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ENGINE NET TORQUE COMPENSATION THROUGH DRIVELINE TORQUE ESTIMATION IN A PARALLEL HYBRID VEHICLE

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ABSTRACT−In recent years, interest in smart and green vehicles has increased. There are many cases where engine net torque related control is performed when building smart and green car systems. Speed tracking control in autonomous driving, or optimal transmission shift control is an example. The engine net torque is the sum of the engine indicated torque, accessory load torque, and frictional torque, and the starter motor torque in the case of a parallel hybrid vehicle. However, the estimation error of these torque items can cause the estimation error of the engine net torque. In this paper, a compensation method for the slowly varying uncertainty of the engine net torque in a parallel hybrid vehicle using a multiplicative constant is proposed. The adaptation of the multiplicative constant is conducted using the amount of change in the engine net torque estimated in the backward direction of the driveline. The proposed algorithm is verified based on production vehicle data.

KEY WORDS : Engine torque estimation, Engine net torque estimation, Engine torque compensation, Engine net torque compensation, Vehicle driveline model, Parallel hybrid vehicle

NOMENCLATURE

T_e : engine net torque, N·m
$T_{e.n}$: nominal engine net torque, N·m
T_{ec} : engine clutch torque, N·m
T_m : motor torque, N·m
T_c : transmission clutch torque, N·m
T_o : output shaft torque, N·m
T_L : load resistance torque, N·m
J_e : engine inertia, kg·m^2
J_m : motor inertia, kg·m^2
J_c : clutch inertia, kg·m^2
J_v : vehicle inertia, kg·m^2
J_{mc} : motor and clutch inertia, kg·m^2
i_t : transmission gear ratio, -
i_f : final gear ratio, -
l : torque constant, -
L_1 : lower bound of actuator displacement, mm
L_2 : upper bound of actuator displacement, mm
d_a : actuator displacement, mm
ω_e : engine angular speed, rad/s
ω_m : motor angular speed, rad/s
ω_c : clutch angular speed, rad/s
ω_w : wheel angular speed, rad/s
θ_c : rotational angle of the transmission shaft, rad
θ_w : rotational angle of the wheel, rad
m_v : vehicle mass, kg
g : gravitational acceleration, m/s^2
Φ_{road} : road grade, °
K_{rr} : rolling resistance coefficient, -
ρ : air density, kg/m^3
V_{air} : relative speed of a vehicle to the air, m/s
C_d : air drag coefficient, -
A : vehicle frontal area, m^2
r_w : wheel radius, m
λ : adaptation gain, -
ε : adaptation error, N·m
Δ : amount of variation, -
t_s : gear holding time, s
α : lower bound of engine torque mm
β : lower bound of wheel angular speed, rad/s
γ : lower bound of gear holding time, mm
δ : upper bound of gear holding time, mm

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1. INTRODUCTION

Drivers' expectations for car convenience are increasing and automobile exhaust gas regulations are being strengthened continually. Thus, research on intelligent vehicles and eco-friendly vehicles has been actively conducted recently. Engine net torque is one of the most important control variable to realize a smart and green car system. For example, precise control of engine net torque is required in a system of vehicle dynamics control, active engine control, optimal powertrain control, predictive energy management, etc.

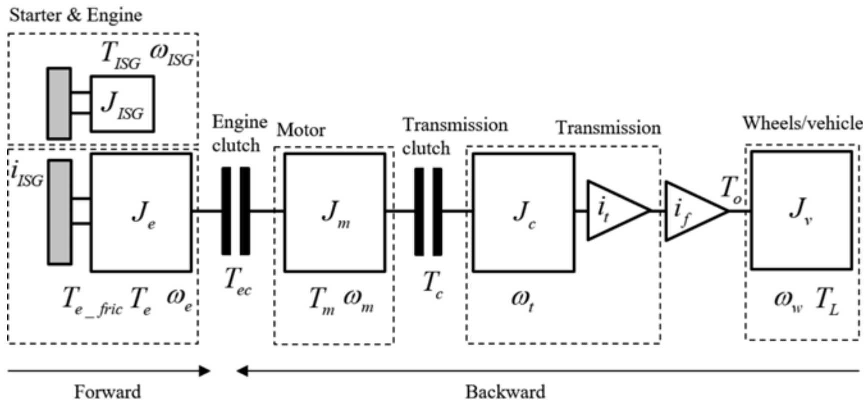

Figure 1. Methods of engine net torque estimation.

The engine net torque mentioned in this paper refers to the torque that can be transmitted from the engine crankshaft end flywheel. A torque sensor that can measure driveline torque, e.g., the engine net torque on the engine flywheel shaft, is not installed in a real car due to their high cost and spatial limitation (Gao *et al*., 2011; Kim *et al*., 2018; Yi *et al*., 2000). Therefore, the engine net torque must be estimated without accurate measurement, even though it is important information in various control systems.

Figure 1 shows a lumped driveline model of a parallel hybrid vehicle and methods of engine net torque estimation. The engine net torque can be calculated by accurately estimating and summing the engine indicated torque generated by fuel combustion, the accessory load torque, the frictional torque, and the starter motor torque in the case of a parallel hybrid vehicle: this is known as the forward direction estimation method.

When estimating the engine indicated torque, a map whose inputs are throttle angle and engine speed, and whose output is the engine indicated torque is often utilized (Rajamani, 2011). On the other hand, when the altitude of the environment in which a vehicle is traveling changes, the atmospheric pressure also changes, and the amount of air sucked into an engine with respect to the same throttle angle and engine speed is also changed. Additionally, when the intake line is modified, the amount of intake air can also be changed. The engine indicated torque map of throttle angle and engine speed will then be changed from the original map, and as a result the engine indicated torque can be inaccurately estimated.

Also, if an additional accessory is installed for the user's convenience, the error of the accessory load torque can occur. In addition, it is difficult to estimate the friction torque since it varies depending on the type of engine oil and the engine wear. Therefore, when estimating the engine net torque in the forward direction, uncertainty on the engine indicated torque, the accessory load torque, and the frictional torque causes uncertainty in the engine net torque.

The engine indicated torque can be estimated based on a torque model instead of a torque map (Eriksson and Nielsen, 2014; Guzzella and Onder, 2009), and some studies have been conducted to improve the accuracy of the torque model in the engine transient state (Chevalier *et al*., 2000; Smith *et al*., 1999).

Also, the engine indicated torque was estimated as a function of crankshaft speed and the amplitude of crankshaft speed fluctuation (Stotsky, 2005, 2009) (Rizzoni, 1989), derivative terms of crankshaft angle (Lee *et al*., 2001), crankshaft speed and engine block vibration (Azzoni *et al*., 1998), and crankshaft speed and an index that was newly proposed in the papers (Jianqiu *et al*., 2002a, 2002b).

The sum of the friction torque and the accessory torque was estimated using the engine indicated torque when an engine is idling (Stotsky, 2009).

The second way of estimating the engine net torque is the backward direction method. This method estimates the output shaft torque or road load torque, and calculates the engine net torque in the backward direction considering the inertia effect. By using this backward engine net torque estimation method, it is possible to correct the uncertainty of the engine net torque in the aforementioned engine net torque estimation method in the forward direction.

However, little research on the backward engine net torque estimation method using a vehicle driveline model has been conducted.

In some papers (Choi and Hedrick, 1996; Rizzoni and Zhang, 1994), the engine net torque was estimated based on the engine load torque which is assumed to be measured using a dynamometer. However, the engine load torque cannot be measured, also cannot be estimated easily in a real vehicle.

Furthermore, the adaptation method of the engine net torque was studied in Oh *et al*. (2013). An additive constant, which represents the engine net torque uncertainty, and the output shaft torque were estimated simultaneously using the nominal engine net torque and a driveline model. However, the convergence speed can be problematic when two parameters are estimated simultaneously in one model equation.

Also, in many studies, the output shaft torque is modeled using the shaft compliance model (Glielmo *et al.*, 2006; Jeong and Lee, 2000b; Oh *et al.*, 2014, 2017a; van Berkel *et al.*, 2014). However, in a production vehicle, the shaft angle cannot be measured and therefore should be calculated by integration of the shaft speed. However, the shaft angle can drift due to the noise of the shaft speed. Also, the shaft compliance model cannot describe the backlash of shaft joints. Thus, the estimate of the output shaft torque itself can be inaccurate due to these reasons.

This paper proposes a compensation method for the slowly varying uncertainty of the engine net torque estimated in the forward direction of the driveline in a parallel hybrid vehicle using a multiplicative constant, which is called the torque constant in this study, and mainly addresses the adaptation algorithm of the torque constant. The adaptation of the torque constant is conducted using the amount of change in the nominal engine net torque estimated in the forward direction of the driveline and the amount of change in the engine net torque estimated in the backward direction. The reason why the amount of change in the engine net torque is utilized instead of the engine net torque itself is due to the drift issue of the output shaft torque which is used to estimate the engine net torque in the backward direction. The output shaft torque is modeled using the shaft torque compliance model in this study.

The remaining part of this paper is organized as follows. Section 2 introduces the compensation method for the uncertainty of the nominal engine net torque and the adaptation algorithm of the torque constant. Section 3 addresses the experiment results in a parallel hybrid production vehicle. Section 4 concludes this paper.

2. ENGINE NET TORQUE COMPENSATION METHOD

In this section, the compensation method for the slowly varying uncertainty of the engine net torque estimated in the forward direction of the driveline in a parallel hybrid vehicle using a multiplicative constant (which is referred to as the torque constant in this paper), and the adaptation algorithm of the torque constant are addressed.

The adaptation of the torque constant is performed using the amount of change in the nominal engine net torque estimated in the forward direction of the driveline and the amount of change in the engine net torque estimated in the backward direction. Hereinafter, the engine net torque estimated in the forward direction of the driveline is called the nominal engine net torque and the engine net torque estimated in the backward direction is called the estimated engine net torque.

A driveline model of a parallel hybrid vehicle and an engine net torque estimation method in the backward direction of the driveline are introduced in subsection 2.1. In addition, the adaptation algorithm of the torque constant is dealt with in subsection 2.2. Lastly, the application condition of the adaptation algorithm is mentioned in subsection 2.3.

2.1. Driveline Model

Figure 1 shows a lumped inertia driveline model of a parallel hybrid vehicle. The mathematical driveline model of a parallel hybrid vehicle using a lumped inertia is as follows, referring to the driveline model of other studies (Jeong and Lee, 2000a; Ni *et al.*, 2009; Oh *et al.*, 2017b; Oh and Choi, 2015).

$$J_e\dot{\omega}_e = T_e - T_{ec} \tag{1}$$

$$J_m\dot{\omega}_m = T_{ec} + T_m - T_c \tag{2}$$

$$J_c\dot{\omega}_c = T_c - \frac{T_o}{i_t i_f} \tag{3}$$

$$J_v\dot{\omega}_w = T_o - T_L \tag{4}$$

In this study, it is considered that the adaptation of the torque constant, and transmission gear shift control are not performed at the same time. So, it is assumed that the transmission clutch is fully engaged during the adaptation period of the torque constant. Equations (2) and (3) can then be expressed as follows.

$$J_{mc}\dot{\omega}_m = T_{ec} + T_m - \frac{T_o}{i_t i_f} \tag{5}$$

$$J_{mc} = J_m + J_c \tag{6}$$

The engine net torque can then be estimated from the output shaft torque in a backward manner in the driveline as follows by summing Equations (1) and (5).

$$T_e = \frac{T_o}{i_t i_f} - T_m + J_e\dot{\omega}_e + J_{mc}\dot{\omega}_m \tag{7}$$

Here, it is assumed that the engine speed and motor speed in the right side are measurable, and the motor torque is also measurable by current measurement.

The output shaft torque is not generally measurable in a production vehicle so should be estimated using a model.

Currently, there are two possible models to estimate the output shaft torque (Kim *et al.*, 2018; Kim and Choi, 2018; Ni *et al.*, 2009). The first is the shaft torque compliance model, and the second is the driving resistance torque model, like below.

$$T_o = b_o\left(\frac{\omega_t}{i_t i_f} - \omega_w\right) + k_o\left(\frac{\theta_t}{i_t i_f} - \theta_w\right) \tag{8}$$

$$T_o = r_w\left\{\begin{aligned} &m_v g\sin(\Phi_{road}) + K_{rr} m_v g\cos(\Phi_{road}) \\ &+ \frac{1}{2}\rho v_{air}^2 C_d A + m_v\dot{\omega}_w r_w \end{aligned}\right\} \tag{9}$$

The shaft torque compliance model consists of a spring constant and damping constant of a shaft which hardly changes over time. But, the driving resistance torque model consists of many uncertain variables such as the wheel radius, rolling resistance coefficient, air density, relative speed of a vehicle to the air, air drag coefficient, vehicle frontal area, especially, vehicle mass, and road grade.

Thus, in this study, the shaft torque compliance model which has less uncertain variables is mainly utilized rather than the driving resistance torque model to estimate the output shaft torque.

2.2. Adaptation Algorithm of Torque Constant

In Equation (8), the torque compliance model of the output shaft is expressed with the rotational angle of the transmission and the wheel. However, in a production vehicle, the rotational speed of shafts is measured rather than the rotational angle, and therefore Equation (8) should be modified as given below for application to a production vehicle.

$$T_o = b_o\left(\frac{\omega_t}{i_t i_f} - \omega_w\right) + k_o \int_0^t \left(\frac{\omega_t}{i_t i_f} - \omega_w\right) dt \tag{10}$$

However, the rotational angle of the transmission and the wheel is integrated from the rotational speed. Thus, the estimated value of the output shaft torque may become inaccurate over time if the small error of the rotational angle of the transmission and the wheel is accumulated by sensor noise.

Also, due to the backlash of shaft joints, the estimate of the output shaft torque may become inaccurate. In the case of a vehicle equipped with a dual clutch transmission(DCT), it is difficult to determine the shaft speed and the shaft gear ratio when the transmission gear shift is performed, and discontinuity of the output shaft torque occurs before and after the shift. For these reasons, the estimated output shaft torque can drift, and this value cannot be used to compensate for the uncertainty of the engine net torque directly. Further details of the drift issue of the output shaft torque are discussed in the results section.

On the other hand, the amount of change in the output shaft torque during a specific period of time can be more accurate than the value of the output shaft torque itself.

Therefore, in this study, the amount of change in the engine net torque is estimated using the amount of change in the output shaft torque over a specific period of time and the adaptation of the torque constant is conducted using the amount of change in the nominal engine net torque and the amount of change in the estimated engine net torque instead of using the estimated engine net torque itself. Further details of the specific period of time is addressed in the next subsection.

By modifying Equation (7), the following torque variation formula can be obtained.

Figure 2. Experimental vehicle.

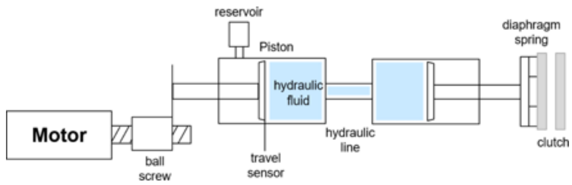

Figure 3. Schematic diagram of the engine clutch actuator.

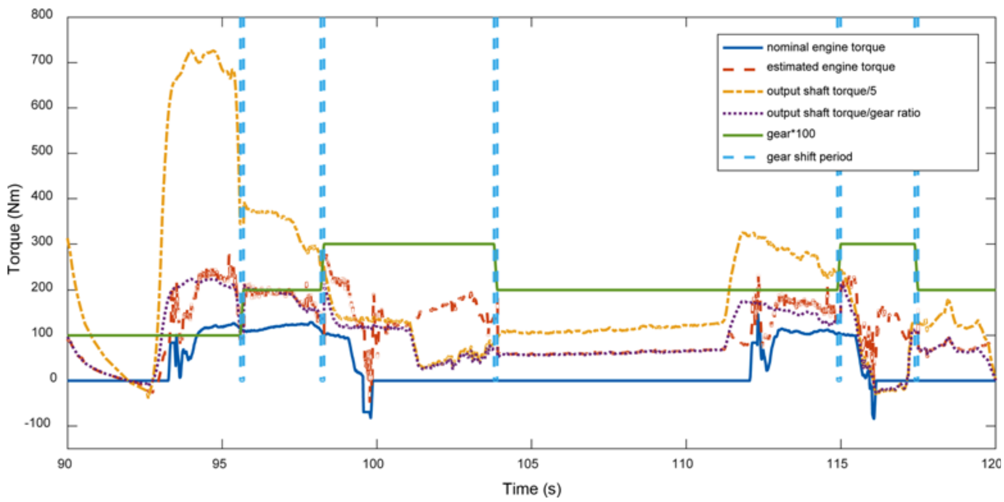

Figure 4. Output shaft torque according to gear shift.

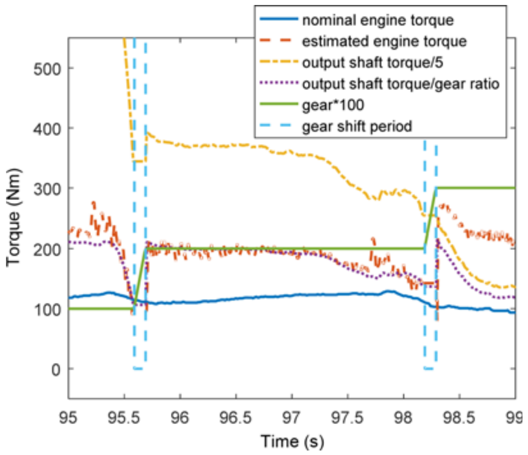

Figure 5. Enlarged figure of output shaft torque according to gear shift.

$$\Delta T_{\mathrm{e}} = \frac{\Delta T_{\mathrm{o}}}{i_{\mathrm{t}} i_{\mathrm{f}}} - \Delta(T_{\mathrm{m}} + J_{\mathrm{e}}\dot{\omega}_{\mathrm{e}} + J_{\mathrm{mc}}\dot{\omega}_{\mathrm{m}}) \tag{11}$$

Applying the torque constant to the engine net torque, the following equation can be obtained.

$$\Delta T_{\mathrm{e}} = l \Delta T_{\mathrm{e.n}} \tag{12}$$

Also, the estimate of the torque constant can be expressed as follows.

$$\Delta \hat{T}_{\mathrm{e}} = \frac{\Delta \hat{T}_{\mathrm{o}}}{i_{\mathrm{t}} i_{\mathrm{f}}} - \Delta(T_{\mathrm{m}} + J_{\mathrm{e}}\dot{\omega}_{\mathrm{e}} + J_{\mathrm{mc}}\dot{\omega}_{\mathrm{m}}) \tag{13}$$

$$\Delta \hat{T}_{\mathrm{e}} = \hat{l} \Delta T_{\mathrm{e.n}} \tag{14}$$

In order to consider both situations where the engine net torque increases or decreases, the adaptive error is defined as follows by taking the absolute value of the engine net torque in Equations (12) and (14).

$$\begin{aligned} \varepsilon &= |\Delta T_e| - |\Delta \hat{T}_e| = (l - \hat{l})|\Delta T_{\mathrm{e.n}}| \\ &= \left|\Delta\left(\frac{T_{\mathrm{o}}}{i_{\mathrm{t}} i_{\mathrm{f}}} - T_{\mathrm{m}} + J_{\mathrm{e}}\dot{\omega}_{\mathrm{e}} + J_{\mathrm{mc}}\dot{\omega}_{\mathrm{m}}\right)\right| - \hat{l}|\Delta T_{\mathrm{e.n}}| \end{aligned} \tag{15}$$

Finally, the adaptive law of the torque constant is defined as follows using a simple gradient method (Ioannou and Sun, 1996; Sastry and Bodson, 2011).

$$\dot{\hat{l}} = \lambda |\Delta T_{\mathrm{e.n}}| \varepsilon, \ \lambda > 0 \tag{16}$$

the adaptation of the torque constant is conducted at the end of each specific period of time using the amount of change in the engine net torque.

To prove the stability of the error dynamics during the adaptation, the estimation error of the torque constant is defined as follows.

$$\tilde{l} = l - \hat{l} \tag{17}$$

Also, the estimation error dynamics of the torque constant is given as follows.

$$\dot{\tilde{l}} = -\lambda \tilde{l} |\Delta T_{\mathrm{e.n}}|^2, \ \lambda > 0 \tag{18}$$

The stability of the error dynamics then can be proven using a simple Lyapunov function as follows.

$$V(\tilde{l}) = \frac{\tilde{l}^2}{2\lambda} \tag{19}$$

$$\dot{V} = -\tilde{l}^2 |\Delta T_{\mathrm{e.n}}|^2 \le 0 \tag{20}$$

The amount of change in the nominal engine net torque satisfies the persistence of excitation (PE) condition, and the error of the torque constant will converge to zero.

2.3. Application Condition

In the previous subsection, it was noted that the adaptation of the torque constant is performed at the end of each specific period of time using the amount of change in the engine net torque over the specific period of time. Hereinafter, the specific period of time when the amount of change in the engine net torque is calculated is called "application period".

Also, it was mentioned that the output shaft torque which is estimated using the shaft torque compliance model can become inaccurate if the small errors of the transmission input shaft and wheel speed are accumulated due to the integration of the rotational speeds.

Thus, the engine net torque which is calculated using the estimated output shaft torque drifts as well over time and the error of the amount of change in the engine net torque would be large when an application period is long. Also, the amount of change in the engine net torque over an application period should be large considering the error of the amount of change.

Therefore, it is noticed that an application period should be short and the amount of change in the engine net torque over an application period should be large.

In the case of a parallel type hybrid vehicle, the engine net torque changes greatly and monotonically when the

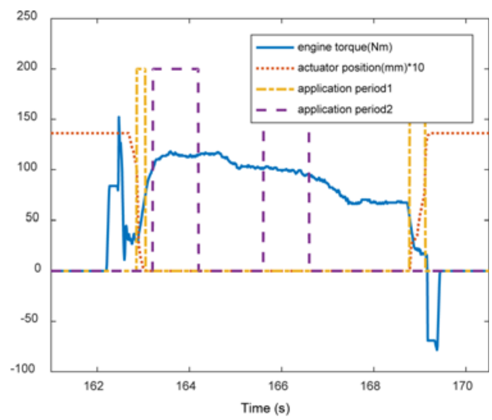

Figure 6. Engine clutch torque and actuator position while the engine clutch is engaged or disengaged.

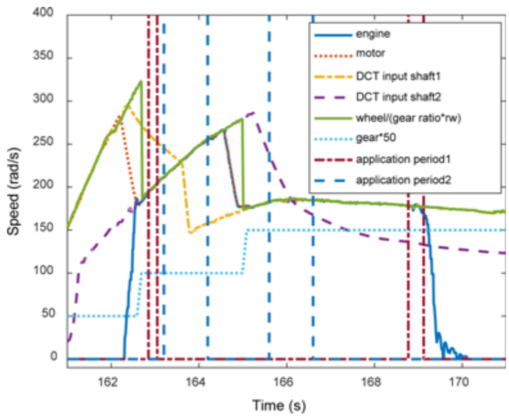

Figure 7. Driveline speed while the engine clutch is engaged or disengaged.

engine clutch is engaged and disengaged, that is discussed in the result section. Thus, this study proposes to use the period, when the engine clutch is engaged and disengaged, i.e., when the driving mode of a parallel hybrid vehicle is transferred from the electric vehicle (EV) mode to the hybrid electric vehicle (HEV) mode and from the HEV mode to the EV mode, as an application period. Hereinafter, this application period is called "application period1".

Referring to the schematic diagram of the engine clutch actuator of the experimental vehicle like Figure 3, In this study, the piston position signal of the engine clutch actuator is utilized to check the engagement or disengagement of the engine clutch. Thus, the application period1 is defined as the period when the piston position of the engine clutch actuator is in a specific range like below.

$$L_1 < d_a < L_2 \tag{21}$$

Also, to compare the adaptation performance of the torque constant in the environment of the application period1 with the performance in the environment of another application period, the period, when the amount of change in the engine net torque is not large and the condition below is satisfied, is defined as another application period. Hereinafter, this application period is called "application period2".

$$T_e > \alpha,\ \omega_w > \beta,\ \gamma < t_s < \delta \tag{22}$$

3. EXPERIMENT RESULTS

In this paper, the adaptation algorithm of the torque constant described above was verified based on the daily driving data of an original production hybrid vehicle. The schematic diagram of the experimental vehicle's powertrain is shown in Figure 1.

Figure 4 shows an example of the estimated output shaft torque and the estimated engine net torque using Equations (7) and (8). Figure 5 is an enlarged figure of Figure 4 for a certain period. For a vehicle equipped with a DCT, as described in subsection 2.2, the engaged shaft's gear ratio must be determined in order to estimate the output shaft torque before and after the transmission gear shift.

On the other hand, since it is difficult to determine the engaged shaft and the engaged shaft's gear ratio during the shift, the output shaft torque estimation is suspended during the shift and the estimation starts again after the shift is completed. In this case, the output shaft torque does not change after the shift but $T_o/i_t i_f$ shows a discontinuity before and after the shift since the speed ratio is changed. Also, angular velocity noise, and backlash between the shaft joints also cause error in the output shaft torque estimation. This can be seen in Figures 4 and 5.

Figure 6 shows examples of the application periods when the amount of change in the engine net torque is calculated. The experimental vehicle is equipped with a normally closed engine clutch, which is open when the value of the actuator position is large and closed when the value of the actuator position is small. Also, Figure 7 shows examples of the driveline speed during the application periods.

In Figure 6, it is noticed that the engine net torque is changed greatly and monotonically during the application period1, which is the period when the engine clutch is engaged and disengaged, or the engine clutch actuator piston position is within a certain level. In contrast, the engine net torque is not changed greatly during the application period2, which is the period when the condition of the inequality (22) is satisfied.

The adaptation performance of the proposed algorithm was verified by investigating whether the torque constant tracks the reciprocal of the constant, which is multiplied to the engine net torque intentionally, assuming that there is uncertainty in the nominal engine net torque.

Figures 8 (a) and (b) shows the estimated torque constant in the environment of the application period1 and the application period2, respectively when the proposed algorithm was applied to the experimental data for 600 seconds, assuming that there is no uncertainty in the nominal engine net torque, which is when constant 1 was multiplied to the nominal engine net torque. The torque constant in the proposed algorithm must follow the reciprocal to cancel the multiplied constant. Figure 8 (a) shows that the torque constant followed 1 and the error converged to within 0.1. However, Figure 8 (b) shows that the torque cosntant did not follow 1 and the error was getting bigger.

Figures 9 (a) and (b) shows the amount of change in the estimated engine net torque and the nominal engine net torque over the application period1, and the application period2, respectively. In Figure 9 (a) shows that the amount of change in the estimated engine net torque and the nominal engine net torque over the application period1 show a similar tendency to each other, and the torque constant is estimated by comparing the two amounts of

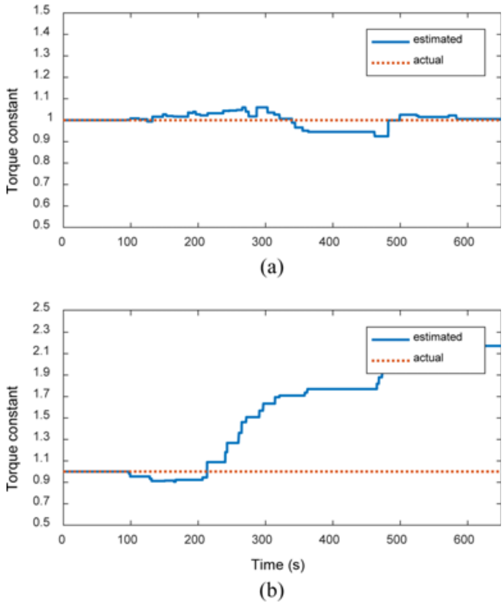

Figure 8. Estimated torque constant in the environement of (a) Application period1; (b) Application period2 when the nominal engine net torque was multiplied by 1.

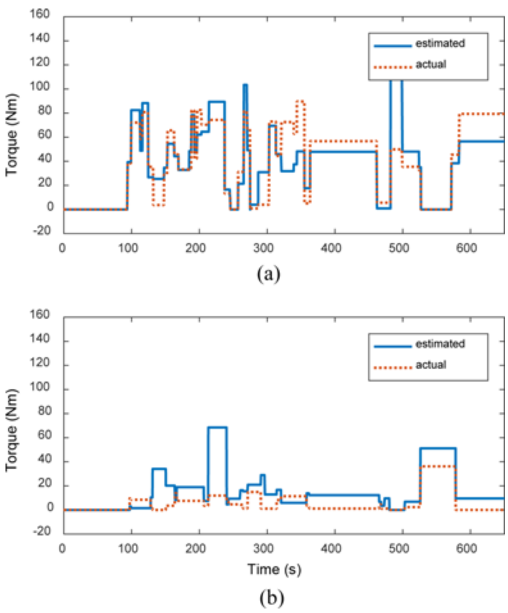

Figure 9. Amount of change in the estimated engine net torque and the nominal engine net torque over (a) Application period1; (b) Over the application period2 when the nominal engine net torque was multiplied by 1.

change. However, Figure 9 (b) shows that the amount of change in the estimated engine net torque and the nominal engine net torque over application period2 does not show a similar tendency to each other.

This shows that the output shaft torque which is calculated based on the shaft torque compliance model can

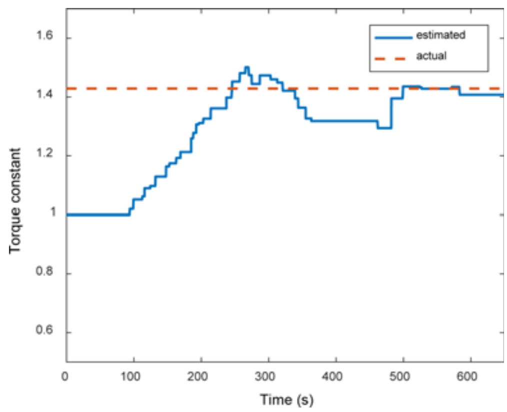

Figure 10. Estimated torque constant in the environement of the application period1 when the nominal engine net torque was multiplied by 0.7.

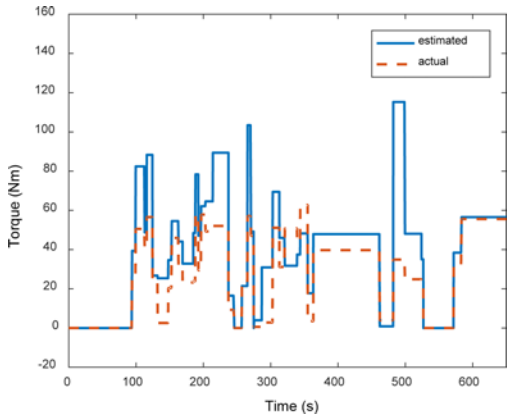

Figure 11. Amount of change in the estimated engine net torque and the nominal engine net torque over the application period1 when the nominal engine net torque was multiplied by 0.7.

become inaccurate over time due to the integration of the transmission input shaft speed and the wheel speed and the specific period of time that the amount of change in the engine net torque is calculated should be short enough and the amount of change in the engine net torque should be large over the specific period.

Futhermore, Figures 10 and 12 show the estimated torque constant in the environment of the application period1 when the nominal engine net torque was multiplied by the constant 0.7, and 1.5, respectively. In Figures 10 and 12, to cancel the multiplied constant, the torque constant converged to 1/0.7, and 1/1.5 within the error of 0.1. Figures 11 and 13 show the amount of change in the estimated engine net torque and the nominal engine net torque over the application period1.

In Figure 11, it is shown the amount of change in the estimated engine net torque is larger than that of the nominal engine net torque since the nominal engine net torque is multiplied by 0.7. However, in Figure 13, it is

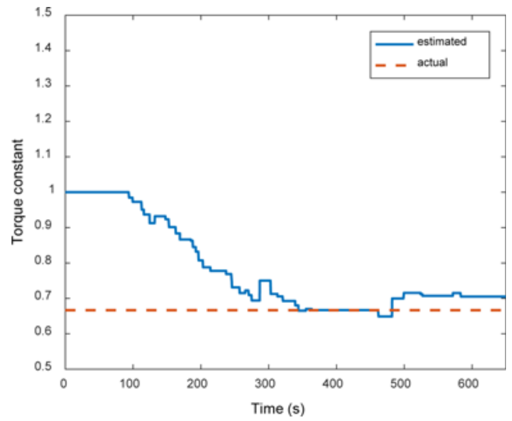

Figure 12. Estimated torque constant in the environement of the application period1 when the nominal engine net torque was multiplied by 1.5.

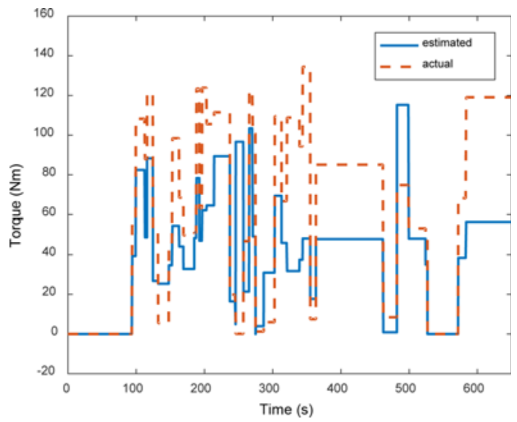

Figure 13. Amount of change in the estimated engine net torque and the nominal engine net torque over the application period1 when the nominal engine net torque was multiplied by 1.5.

shown that the amount of change in the nominal engine net torque is larger than that of the estimated engine net torque since the nominal engine net torque is multiplied by 1.5. The proposed algorithm adapts the torque constant using the difference of the two variations.

However, in Figure 9 (a), it can be seen that the amount of change of the estimated engine net torque sometimes differs greatly from that of the nominal engine net torque. This is due to the error of the amount of change in the output shaft torque. Therefore, the torque constant should be averaged over a long period of time to reduce the effect of this error, while the estimated and nominal engine net torque data are accumulated.

4. CONCLUSION

This paper proposed a compensation method for the slowly varying uncertainty of the nominal engine net torque estimated in the forward direction of the driveline in a parallel hybrid vehicle using a multiplicative constant which was called the torque constant. The adaptation of the torque constant was conducted using the amount of change in the nominal engine net torque and the amount of change in the estimated engine net torque instead of the estimated engine net torque value itself due to the drift issue of the output shaft torque, which is modeled using the shaft torque compliance model. The amount of change in the engine net torque was estimated in the backward direction of the driveline using the amount of change in the output shaft torque.

Furthermore, the period when the engine clutch is engaged and disengaged was considered as the specific period of time when the amount of change in the engine net torque is calculated. The adaptation performance of the torque constant was verified using the daily driving data of a production parallel hybrid vehicle.

For future work, robustness of the proposed algorithm will be investigated and refined using more vehicle data in many different environmental conditions.

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