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Development of e-AWD Parallel Hybrid System

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ABSTRACT: This paper describes the development of a new e-AWD parallel hybrid system. This hybrid powertrain system consists of a high-torque 2.4-liter turbocharged engine and a front unit that contains a 6-speed automatic transmission, an electric motor, and an inverter. It also includes a rear eAxle unit that contains a water-cooled high-power motor, an inverter, and a reduction gear, as well as a bipolar nickel-metal hydride battery. By combining a turbocharged engine that can output high torque across a wide range of engine speeds using two electric motors (front and rear), this system achieves both smooth acceleration with a torquey driving feel and rapid response when the accelerator pedal is pressed. In addition, a new AWD control using the water-cooled rear motor realizes more stable cornering performance than the previous e-AWD system. In this way, developing a hybrid system with appealing new driving characteristics increases the variety of electric powertrains available to customers as part of measures to help achieve carbon neutrality.

KEY WORDS: hybrid electric vehicle, hybrid electric vehicle, parallel hybrid system, e-AWD, eAxle

1. INTRODUCTION

Electric vehicles, including hybrid electric vehicles (HEVs), are being increasing regarded as a promising means of helping to achieve carbon neutrality in the automotive industry. A new hybrid powertrain system with a turbocharged engine that is suitable for SUVs was developed to increase customer choice of electrified vehicles, raise public expectations for an electrified society, and help increase product competitiveness through improved driving performance. This paper describes the objectives, configuration, and performance of this newly developed hybrid powertrain system.

2. SYSTEM OVERVIEW

2.1. Objectives and configuration of the system

The main objective of this hybrid system is to help improve driving performance. Specifically, by combining the quick torque response of a motor with the large torque of a turbocharged engine over a wide range of engine speeds, it is possible to achieve both high response when the accelerator pedal is depressed, and smooth acceleration up to high vehicle speeds. In addition, a high-output motor was installed in the rear eAxle of the system to enhance the grip of the front and rear tires through precise e-AWD control, while also controlling the vehicle's pitch attitude.

Figure 1 shows the configuration of this hybrid system and Table 1 shows its basic specifications. A 2.4-liter turbocharged engine with a maximum torque of 460 Nm and a front unit that contains a 6-speed automatic transmission, a motor, and an inverter are mounted in the engine compartment area. A wet start clutch (WSC) was adopted instead of a conventional torque converter for starting the vehicle. This clutch is incorporated inside the motor to shorten the total length of the transaxle. It also helps to improve response to downshifts due to its low moment of inertia. Furthermore, the overall height of the system was reduced by mounting the DCDC converter directly above the front unit. As a result, this hybrid system can be mounted on a common platform with conventional vehicles.

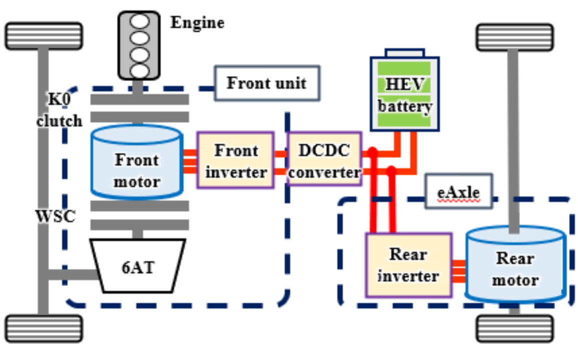

Fig. 1 Schematic Diagram of the HEV System

Table 1 Specifications of the HEV system

HEV System			
	Power	[kW]	273
Engine			
	Power	[kW]	202
	Torque	[Nm]	460
Front Motor			
	Power	[kW]	64（250V）
	Torque	[Nm]	292
Rear Motor			
	Power	[kW]	76（288V）
	Torque	[Nm]	169
HEV Battery			
	Type	[-]	NiMH
	Cell Number	[cell]	240
	Battery Capacity	[Ah]	5
	Rated Voltage	[V]	288

2.2. System operation modes

Figure 2 shows the main system operation modes. During a normal vehicle start, EV driving mode, in which the front and rear motors are operated, is selected. In addition, when starting with the engine running, such as when the battery state of charge (SOC) is low or during engine warm-up, the vehicle runs using both the engine and the motors. In this case, the WSC slips to absorb the speed difference between the engine and the transmission input shaft, and transmits the total torque of the engine and front motor to the transmission. During acceleration and turning, a part of the engine power is used to generate electricity using the front motor, which is then used to drive the rear motor. Depending on the driving conditions, the driving force distribution to the rear wheels is actively increased to improve acceleration performance and driving stability. During deceleration (accelerator off), the power transmitted from the wheels operates the front and rear motors as generators, converting kinetic energy into electrical energy and recovering it in the battery.

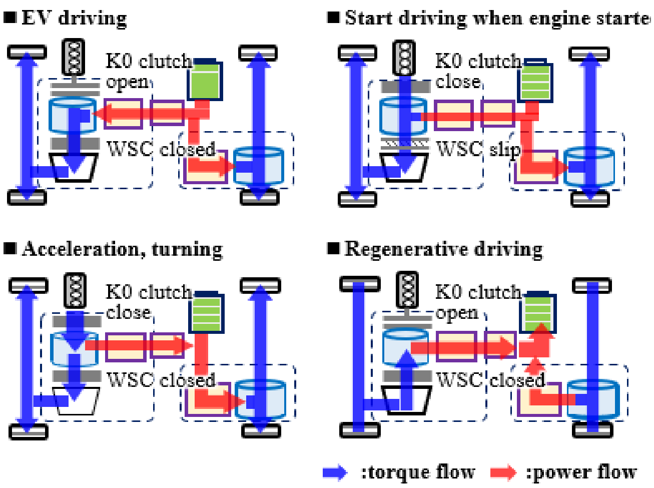

Fig. 2 Driving Modes of the HEV System

3. SYSTEM PERFORMANCE

3.1. Power performance and drivability

The development aimed to achieve both a linear and torquey driving feel with direct response to accelerator pedal operation, and low noise.

3.1.1. In the low and medium speed ranges

In the low to medium vehicle speed range in which the engine speed is relatively low, such as in the city or on winding roads, the aim is to achieve linear acceleration with a direct response to accelerator pedal operation. Issues when accelerating from a low engine speed are the initial response delay due to engine turbo lag, and the generation of engine booming noise due to an increase in engine torque fluctuations transmitted to the vehicle body when operating at high engine torque. The acceleration delay was improved by estimating the actual engine torque rise on-board and using the motor to compensate for the difference between the torque required for vehicle driving and the estimated actual engine torque. In addition, the engine booming noise at low rpms was addressed by adopting a flywheel damper that includes a centrifugal pendulum absorber (CPA), and damping control using the front motor (Fig. 3), which reduces the transmission of engine torque fluctuations to the vehicle body. Through these countermeasures, the usable range of engine torque was expanded while reducing engine booming noise. Furthermore, the front motor assist can be utilized to expand the coverage of each gear by about 40% in terms of accelerator operation compared to a conventional vehicle, thereby realizing acceleration with less downshifting (Fig. 4). The acceleration that can be achieved from the battery and engine power is constantly calculated, and the shift timing is optimized according to the accelerator operation and driving conditions. The drop in acceleration that occurs during gear shifting was reduced significantly and shift shock was reduced by coordinating precise motor torque control with the hydraulic control of the automatic transmission. As a result, it was possible to achieve linear acceleration in response to accelerator pedal operation (Fig. 5).

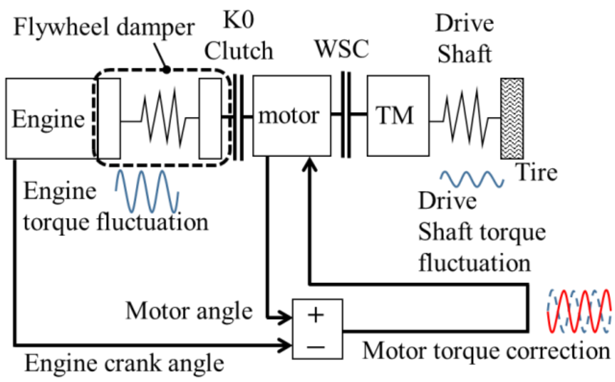

Fig. 3 Torque fluctuation control

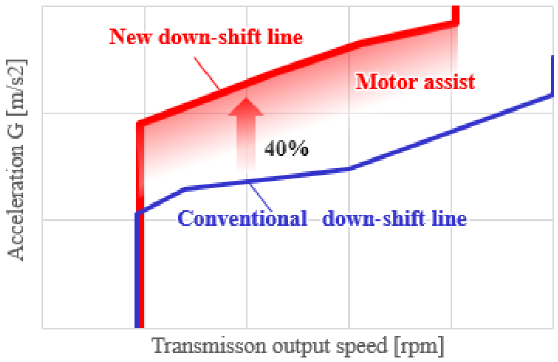

Fig. 4 Transmission Output Speed and Gear Coverage

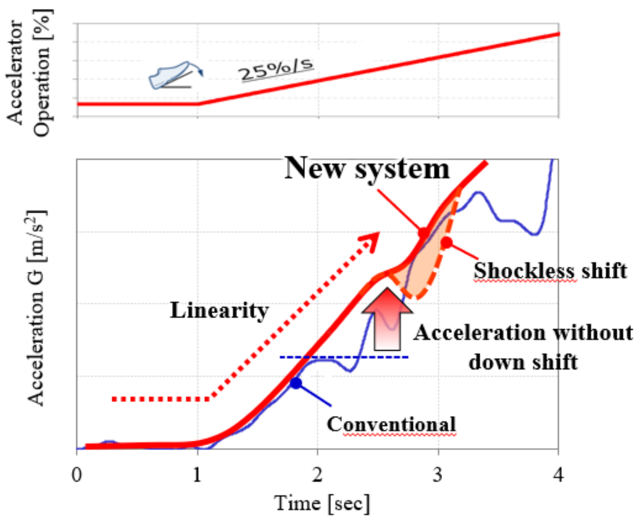

Fig. 5 Acceleration in Low to Medium Vehicle Speed Range

3.1.2. In the high speed range

In driving scenarios such as merging and overtaking on highways, the development aimed to achieve a torquey and quiet acceleration feel. The issue of front-wheel drive with high driving torque is noise. High driving torque is required during merging and overtaking on highways. In these scenarios, the deflection and rigidity of the engine mounts increases. As the rigidity increases, the engine vibration damping performance of the mounts deteriorates, more engine vibration is transmitted to the body, and as a result, noise increases. Although one way of reducing the transmission of engine vibration is to reduce the engine torque itself, this means that the large torque characteristic of a turbocharged engine cannot be utilized. By actively generating electricity with the front motor and using this electricity at the rear motor, it is possible to reduce the input torque to the engine mounts, while keeping the total (front and rear) driving torque unchanged. Suppressing the deflection of the engine mounts ensures the damping performance of the engine mounts, and reduces the transmission of engine vibration to the body. As a result, higher torque can be used from the low engine speed range. This battery power assist achieves a torquey driving feel that surpasses 3.0-liter turbocharged vehicles while also reducing noise (Fig. 6).

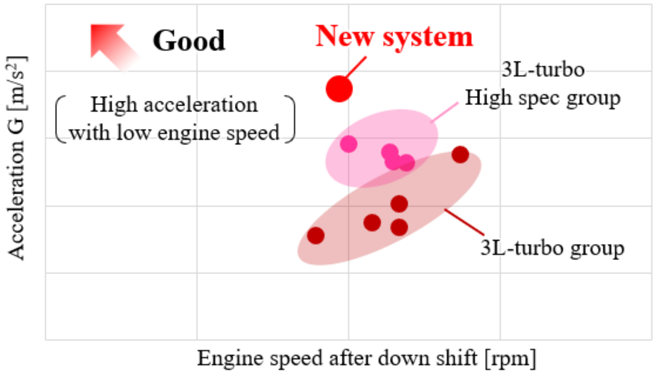

Fig. 6 Acceleration in High Load Range

3.2. AWD performance

An eAxle with a high-power water-cooled motor was adopted for driving the rear wheels. With this newly developed e-AWD system, it is possible to precisely control the front and rear torque ratio between 100:0 and 20:80 according to the driving and road conditions, which helps to improve vehicle driving performance. It also expands the range of the rear driving force distribution on both low- and high-μ roads compared to the previous e-AWD system (E-Four), which significantly improved maneuverability.

Driving force distribution is based on feedforward control that utilizes information such as the driver's accelerator operation and steering angle. This realizes natural vehicle behavior without delay in response to driver operations. To improve maneuverability and vehicle stability, the front and rear driving force ratio was set based on the front and rear dynamic load ratio of the inner tires during cornering, which have smaller friction circles than the outer tires. With improved cooling performance and a high-power rear motor, the friction circles of the front and rear tires can be used evenly by distributing more driving force to the rear tires than the front tires, even under high lateral acceleration, such as when cornering on a dry road. Maximum performance was improved by about 25% compared to the previous e-AWD system (Fig. 7).

In contrast, in the low lateral G range, if the rear-wheel driving force is large, the turning response at the initial stage of steering deteriorates. Therefore, the front-wheel driving force was increased to improve the vehicle turning speed (Fig. 8).

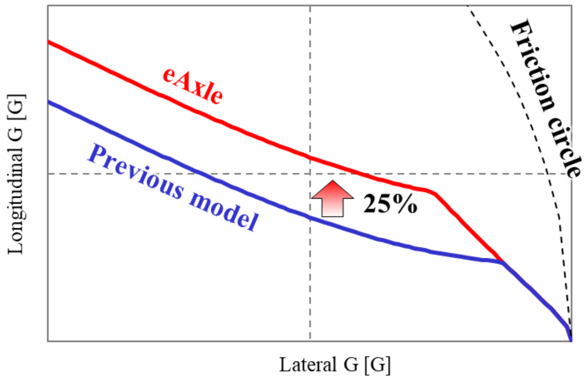

Fig. 7 AWD Performance

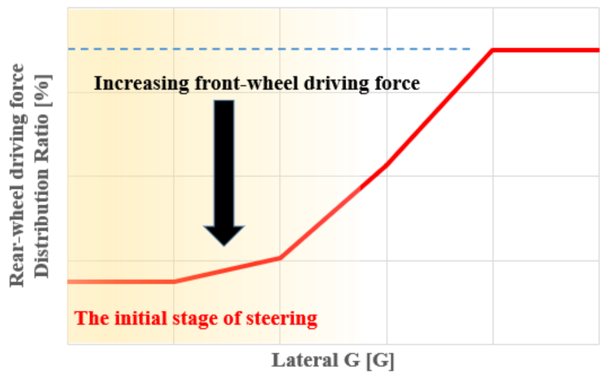

Fig. 8 Rear-wheel driving force Distribution Ratio during turning

3.3. Fuel efficiency

To improve fuel efficiency, new control logic was introduced that charges the battery when the driving load is low, and actively provides battery assist when the driving load is high to keep the thermal efficiency of the engine operating point high regardless of the vehicle driving load (Fig. 9). The average engine thermal efficiency in the US LA#4 test cycle is approximately 2% higher with this control logic, and fuel economy in this test cycle is more than 30% higher than a conventional powertrain.

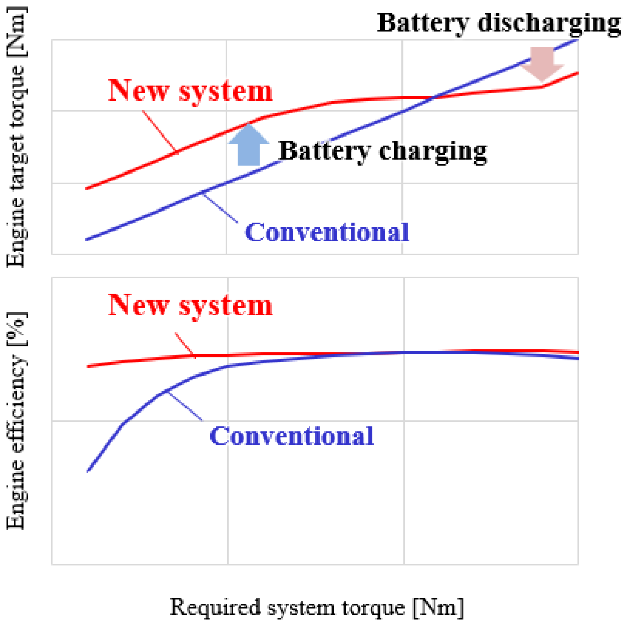

Fig.9 Battery Charge and Discharge Strategy

4. COMPONENTS

4.1. Engine

A 2.4-liter four-cylinder turbo engine was adopted that can realize powerful driving from the low rpm range and smooth acceleration at the high rpm range. The alternator and starter of a conventional vehicle were eliminated by using the front motor as a generator and engine starter. In addition, maximum engine torque was increased by 30 Nm compared to a conventional engine (Fig. 10). The cooling circuit of the engine intercooler, front and rear inverters, and DCDC converter was integrated, which helps to simplify the entire cooling system, and reduces cost and weight.

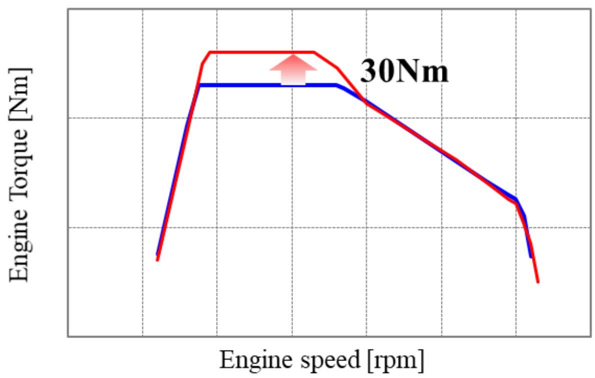

Fig.10 Engine torque characteristics

4.2. Front unit

A parallel hybrid configuration was selected for the front transaxle to adapt to the large engine torque, and a 6-speed automatic transmission was adopted to avoid busy shifting. By installing the engine disengaging clutch (K0 clutch) and WSC inside the motor (Fig. 11), the total length of the front transaxle was reduced, enabling it to be mounted on the same platform as conventional vehicles. The total height of the front unit was kept low by mounting the inverter directly above the transaxle, so that vehicle packaging was not affected. To achieve both NV performance and response, a new low-inertia flywheel damper equipped with the aforementioned CPA was developed. A direct and highly responsive drive feeling with good synchronization between vehicle speed and engine rpm was realized by direct torque transmission from the WSC with the aid of precise and high-response clutch control using a hydraulic sensor. The shape of the friction material grooves of the clutch were optimized, and improved on-board temperature estimation logic was adopted that predicts the temperature of each part of the clutch in various driving patterns to maintain the thermal tolerance of the clutch under severe driving conditions. The calibration of the electric oil pump motor was optimized to achieve both cooling performance and low power consumption. The durability and reliability of the WSC were ensured by carrying out vehicle simulations taking into account the distribution of front and rear driving force to precisely estimate the accumulated heat generation of the clutch in various driving patterns. The feasibility was confirmed by using actual driving data in typical steep slope roads in the market.

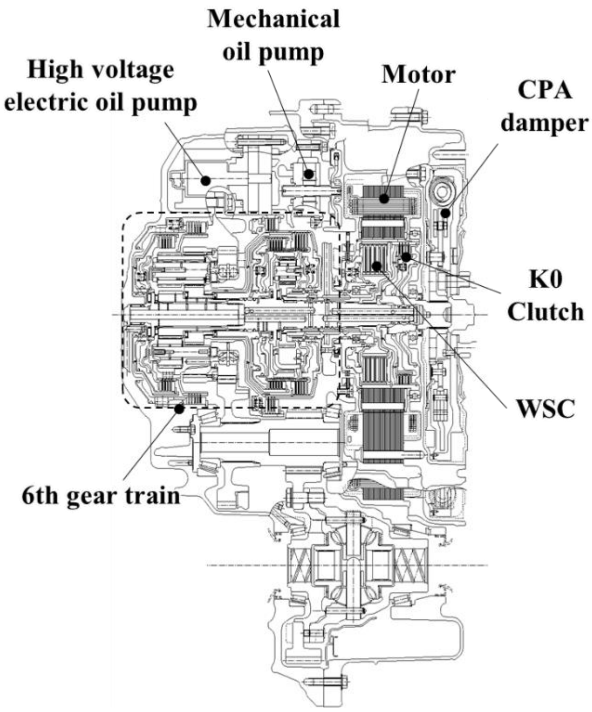

Fig.11 Cross section of front unit

4.3. Battery

A bipolar nickel-metal hydride battery was adopted to increase system power (Fig. 12). Battery cell output power was significantly improved by the bipolar structure, which reduces the internal resistance of the battery. Power output per cell was increased by approximately 80% compared to a conventional nickel-metal hydride battery. This increase in power was realized without changing the battery unit volume, enabling it to be mounted compactly under the rear seats without sacrificing interior or cargo space.

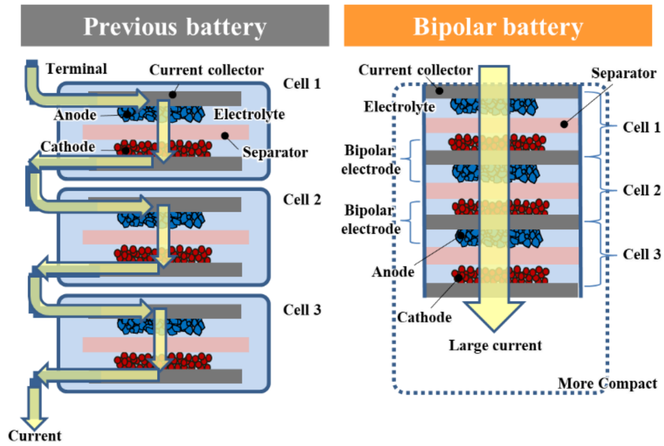

Fig.12 Structure of bipolar battery

5. CONCLUSION

To improve driving performance, a new hybrid powertrain was developed that combines a 2.4-liter turbocharged engine with electric motor units. Combining the high torque characteristics of this turbocharged engine over a wide rpm range with the excellent torque response of the motors enables a linear and direct acceleration feel in response to accelerator pedal operation. Furthermore, by combining various noise and vibration (NV) countermeasures, it was possible to achieve a torquey driving feel that surpasses a 3.0-liter turbocharged vehicle with lower engine noise.