupling mechanism can realize the decoupling of engine speed, torque and road load within the constraint range, so that it is easy to achieve the optimal control of the engine, reduce the impact of the transmission system, and improve the smoothness of the vehicle [8].

It can be seen from Figure 1 that the power coupling mechanism system consists of two rows of planetary gears. The front row is a power distribution planetary gear. The front sun gear is connected to the MG1 motor. The front row planet carrier is connected to the engine through a torsional vibration damper. The rear row is a motor reduction planetary gear, and the rear row sun gear is connected to the MG2 motor. The row of planet carriers is fixed. The front and rear rows share the composite ring gear, and the power of the system is finally output to the reduction gear to drive the vehicle through the composite ring gear. The system flexibly switches between and combines different power sources of the engine and the motor depending on the vehicle driving demand.

![Fig. 1 Power coupling system](image1)

1— Engine, 2— Torsional damper, 3— MG1 Motor, 4a— Power distribution planetary row, 4b— Motor deceleration planetary row, 5— MG2 Motor, 6— Composite ring gear, 7— Main reducer gear, 8— Drive axle

![Fig. 2 Block diagram of power split](image2)

The power split of the system is shown in Figure 2. The front planetary row in this system determines the power splitting characteristics of the system, and the rear planetary row affects the motor torque and speed range[9].

Without considering the friction loss and rotational inertia of the system itself, the relationship between the basic speed and torque of the planetary gear mechanism can be obtained by Equation (1), (2):
where $r$ is the rotation, $\omega$ is the speed, $k_1$ is the characteristic parameters of the front planetary row, $k_2$ is the characteristic parameters of rear planetary row, $C1$ is the planetary carriers of the front planetary row, $C2$ is the planetary carriers of rear planetary row, $S1$ is the sun gears of the front planetary row, $S2$ is the sun gears of rear planetary row, $R1$ is the ring gears of the front planetary row, $R2$ is the ring gears of the rear planetary row.

By further analyzing the relationship between the planetary gears of each power source, the relationship between the system's output torque and speed can be obtained,

\[
\begin{align*}
T_{out} &= \frac{k_1}{1+k_1} T_{e} + \frac{1}{1+k_2} T_{m12}, \quad r = \omega_{e} + \omega_{g} \\
\omega_{out} &= \frac{\omega_{e}(1+k_1) - \omega_{g}}{k_1} \frac{\omega_{m}}{l_2}
\end{align*}
\]  

(3)

Where out, e, g and m represent the system output shaft, engine, motor MG1 and motor MG2.

3. Mode switching dynamic coordination control strategy

3.1 System Mathematical Model

According to the relationship between each power source and the planetary gear, the dynamic relationship of the front planetary row can be obtained, as shown in Equation 4 and 5[9].

\[
\begin{align*}
\begin{bmatrix}
I_{c1} + I_{g} & 0 & 0 & \omega_{c1} \\
0 & I_{c1} + I_{g} & 0 & \omega_{c1} \\
0 & 0 & I_{c1} & \omega_{c1}
\end{bmatrix}
= \begin{bmatrix}
F_e & -(R_{c1} + R_{c}) \\
R_{c1} & R_{c}
\end{bmatrix}
+ \begin{bmatrix}
T_e \\
-T_{c1}
\end{bmatrix}
\end{align*}
\]  

(4)

\[
\begin{align*}
\begin{bmatrix}
I_e & 0 & \omega_{e} \\
0 & I_e & \omega_{e}
\end{bmatrix}
= \begin{bmatrix}
T_{e} \\
-T_{c1}
\end{bmatrix}
\end{align*}
\]  

(5)

Where $I$, $\omega$, $T$, $R$ represent the moment of inertia, angular velocity, torque and radius, $F_i$ represents the internal force of the front planetary row. The subscripts e and g indicate the engine and motor MG1. Combining equations (4) and (5), the input of the front planetary row can be obtained by Equation (6).

\[
\begin{align*}
\begin{bmatrix}
I_{c1} + I_{g} & 0 & 0 & \omega_{c1} \\
0 & I_{c1} + I_{g} & 0 & \omega_{c1} \\
0 & 0 & I_{c1} & \omega_{c1}
\end{bmatrix}
= \begin{bmatrix}
F_e & -(R_{c1} + R_{c}) \\
R_{c1} & R_{c}
\end{bmatrix}
+ \begin{bmatrix}
T_e \\
-T_{c1}
\end{bmatrix}
\end{align*}
\]  

(6)

According to the rotation speed relationship of the planetary gear mechanism, the rotation speed relationship of each component of the front planetary row can be obtained by Equation (7).

\[
\omega_{e}(1+k_1) = \omega_{c1} k_1 + \omega_{g}
\]  

(7)

Similarly, according to the dynamics and connection relationship of the rear planetary row, the relationship between the input and output of the rear planetary row can be obtained by Equation (8).
\[ \begin{bmatrix} I_m + I_{c1} \\ 0 \\ 0 \\ 0 \\ 0 \\ I_{c2} \end{bmatrix} \begin{bmatrix} \omega_m \\ \omega_{c1} \\ \omega_{c2} \end{bmatrix} = \begin{bmatrix} -R_{c2} \\ R_{c2} + R_{c2} \\ -T_{c2} \end{bmatrix} \begin{bmatrix} I_m \\ -I_{c1} \end{bmatrix} \] \tag{8}

The subscript \( m \) represents the motor MG2. It is the internal force of the rear planetary row.

According to the rotation speed relationship of the rear planetary row, the rotation speed relationship between the motor MG2 and the output shaft can be obtained by Equation (9).

\[ \begin{align*}
\omega_{c2} &= \frac{\omega_m}{k_2 + 1} \\
\omega_{c1} &= \omega_{c2}
\end{align*} \tag{9} \]

\subsection*{3.2 Model predictive controller design}

According to the principle of the model predictive controller, the designed model predictive control structure is shown in Figure 3. At the moment when the model predictive controller starts to function, the future state of the system is predicted based on the feedback of the vehicle control model. The controller obtains the optimal control amount by solving the optimization problem. That is, the engine torque optimal control, the motor MG1 torque coordination control, and the motor MG2 active compensation control, Then each component is controlled in response to the optimal torque. During the engine starting process, quadratic programming can be used to achieve optimal torque control of MG1, and model prediction to achieve active compensation control of motor MG2, which effectively achieves dynamic coordinated control of the mode switching process.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{model_preactive_controller_structure.png}
\caption{Model predictive control structure diagram}
\end{figure}

\section{Simulation Analysis of Dynamic Coordinated Control during Engine Startup}

A hybrid electric vehicle power system is complicated in structure and has a variety of working conditions. Therefore, the vibration and noise characteristics have changed significantly compared with ordinary internal combustion engine vehicles. The engine of a hybrid vehicle needs to start and stop frequently during operation, and the transient shock vibration noise caused by power switching is particularly obvious when the pure electric mode is switched to the engine-motor combined drive mode [10]. In this paper, the dynamic characteristics of the dynamic coupling system were selected in the hybrid power train switching condition (engine starts under pure electric conditions).

To study the dynamic characteristics of the mode switching power coupling mechanism, Here, the simulated engine starting process was selected as an example, and the dynamic coupling mechanism was simulated and analyzed by applying a corresponding load and driving.

During the engine starting process, the engine and the motor MG1 jointly output torque, implement the motor MG1 torque coordinated control, and contribute to the engine speed. When the motor MG1 outputs positive torque, the system generates shock in the negative direction. In order to reduce the shock at this time, the motor MG2 should be used for active torque compensation control.

In this paper, the starting conditions of the hybrid vehicle engine are selected to analyze the dynamic characteristics of the power coupling system. As a result, the power switching of the system's
power coupling system is stable, which is conducive to improving the vibration and noise level of the vehicle.

Based on the dynamic coupling mechanism system, by analyzing the dynamic characteristics of each power source and the dynamic characteristics of the dual planetary row dynamic coupling mechanism, the basic theoretical analysis of mode switching is applied, and they are converted into simulation models for simulation analysis and verification. The simulation results are shown in Figure4-5.

Fig. 4 Output torque of each power source before coordination

Fig. 5 Output torque of each power source after coordination

It can be seen from Figure4 and Figure 5, In the process of mode switching, before coordinated control is adopted, each power source is controlled according to the target torque, the motor responds quickly, and the engine responds slowly, and the target torque cannot be quickly reached. after adopting dynamic coordinated control, the motor does not immediately change according to the original target torque at the moment of switching, but instead compensates for torque fluctuations caused by the slow engine start to reduce the impact and fluctuation of output torque.
Fig. 6 Change of impact degree before and after coordination

As can be seen from Figure 6, the comparison effect of the impact of the whole vehicle before and after the dynamic coordination control in this process can be seen. There is a sudden change in the impact of the vehicle before the coordination, and the impact of the vehicle after the coordination is stable.

5. Conclusions

This paper analyzed the dynamic characteristics of the coupling mechanism for the pure electric to engine starting mode switching process of the hybrid power system. A dynamic coordinated control method is proposed based on model predictive control, and simulation experiments were carried out. The results show that the dynamic coordinated control strategy can effectively reduce the impact of the whole vehicle mode switching, ensure the smoothness of the mode switching, and verify the effectiveness of the proposed control strategy. It is of great significance to study the process of mode switching of hybrid electric vehicles.

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