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Mode Transition Control of Plug-In Hybrid Electric Vehicle During Clutch Engagement

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Summary

Proper mode transitions in plug-in hybrid electric vehicles (PHEVs) can improve the vehicle efficiency. However, the transitions consume energy and affect drivability whenever the clutch engages. In this paper, we propose a mode transition control, including two strategies during clutch engagement. One is an engine torque generating for the reduction of a sudden change of acceleration. The other is a clutch actuating rapidly after a sufficient condition of clutch. A PHEV simulator evaluated the energy consumption and vehicle acceleration of these two strategies. In conclusion, we found that the mode transition control helped to improve the drivability and energy efficiency.

Keywords: PHEV (plug-in hybrid electric vehicle), Control system, Energy consumption, Simulation, Vehicle performance

1 Introduction

The electrification of a powertrain is necessary for energy efficiency and driving performance [1]. Various electrified vehicles are already road-ready, from mild hybrid electric vehicles to battery electric vehicles (BEVs). Above all, the plug-in hybrid electric vehicle (PHEV) has become a promising system for bridging internal combustion engine (ICE) vehicles and BEVs [2]. PHEVs have larger battery packs than conventional hybrid electric vehicles (HEVs), and PHEVs flexibly uses electrical energy [3]. PHEVs and HEVs have ICE and electric motors, and should thus manage different power sources according to driving modes. This energy management strategy determines the current driving mode by using power sources more efficiently [4]. An electric driving mode uses only an electric motor (EM). A hybrid driving mode uses both the ICE and EM. Mode transition occurs from the electric driving mode to the hybrid driving mode, or vice versa. However, the mode transition consumes additional energy, not using tractive power to rotate wheels. In addition, the transition accompanies clutch engagement and disengagement, which affects vehicle drivability.

Many researches have dealt with drivability during mode transition. To reduce jerk or acceleration change, they have proposed various methods of mode transition, considering ICE torque, integrated starter and generator (ISG) torque, clutch actuation, and so on [5-7]. Meanwhile, Kim [8] has developed control methods to improve energy efficiency during mode transition. In this paper, we have developed a control of mode transition to improve drivability and reduce energy consumption.

Previously, we developed a basic algorithm of mode transition and analyzed its behaviors. However, this algorithm has some issues. Mode transition includes two important factors – transition duration and acceleration change (peak-to-peak acceleration). These two factors have a trade-off relationship. For instance, a short transition duration can result in a large change of acceleration, which makes driver uncomfortable. While a long transition duration can cause a low change of acceleration, the delay in mode transition increases unnecessary energy consumption.

The researched type of PHEV is parallel and pre-transmission hybrid configuration, which has an ISG to drive the engine-cranking shaft by a belt pulley. An engine clutch mounts between the ICE and EM. Like conventional ICE vehicles with a stepped automatic transmission, this hybrid configuration includes a conventional transmission. The researched PHEV has a dual clutch transmission (DCT), which is an automated manual transmission (AMT) with two clutches. The DCT performs by pre-selecting the gears using synchronizers to reduce the duration of the clutch-to-clutch process. This paper does not explain the modeling process of the PHEV simulator, which was developed using MATLAB/Simulink. For this study, we used the PHEV simulator to analyze driving modes and their transition. For more on that development, please refer to preceding research in [9].

2 Mode Transition

In Fig.1, the parallel and pre-transmission hybrid configuration has a clutch between an ICE and EM [10]. The clutch plays important roles for mode transitions. When a PHEV needs high power or when the battery is of a low state of charge (SOC), a hybrid control unit (HCU) selects a hybrid-driving mode using the ICE as its main power source. The hybrid-driving mode engages the clutch to deliver ICE power to the drivetrain, while the electric-driving mode keeps the clutch disengaged. From the electric-driving mode to the hybrid-driving mode, the PHEV needs to progress with clutch engagement. This paper focuses on the mode transition, including clutch behaviour for ensuring drivability. The discussion divides mode transition by clutch speed synchronization and actuation.

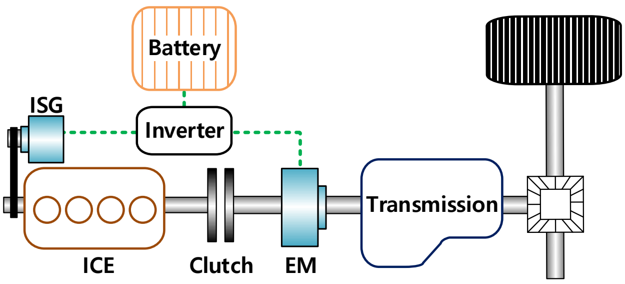


Figure1: Diagram of parallel and pre-transmission hybrid configuration

2.1 Clutch Speed Synchronization

During electric-driving mode, when only the EM drives and the clutch is disengaged, the clutch side of the ICE is stationary, but the other side of the EM connected to the drivetrain is rotating. When the hybrid-driving mode converts, the clutch rotational speeds of ICE and EM should be synchronized and the clutch be fully engaged at a low speed difference for smooth engagement [6]. Therefore, an ISG connected to an engine-crank shaft generates torque to run up the speed of the ICE side (ω_e). In addition, the ICE also generates torque for rapid synchronization above the idling speed of the ICE (ω_{idling}). This is a control of engine compensating torque. Fig.2 shows the flow of mode transition, where left side of the figure describes the speed synchronization.

2.2 Clutch Actuation

A clutch engaging at a high difference between clutch speeds causes acceleration change [11]. If the speed difference is lower than the constraint speed, a clutch actuator moves a clutch plate until the clutch transmits an ICE torque and is fully engaged. Although the mode transition is properly controlled for reducing the duration and acceleration change during the speed synchronization, the mode transition still needs more improvement when actuating a clutch. A long mode transition causes unnecessary energy consumption. Besides of the duration, acceleration change with a large value has uncomfortable drivability. We thus propose controls to improve drivability and energy efficiency.

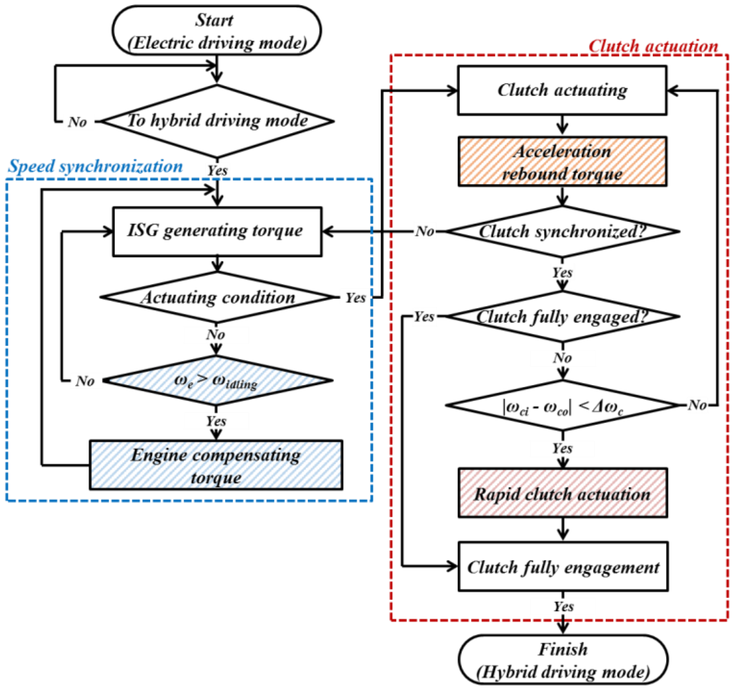


Figure2: A flow of mode transition with the proposed controls

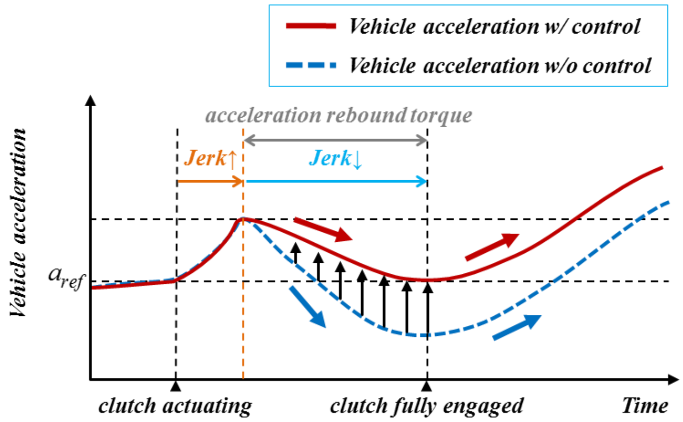


Figure3: A concept of acceleration rebound torque control

3 Control of Mode Transition

3.1 Acceleration Rebound Torque Control (ARTC)

During clutch engagement, drivetrain inertia increases because both the ICE and ISG create additional load on the drivetrain, which can decrease vehicle acceleration. In order for the lowered acceleration to rebound to a value before clutch actuating, the ICE generates additional torque during clutch actuating and slipping. The torque is defined as the acceleration rebound torque. Vehicle acceleration and jerk are used as inputs of the control. Jerk is a rate of change of acceleration. At the moment of clutch actuating, an acceleration (a_{ref}) is memorized as a reference value. When jerk increases and then decreases sequentially, the rebound torque is generated toward reducing the acceleration change, which depends on the difference between the reference acceleration (a_{ref}) and the current acceleration (a_i). Fig. 3 shows the concept of control with vehicle acceleration.

3.2 Rapid Clutch Actuating Control (RCAC)

When the difference in clutch speeds (input side speed, ω_{ci} and output side speed, ω_{co}) is much lower than the constraint value (ω_c), a clutch actuator rapidly engages a clutch. The duration of mode transition can thereby be reduced. This process helps to improve energy efficiency by removing unnecessary consumption. A control suggests that determining a rate of actuation has two steps. In typical conditions, the clutch actuator operates according to a nonlinear fixed trajectory, shown in the topmost rectangle on the right side of Fig. 4. When the clutch is synchronized to be sufficient for full engagement, the actuator operates the clutch more rapidly. Time integral gain is defined as K_t to adjust the actuating rate. When the gain is high, the actuator moves faster than in typical conditions. This process is defined as rapid clutch actuating control. Fig. 4 illustrates the flow of the clutch control. In summary, the right-side rectangle in Fig. 2 shows the flow of the proposed controls of mode transition.

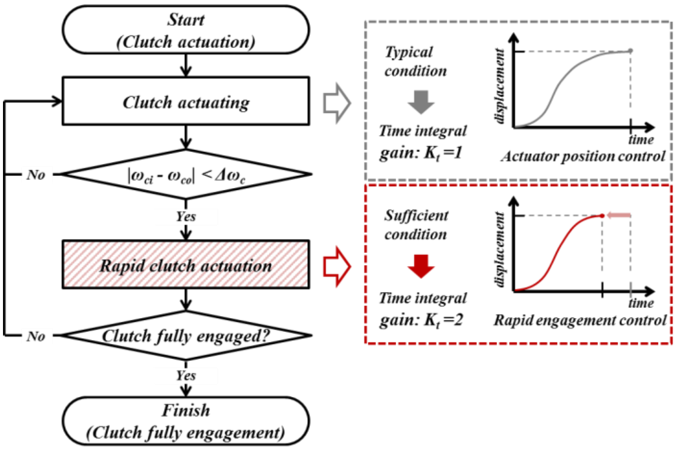


Figure4: A flow of the rapid clutch actuating control

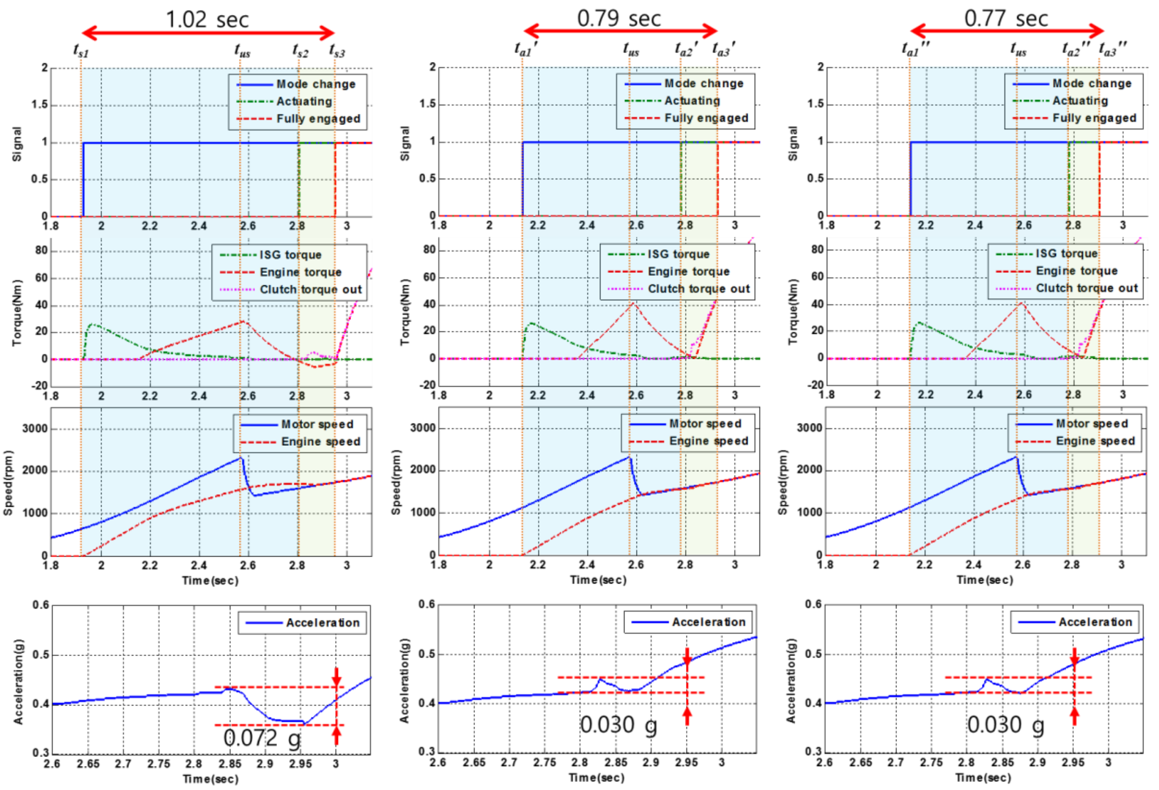
4 Simulation

Table 1 describes the parameters of the PHEV components. Simulation based on MATLAB/Simulink was conducted on the transition from electric-driving mode to hybrid-driving mode. Fig. 5 shows simulation results with and without the proposed controls. The basic simulation is without the controls, as shown in Fig. 5 (a). It resulted in a duration of transition of 1.02 sec, and the acceleration change during clutch engagement, peak-to-peak acceleration, was 0.072 g. With the acceleration rebound torque control, the duration was 0.79 sec, and the acceleration was 0.030 g, as shown in Fig. 5 (b). The duration and acceleration reduced by 22% and 59%, respectively. The duration can be reduced because it was considered that the starting time of mode transition shifted close to the moment when clutch speeds completely synchronized. Although a short duration makes a large change of acceleration because of a trade-off relationship of duration and acceleration change, the acceleration rebound torque control can lessen acceleration change a lot without drivability. Fig. 5 (c) shows simulation results with the controls of both rapid clutch actuating and acceleration rebound torque. The duration was 0.77 sec and its additional reduction was 3.3% by the rapid clutch actuating control. In addition, the acceleration change was still

0.030 g, which is the same value without the rapid clutch actuating control. The rapid clutch actuating maintained the lower change of acceleration. Table 2 summarizes the simulation results. With both controls, the improvements in duration and acceleration change were 25% and 59%, respectively. The decreased duration reduced energy consumption by 15%.

Table1: Parameters of PHEV components

Component	Type/Parameter	Value	Unit
ICE	Diesel	3	cylinder
	Displacement	0.98	L
	Speed range	1000-4000	rpm
EM	Maximum power	30	kW
	Speed range	0-6000	rpm
ISG	Maximum torque	28	Nm
	Speed range	0-5500	rpm
Clutch	Dry	-	-
Transmission	DCT	-	-
Battery	Li-ion	-	-
	Capacity	26.2	Ah
Vehicle	Mass	1,321	kg
	Frontal area	2	m^2
	Drag coefficient	0.33	-
	Rolling resistance coefficient	0.014	-



(a) w/o controls

(b) w/ acceleration rebound torque control

(c) w/ controls of rapid clutch actuating and acceleration rebound torque

Figure5: Simulation results of mode transition with the proposed controls

Table2: Summary of simulation results

Results (Improvement)	w/o controls	w/ ARTC	w/ ARTC and RCAC
Duration	1.02 sec	0.79 sec (22%)	0.77 sec (25%)
Acceleration change	0.072 g	0.030 g (59%)	0.030 g (59%)
Energy consumption	12.15 kJ	10.95 kJ (10%)	10.37 kJ (15%)

5 Conclusion

This paper proposed controls for the mode transition of PHEVs. A mode transition algorithm was developed and the proposed controls were mounted to a PHEV simulator. With the acceleration rebound torque control, an ICE generated the compensated torque to overcome the drivetrain load of additional rotational inertia during clutch engagement by sustaining acceleration. Furthermore, the rapid clutch actuating control reduced an unnecessary delay of mode transition, which decreased energy consumption. Combined with these two controls, the mode transition improved drivability and energy efficiency.

Acknowledgments

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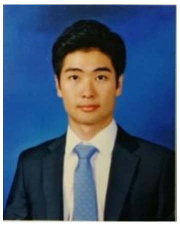

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