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THS Engine Torque Detection System Using Motor/Generator Resolver

- xEV Technology That Utilizes the Potential of Engine for the Multi-Pathway Approach -

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ABSTRACT: This paper presents the onboard engine torque detection system in the THS. Each type of torque can be calculated based on a physical model using the motor-generator resolvers and engine crank angle sensor signals. High-precision torque estimation is possible by synchronously calculating each sensor signal utilizing the engine crank angle signal as a trigger. Countermeasures against misalignment due to mass production, such as eccentricity of the timing rotor and resolver, are also implemented. Experimental results show that engine torque can be estimated with high precision. This method is expected to improve the NV performance, efficiency, and emissions of electric vehicles such as HEVs and PHEVs, further contributing to carbon neutrality.

KEY WORDS: Hybrid Electric Vehicles, Motor Resolver, Toyota Hybrid System (THS).

1. INTRODUCTION

Initiatives to achieve carbon neutrality by 2050 across the entire lifecycle of vehicles have been underway for some time. To accomplish this, a multi-pathway approach, which addresses the future of energy and aligns with regional realities while steadily reducing CO2 emissions, has been adopted as part of efforts to put electric vehicles into practical use. Among these, hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) with internal combustion engines have been contributing to those efforts as effective carbon neutral (CN) options [(1)].

The first mass production HEV was the Prius, introduced in 1997 with the Toyota Hybrid System (THS), which has been widely deployed in many vehicles all over the world. The THS is classified as a two-motor power split strong HEV system and is equipped with motor-generator resolvers. The engine torque can be detected using the resolvers and a physical model.

This function is the key technology for maximizing the potential of internal combustion engines. This feature has already been installed in the 2022 Prius and is being used in several functions, such as the engine misfire detection system. This paper describes the details of the THS engine torque detection system, and of how it will be used in the future.

2. PRINCIPLE OF THS TORQUE DETECTION

2.1. Toyota Hybrid System (THS)

Figure 1 shows a system diagram of the THS. The transaxle, which contains the motor for driving the vehicle, generator for generating electrical power and power split device, enables operation of the continuously variable transmission, maintaining output power at optimal engine efficiency while also achieving smooth and quiet performance.

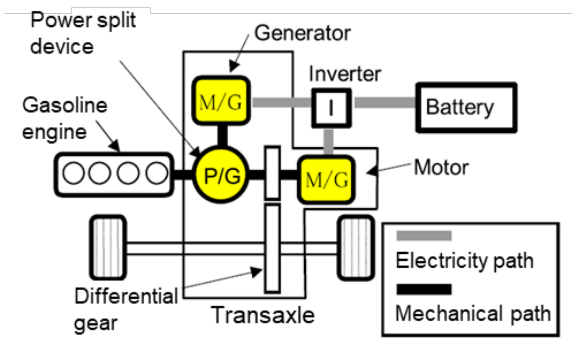

Fig. 1. System Diagram of THS

2.2. Torsional Dynamics of THS

Figure 2 shows the torsional diagram of the THS power train. A motion equation can be derived based on D'Alembert's principle and the Lagrange mechanics for a planetary gear set as follows:

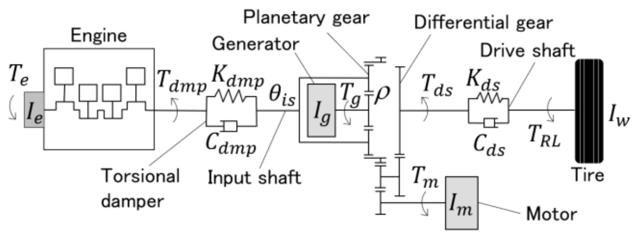

Fig. 2. Torsional Diagram of THS Powertrain

Generator

$$I_e \frac{d\dot{\theta}_e}{dt} = -T_{dmp} + T_e \quad (1)$$

$$I_{is} \frac{d\dot{\theta}_{is}}{dt} = T_{dmp} - \lambda \quad (2)$$

$$I_g \frac{d\dot{\theta}_g}{dt} = -\frac{\rho}{1+\rho}\lambda + T_g \quad (3)$$

$$I_m \frac{d\dot{\theta}_m}{dt} = -\frac{1}{G_m}T_{ds} - \frac{G_c}{1+\rho}\lambda + T_m \quad (4)$$

$$I_w \frac{d\dot{\theta}_w}{dt} = T_{ds} - T_{RL} \quad (5)$$

$$T_{dmp} = C_{dmp}(\dot{\theta}_e - \dot{\theta}_{is}) + K_{dmp}(\theta_e - \theta_{is}) \quad (6)$$

$$T_{ds} = C_{ds}\left(\frac{1}{G_m}\dot{\theta}_m - \dot{\theta}_w\right) + K_{ds}\left(\frac{1}{G_m}\theta_m - \theta_w\right) \quad (7)$$

where λ is Lagrange's undetermined multiplier, which corresponds to internal torque between planetary gear set.

T_e : Engine net torque [Nm]
T_g : Generator torque [Nm]
T_m : Motor torque [Nm]
T_{dmp} : Torsional damper torque [Nm]
T_{ds} : Drive shaft torque [Nm]
T_{RL} : Road load torque [Nm]
λ : undetermined multiplier [Nm]
θ_e : Engine angular [rad]
θ_{is} : Transaxle Input Shaft angular [rad]
θ_g : Generator angular [rad]
θ_m : Motor angular [rad]
I_e : Engine inertia [kg_m2]
I_{is} : Transaxle input shaft inertia [kg_m2/rad]
I_g : Generator inertia [kg_m2/rad]
I_m : Motor inertia [kg_m2/rad]
I_w : Wheel inertia [kg_m2/rad]
C_{dmp} : Torsional damper damping coefficient [Nm_s/rad]
C_{ds} : Drive shaft damping coefficient [Nm_s/rad]
K_{dmp} : Torsional damper stiffness [Nm/rad]
K_{ds} : Drive shaft stiffness [Nm/rad]
ρ : Gear ratio of planetary: sun gear to ring gear
G_m : Gear ratio: motor gear to differential gear
G_c : Gear ratio: external gear of planetary ring to motor gear

The angular velocities of the planetary gear are constrained by the following equation.

$$\frac{\rho}{1+\rho}\dot{\theta}_g - \dot{\theta}_{is} + \frac{G_c}{(1+\rho)}\dot{\theta}_m = 0 \quad (8)$$

The engine torque and the damper torque can be derived as follows:

$$T_e = I_e \frac{d\dot{\theta}_e}{dt} + I_{is}\frac{d\dot{\theta}_{is}}{dt} + \frac{1+\rho}{\rho}\left(I_g \frac{d\dot{\theta}_g}{dt} - T_g\right) \quad (9)$$

$$T_{dmp} = I_{is}\frac{d\dot{\theta}_{is}}{dt} + \frac{1+\rho}{\rho}\left(I_g \frac{d\dot{\theta}_g}{dt} - T_g\right) \quad (10)$$

Since this torque is correlated to vehicle performance such as noise and vibration (NV), it is important to detect and utilize it onboard for vehicle control. As shown in Figure 3, the frequency characteristics from the engine torque to damper torque and drive shaft torque in a typical THS are resonant. For example, when an engine misfires unintentionally, torque fluctuations can occur. These torque fluctuations will cause the damper to resonate, resulting in gear tooth striking noise as shown in Figure 4.

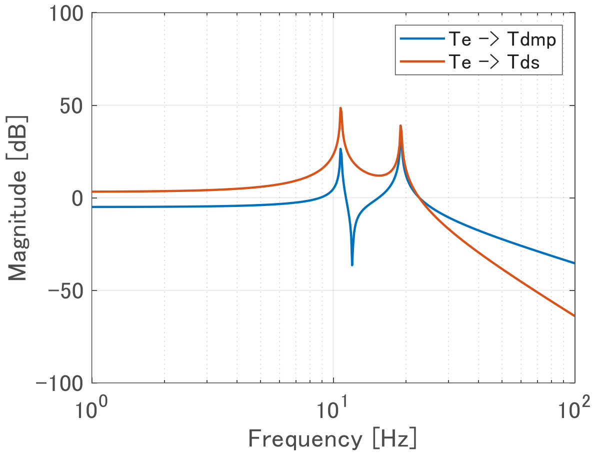

Fig. 3. THS Frequency Response

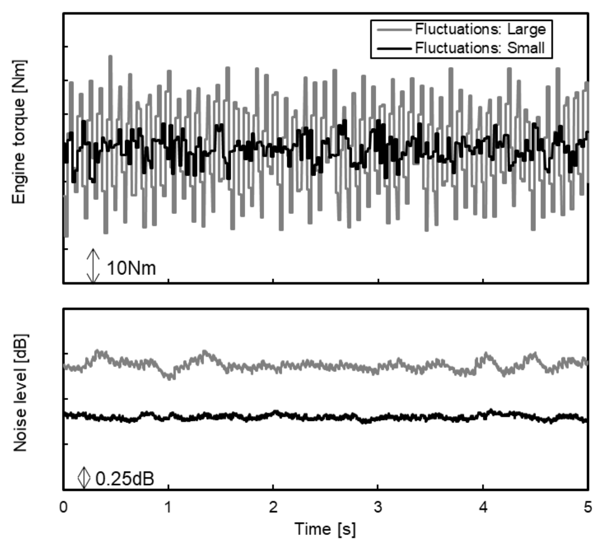

Fig. 4. Effect of Engine Torque Fluctuation on Noise in THS (Measurement)

3. ONBOARD ENGINE TORQUE DETECTION SYSTEM

To implement the engine torque derivation formula (Equation 9) in THS, the angular accelerations of the engine, motor, and generator are required. These angular accelerations are detected using different sensors and electronic control units (ECUs). In the THS, the engine torque detection system can be configured using existing sensors without the need for additional new sensors. These sensor signals are aggregated in the motor/generator ECU (MG-ECU), and the engine torque is calculated in real time onboard. (See Figure 5.)

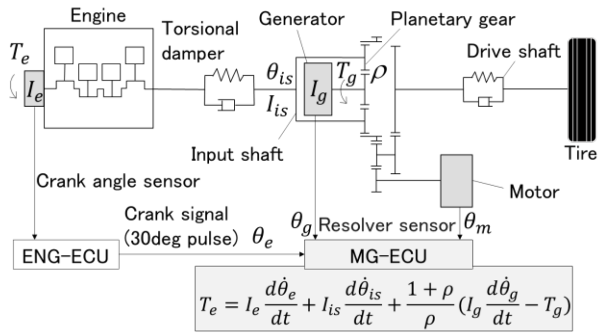

Fig. 5. Engine Torque Detection System

3.1. Calculation of Engine Torque Based on Crank Angle

To calculate the engine torque from the signals aggregated in the MG-ECU, each signal must be synchronized. This synchronization is achieved using the engine crank signal as a trigger. The sensor signal from the crank angle sensor input to the engine ECU (ENG-ECU) is formatted into pulse signals for every 30° of crank angle (CA) (crank signal) linked to the engine cycle. Simultaneously, a single pulse signal (cam signal) linked to the engine reference point is generated. These signals are output from the ENG-ECU to the MG-ECU, where the engine crank angle is identified by the MG-ECU and serves as a trigger for calculating the engine torque. By synchronizing the operation of the MG-ECU with the crank and cam signals, the engine torque can be calculated with a focus on the combustion stroke of each cylinder. (See Figure 6.)

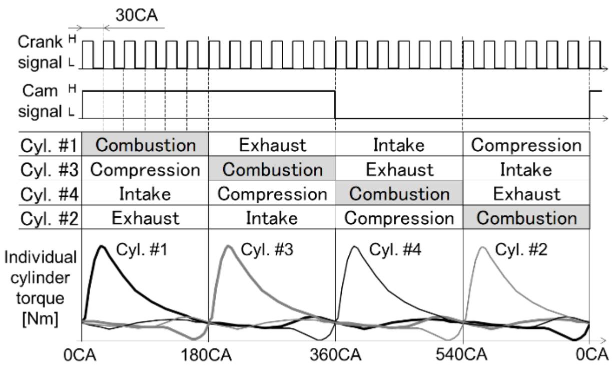

Fig. 6. Input Signals and Cycle Identification by MG-ECU

3.2. Implementation of Engine Torque Detection System

To calculate the engine torque in the MG-ECU, synchronized information from the engine, motor, and generator is required. The crank signal serves as a trigger for calculating the engine torque.

Engine torque detection system implemented in the THS follows steps [1]- [5] below to calculate the engine torque when the crank signal is input to the MG-ECU. (See Figure 7.)

[1] Add +30° CA to the crank angle (θ_e)

[2], [3] Reference the angle information of the motor (θ_m) and generator (θ_g) from the resolver sensors

[4] Reference the command torque of the generator (T_g)

[5] Calculate the time interval (dt) between the current crank signal input and the previous input.

Using the obtained angle and time information, the angular accelerations of the engine, motor, and generator can be calculated.

The engine torque is calculated using the predetermined inertia values, the planetary gear ratio, and the calculated angular acceleration.

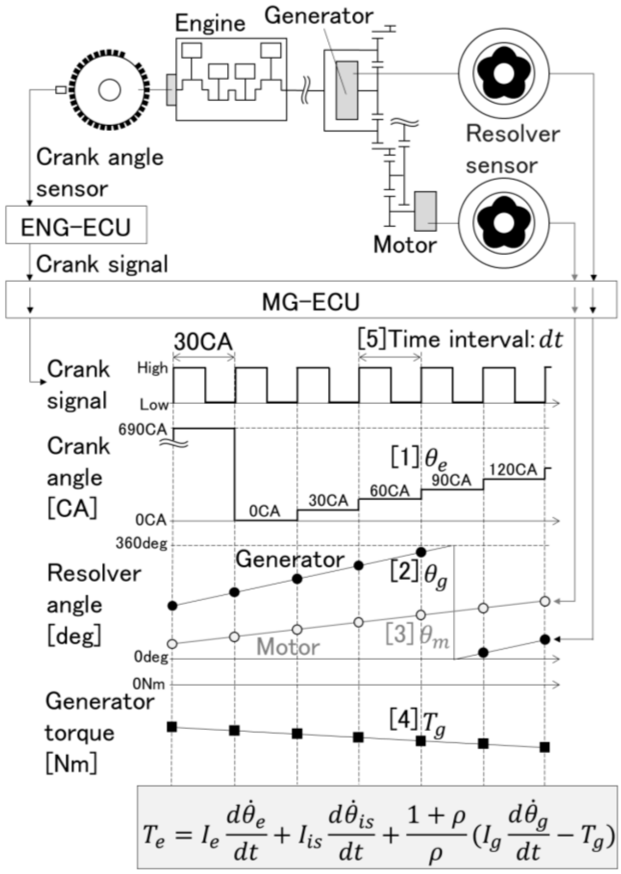

Fig. 7. Engine Torque Calculation Logic

3.3. Robust System for Mass-Produced THS

In mass-produced THS systems, various additional functionalities have been implemented to develop a robust engine torque detection system capable of withstanding the effects of manufacturing variations and real-world driving conditions.

The eccentricity of the crank timing rotor due to manufacturing variations causes a change in the distance from the crank angle sensor, which affects the crank interval time and angle information, and leads to the engine torque of specific cylinders being calculated as excessively high or low. To address this issue, THS implements a function that compensates for the eccentricity of the timing rotor. This function learns and corrects the amount of eccentricity by running the engine at a constant speed using the motor and generator. This correction can prevent the engine torque of specific cylinders from being miscalculated as excessively high or low.

Figure 8 demonstrates the effectiveness of this correction control by comparing the engine torque calculated using a timing rotor with intentionally large eccentricity before and after the correction. Before the correction, the engine torque of specific cylinders is calculated as excessively high or low due to the influence of the eccentric timing rotor. However, after learning and correcting the amount of eccentricity, the engine torque of each cylinder approaches the same value. This type of correction is applied not only to the timing rotor but also to the resolvers of the motor and generator.

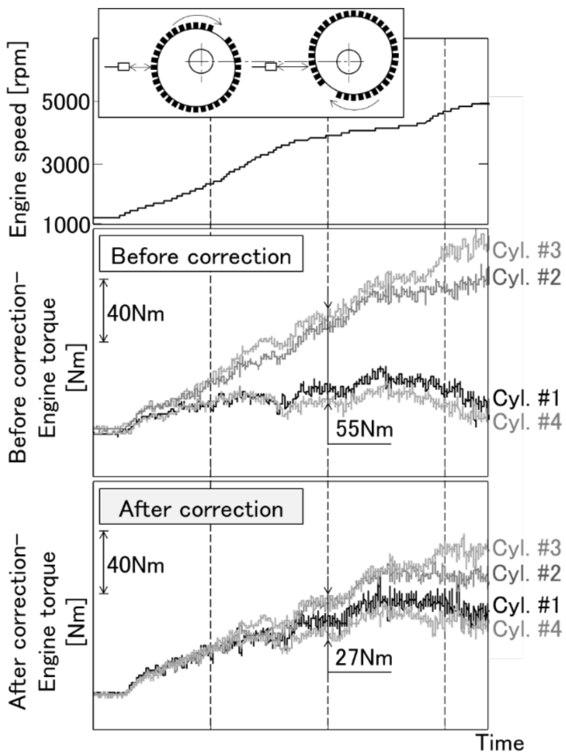

Fig. 8. Crank Eccentricity Learning (Measurement)

4. ACCURACY VERIFICATION

The accuracy of the engine torque was verified using a system equivalent to the 2022 Prius, which has a torque detection system implemented in the ECU.

4.1. Testing Environment

Engine torque can be calculated from the pressure inside the cylinder [(2)]. Cylinder pressure sensors (CPS) were attached to each cylinder of the engine. (See Figure 9.)

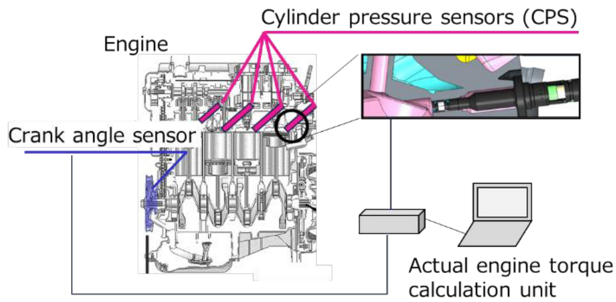

Fig. 9. Testing the Engine Torque Environment

4.2. Result of Actual Vehicle Test

Figure 10 compares the average value of the estimated engine torque calculated by the MG-ECU and the actual torque calculated by the CPS every 180° CA (the process interval of the individual cylinders in the engine). To verify the estimation accuracy for each cylinder in the engine, the torque difference during the combustion stroke of each cylinder was intentionally controlled to be large, and the engine torque detector using this method was able to capture this tendency.

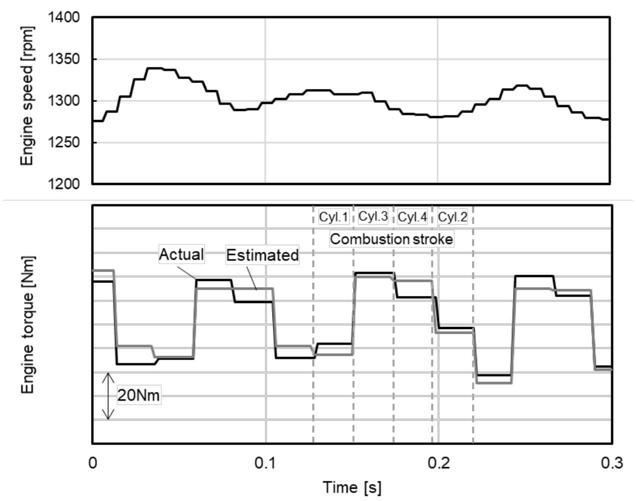

Fig. 10. Average Value of the Estimated and Actual Engine Torque Every 180° CA (Measurement)

Figure 11 shows the correlation between the estimated and actual engine torque of each cylinder for every 180° CA. The torque of each cylinder was plotted against the engine speed. The error rate between the estimated torque and actual torque for each cylinder was within ±10%, which means that torque variations between cylinders can be detected and used for control. The results show that the system functioned as a highly accurate onboard engine torque detector at the cylinder-by-cylinder level.

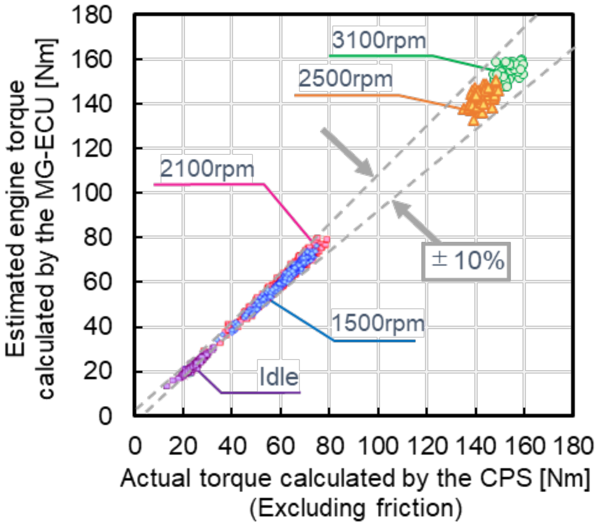

Fig. 11. Correlation between Estimated and Actual Engine Torque of Each Cylinder for Every 180° CA (Measurement)

5. EXAMPLES OF SPECIFIC APPLICATION CASES

With the THS, the torque of the engine and damper can be detected onboard, which improves failure diagnostics function performance, efficiency, and NV performance, decreases emissions, and reduces the cost of products.

5.1. Engine Misfire Detection (OBD) (3)

Using the high-precision engine torque calculated by the proposed engine torque detection system, the THS performs engine misfire detection as part of OBD.

In the conventional method, the engine torque was calculated using Equation 11, and the torsional damper stiffness (K_{dmp}) was designed as an adjustable parameter, but it is difficult to represent the complex damper dynamics with just one parameter.

$$T_e \cong \{I_e \frac{d\dot{\theta}_e}{dt} + K_{dmp}(\theta_e - \theta_{is})\} \quad (11)$$

In contrast, the proposed engine torque detection system does not require the design of torsional damper stiffness (K_{dmp}), which has led to reduced design effort.

Figure 12 compares the results of engine torque calculation performed by the proposed engine torque detection system and by the conventional method using equation 11.

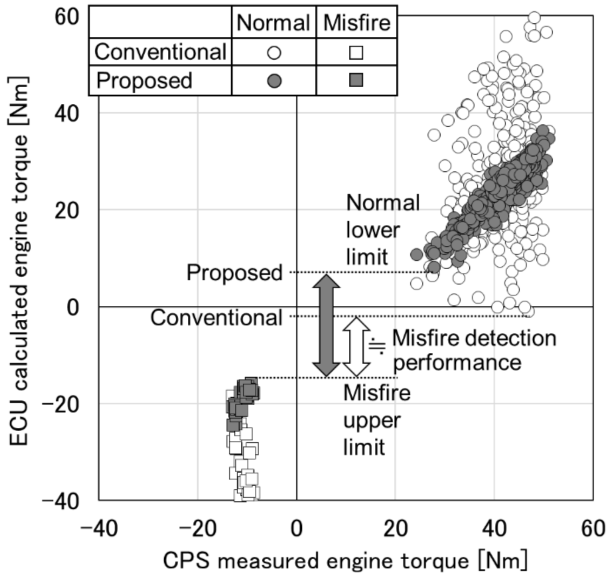

Fig. 12. Comparison of Misfire Detection Performance

The larger the gap between the lower limit of normal combustion (Normal) and the upper limit of misfire (Misfire), the higher the misfire detection performance is. It can be observed that the proposed engine torque detection system demonstrates superior misfire detection performance compared to the conventional method.

The proposed engine torque detection system achieves both reduced design effort and superior misfire detection performance.

5.2. Improvement of Emission Performance (3)

By improving misfire detection performance, the ignition timing during cold engine starts can be further retarded, contributing to reduced emissions.

Figure 13 shows the relationship between the ignition retard angle, exhaust temperature, and total hydrocarbon (THC) emissions under low-temperature conditions. In the conventional method, misfire detection performance limits the amount of ignition retard. With the proposed engine torque detection system, the improvement in misfire detection performance allows further retardation of the ignition timing, which increases the exhaust gas temperature necessary to activate the catalyst. As a result, total hydrocarbon emissions are reduced.

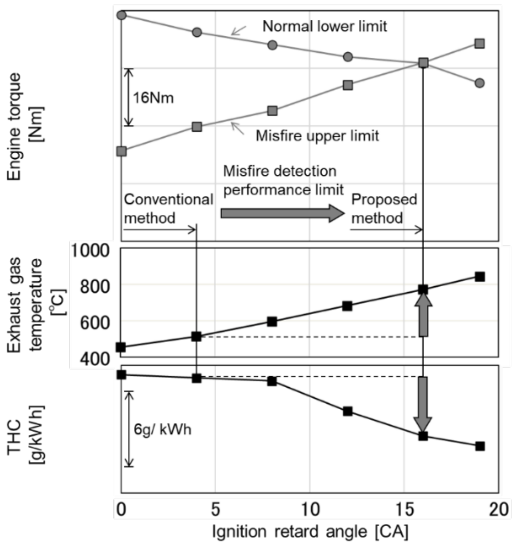

Fig. 13. Improvement of Emission Performance

5.3. Engine Combustion Limit Control Without CPS

Engine thermal efficiency improvement technologies such as exhaust gas recirculation (EGR) enable maximum thermal efficiency near the combustion limit. Near the combustion limit, combustion state variations cause engine torque fluctuations, which lead to the vehicle vibration and gear noise shown in Fig. 4 via the resonant transfer characteristics shown in Fig. 3. To address this issue, technology using CPS to provide feedback on combustion state variables has been developed [(4)]. As shown in Figure 14, feeding back the combustion state variation using the torque detected by this method suppresses engine torque fluctuations without CPS, and reduces gear noise. This method can achieve both NV performance and efficiency while reducing the cost of products.

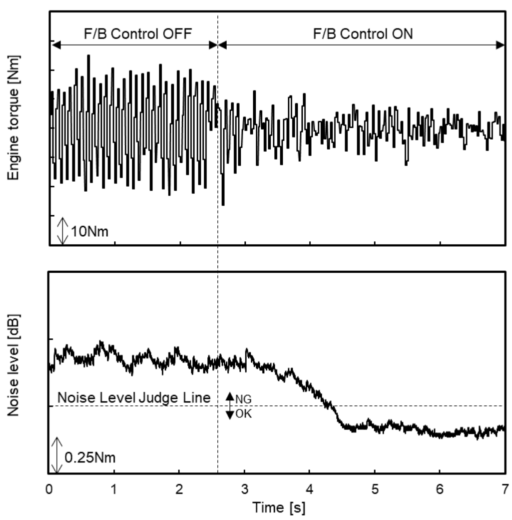

Fig. 14. Effect of Combustion Feedback Control Using Engine Torque Detection System (Proposed Method) (Measurement)

6. CONCLUSION & FUTURE PLANS

To contribute to carbon neutrality, the presented technology was developed to detect the engine torque in the two-motor power split THS, which accommodates various internal combustion engines in electric vehicles such as HEVs and PHEVs. Furthermore, this technology is integrated into the onboard ECU using existing sensors without additional components. As a result, engine torque can be detected in the THS with the accuracy close to that of the CPS.

Currently, this function is limited to specific areas such as engine misfire detection. A control method that detects engine torque and combustion state, and provides combustion feedback control using the individual engine actuators is being investigated. In the future, this will enable robust optimization of engine combustion, improving efficiency and reducing emissions. Furthermore, since it can also detect the torque state within the transaxle, we are considering a technology that provides optimal feedback control of the three actuators, namely the engine, motor, and generator, to achieve overall optimal control of the vehicle system.

With the utilization of THS technology, electric vehicles such as HEVs and PHEVs are expected to continue evolving as an effective option toward achieving carbon neutrality.

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