

Research on Gear-Shift Strategy without Disengaging the Clutch for Automated Manual Transmission in Hybrid Electric Vehicle

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Abstract. In order to realize a quick, smooth and precise shifting process of hybrid electric vehicle (HEV) equipped automated manual transmission (AMT), a research platform for HEV driven by electrically controlled engine and drive motor was established. The key technologies including its system components, working principle, control strategy of engine and motor during shifting process were analyzed. A technology of AMT shift without disengaging the clutch was proposed. According to the dynamic characteristics of the HEV's engine, motor, and transmission, the dynamic model of transmission system was established. The various stages of shifting process were emphatically analyzed. Its shift characteristics and the key factors affecting the shift quality were grasped. On the basis of the above researches, the shift control strategy without disengaging the clutch was acquired. It was verified on a demo HEV platform. The results showed that the technology of AMT shift without disengaging the clutch for HEV not only ensured smooth shifting through the coordinated control of engine, motor and actuator, but also shortened the shift time and improved the shift quality significantly.

1. Introduction

HEV with AMT can achieve three different driving mode, which are pure electric, pure engine and hybrid, through clutch engagement and disengagement [1]. Shifting process of hybrid mode is most complex, so this research focuses on the shifting of hybrid mode.

Shifting jerks of AMT are mostly caused by the clutch's engagement and disengagement in shifting process [2]. Shifting without clutch disengagement technology can not only eliminate shifting jerks, simplify control logic and reduce difficulty of controlling, but also effectively shorten shifting time as well as improving shifting quality. This technology of heavy-duty truck is put forward in paper [3], and the key point is how to realize precise torque and speed control of diesel engine. Because of the existence of auxiliary motor, it is easier for HEV to achieve than conventional engine vehicles.

HEV's shifting strategy is different from traditional vehicles. Thus the shifting process of HEV is analyzed and its shifting control is simulated. In hybrid mode, in order to realize shift without clutch disengagement, it is needed to coordinated control the two power sources, the engine and the motor [4]. At the same time, the control effects will directly affect shift quality and driving performance.

2. System Composition and Working Principle

This research is based on a HEV with 4-speed AMT. 4 forward gears are driven by constant mesh gear sets through shift sleeves without synchronizers, and motor rotates in reverse to achieve reverse gear.



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2.1. System Composition

Figure 1 shows the system composition of a HEV. Power provided by engine and motor is transmitted to wheels through gearbox, drive shaft, and final drive. AMT system consists of gear sets, shift actuator, clutch, clutch actuator, TCU and corresponding position sensors, etc. TCU communicates with VCU, ECU, MCU and BMS through CAN bus.

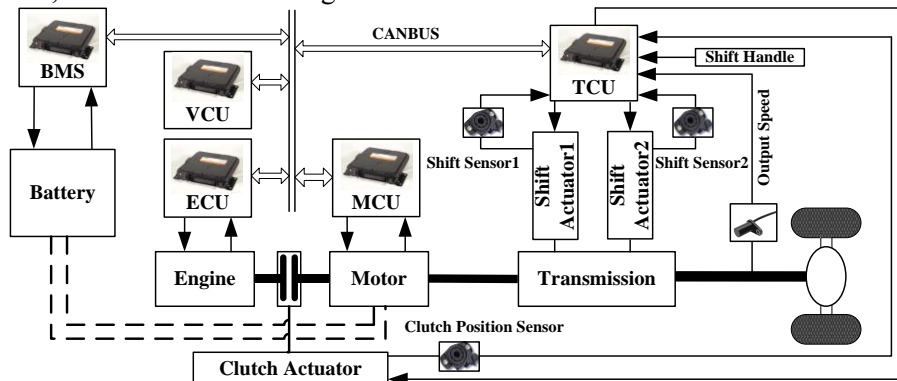


Figure 1. AMT System Composed of Hybrid Vehicle

In order to guarantee the vehicle starting with pure electric mode and mode switches of pure electric and hybrid, engine transmits power to motor through clutch, and motor output shaft is connected to the input shaft of the gear box by splines.

When the vehicle starts, clutch is disengaged, and motor is used to start vehicle. When switching from pure electric to hybrid, the speed differences between clutch driving plate and driven plate is eliminated by closed-loop speed regulation function of the engine, then the clutch is engaged, and finally hybrid driving is achieved.

2.2. Working Principle

The key point of AMT shift without clutch disengagement is the coordination control of engine and motor in different phases of shifting process. The control process is as follows:

1. Before shift to neutral, transmission input torque is reduced closely to zero through the coordination control of the engine and motor torque to ensure shifting easily and swift.
2. Eliminate speed difference between the two shift elements through the engine and motor speed coordination control.
3. When the speed difference is in acceptable range, the engine and motor is controlled in again to reduce transmission input torque closely to zero and then shift sleeve is engaged with the target gear.
4. The engine and motor torque is synergistically controlled to satisfy the power distribution requirements between engine and motor set in the control strategy.

Advantages of AMT shift without clutch disengagement are as follows:

1. Control of clutch in shift process is cancelled, so the control logic is simplified and the control difficulty is reduced.
2. A range of issues such as clutch wear due to long time slipping, shift shock and engine extinguishment due to the driver's improper manipulation are eliminated, which extend clutch service life of and reduce driver's burden .
3. The power interruption time during shifting process is shortened and the power and economy of the vehicle is effectively improved.

3. Dynamics Analysis of Shifting Process

When driving in hybrid mode, the power required for driving is provided by engine and motor according to the power distribution set. AMT shift process based on the rev-synchronization is mainly composed of shifting to neutral phase, speed adjustment phase, gear engaging phase and torque recovery phase. Not only the gearbox, but also the engine and motor are involved in any phase. In order to establish an effective transmission model, following assumptions are first made:

1. The system is composed of inelastic inertia elements.
2. Each rotary member has only one degree of freedom.

Based on above assumptions, the system can be simplified as a discrete equivalent system as shown in figure 2. Parameters or variables before and after the sleeve are respectively converted into the gearbox input shaft and output shaft, and parameters or variables after the final drive are converted into the vehicle. Kinematics and dynamics relationships of powertrain in hybrid mode are as follows:

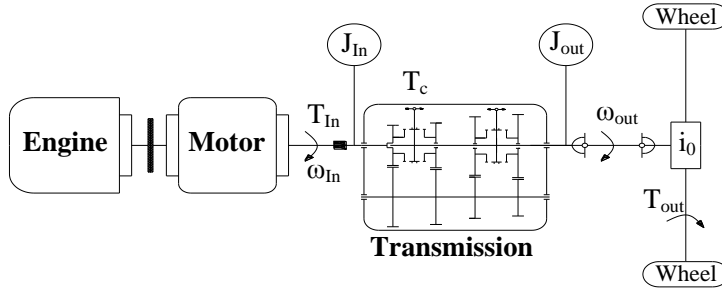


Figure 2. Model of Powertrain System for Hybrid Vehicle

$$\frac{T_c}{i_g} = T_{In} - J_{In} \cdot \dot{\omega}_{In} \quad (1)$$

$$\frac{T_{out}}{i_o} = T_c - J_{out} \cdot \dot{\omega}_{out} \quad (2)$$

Where, T_c is the torque transmitted by sleeve, T_{In} is the sum of engine and motor output torque, T_{out} is the vehicle driving resistance torque, J_{In} and J_{out} are respectively the inertias converted to the transmission input and output shafts, ω_{In} and ω_{out} are respectively the speed of transmission input and output shafts, and i_g and i_o are respectively the gearbox ratio and final drive ratio.

3.1. Shifting to Neutral Phase

Figure 3 shows the forces applied on the sleeve in this phase. F is shifting force, F_c is tangential force between the sleeve and gear, F_f is friction force between mesh gears, and f is friction coefficient.

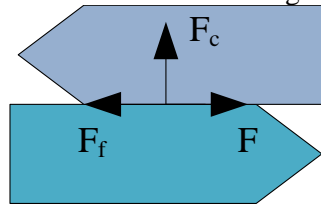


Figure 3. Force Applied on Gears in Shifting to Neutral

R is referred as the radius of the point at which the forces apply on meshed gears.

$$F_f = F_c * f = T_c f / \int dR \quad (3)$$

As shown in equation (3), in order to reduce the friction force to the lowest level, T_c should be minimized as much as possible. T_c shown in equation (4) can be derived from equation (1) and (2).

$$T_c = \frac{J_{In} \cdot T_{out} \cdot \frac{i_g}{i_o} + J_{out} \cdot T_{In}}{J_{In} \cdot i_g + \frac{J_v}{i_g}} \quad (4)$$

Equation (4) shows that the magnitude of T_c is determined by T_{in} and T_{out} . Assuming T_{out} is a constant when shifting, so if T_{in} is reduced to zero, the torque transmitted by the sleeve will reach minimum. Therefore, the engine and motor torque are co-ordinately controlled to make T_{in} to zero.

3.2. Speed Adjustment Phase

After shifting to neutral, the engine and motor are unloaded. In order to reach the input speed needed for target gear, the engine and motor speed should be swiftly adjusted. The target speed and the speed adjustment range can be respectively expressed as:

$$\omega_{in} = \omega_{out} * i_g \quad (5)$$

$$\Delta\omega = (i_{g2} - i_{g1}) \frac{u_a i_0}{0.377r} \quad (6)$$

Where, $\Delta\omega$ is speed adjustment range, u_a is current vehicle speed, r is wheel rolling radius, and i_{g1} and i_{g2} are respectively current and the target gear ratios.

The duration of power interruption determined by the time of speed adjustment affects shifting performance, especially when the vehicle is going uphill, because a long-time power interruption will cause vehicle speed drops too much, not only influencing the driving experience, but also leading to security threat. Therefore, the engine and motor response speed and speed adjustment precision are essential to determine shift time as well as shift quality.

3.3. Gear Engaging Phase

The gear engaging phase is divided into "chamfer touching" and "chamfer crossed"[5]. Since the absolute rev-synchronization cannot be guaranteed during speed adjustment phase, a certain adjustment of speed synchronization is still needed at the beginning of this phase using gear chamfer. The force applied on the gears in this phase is showed in figure 4.

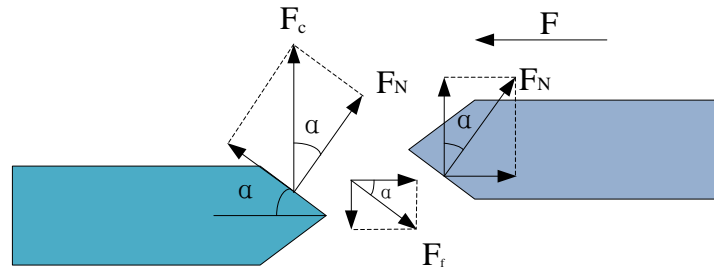


Figure 4. Force Applied on the Gears in Gear Engaging Phase

$$F_f = F_N \cdot f = F_c \cdot \cos \alpha \cdot f \quad (7)$$

Where F_N is the normal pressure on the contact surface and a is the cone angle of the contact surfaces. Shifting force F should satisfies equation (8).

$$F > F_N \sin \alpha + F_f \cos \alpha \quad (8)$$

Equation (9) can be derived from equation (3), (6), (7) and (8),

$$F > \frac{T_c}{\int dR} \cos \alpha \sin \alpha + \frac{T_c}{\int dR} \cos \alpha \cdot f \cdot \cos \alpha = kT_c \quad (9)$$

Substitute equation (1) to equation (9), equation (10) is obtained.

$$F > k i_g (T_{In} - J_{In} \cdot \dot{\omega}_{In}) \quad (10)$$

Equation (10) suggests that shift success or not is determined by T_{In} , and $\dot{\omega}_{In}$. Thus in order to shift smoothly, on the one hand, T_{In} during this phase should be reduced closely to zero; on the other hand, to decrease $\dot{\omega}_{In}$, the speed difference of actual speed and target speed should be as small as possible.

After sleeve crosses the chamfer, the speed difference is fully eliminated, and cone angle α becomes 0. Resistance of gear engaging is mainly friction force, which is much smaller than shifting force. Then the engagement of sleeve to target gear can be quickly completed.

3.4. Torque Recovery Phase

After gear engaging phase finishes, torque should be recovered as soon as possible according to the vehicle requirement by coordination control of engine and motor to ensure shifting smoothly without shocks. Jerk, referenced as j , which is the change rate of vehicle longitudinal acceleration during shifting, is usually used to evaluate shift smoothness [6]. Since the torque recovery phase is very short, the driving force is assumed constant in this phase. Jerk can be calculated in equation (11).

$$j = \frac{da}{dt} = \frac{d^2 u_a}{dt^2} = \frac{i_g i_0 \eta_T}{\delta m r} \frac{dT_{In}}{dt} \quad (11)$$

Where η_T is the efficiency of transmission, δ is the correction coefficient of rotating mass, m is the vehicle mass and r is the wheel rolling radius.

Equation (11) shows that the jerk is proportional to the change rate of torque. So the maximum jerk that passengers can withstand should be as a boundary condition and the torque recovery rate of each gear is calculated according to vehicle power distribution requirement. Another conclusion that can be drawn from equation (11) is the torque recovery of low gear is slower than that of high gear.

4. Shift Control Strategy without Disengaging Clutch

4.1. Coordination Control of Multi Controllers

Shift of HEV is a coordination control process between multi controllers, which communicate with each other through CAN bus network [7]. VCU is used to collect vehicle state, forward CAN messages as well as arbitrating vehicle control right; ECU and MCU are respectively used to collect engine and motor states, speed, torque, etc. and respond the VCU torque and speed request; TCU is responsible for collecting handle information and sending speed and torque requirements to engine and motor.

4.2. Shift Process Control Strategy

From the view of powertrain structure, the engine and motor can be considered as a whole. The shift control process of hybrid vehicle without clutch disengagement is shown in figure 5[8].

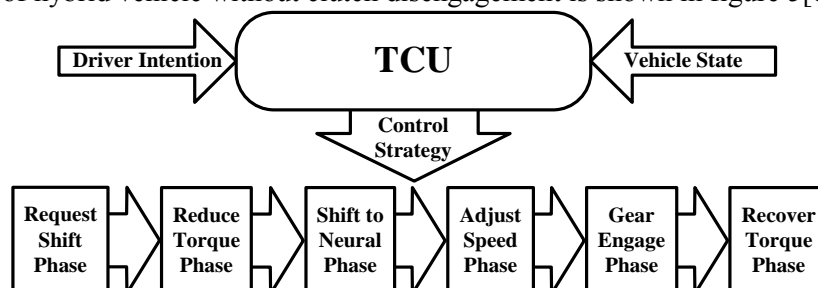


Figure 5. Shift Process Control of AMT for Hybrid Vehicle

When driving normally, driver's intends are determined by TCU according to vehicle driving state and then the shift decision is made.

1. Requesting shift phase. When the driving states satisfy shift condition, shift request is sent to VCU. After permission of VCU, the highest control rights of engine and motor are obtained by TCU.

2. Reducing torque phase. The engine and motor are co-ordinately controlled by TCU to make the transmission input torque close to zero as soon as possible [9].

3. Shifting to neutral phase. The shift actuators are controlled by TCU to pick neutral.

4. Adjusting speed phase. The target speed is sent to ECU and MCU, and the engine and motor are controlled co-ordinately to adjust speed. When the speed difference is smaller than setting range, this phase is finished.

5. Gear engaging phase. In order to prevent the output torque of the engine and motor after rev-synchronization and protect against shift shock and noise, engine and motor torque are co-ordinately controlled again. So the AMT input torque is close to zero and then shift to target gear.

6. Recovering torque phase. Engine and motor are co-ordinately controlled to recover torque and drive normally according to the power distribution relationship between engine and motor.

Shift without clutch disengagement is simpler, because clutch control is avoided, and a range of issues such as clutch wear due to long time slipping, shift shock and engine extinguishment due to the driver's improper manipulation are eliminated, which extend the service life of clutch[10].

5. Experiment Verification and Analysis

A hybrid demo vehicle is selected for shifting experiment. Parameters of vehicle are shown in Table 1.

Table1. Vehicle main parameters

Number	Parameters	Value	Number	Parameters	Value
1	Curb Weight	13500kg	5	Engine Type	NQ210KN5
2	Final Drive Ratio	4.875	6	Engine Max Power	140KW
3	Tire Radius	0.465m	7	Motor Voltage	600V
4	Gear Ratio	4.43/2.41/1.46/1	8	Motor Max Power	80KW

Figure 6 shows the curves of shifting from 1 gear to 2. It can be seen that the variation of the current gear, the position of shift fork 1 and 2, the engine/motor speed, the output speed of gearbox, the engine throttle, the motor torque and the jerk. The time of six phases is shown in table 2.

Table2. Time of Six Shift Phases

Number	Phases	Time (ms)	Number	Phases	Time (ms)
1	Requesting Shift	30	4	Adjusting Speed	541
2	Reducing Torque	208	5	Gear Engaging	133
3	Shifting to Neutral	118	6	Recovering Torque	241

Shift time and power interruption time are comprehensive indexes to evaluate shift quality [11]. In this study, the shift time is defined as the duration from the moment TCU sends out shift request to the end of recovering torque phase. The power interruption time is defined as the duration from the beginning of shifting to neutral phase to the end of gear engaging phase. The shifting time from 1 gear to 2 is 1271ms, and the power interruption time is 792ms, which satisfy the requirements of the shift time of the hybrid vehicle. And there is no significant power interruption sense during driving process.

In shift process, the time of adjusting speed is 541ms, which accounts for about 42.6% of the total time. It shows that the coordinate control of engine and motor speed has great affect on shift quality. It can be seen from the figure 6 that the engine throttle needn't fully close and only maintain an appropriate degree of opening in the adjusting speed phase. At this time, the motor torque is negative, which indicates that the motor is generating. The time of reducing torque is 208ms and accounts for about 16.4%. Without prejudice to shift to neutral, it is allowed to properly amplify the residual torque range of engine and motor before shifting to neutral. The time of shifting to neutral and engaging gear is 251ms, which accounts for about 19.7% and mainly depends on factors such as how big the synchronous speed difference is, the efficiency of shift actuators as well as the response of shift motors. The time of recovering torque is 241ms and accounts for about 19%. The rate of recovering torque is dependent on the vehicle power distribution requirement and the acceptable jerk.

The degree of jerk is an important index to evaluate shift quality. As can be seen from figure 6, the curve of jerk shows that there is great degree of jerk during reducing torque phase and recovering

torque phase. Jerk is mainly caused by torque mutations of the gearbox output torque. jerk is proportional to gear ratio. The bigger the speed ratio is, the greater the jerk is. In the shift process, the maximum of jerk is 14.62m/s^3 which is smaller than industry-recommended 17.64m/s^3 .

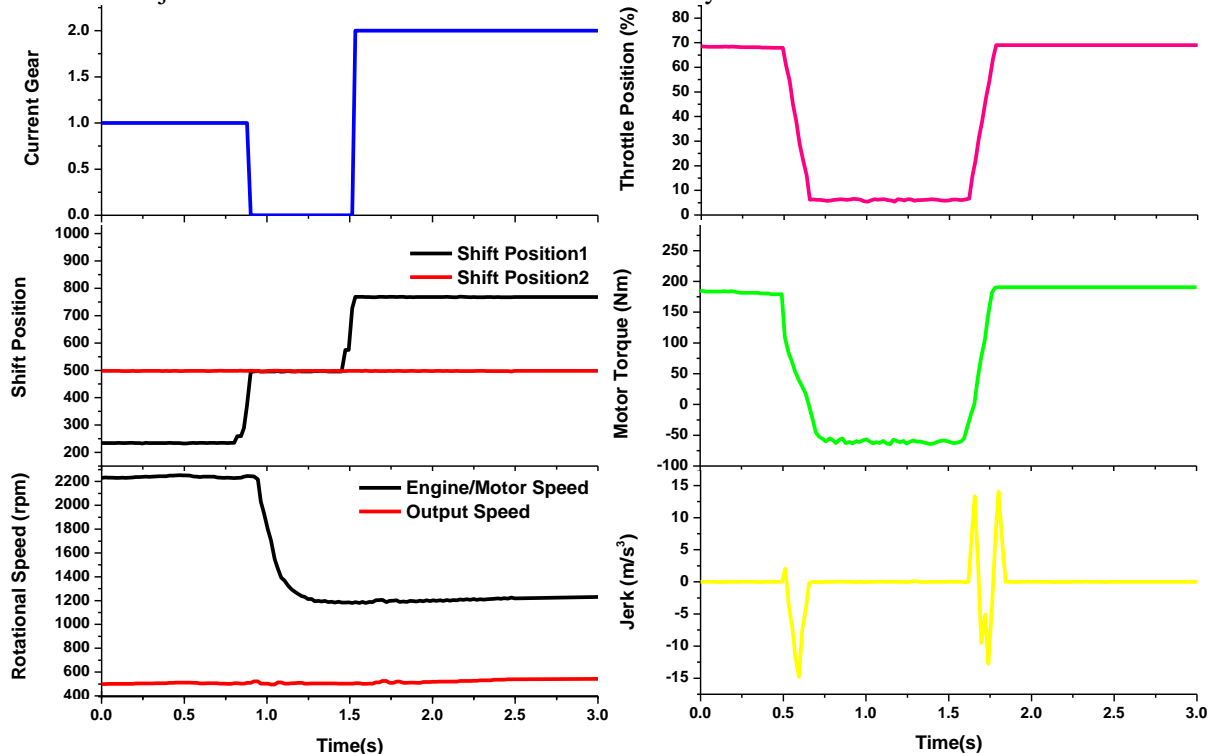


Figure 6. Shift Curves of 1-2 Process

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 be. Therefore, controlling speed difference effectively is very important to improve shift quality. The speed difference range of each gear permitted can be obtained by method of experimental calibration. Taking hybrid AMT demo-car as an example, the speed difference range of the first gear is $(-35, 40)$ rpm, the second gear is $(-25, 30)$ rpm, the third and forth gear is $(-10, 15)$ rpm. In this speed range, there is no shock and jerk when shifting, the shift time is short, and the quality of shift is good.

6. Conclusions

For the structural features and technical requirements of HEV with AMT, the key technologies such as system composition, working principle, shift process and control of engine and motor are analyzed deeply. A control technology that can realize shift without disengaging clutch is proposed, and corresponding shift control strategy is developed. The strategy is verified and optimized through the experiment based on a hybrid demo vehicle. Road test of 5000km proved that HEV equipped with AMT controlled by the strategy could effectively extend the service life of clutch, shorten the shifting time and reduce shifting impact as well as improving the driving performance and comfort.

Acknowledgments

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