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Powertrain Modeling for Analyzing the Transient Response of the Parallel HEV

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Abstract

This paper presents a dynamic model of a parallel HEV (Hybrid Electric Vehicle) which can simulate torque vibration during transient maneuvers. The target HEV has an engine clutch between the engine and the traction motor; and has a ISG (Integrated starter & generator) to start the engine after EV(electric vehicle) mode. In this configuration, the drive-train torque vibration during transient maneuver is one of the major control issues. However, because of lack of the dynamic model of the system, the research for the issues heavily depends on the actual test; and the control strategy is hard to be designed from the systematic approach. Therefore, as the first step for the development of the systematic supervisory control strategy, this paper focuses on the dynamic modeling and validation of the parallel HEV.

Keywords: HEV (hybrid electric vehicle), ICE (internal combustion engine), modelling, parallel HEV, permanent magnet motor

1 Introduction

Compared to the other hybrid propulsion system, a parallel Hybrid Electric Vehicle (HEV) has advantages in both development period and cost. This is because the parallel HEV has similar structure to the conventional gasoline vehicles.

However, the advantages mentioned before make it hard to improve the fuel economy and the exhaust emissions as much as other types of HEV. This is because the engine speed cannot be controlled independently to minimize the Specific Fuel Consumption (SFC) [1]-[3].

The target parallel HEV has an engine clutch between the engine and the traction motor; and has a belted Integrated starter & generator (ISG) to start the engine after EV (electric vehicle) mode which makes the engine operating point to be set out of the high SFC region. (See Fig.1)

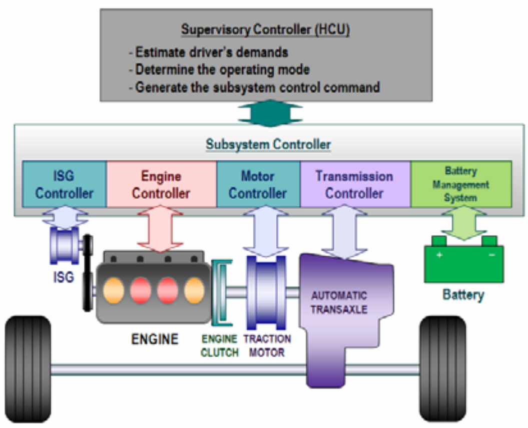

Figure1: Structure of the target parallel HEV

In this configuration, however, the drive-train torque vibration during transient maneuvers is severe comparing to other types of the parallel HEV due to the discontinuity of the engine clutch [2][3][5].

Because of lack of the dynamic model of the system, the research for the issues heavily depends on the actual test [4]-[6]; and the control strategy is hard to be designed from the systematic approach.

Therefore, as the first step for the development of the systematic supervisory control strategy, this paper focuses on the dynamic modeling and validation of the parallel HEV.

The model of the parallel HEV has following characteristics to show the transient torque vibration and the torque response of a control input from the supervisory controller.

- Torsional vibration of the crankshaft
- Torque response of the engine
- Torque response of PMSM

The model has also following simplified characteristics of the electrical systems. They show basic functions of the electrical system in the parallel HEV.

- Energy exchange between the PMSM and the battery through the inverter
- Electrical Characteristics of the battery according to the SOC

2 Model structure

Torque response of the engine and the PMSM according to torque commands are modelled to represent a torque vibration of the parallel HEV during transient maneuvers. The subsystem models constructing the Vehicle model are divided into two groups according to the modelling environment. (See Fig.2)

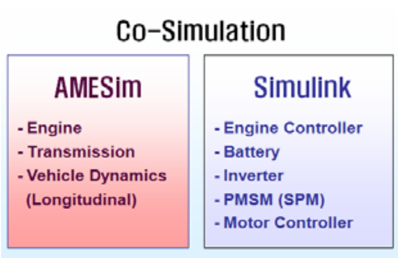

Figure2: Subsystem Model classification

A computational stability and components library are the most important factors to decide the modelling environment of each subsystem model. In the case of the mechanical system, including the engine, the AMESim is appropriate to modelling them, because of a mechanical system library and an engine library. Especially, the engine model is designed based on the IFP engine library in the AMESim. However, the electrical system is designed in the Simulink; because the computational effort to calculate the AMESim electrical model is too large and the solution of the model frequently diverges unlike the Simulink model.

3 Gasoline engine model

A structure of the physical engine model designed in this paper to represent the transient response of the engine torque is illustrated in Fig.3.

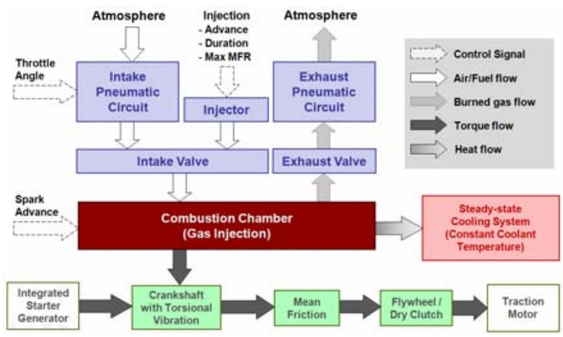

Figure3: Structure of the engine model

The torque delay of the engine is determined by two factors. The first one is manifold filling delay; and the other one is fuel injection delay. In this paper, the plant model is designed using dynamic models to represent these nonlinear delay characteristics.

The plant model is composed of pneumatic circuit models which represent the intake/exhaust air dynamics, combustion model of the cylinder, and a dynamic model of the crankshaft. The engine controller which includes spark timing control, lambda control, VVT control, and electronic throttle control is also designed based on the Simulink.

3.1 Intake/Exhaust air-path model

The intake/exhaust air-path model is designed using the pneumatic circuit components which have some assumptions below [7].

- Speed of the air is less than the speed of sound
- Uniform gas properties over the cross section (Dimension of the flow characteristics is one)
- The air is assumed to be an ideal gas
- Ignore the effects of gravity
- Distribution of the gas pressure and temperature is homogeneous in the chamber
- Kinetic energy of the air in the chamber is ignored

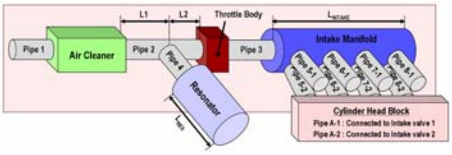

Figure4: Structure of the intake air-path model

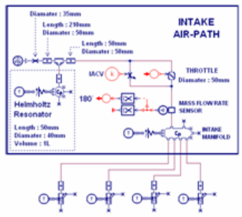

Figure5: Intake air-path model

3.2 Combustion chamber model [7]

There are 3-types of combustion chamber model in the IFP engine library. If it is necessary to observe characteristics from the geometry variation of the cylinder, ECFM 3Z model which can represent the 3-dimensional gas flow and the combustion is required. In the case of this paper, however, the geometry of the cylinder and the engine controller are all fixed. This is why the CFM 1D model is applied in this paper.

The function of the cylinder block is divided into two different functions: variable volume pneumatic chamber with heat exchange, and 1-dimensional combustion model.

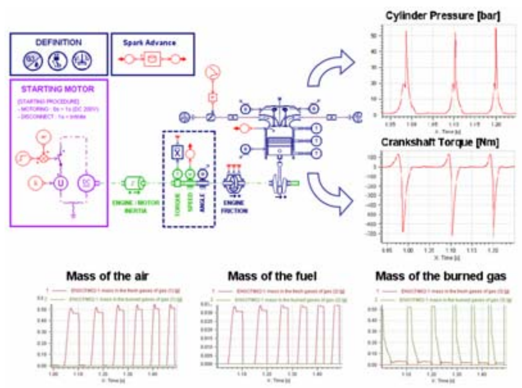

Figure6: Single cylinder engine model simulation

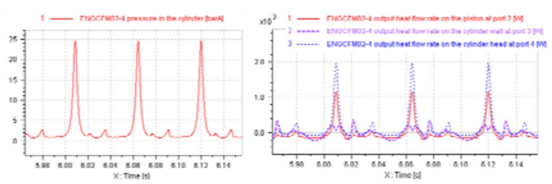
Figure7: Cylinder pressure [bar] / Heat exchange [W]

The CFM 1D model provided by AMESim can show the cylinder pressure variation according to the spark advance. This feature cannot be realized in the experimental model. (See Fig.8)

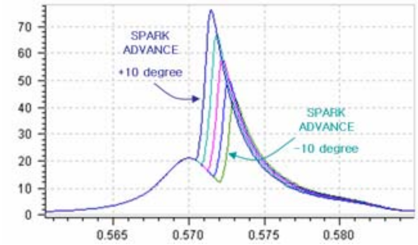

Figure8: Combustion chamber pressure variation versus Spark advance

3.3 Crankshaft model

The crankshaft has 3-types of dynamics varied with a direction of the motion: compressive, bending, and torsional direction [3][8]-[10]. To represent every effect of these dynamics, it is necessary to model not only the vehicle dynamics which has high DOF but also some dynamics of the engine room components such as an engine mount.

In this paper, dynamics in the compressive direction and the bending direction are not modelled; because they do not have much relation with the driveline torque fluctuation.

The crankshaft model with dynamics of torsional direction is illustrated in Fig.9; and the simulation result of the crankshaft model is Illustrated in Fig.10.

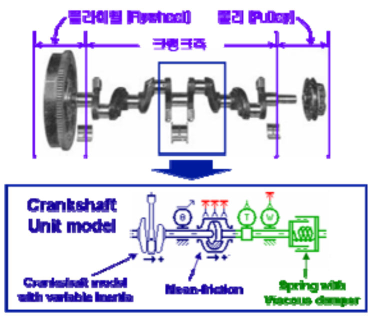

Figure9: Unit model of the crankshaft with the torsional vibration

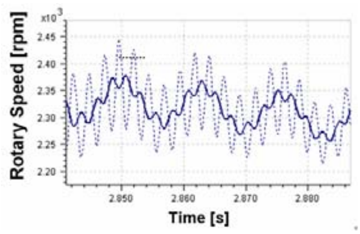

Figure10: Speed difference between the flywheel and the pulley wheel because of torsional vibration

3.4 Entire engine model validation

The entire model of the engine described in the section 3.1 to 3.3 is illustrated in Fig.11. The model contains not only described subsystem models, but also some interfaces to the Simulink. These interfaces connect the engine controller and the plant model to each other.

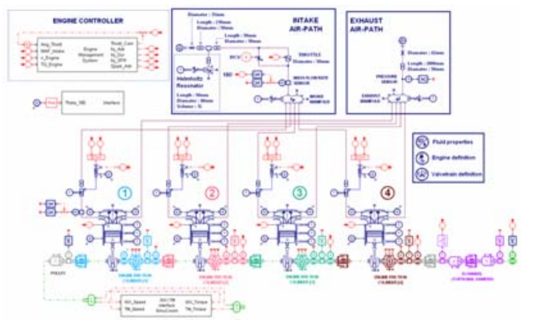

Figure11: Entire engine model

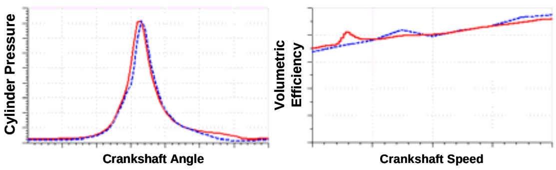

Figure12: Cylinder pressure / Volumetric efficiency (Dotted line: Experiment / Solid line: Simulation)

As the first step of validation process, the volumetric efficiency of the engine model is compared with the experimental results to check the validity of the air-path model. The second step of validation process is checking the validity of combustion chamber model by Comparing the cylinder pressure of the engine model to the experimental result.

The results illustrated in Fig.12 bring to a conclusion that the engine model is valid for the air-path model and the combustion chamber model because the simulation results are similar to the experimental results.

4 Electrical system model

The target HEV has two kinds of motors. The first one performs the starting and generating operation of the engine with 10kW rated output power; and the other one performs the traction and recuperation braking operation with 50kW rated output power. Each of the motors is permanent magnet synchronous type.

To represent the characteristics of the torque response, it is necessary to simulate the real control algorithm. It means that the interfaces between the controller and the PMSM such as a 3-phase inverter and a battery need to be modelled.

The complete electrical system model structure which satisfies the above requirements is illustrated in Fig.13

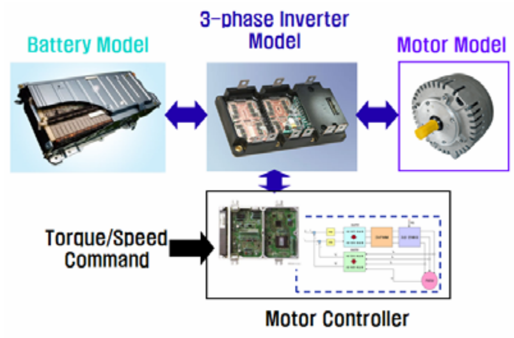

Figure13: Structure of entire electrical system

4.1 Battery model [11]

Because this paper focuses on the torque response and the torque transfer characteristics, a designed battery model does not contain any thermal dynamics or effects from the BMS (Battery Management System). The battery model is based on the internal resistance model and an ideal SOC estimator. This structure is illustrated in Fig.14.

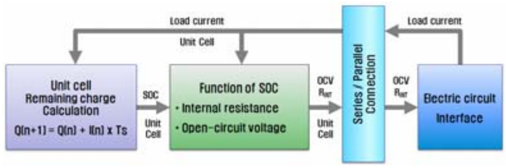

Figure14: Structure of the battery model

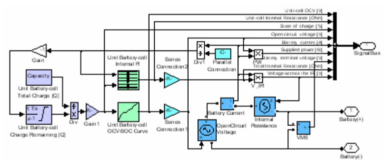

Figure15: Battery model

4.2 Inverter model

Real inverter hardware is composed of many power electronics semiconductors such as an IGBT or a MOSFET. To represent detailed voltage and current characteristics between the various power electronics components, Therefore, the inverter model need to be modelled in the component level.

However, some of characteristics such as an on/off characteristic require too small simulation time step; and this makes the calculation time too long.

In this paper, to maximize the simulation speed, the IGBT is modelled as unidirectional ideal switch with a reverse parallel diode which is illustrated in Fig.16.

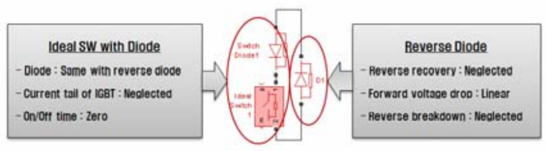

Figure16: Unit model of the inverter switch

4.3 PMSM model

The PMSM is appropriate to the traction application such as the traction motor of the HEV because of a high efficiency and a high power density. Especially, applied cases of the Interior mounted PM machine (IPM) is increasing because of higher power density and lower cost than the Surface mounted PM machine (SPM) [12]. The traction motor of the Toyota PRIUS II can be a example.

In this paper, a synchronous motor model in a SimPowerSystems library is used for the ISG and the traction motor. This model is based on the equivalent circuit model which can be applied to the both of the SPM and the IPM.

The PMSM model is designed on the d-q coordinate which is transformed coordinate from the a-b-c coordinate. This coordinate transformation algorithm is described in the section 4.4.

$$\frac{dL_d i_d}{dt} = u_d - Ri_d + p\omega L_q i_q \qquad (1)$$

$$\frac{dL_q i_q}{dt} = u_q - Ri_q - p\omega L_d i_d - \psi_m p\omega \qquad (2)$$

$$T_e = \frac{3}{2} p[\psi_m i_q + (L_d - L_q) i_d i_q] \qquad (3)$$

Formula (1) and (2) mean the equivalent circuit model of the PMSM in each of d and q axis. These include resistive, self inductive, and mutual inductive characteristics.

Formula (3) means a torque generation model. In this formula, it can be described that the torque of the SPM is only dependent on the q-axis current because the L_d is same with the L_q [12]-[13].

The PMSM model has some assumptions below.

- L_d, L_q, ψ_m are Time invariant constants.
- The iron loss and copper loss are ignored.

4.4 Coordinate transformation [13]-[14]

To apply the vector control method to the PMSM, A coordinated transformation algorithm is used. This transformation includes the park transform and the clarke transform. The equations about these transformations are shown in formula (4)-(9).

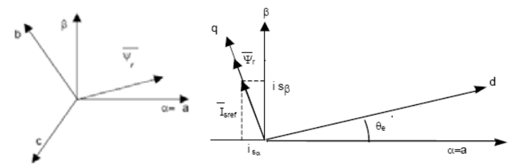

Figure17: Coordinate transformation
(Left: abc-αβ frame / Right: αβ-dq frame)

- Park & Clarke transform (Integrated)

$$i_q = \frac{2}{3}(i_a \times \cos(\theta)) + i_b \times \cos\left(\theta - \frac{2\pi}{3}\right) + i_c \times \cos\left(\theta + \frac{2\pi}{3}\right) \qquad (4)$$

$$i_d = \frac{2}{3}(i_a \times \sin(\theta)) + i_b \times \sin\left(\theta - \frac{2\pi}{3}\right) + i_c \times \sin\left(\theta + \frac{2\pi}{3}\right) \qquad (5)$$

$$i_0 = \frac{1}{3}(i_a + i_b + i_c) \qquad (6)$$

- Inverse Park & Clarke transform (Integrated)

$$i_a = i_q \times \cos(\theta) + i_d \times \sin(\theta) + i_0 \qquad (7)$$

$$i_b = i_q \times \cos\left(\theta - \frac{2\pi}{3}\right) + i_d \times \sin\left(\theta - \frac{2\pi}{3}\right) + i_0 \qquad (8)$$

$$i_c = i_q \times \cos\left(\theta + \frac{2\pi}{3}\right) + i_d \times \sin\left(\theta + \frac{2\pi}{3}\right) + i_0 \qquad (9)$$

4.5 PMSM controller

The electrical system controller contains a PWM generator, a coordinate transformation logic, current controller, and a field weakening controller. This is illustrated in Fig.18 [14]-[15].

At the first step of the torque control, the field weakening controller determines the target current on the d-axis and the q-axis. These values are references of the current controller which is similar to a current controller of a DC motor.

The current controller determines the target phase voltage according to the current error; and lastly, the PWM generator determines the optimal output duty ratio to minimize the phase voltage error [12]-[13].

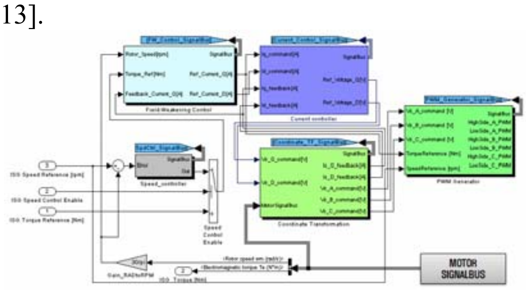

Figure18: PMSM controller

4.6 Entire electrical system validation

The structure of the entire electrical system and its model are illustrated in Fig.19. To validate this model, several simulations are executed.

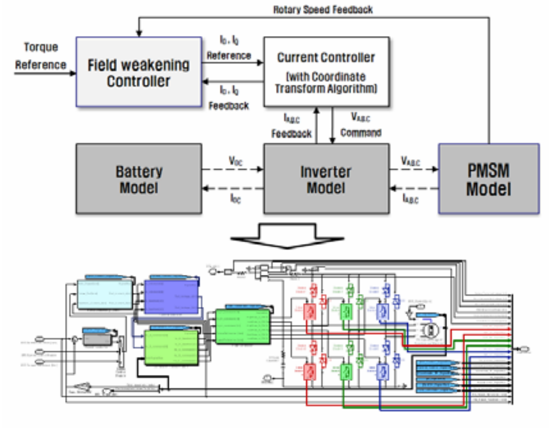

Figure19: Entire electrical system model

Simulation results about a torque control and a speed control are illustrated in Fig.20. In the torque control mode, the actual torque is limited because a maximum output torque decreases as the speed increases. These results are also found in the q-axis current response of the Fig.20.

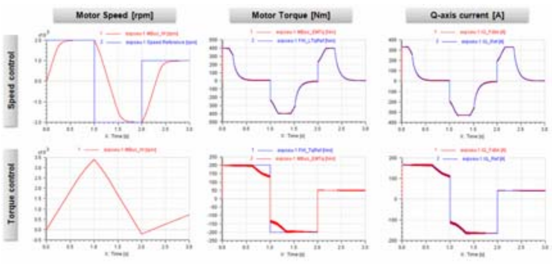

Figure20: Speed control / Torque control

To validate the model quantitatively in the view of torque characteristic, maximum output torque graph of the target PMSM is calculated and illustrated in Fig.21. This result shows that the designed electrical system model is valid.

The target PMSM of the validation is 50kW traction motor; and the parameters are as listed below.

- Pole pairs (n_p): 4
- D-axis inductance (L_d): 1.916 mH
- Q-axis inductance (L_q): 5 mH
- Armature resistance (R_a): 0.065 Ohms
- Torque constant (K): 0.2

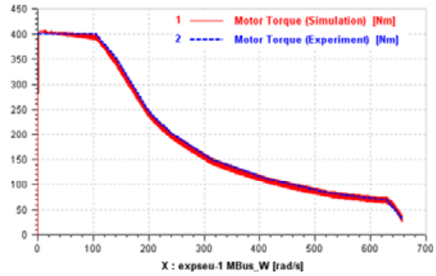

Figure21: Speed-Torque performance curve

5 Entire vehicle model

To construct the entire vehicle model, the model of a torque transfer device such as a transmission is required. In this paper, a 6-speed AT demo model and a dry clutch model in the AMESim is applied to construct the vehicle model. These models are illustrated in Fig.22.

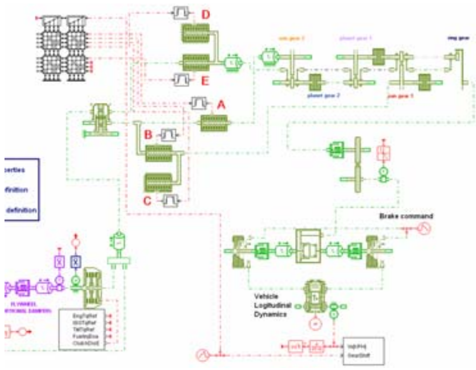

Figure22: 6-speed AT model / Clutch model

The entire vehicle model including the engine model, the electrical system model, the transmission model, and controller models of each subsystems are illustrated in Fig.23 and Fig.24..

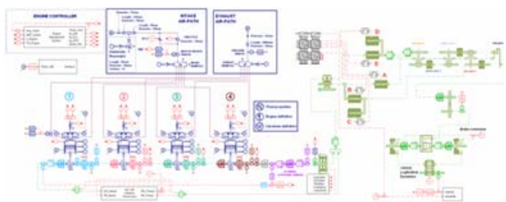

Figure23: Engine model / Transmission model

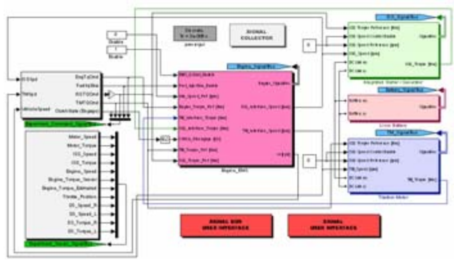

Figure24: Top level model (EMS / Electrical system)

6 Simulation results

To show the drivetrain torque vibration of vehicle model, a simple supervisory controller for single transition from the EV-mode to the HEV-mode is designed. This controller is tuned to show the response of a worst case as described in [4]-[6].

The supervisory controller is simulated with the designed vehicle model; and the results are illustrated in Fig.25 and below.

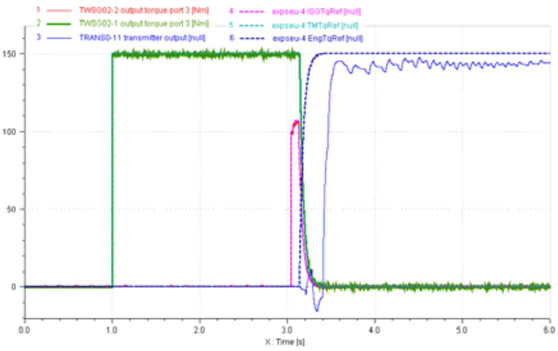

Figure25: Single transition(EV→HEV) torque response [Nm]

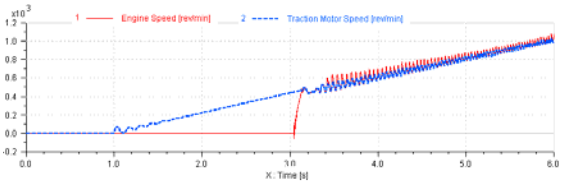

Figure26: Single transition(EV→HEV) shaft speed response [rpm]

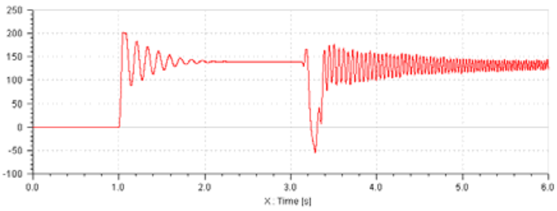

Figure27: Single transition(EV→HEV) Transmission input torque [Nm]

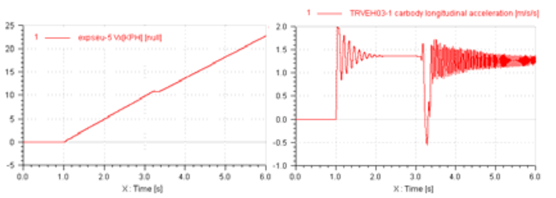

Figure28: Single transition(EV→HEV) vehicle speed [kph] / acceleration [m/s^2]

These results shows the characteristics of the controller which is designed with an assumption: all torque generation device can change output torque with no delay. Because of this, the transmission torque has large fluctuation in the mode transition period. This torque fluctuation makes a large jerk of longitudinal vehicle dynamics as illustrated in Fig.28.

7 Conclusion

This paper proposes a parallel HEV model with a complex powertrain model based on the physical model to represent a torque vibration and delay of the torque generator such as an engine. A transmission model and a longitudinal vehicle model are added to the designed engine model and electrical system model.

The proposed model enables control engineers to develop the supervisory controller of the parallel HEV by using not only the experimental method but also the systematic model based design method. Moreover, this model enables the estimation of the torque response even if the vehicle parameter is varied from the original parameter. This is because the subsystem model is based on the physical model. Therefore, the supervisory controller can be developed systematically when the specification of the target HEV is not fixed and the prototype vehicle is not available.

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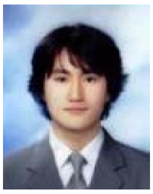
His fields of interest are optimal control theory and its application to hybrid electric vehicle



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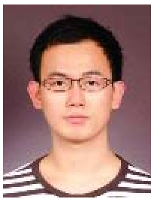

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