Coordinated Control of Downshift Powertrain of Combined Clutch Transmissions for Electric Vehicles

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Abstract

In order to improve the shift quality of electric vehicles equipped with combined clutch transmission, a dynamic model of shifting process is established. The shift jerk and friction work are chosen as a comprehensive control target. Linear quadratic optimal control to optimize the shifting process of planetary transmission is used, in which motor is involved. The simulation results show by the coordinated control of the motor torque and oil pressure the shift jerk and friction work are decreased by 32% and by 48% respectively, compared with combined clutch control only.

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1. Introduction

Electric vehicles (EVs) are paid wide attention to in recent years. To keep climbing and high speed performance, large EVs need transmissions with fewer gears. The two-speed planetary transmission studied in this paper uses planetary gear set to change the gear ratio, but the torque converter is removed, therefore it integrates the advantages of automatic transmissions and automated mechanical transmissions [1]. The essence of coordinated control of power is coordinated control of the engine/motor and clutch to improve shift quality. With respect to engine vehicles, M. Goetz [2] studied integrated powertrain control on twin clutch transmissions, and a gearshift controller is developed. With regard to EVs, Hu Jianjun and Zhang Chengning et al. [3-4] presented a control strategy of the motor torque and speed to perform the smooth gear shifts in AMTs without releasing the clutch. However, at present the research on coordinated control for clutch-to-clutch shifting isn’t so common.

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This paper studies two-speed combined clutch transmission for EVs. The motor torque and pressure of combined clutch are coordinately controlled to improve shift quality by linear quadratic optimal control.

2. System description and dynamic model

The clutch/brake pistons of combined clutch are structurally connected. The shift actuator adopts a single hydraulic system to drive the brake piston to complete the shift action. The structure diagram of powertrain with combined clutch transmission adopted by this paper is shown in Fig. 1.

![Fig. 1 The structure diagram of powertrain with combined clutch transmission](image)

During downshift, hydraulic oil fills brake cylinder, making clutch C disengaged. Then there is a free phase, where both clutch and brake are disengaged. Lastly, brake B engages. When it’s engaged fully, the powertrain operates in the 1st gear with speed ratio \( k+1 \) (\( k \) is the ratio of the number of teeth of ring gear and sun gear). The focus is put on the downshift in this paper, which is divided into three phases: clutch C disengagement phase, free phase, and brake B engagement phase.

Combined clutch transmission shifting dynamics model can be expressed in the following form [5]:

\[
\begin{bmatrix}
J_{11} & J_{12} \\
J_{21} & J_{22}
\end{bmatrix}
\begin{bmatrix}
\dot{\omega}_m \\
\dot{\omega}_b
\end{bmatrix} =
\begin{bmatrix}
T_m - \frac{1}{k} T_{br} - \frac{k+1}{k} T_{cl} \\
-\frac{k+1}{k} T_{br} + \frac{k+1}{k} T_{cl} - T_f
\end{bmatrix}
\]

\( J_{11} = J_1 + J_r a_{11}^2 + J_p a_{12}^2, J_{12} = J_{21}, J_{22} = J_2 + J_r a_{12}^2 + J_p a_{22}^2 + m r_c^2. J_f, J_2, J_r, J_p \) are the equivalent moment of inertia of motor, vehicle, ring gear and planet gears individual. \( r_c \) is the distance between sun gear and planet gears. \( T_m, T_{cl}, T_{br}, T_f \) are torque of motor, clutch, brake and resistance. \( \omega_m, \omega_r, \omega_b \) are the angular speed of motor, transmission output shaft and ring gear respectively.

3. Optimal control for downshift

The shift jerk is to evaluate the smoothness, and the friction work to evaluate dissipated energy, which has positive correlation with the shift time[6]. Since the three phases have a lot in common in optimal control, this paper only studies the clutch disengagement phase in detail.

Considering the shift jerk and sliding friction work of downshift process and the coordinated control idea, the following state variables, control variables are introduced below

\[
x_1 = \omega_m - \omega_r, x_2 = T_m, x_3 = T_{cl}, u_1 = \frac{dT_m}{dt}, u_2 = \frac{dT_{cl}}{dt}
\]

During clutch C disengagement phase, \( T_{br}=0 \), and considering state variables and control variables, equation (3) can be expressed below

\[
\dot{X} = AX + BU + V
\]
In this phase, the shift jerk $j$ and the friction work $W$ are expressed as equation (4). For a compromise of evaluation criterions in contradiction, an objective function $J$ is proposed as equation (5).

\[
j = \frac{r_w}{i_0(J_{11}J_{22} - J_{21}J_{12})} \times \left[ a_{12}(J_{11} + J_{21})u_2 - J_{22}u_1 \right], \quad W = \int_0^{t_m} T_c (\omega_w - \omega_j)dt = \int_0^{t_m} x_i x_j dt
\]

\[
J = \frac{1}{2} \int_0^{t_m} (W + \eta j^2)dt = \frac{1}{2} \int_0^{t_m} \left( x_i x_j + \eta \left[ a_{12}(J_{11} + J_{21})u_2 - J_{22}u_1 \right]^2 \right) dt
\]

Where, $r_w$ is wheel radius. $i_0$ is main reducer ratio. $\eta (0 < \eta < 1)$ is weight coefficient of the shift jerk. $t_m$ is the end time of this phase. According to

\[
T = \mu NR_e \left[ F_s - pA \right]
\]

Where $T$ is the clutch/brake transmission torque. $\mu$ is the friction coefficient of clutch disc. $R_e$ is effective radius of clutch disc. $N$ is the number of disc. $A$ is the piston area. $p$ is the oil pressure.

So, the motor torque and oil pressure curves can be obtained by solving the Riccati equation.

4. Simulation results and analysis

Based on the MATLAB, a simulation model is built up to analyze the above shifting control. Fig 2 displays the simulation results. Let us suppose that the throttle opening is 50% and road ramp is 5% at the beginning of the shifting process.

In Fig 2.(c), $n_m$ represents the motor speed, $n_o$ indicates the transmission output shaft speed, and $n_r$ shows the ring gear speed. As can be seen from profiles of the motor torque of coordinated control, in free
phase, the motor torque is increased to regulate the gear ring speed to the specified range. From (b), after shifting, the oil pressure is raised to the main pressure in the hydraulic system. The rapid increase of oil pressure will not affect the driving comfort for the driving and driven parts of the brake already have achieved synchronization.

It should be noted that the oil fills combined clutch promptly without control, once the reversing valve opens. Thus, shift time is very short, which makes friction work less than the clutch control only and shift jerk reaches up to 50 m/s³. By the coordinated control of power, the maximum shift jerk and friction work are 5.1 m/s³ and 1.34 KJ, which are decreased by 32% and by 48% respectively, compared with combined clutch control only.

5. Conclusion

The combined clutch studied in this paper whose clutch and brake are structurally connected is significant different from the traditional wet clutch. Single hydraulic system is enough to complete the shift action, oil pressure acting on the brake piston only. This structural difference leads to distinct shifting process. Downshift as presented is divided into three phases: clutch C disengagement phase, free phase, and brake B engagement phase.

The dynamic coordinated system for EVs regards the motor and transmission as a whole. Through coordinated control of the motor torque and the oil pressure of combined clutch, the shift jerk is reduced. Meanwhile, the shift time can be lowered, and then the friction work is decreased by a large margin. In other words, an effective method is provided to solve the shifting problem.

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References


Biography

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