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Research Article

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The research on gearshift control strategies of a plug-in parallel hybrid electric vehicle equipped with EMT

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ABSTRACT

In view of the limitations of automated mechanical transmission (AMT) for plug-in hybrid electric vehicle (PHEV), as a scheme of new transmission system without synchronizer Electric-drive Automated Mechanical Transmission (EMT) was proposed. Taking use of the electric machines' speed quick response characteristic, EMT uses active synchronous gearshift instead of the passive friction gearshift in AMT. To optimize the gearshift quality in PHEV, the gearshift control strategies in which engine、motor and clutch are coordinative controlled. Then validate the control strategies by simulation and real bus tests, the results reveal that the proposed control strategies can noticeably improve the gearshift quality of PHEV equipped with EMT.

Keywords: plug-in hybrid electric vehicle; EMT; AMT; gearshift control strategies

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INTRODUCTION

In recent years, hybrid Electric Vehicles (HEVs) have been considered as one of the most effective way to solve the vehicle energy saving and the environmental issues[1-3]. Compared with traditional HEVs, Plug-in Hybrid Electric Vehicles (PHEVs) which are charged from the grid have larger capacity energy storage device, then the pure electric driving range can be increased, and the fuel consumption and exhaust emissions can be greatly decreased [4,5].

The transmission systems of the PHEVs directly affect the dynamic performance and fuel economy, and by using automatic transmission in PHEVs to get excellent compatibility. Nowadays, the Automated Manual Transmission (AMT) has drawn the attention of vehicle manufacturers due to its high transmission efficiency, compact structure good performance, and high reliability [6]. However, in vehicles equipped with an automated mechanical transmission (AMT) which has a fixed transmission ratio, there exists the problem of shift jerk and inevitable power interruptions due to its structure [7-9]. In order to solve these problems， we put forward Electric-drive Automated Mechanical Transmission (EMT), which integrate the automated mechanical transmission and motor together. With the speed rapid response and adjustable speed characteristics of the motor, in gearshift progress, the electric machine speed and torque are well controlled to reduce the gearshift jerk and power interruption time.

In this paper， gearshift strategy of the EMT in the PHEV is designed. For this purpose, the model of EMT is integrated to a single driveshaft parallel hybrid electric bus. In addition, the vehicle driving performance characteristics are considered as the optimization constraints. Then the gearshift progress simulation is taken in the dynamic simulation software-ADAMS and Matlab/Simulink, and real bus testing is completed simultaneously. The results show that the proposed gearshift strategies can reduce the shift jerk and power interruption time, and the shifting quality can be improved greatly.

2 The structure and working principle of EMT in parallel PHEV
As shown in Figure 1is the power system of the parallel PHEV with EMT, which composed of engine, EMT and

automatic clutch. The mechanical transmission input shaft and the drive motor shaft are integrated, then the motor and transmission integrate to the EMT. This paper takes the powertrain system of a 12 meters hybrid electric bus as an example to do researches. In this system, the transmission has four forward gears and no reverse. The engine is connected to the motor of the EMT by the automatic clutch. When vehicle is in the hybrid driving mode or engine mode, the clutch is in the coupling position, while in motor driving mode, the clutch disengage.

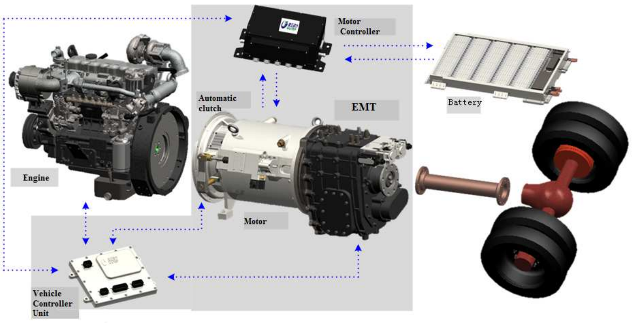

Figure1 The configuration of a parallel PHEV powertrain with EMT

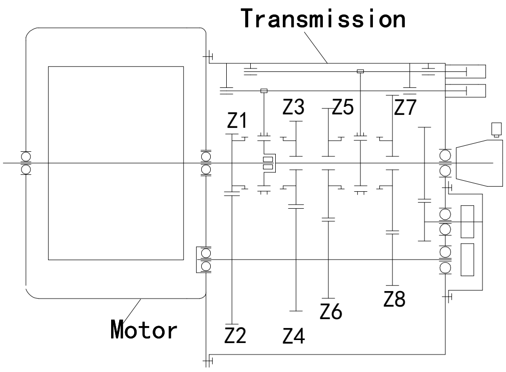

Figure2 The diagram of four gear EMT

As shown in figure 2, the EMT is composed of an electric motor and an AMT without the synchronizer, which is good for shorten the axial dimension, while the shifting action is realized by the sliding sleeves. In the gear shifting process, make use of the characteristics of high efficiency, control accuracy and quick response, adjust the speed of the transmission input shaft (that is the motor shaft), making the speed of the mesh coinciding with the meshing gearing. As the results the EMT realize active synchronous shift without synchronizer, shorten the power interruption time and improve the shifting comfort during the shifting progress.

The main effect factors of shifting quality of this PHEV based on EMT are as follows:

(1)The power interruption time
The power interruption time refers to the time when vehicle is under deceleration during the shifting progress, namely the time when the acceleration is negative:

$$t \in \{t | \frac{dv}{dt} < 0\} \tag{1}$$

Where v is the vehicle velocity, t is the power interrupting time.

$$t=t_1+t_2+t_3 \tag{2}$$

Where t_1 is the time of shifting to neutral gear, t_2 is the time of regulating the motor speed, t_3 is the time of shifting to the target gear.

(2) The shift jerk
The shift jerk is the rate of change of vehicle longitudinal acceleration, its size with that vehicle longitudinal acceleration. The equation is as follows:

$$j = \frac{da}{dt} = \frac{d}{dt}(\frac{du}{dt}) \quad (3)$$

Where a is vehicle longitudinal acceleration; u is vehicle longitudinal velocity.

3 Gearshift Strategies

In automatic transmissions, gearshift is performed according to the predefined gearshift strategies. In PHEV equipped with EMT the shift controller receives inputs from various sensors such as current vehicle speed, clutch schedule and engine speed. Based on these input s the controller makes a decision on whether to upshift, downshift or hold the gear position. Generally, gearshift strategies are based on the engine and motor working states and the driver’s intention, to move the engine and motor operating points towards points at which lower energy consumption, better performance and even higher lifetime could be achieved. The driver’s intention is interpreted from the accelerator and brake pedal displacement rate.

In this paper, the gearshift strategy is based on the operating condition of the ICE and motor. The flow chart of the EMT shifting control process for PHEV is proposed as shown in figure 3, and the flow chart of the EMT shifting operating process is shown in figure4.

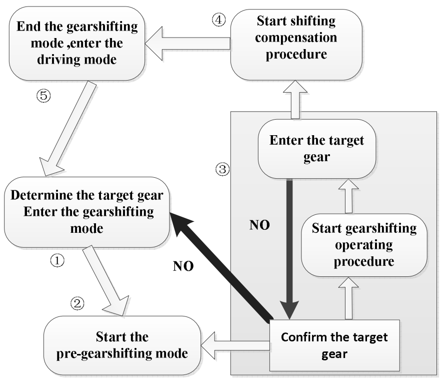

Figure3 Flow chart of EMT shifting control progress

(1) When confirm the vehicle needs to shift (step① in the figure3), start the pre-shift progress(step② in the figure3), by reducing the vehicle acceleration to 0 to reduce the shift jerk, then transition to the shift operational process(step③in the figure3).

(2) As shown in figure 4(step③in the figure3), first of all is to confirm the target gear again, rule out the condition that driving intention mutation changing the target gear. After confirming the target shift, enter the shift operation process, real-time monitoring of this process at the same time, if the shift is not normal, confirm the target gear once again and for a second shift operation, until gearshift to the target gear. When step ③multiple cycle the system will correct it.

(3) After entering the target gear, start shift compensation program. Then according to the throttle opening, increase or decrease power system output torque (as shown in step ④); when the output power match the driving intention ,the shift mode end, then enter to the interruptions drive mode(as shown in step⑤).

4. Simulation and Results Analysis

For analyzing the above discussed shifting control strategies, construct the 3D model for this PHEV equipped EMT and simulate on the software ADAMS (Automatic Dynamic Analysis of Mechanical Systems). The powertrain system and vehicle parameters of the PHEV are shown in Table 1.

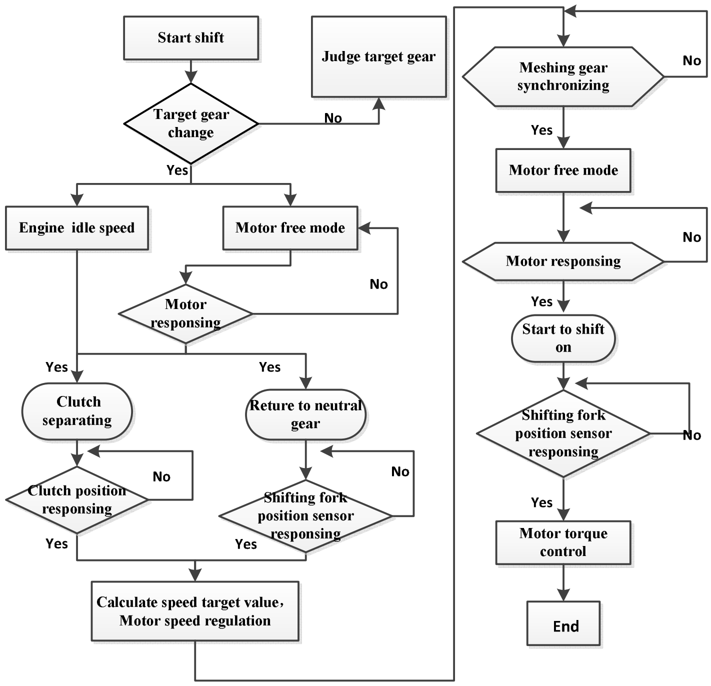

Figure 4 Flow chart of EMT shifting operating process

Table1. The powertrain system and vehicle parameters of the PHEV

Parameters	value
Curb weight /kg	13500
Full load gross mass/kg	18000
Frontal area/m^2	7.02
Tire radius /m	0.493
Main reducer ratio	6.2
Transmission ration (5gear)	5.82;3.23;1.79;1
Engine displacement/L	2.98
Maximum power (kW)/speed(rpm)	95/3200
Maximum torque (Nm)/speed(rpm)	345/1600~2400
Motor	three-phase induction motor
Rated/peak power（kW）	80/160
Rated/peak speed(rpm)	1600/3200
Maximum torque(N • m)	954
Battery	Lithium ion battery
Capacitor(Ah) /Rated voltage(V)	160/576
Peak Power(kW/30s)	165

For simulating the shift progress of the bus equipped with EMT, built up the EMT simulation model on the software ADAMS and the control program was realized on the Matlab/Simulink. As shown in figure 5, in order to simplify the simulation, the 4-speed EMT was instead by the 2-speed EMT. Then the simulation results of the gearshift process were analyzed. As the simulation was made to verify the feasibility of the EMT shift control process, the model can’t simulate the vehicle inertia accurately, so the output shaft speed had small fluctuations.

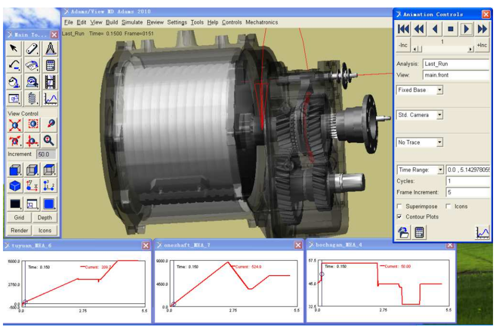

Figure 5 EMT Simulation mode on ADAMS

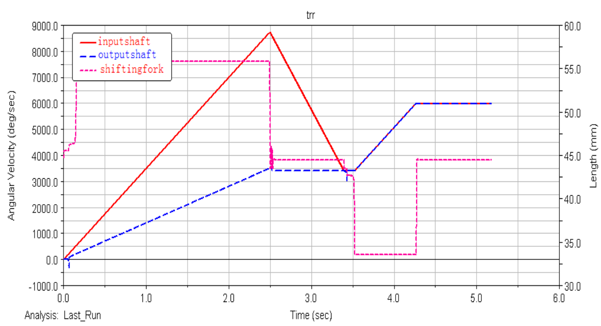

Figure 6 Simulation results of EMT shift progress

Through the simulation analysis results, it can be seen that the EMT shift process control method can completely meet the gearshift demands. As shown in Figure 6, on the progress of 1st shift to 2nd gear, motor drives the transmission input shaft speed close to the output shaft speed, then the actuator motion, the transmission shift to 2nd gear. During the whole gearshift process, the speed fluctuation of every shaft is small, and the shifting jerk is small.

By optimizing the simulation parameters, including the motor control torque of speed adjusting, the shifting force of actuator motor speed, the engage gear timing and so on, get the various shift results on different speed control torque, as shown in table 2, the sampling frequency is 25ms.

Table 2 gearshift results on the same shift force and shift timing, different speed control torque

Regulating speed control torque /T_m	Shifting to neutral gear time /ms	Regulating motor speed time /ms	Engaging to target gear time /ms	Power interruption time time/ms	Gearshift jerk/ m/s^3
	t_1	t_2	t_3	t	J
40%	150	625	75	850	6.9
60%	150	400	75	625	7.8
80%	150	325	75	550	8.2
100%	150	250	75	475	9.6
150%	125	200	150	475	15.6

5. Real Vehicle Road Tests and Results Analysis

In order to validate the proposed gearshift control strategies in EMT, a bus equipped with EMT was adopted as the road test vehicle, which is shown in figure 7.

Figure7. Road test of the hybrid electric bus equipped with EMT

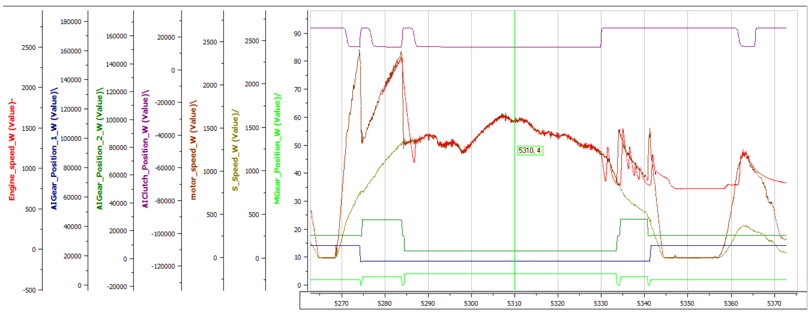

Figure8. Vehicle powertrain system parameters test curves

Tested the powertrain system according to the control strategies in Figure 4, The test results of the engine speed、gear position sensor signals、clutch position sensor signals、motor speed、output shaft speed and speed ratios are shown in Figure 8. The curves shows the test process which vehicles starting from the 2nd gear and accelerating to 4th gear, then decelerate and downshift to the 2nd gear.

Figure 9 shows the powertrain system speed test curves. From the figure we can see that in the upshift and downshift process, the output shaft speed change is small, and this system shift is smoothly, shift impact is small.

Figure 10 is the magnification of the 3rd gear upshift to 4th gear test curves, through the speed, gear and clutch position curves, the upshift power interruption time is no more than 0.75s.

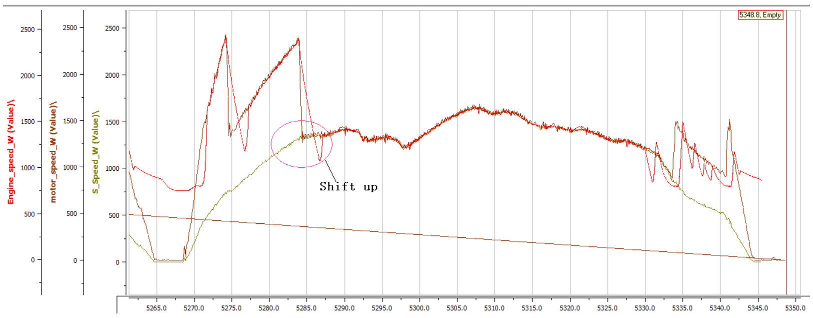

Figure 9 Vehicle speed test curves

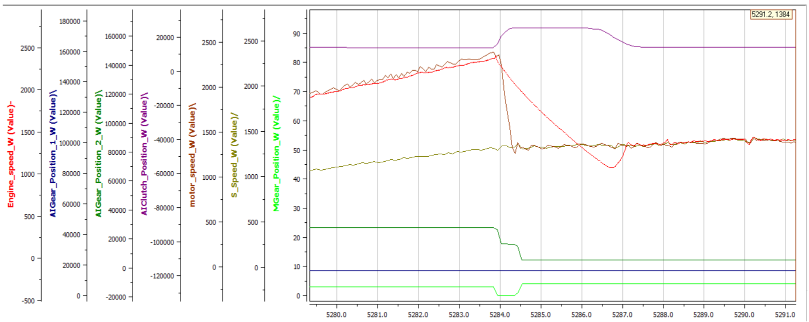

Figure 10 Vehicle test curves magnification in shift up process

Based on the analysis of the simulation results （the above simulations sampling time are all 25ms）, get the following conclusion,

(1) Under different control torque the power interruption time are less than 0.9s;
(2) When the control torque is appropriate, the shift jerk is less than $10m/s^3$.

CONCLUSION

To reduce the AMT gearshift power interruption time, a new type of transmission is proposed in this paper, which is equipped with electric motor and without synchronizer. The structure as well as the operating principle of the proposed transmission is introduced. The gearshift control strategies are verified on the simulation software Adams and a real bus test. The results reveal that taking this gearshift control strategies in parallel PHEV equipped with EMT can reduce power interruption time which is 0.75s in the upshift process, and the gearshift jerk is no more than 10 m/s^3.These results prove that the EMT with the control strategies in parallel PHEV can overcome the disadvantages of the AMT in parallel PHEV. This investigation can be followed to HEVs as further works.

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