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Development of New Hybrid Transmission for 2009 Prius

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Abstract

The new P410 hybrid transmission has been developed for use in the next generation of FWD compact class vehicles, including the 2009 Prius. To exceed both the top-level fuel efficiency and dynamic performance of the previous model, the new Prius employs a powerful high-efficiency motor and a newly developed 1.8-liter engine. The supply voltage has been raised to 650V, contributing to motor efficiency, and a motor speed reduction device is utilized to reduce the size and weight of the transmission. The structure of the transmission has also been designed so that the resonance points of its component parts are dispersed to reduce noise and vibration. This paper describes the new motor and other features of this new hybrid transmission.

Keywords: hybrid electric vehicles, passenger cars, motor, transmission, planetary gear

1 Introduction

The original Prius made its debut in 1997, followed by the second generation Prius in 2003. Under the new hybrid synergy drive concept, the 2003 Prius provided even better fuel economy and performance that made it fun to drive. The hybrid concept was expanded to a 3-liter class sport utility vehicle (the Lexus RX400h) in 2005, and a rear wheel drive luxury car (the Lexus GS450h) in 2006. Subsequently, the third generation Prius debuted in 2009. In the face of great concerns about depletion of fossil fuels and the greenhouse effect, it is Toyota's aim to produce and popularize fuel-efficient low-emission vehicles on a global basis as quickly as possible. The new Prius is easier to mass-produce, and features various new technologies for improving fuel efficiency and reducing emissions. It also integrates a large number of outstanding existing technologies, and should play an important role in further popularizing hybrid vehicles. This paper describes the new P410 hybrid transmission for new compact class cars, including the new Prius.

Fig. 1 The New Prius

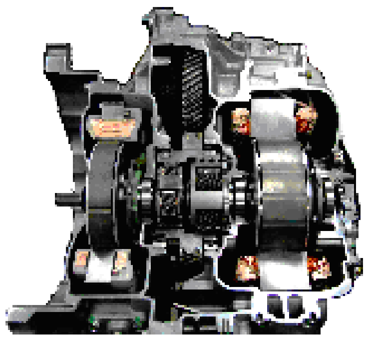

Fig. 2 P410 Transmission

2 General Construction

This section describes the basic construction of the P410. Fig. 3 shows a cross section of the transmission, and Table 1 shows its main specifications. The basic structure is the same as that of the P310 used in the RX400h, which features a motor speed reduction device. Fig. 2 shows a schematic of the gear train. Starting on the right side of the engine, a 2-stage hysteresis damper with a torque limiter, a generator, two planetary gears, and a traction motor are provided on the first axle. The planetary gear on the right side functions as a power split device that divides the power from the engine into motive force for the vehicle and force for operating the generator to charge the battery. The planetary gear on the left side functions as the motor speed reduction device. The compound gear has an integrated structure with two ring gears, a counter drive gear, and a parking gear. It transmits the integrated driving force of the engine and motor to the second axle through the counter driven gear and the drive pinion gear, which replaces the chain gear system of the P112 used in the previous model. The driving force is finally transmitted to the final axle through the ring gear and the differential.

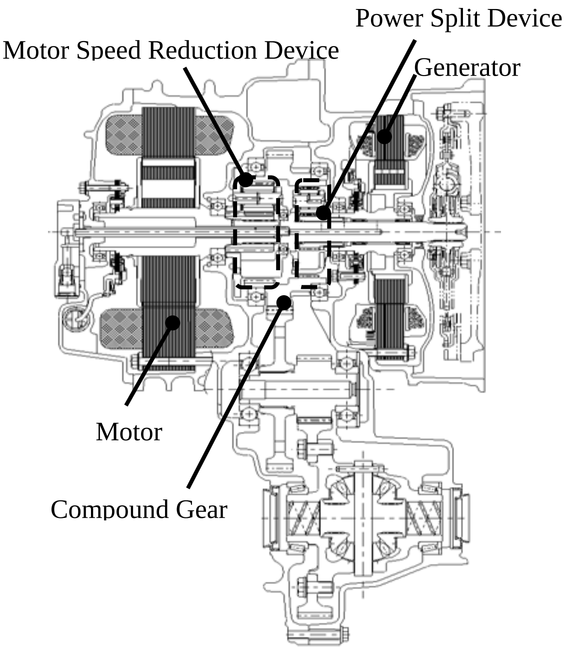

Fig. 3 P410 Cross Section

Table 1 Main Specifications of P410

		P410	P112
Max. Engine Torque		142Nm	115Nm
Max. Engine Output		73KW	57KW
Motor	Type	Synchronous AC motor	←
	Max. Output	60KW	50KW
	Max. Torque	207Nm	400Nm
	Max. Speed	13900rpm	6000rpm
Motor Reduction Gear Ratio		2.636	–
Differential Gear Ratio		3.267	4.113
Weight (Including ATF)		88kg	109kg
Overall Length		372.0mm	384.5mm

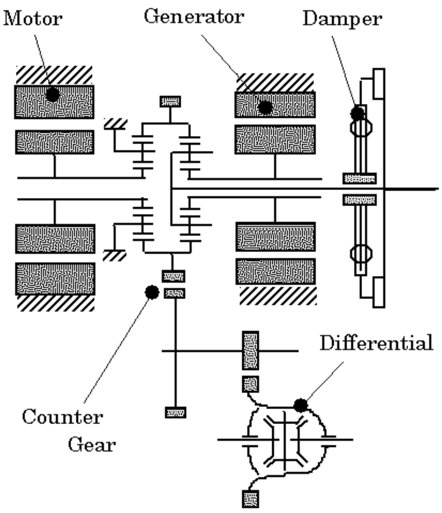

Fig. 4 Cross Section of P410

3 Motor Speed Reduction Device

Fig. 5 shows the structure of the motor speed reduction device of the P410. The motor speed is reduced at the planetary gear in accordance with the reduction gear ratio. The reduction gear ratio is set to 2.636, compared with the 2.478 of the P310 (RX400h). By using a low-torque motor, the device provides torque that is 2.636 times larger than that output by the motor (Fig. 6). Since motor size is proportional to motor torque, adopting this device in the P410 allowed a compact motor to be achieved. However, in order to use the device to obtain large torque, the motor must run at high-rotational speeds. The maximum motor speed of the P410 is 2.3 times higher than that of the P112, hence the magnets are fixed in the rotor slots without any empty space by resin injection to reduce centrifugal stress.

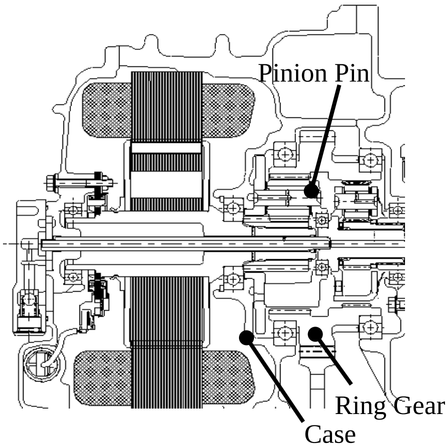

Fig. 5 Cross Section P410

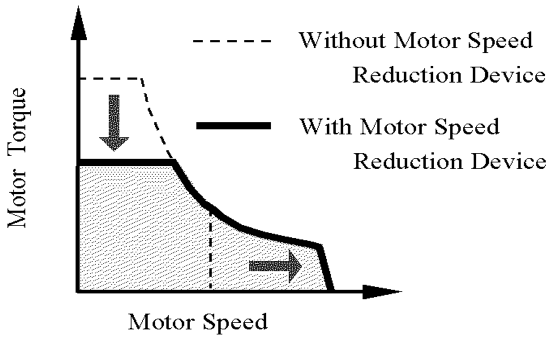

Fig. 6 Downsizing of Motor

4 New Motor

A new motor has been developed for the P410. Its structure combines a 3-phase 8-pole 48-slot distributed winding stator with an IPM rotor. This section describes the structural differences from the P112. The rotor uses high-energy magnets to reduce motor size and mass, and the magnet layout has been changed to reduce the centrifugal stress on the electromagnetic steel plate and magnets. Furthermore, instead of the 0.35-mm plate used in the P112, a thinner 0.3-mm electromagnetic steel plate has been employed to reduce iron loss. For the stator of the traction motor, a new compression forming method was devised, featuring new methods of winding and pre-processing, which has shortened the coil end length by 20%. In addition, for the stator of the generator, concentrated winding was employed instead of distributed winding to reduce motor size. Compared to the P112, the total mass of the motor has been reduced by 35 %, the combined volume by 40%, and the combined overall length by 30%. At the same time, the overall weight of the P410 has been reduced by 20%, and its length has been reduced by 10mm.

Typical issues of compression forming are damage to the enamel layer of the coil and tearing of the insulating paper, which cause a reduction in the coil insulation breakdown voltage. These issues were addressed from the design standpoint through innovations related to the shape, strength and, surface treatment of the insulation paper, and the development of a scratch-resistant coil. Because of the increased supply voltage (from 500V to 650V) and inverter switching speed for improving fuel efficiency, the surge voltage generated by the inverter and high-voltage cables has increased by approximately 30 %. The larger surge voltage causes the distribution voltage difference between the 8 -coils of the same phase to increase. As a fundamental part of the design, the voltage difference between coils must be set to less than the partial discharge inception voltage. To reduce the distribution voltage difference, the new winding shown in Fig. 8(b) has been employed. In a general winding (Fig. 8(a)), the maximum voltage difference arises between coils “1” and “8”. On the other hand, in the new winding (Fig. 8(b)), the voltage difference is reduced by detaching coil “1” from coil “8”. For the insulation between the different phases, 3-layered insulating paper is inserted, which has been designed in consideration of hydrolysis and degradation by ATF at the high temperature. At the same time, the breather of the transmission case has been switched from a spring type (P112) to an open-to-air type to eliminate the atmospheric pressure (altitude difference) effect on the partial discharge inception voltage.

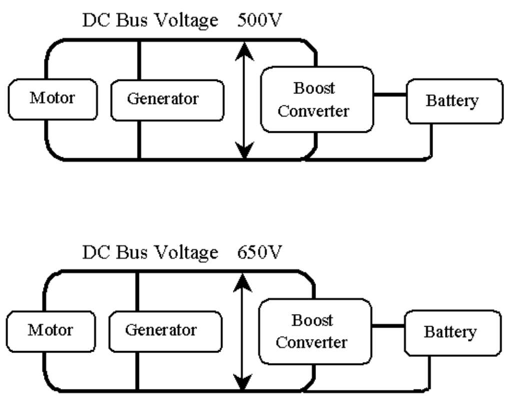

Fig. 7 High Voltage Motor Drive System Employing HV Boost DC/DC Converter

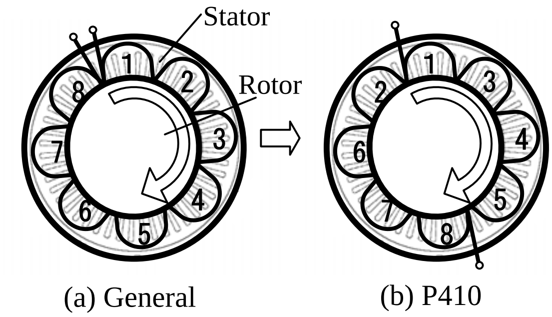

Fig. 8 Coil Winding Distribution Voltage

5 Motor Loss Reduction

Fig. 9 shows the frequency map of the traction motor in city driving. The motor operates in the low-load region. In this region, iron loss accounts for more than half of the total loss, as shown in Fig. 10. This indicates that reducing iron loss is more important for improving fuel efficiency. To reduce iron loss, the reluctance torque has been substantially improved by optimally arranging the permanent magnets into a V-shape on the rotor as shown in Fig. 11. This has substantially reduced iron loss during low-load operation. The shape of the rotor shown in Fig. 12 has been designed to reduce iron loss arising from high frequency current. The use of the thinner 0.3-mm electromagnetic steel plate also contributes to the iron loss reduction. Furthermore, by combining these modifications with other manufacturing improvements such as optimized stator and rotor core stacking method, a significant reduction in motor loss has been achieved compared to the P112. Fig. 12 shows the motor efficiency map of the P410.

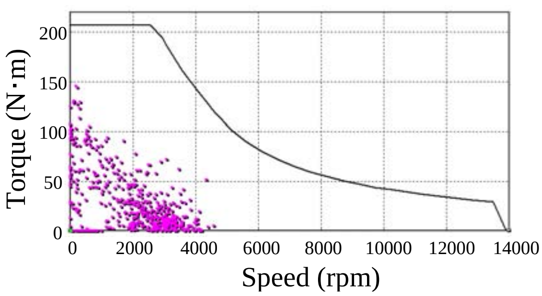

Fig. 9 Frequency Map in City Drive

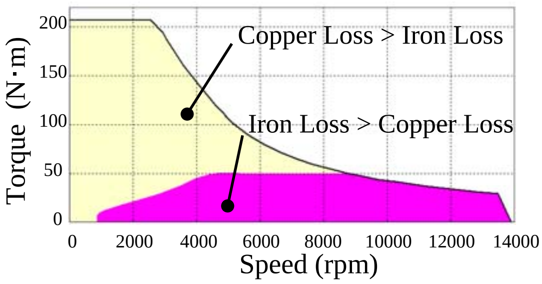

Fig. 10 Motor Loss Rate

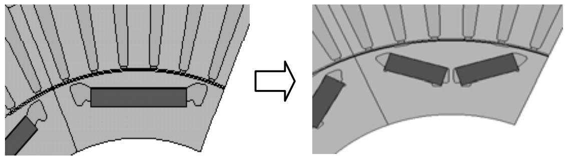

Fig. 11 Rotor Permanent Magnet Layout

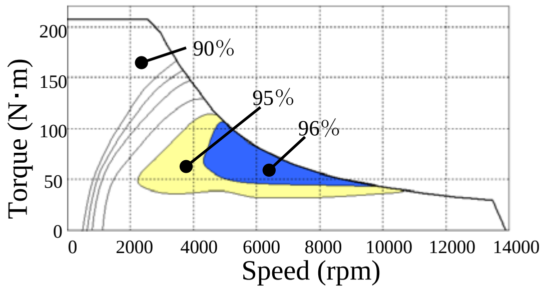

Fig. 12 Motor Efficiency map of P410

6 Oil Cooling and Reduction of Lubrication Loss

In the P410, the heat generated by the gears and motor is dissipated to the transmission case directly or via ATF. Approximately 40% of the total heat is dissipated by the former method, and 60% by the latter. Oil cooling plays an important role in the life of the insulated material (coil and insulating papers) and motor efficiency. Figs. 13 and 14 show the cooling structure. An oil catch tank mounted at the topside of the transmission case collects the ATF pumped up by gears. The trapped oil is distributed to the motor and generator sides, and dripped onto the coil ends. The catch tank also reduces the oil mixing loss by lowering the oil surface. In order to reduce the lubrication loss, a straightening vane is attached between the counter driven gear on the second axle and the ring gear on the third axle. Furthermore, to improve the oil discharge inside the compound gear, oil holes are provided on the bottom of the counter drive gear.

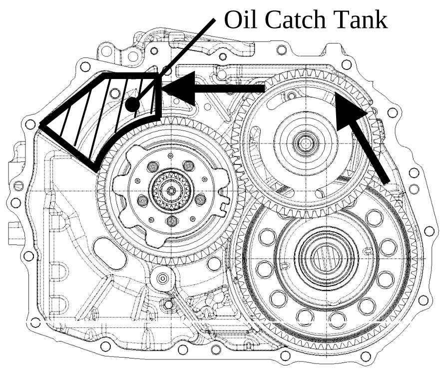

Fig. 13 Conceptual Diagram of Oil Flow

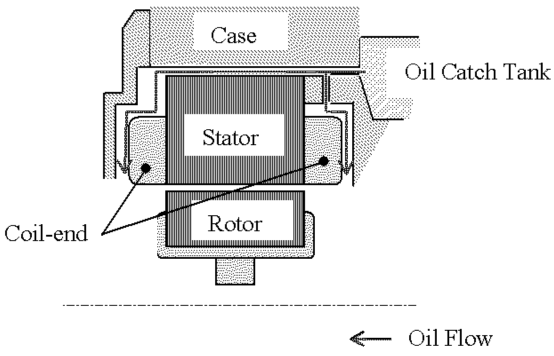

Fig. 14 Conceptual Diagram of Motor Cooling

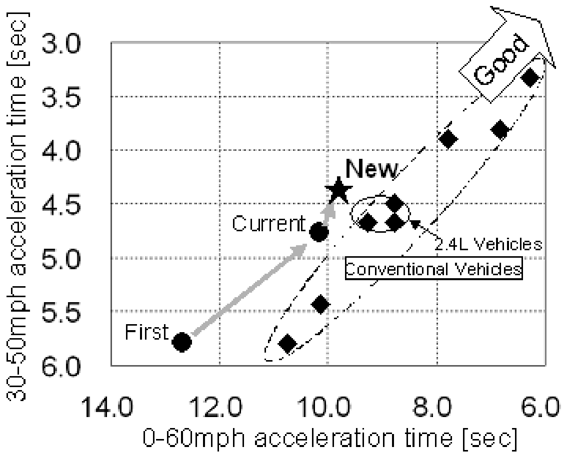

Fig. 15 Vehicle Acceleration

7 Quietness

The structure of the P410 was designed using CAE analysis to disperse the resonance points of the component parts. This has prevented an increase in noise and vibration caused by overlapping the resonance points of multiple components, and has also enabled peak-less transmission characteristics. For the motor, the contact area with the transmission case has been minimized to reduce rotational vibration related to the number of poles and the coil winding, as well as vibration caused by the PWM carrier frequency.

8 Contributions to Vehicle Power Performance

Table 2 shows the test cycle fuel efficiency performance of the 2009 Prius, An improvement of 7 – 14% has been accomplished over the previous model. Fig. 15 shows the relationship between fuel efficiency and power performance. The 0 - 60mph acceleration time has been enhanced by 5%. This power performance is comparable to that of an average 2.4 liter class car. The reduction in motor loss and weight, and the increase in motor power contribute significantly to these improvements.

Table 2 Fuel Consumption Performance

Test driving cycle	Current model	New model (target)
U.S. Comb. (lavel value)	46mpg	50mpg
UDC+EUDC (Europe)	104g/km	89g/km
10.15 (Japan)	35.5km/L	38.0km/L

9 Conclusion

The new P410 hybrid transmission has been developed for use in compact class cars with 1.8-liter engine. This new transmission is compact and lightweight, and achieves excellent fuel efficiency and quiet operation. Its size and weight were reduced by the adoption of a motor speed reduction device, a compound gear, and a compact high-output motor. As a result, the total weight of the P410 transmission is 20% less than that of the P112. The excellent fuel efficiency was achieved by adopting a newly designed rotor structure, the use of high energy magnets and a 0.3-mm thin electromagnetic steel plate, cooling technology that employs an oil catch tank, and the reduction of oil lubrication loss. These technologies have reduced mechanical loss by 20% from the previous model. The required level of quiet operation was achieved by adopting a structure that disperses resonance and the reduction of the motor contact area with the transmission case. As a result, the new hybrid transmission contributes to the achievement of both higher powertrain performance and better fuel efficiency for wide range of compact class cars.

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