Research and Control of Shift Without the Disengagement of the Clutch for Automatic Mechanical Transmission in Hybrid Vehicle

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Abstract For the technical requirements of hybrid electric vehicle (HEV) equipped with automatic mechanical transmission (AMT), this chapter proposed an AMT control technology that shifts without the disengagement of the clutch. The technology' system components, working principle, engine and motor' control during shifting process and other key technologies were analyzed. Through dynamically modeling the various stages of shifting process, the shift characteristics and key factors affecting the quality of shifting were known. At the same time, a demo car without the disengagement of the clutch was tested. The results indicated: through controlling of engine, motor and AMT actuator, the HEV' AMT equipped without disengagement clutch can not only ensure smooth shifting, but also can effectively shorten the shift time, improve the shift quality significantly.

Keywords Hybrid vehicle · Automatic mechanical transmission · Shift without disengaging clutch · Shift quality · Coordinated control

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1 Introduction

Hybrid vehicle with automatic mechanical transmission (AMT) can achieve driving states such as pure electric, pure engine driving and hybrid driving etc. through the mode clutch separation and combination [1]. The shifting process under the engine and motor hybrid driving state is the most complex. So this chapter mainly studies the shift process coordinated control method under hybrid driving state.

In the shifting process of AMT, shifting impacts are mostly caused by the clutch separation and combination. The shift without the disengagement of the clutch technology can not only avoid the impacts of clutch separation and combination, reduce the controlling difficulty, but also shorten the shifting time effectively, improve the shifting quality [2].

For complexity of the hybrid vehicles power assembly, its control strategy for the shifting process has large differences with the traditional automobile [3]. Under hybrid driving state, to realize shift without the disengagement of the clutch needs controlling for the two power sources, the engine and the motor, at the same time, the controlling effects will directly affect the vehicle shift quality and driving performance. Therefore the coordinated control of engine and motor in the hybrid vehicle shift process is the key to achieve shifting without disengaging the clutch, to improve the shift quality and to enhance the driving performance [4].

2 System Composition and Working Principle

This chapter is based on a hybrid vehicle with 6-speed AMT as a development prototype, its forward gears with constant mesh gear transmission and it realizes shifting through the lock ring synchronizer, when reverse, it shifts with straight tooth sliding gear.

2.1 System Composition

Figure 1 is a hybrid vehicle AMT system composition diagram. Power provided by engine and motor, via a 6-speed gearbox, transmission shaft, final drive, eventually transmitted to wheels to drive the vehicle. AMT system consists of gear box, select and shift actuator, clutch, clutch actuator, Transmission Control Unit (TCU) and the corresponding position sensors and other components. TCU and Vehicle Control Unit (VCU), Engine Control Unit (ECU), Motor Control Unit (MCU) and Battery Management System (BMS) realized information interaction through the CAN bus and combined to control vehicle running.

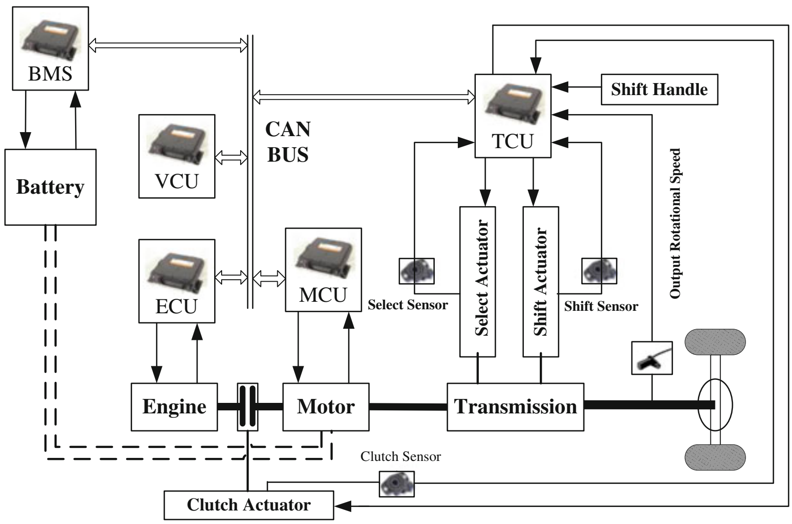


Fig. 1 AMT system composed of hybrid vehicle

Figure 1 shows that engine and motor transmit power through clutch, motor and input shaft of the gear box adopts mechanical connection. This design mainly considered to ensure the vehicle starting with pure electric mode and mode change between pure electric and hybrid.

At the start, the clutch in separating condition, vehicle finishes starting through the low-speed torque and the speed regulation ability of motor. When the mode change from pure electric to hybrid, the speed difference between main part and driven part of clutch was eliminated by the closed-loop speed control function of engine, then through the combination of clutch, engine and motor hybrid driving was achieved.

2.2 *Working Principle*

The key to the shift without the disengagement of the clutch in AMT is to control the two power source include engine and motor co-ordinately in all stages of shifting process [5].

In the shifting process, the AMT control unit TCU communicate with engine control unit ECU and motor control unit MCU through the CAN bus. When shift to neutral, adjust the output torque of the engine and the motor, so that the output torque is close to zero, ensure the shift to neutral process easy and swift; When shift to a new gear, control of the rotational speed of engine and motor to approximate the target speed, at the same time control electric current and the

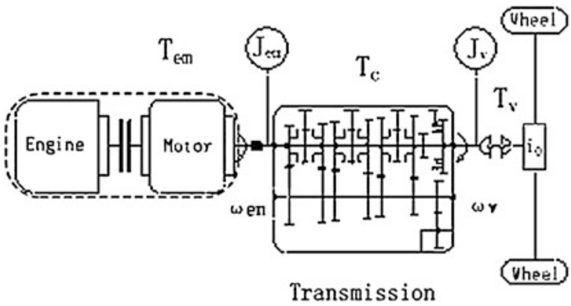


Fig. 2 Model of power train system for hybrid vehicle

position of the shift motor accurately, to achieve the shift without the disengagement of the clutch.

3 Dynamics Analysis of Shifting

The simplified model of transmission system of hybrid vehicles is as shown in Fig. 2.

Under hybrid drive mode, the relationship of power transmission including the kinematics and dynamics are as follows:

$$\frac{T_C}{i_g} = T_{em} - J_{em} \cdot \dot{\omega}_{em} \tag{1}$$

$$\frac{T_v}{i_o} = T_C - Jv \cdot \dot{\omega}_v \tag{2}$$

Where, Tc for synchronizer torque; Tem for engine and motor output torque; Tv for automobile driving resistance torque; Jem, Jv respectively for the moment of inertia converted to the transmission input shaft and output shaft ends; ωem, ωv respectively for transmission input shaft and output shaft speed; ig, io respectively for the gearbox ratio and final drive ratio.

3.1 Picking Neutral Phase

Figure 3 is mesh force model when picking neutral, F for the force of picking neutral; Fc for synchronous transmission force; Ff for friction resistance force between mesh gears; f for friction coefficient between the mesh gears.

If the radius of mesh gear forcing point is for R:

$$F_f = F_C * f \tag{3}$$

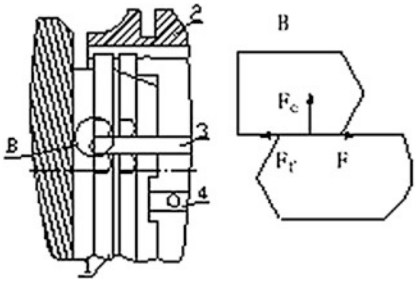


Fig. 3 Force model on teethes in shift to neutral phase

$$F_C = T_C / \int dR \tag{4}$$

By formulas (3) and (4) is:

$$F_f = T_C f / \int dR \tag{5}$$

Because resistance force mainly comes from mesh gear friction force when picking neutral, formula (5) shows that in order to achieve the least resistance force when picking neutral, one should try to reduce Tc as much as possible. By formulas (1) and (2) is:

$$T_C = \frac{J_{em} \cdot T_v \cdot \frac{i_g}{i_0} + J_v \cdot T_{em}}{J_{em} \cdot i_g + \frac{J_v}{i_g}} \tag{6}$$

The formula (6) shows, torque of synchronous transmission is the minimum when Tem is 0. So one should try to make engine and motor not to output torque.

3.2 Speed Adjustment Phase

In the shifting process, the vehicle speed is constant, that is to say the transmission output shaft speed is constant. The target speed of the input shaft can be expressed as:

$$\omega_{\text{em}} = \omega_{\text{v}} * i_g \tag{7}$$

Where, ωem for the input shaft target speed; ωv for the output shaft speed when shifting; ig for new gear ratio.

After calculation of the control unit of AMT (TCU), the input shaft target speed sent to the engine control unit ECU and motor control unit MCU through CAN bus in the process of shifting, then control the speed of engine and motor adjusting to approximate the target speed.

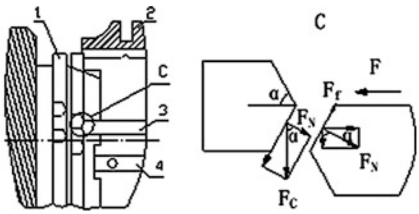


Fig. 4 Force model on teethes in shift gear phase

In order to make shifting smooth and reduce shifting impact, the difference value of engine and motor speed should be in a very small range after adjusting. As smaller the speed difference value is, the smaller impact and the higher the shifting comfort is [6]. Specific speed difference value should be depending on the engine and the motor control precision.

3.3 Engaging Gear Phase

According to position difference, synchronizer can be divided into two states as locking and unlocking in the process of shift gear [7].

Figure 4 is the meshing force model in the synchronization process. F for shift gear force; FN for positive pressure on contact surface; Fc for synchronous transmission force; Ff for friction force between mesh gears; f for the friction coefficient between mesh gears; α for friction cone angle on the contact surface.

$$F_N = F_C \cdot \cos\alpha \tag{8}$$

$$F_f = F_N \cdot f \tag{9}$$

The force analysis model shows that F must satisfy follows so that gear can be picked on successfully:

$$F > F_N \sin\alpha + F_f \cos\alpha \tag{10}$$

$$F > \frac{T_C}{\int dR} \cos\alpha \sin\alpha + \frac{T_C}{\int dR} \cos\alpha \cdot f \cdot \cos\alpha \tag{11}$$

At this time, the relations of vehicle power still satisfy formulas (1) and (2). The formula (11) shows that when the initial conditions of vehicle are constant, in order to make shifting light and smooth, torque of synchronous transmission Tc should be as small as possible, which requires the output torque of the engine and motor should be approximate to zero in the phase of engage gear.

After the speed difference becomes to zero, synchronizer changes into the unlocking state. The gear force is much greater than the resistance friction force, so it can easily drive and complete shifting process.

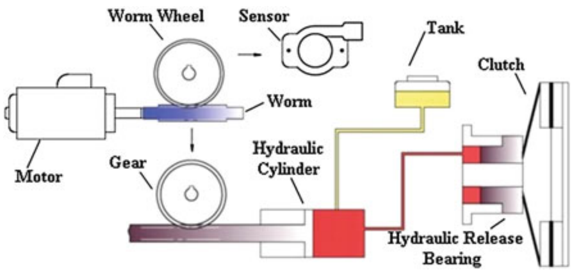


Fig. 5 Working principle of clutch actuator

4 Shift Control Strategy

4.1 Actuator Control

4.1.1 Clutch Control

Clutch actuator is electronically hydraulic control system. Its working principle is as shown in Fig. 5.

Clutch disengagement control: the motor rotating controlled by TCU, then it drives the worm screw rotating, the worm gear and gear coaxial rotating, gear drives the gear rack so that the piston moves to the right, build oil to the hydraulic isolation bearings, hydraulic isolation bearings facilitate separation refers to the small end, so that the clutch; the worm has a self-locking function, not to control the motor, the piston can still to maintain in the original state to maintain pressure, so that the clutch is in a separated state.

Combination process control: motor reverse rotating controlled by TCU, oil pressure removed, clutch combined under the diaphragm spring return force.

4.1.2 Select Shift Control

AMT selecting-shifting actuating mechanism adopts electric control electric way, its working principle as shown in Fig. 6.

Select process control: TCU controls select motor rotating; output torque drives the select axle to move up and down through worm gear to select different gears.

Shift process control: TCU control shift rotation of motor, output torque drives the shift axle clockwise or counters clockwise rotating through g worm gear to pick up gear.

After tests for many times, the clutch actuator and AMT selecting-shifting actuator can achieve the desired function very good.

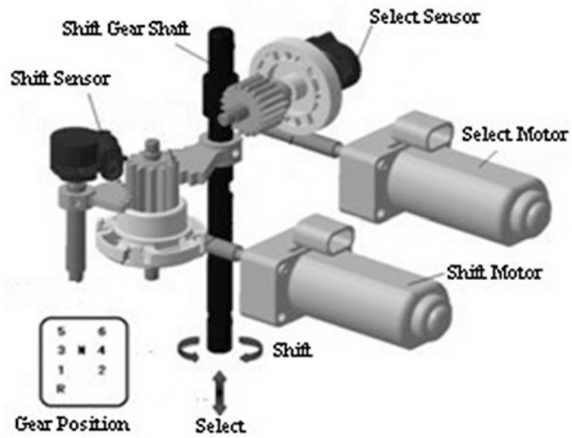


Fig. 6 Working principle of select and shift gear actuator

4.2 Coordinate Control of Multi Controllers

The shift of hybrid electric vehicle is a coordinate control process between multi controllers. The controllers of the electric control system communicate with each other by CAN bus network, ECU, MCU, TCU communicate with VCU respectively. VCU is responsible for collecting vehicle state, forwarding CAN messages, arbitrating vehicle control right; ECU and MCU are responsible for collecting the information such as state, speed, torque and so on as well as responding the VCU torque request and control request; TCU is responsible for collecting the handle information and sending controlling message to the engine and the motor through as well as other actuator by the VCU, required for the vehicle; engine and motor information provided by VCU.

4.3 Shift Process Control

Due to the auxiliary of motor, HEV is more easier to achieve shift without disengaging clutch than the traditional engine vehicles. Its shift control process is as follows:

1. TCU communicates with ECU, MCU by VCU and controls the throttle opening degree of engine and the torque of motor coordinately so that the torque of transmission input axle is close to zero; then TCU controls shift actuator to pick off gear.
2. TCU sends the target speed to engine and motor, controls the speed of engine and the motor, and monitors the speed difference. At the same time, TCU control the actuator to complete gear selection operation.

3. when TCU detects speed difference in the allowable range, in order to prevent engine and motor to output torque after synchronizing which will cause shift jerk, the engine throttle opening degree and the motor torque should be controlled once again so that the transmission input axle torque is close to zero. At the same time the shift actuators complete gear engagement.
4. Coordinately control the throttle opening degree of engine and the motor torque, restore torque according to the power distribution between the engine and the motor to make vehicle running normally.

Compared to shift with disengaging clutch, shift coordinated control without disengaging clutch is simpler, and it can saves the clutch open and close process as well as extend service life of the clutch [8].

5 Test Verification

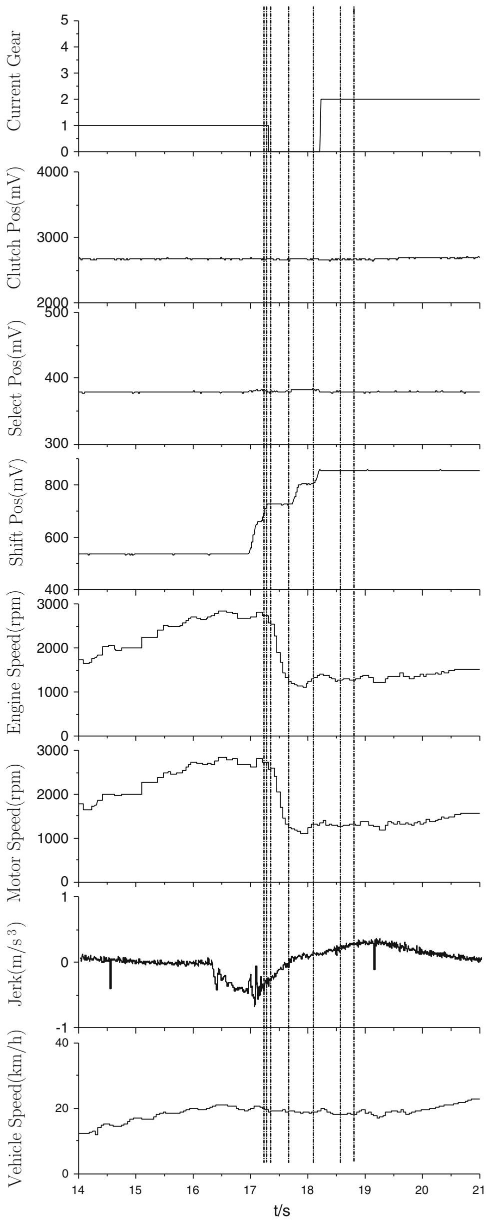
In order to verify the effect of control strategy of shift without disengaging clutch, modify the control parameter and debug the electronic control unit, a hybrid demo car with AMT undertook shift test.

Figure 7 is the shifting curve from first gear to second gear. One can see the variation of gear position, clutch position, select position, shift position, engine speed, motor speed and impact degree during shifting process without disengagement of the clutch from the figure. The shifting process can be divided into six stages as request shift, reduce torque, pick neutral, adjust speed, shift gear and recover torque.

Shift time is a comprehensive index for evaluating shift quality. The time of different stages in shift process is as shown in Table 1. Shift time can be defined as time from the power interruption (began to reduce torque) to the end of recovery of torque. From Table 1, the shift time from first gear to second gear is 0.962 s, which satisfies the technical requirements of less than 1 s. In the whole shift process, time of adjusting speed accounts for about 43.3 % of the total time. It shows that the control of engine speed and motor speed has great affect on the shift quality in the shift process; time of disengage and engage gear accounts for about 36.4 %, which mainly depends on factors such as how big the synchronous speed difference is, the efficiency of select and shift actuators as well as the response of select and shift motors; time of torque recovery is dependent on the driver request torque and the vehicle speed.

The degree of jerk is an important index to evaluate shift quality [9]. It expresses the longitudinal acceleration ratio of the vehicle. The curve of the degree of jerk shows that there is slight degrees of jerk during disengage gear and engage gear. Jerk is caused by torque mutations when disengaging gear; Jerk is caused by the big speed ratio of the first gear and the second gear make torque mutate when shift to a new gear. With the shift position rise, speed ratio difference decreases, the jerk of impact will become small [10]. In the whole shift process, jerk is very

Fig. 7 Curves of vehicle shift 1-2 process



small, and jerk is slight, which in the permitting the degree of jerk range, shift comfort.

In addition, speed difference directly affects the vehicle shift quality: the smaller the speed difference is, the shorter the shift time and the smaller the impact will [11]. The bigger the speed difference is, the longer the shift time and the

Table 1 Shift time

Number	Stage	Time (ms)
1	Request shift	32
2	Reduce torque	65
3	Picking neutral	226
4	Adjusting speed	497
5	Engaging gear	394
6	Restore torque	130

bigger the impact as well as the worse comfort will. Therefore, controlling speed difference effectively is very important to improve the shift quality.

6 Conclusion

For structural features and technical requirements of hybrid vehicle with AMT, this chapter proposes a control strategy that can realize the shift without disengagement of the clutch. Based on Matlab/Simulink to build the control strategy, a hybrid demo car equipped AMT with this shift strategy undertook the road test of 1,000 km in practice. The results showed that hybrid vehicles equipped AMT with this shift strategy effectively shortened the shifting time, reduced shifting impact, improved the ride performance and comfort. The development of AMT shifting without the disengagement of the clutch for hybrid vehicle has great importance for the progress of China's hybrid vehicle technology and industrialization.

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