A New Hybrid Transmission designed for FWD Sports Utility Vehicles

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1 ABSTRACT

A new hybrid transmission (P310) has been developed for FWD 3-liter engine class sportsutility vehicles. The development of this transmission has been aimed at improving power performance and fuel economy, achieving the world's top-level weight reduction and compact size, while maintaining high torque capacity. In order to achieve these goals, the gear train and motor have been newly designed, and advanced technology has been applied. Moreover, this hybrid transmission achieves seamless acceleration and quiet performance. This paper describes the major features and performance of this transmission in detail.

2 INTRODUCTION

Environmental and energy efforts, such as reducing the volume of CO2 emissions and improving the fuel consumption of automobiles, are important activities for the world. Under these circumstances, a hybrid vehicle is able to achieve both high acceleration performance and fuel economy. In 1997, the first Prius was introduced and recognized as the epoch-making Eco friendly vehicle. In 2003, the new Prius proposed a new hybrid drive concept or Hybrid Synergy Drive, which has better fun-to-drive features as well as environmental performance. This year, we have developed a new hybrid transmission for FWD 3-liter engine class sports utility vehicles. This hybrid transmission has been developed to perform under the severe conditions required in a SUV, while maintaining the refinement deserving of a luxury vehicle.

3 DEVELOPMENT OBJECTIVES

The development objectives of this hybrid transmission are as follows:

(1) Compact size

(2) Improved power performance

(3) Improved fuel economy

4 GENERAL CONSTRUCTION

This section describes the basic construction of the new hybrid transmission (P310). Figure 1 shows the cross section, Figure 2 shows the gear train schematic, and Table 1 shows the general specifications. Basic construction of This New hybrid transmission is quiet different from that of Prius transmission (P112). Figure 3 shows the cross section of Prius transmission. The New hybrid transmission has a newly adopted motor speed reduction device and compound gear. A newly adopted motor speed reduction device allows motor torque to increase without increasing motor size. A newly adopted compound gear integrated of the front planetary ring gear, rear planetary ring gear, counter drive gear and parking gear. A compound gear allows the gear train to remain very compact by disusing a chain and reduced from four axes to three axes in comparison with Prius transmission (P112), while maintaining high torque capacity.

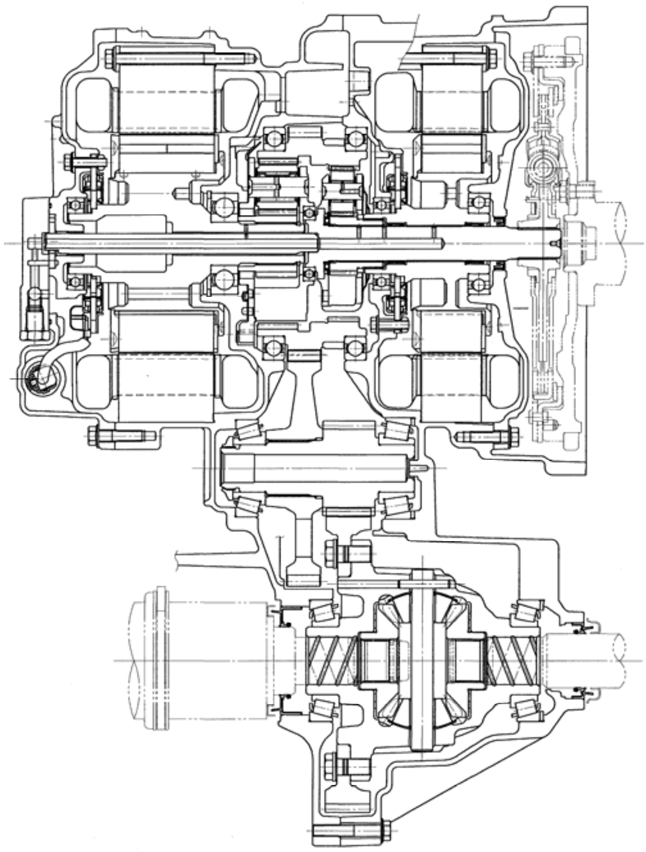

Figure 1: Cross Section of P310

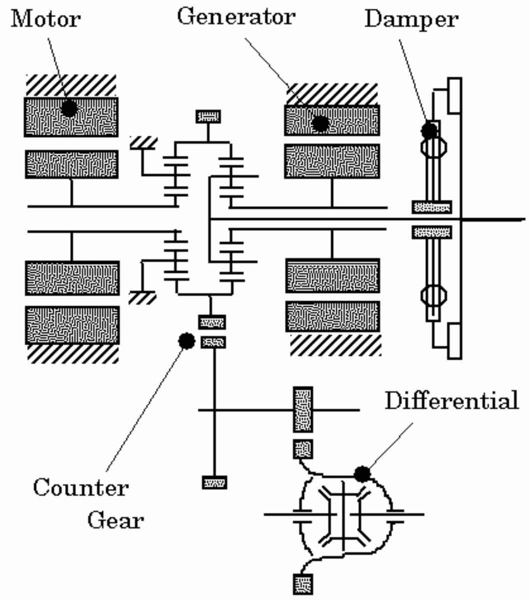

Figure 2: Gear Train Schematic of P310

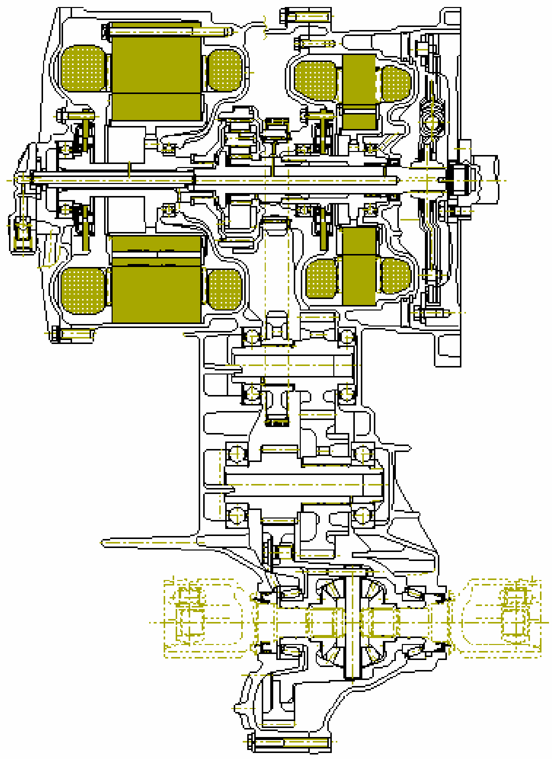

Figure 3: Cross section of P112

Table 1: Specifications of P310

		P310	P112
Max. Engine Torque		288Nm	115Nm
Motor	Type	Synchronous AC motor	←
	Max. Output	123kW	50kW
	Max. Torque	333Nm	400Nm
	Max. Speed	12400rpm	6000rpm
Motor reduction gear ratio		2.478	-
Differential gear ratio		3.542	4.113
Weight (Including ATF)		125kg	109kg

Viewed from the right (engine side) of the cross section, there are a damper with torque limiter, a generator, two planetary gear sets and a motor on the primary axis. A front planetary gear (engine side) is power split device. A rear planetary gear (Motor side) is motor speed reduction device. A Front planetary ring gear, a rear planetary ring gear, a counter drive gear and a parking gear are integrated into a compound gear. On the secondary axis there is a counter driven gear and a final drive gear. A conventional differential axis follows.

5 ACHIEVING COMPACT SIZE

The size of this hybrid transmission is almost equal to that of the Prius transmission (P112), though engine power and motor power increase by more than 2 times. By adopting the motor speed reduction device, compound gear and new high power motor, an overall compact size has been achieved.

5.1 Motor speed reduction device

Figure 4 shows the structure of the new motor speed reduction device. The rear planetary gear set operates as the motor speed reduction device. Its sun gear is linked to the motor and the carrier is fixed at the case and the ring gear is linked to the counter drive gear. The rear planetary gear set is located inside the counter drive gear. With the motor speed reduction device, the rotational speed of the ring gear is slower than that of the sun gear and the torque of the ring gear is higher than that of the sun gear.

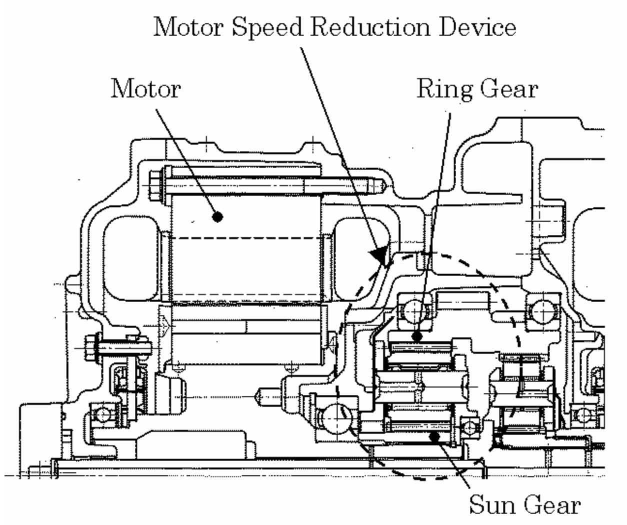

Figure 4: Structure of Motor Speed Reduction Device

This hybrid transmission is designed so that the motor reduction gear ratio is 2.478 and motor maximum speed is 12,400 RPM. By the motor speed reduction device, motor torque becomes 1 to 2.478. Since motor size is proportional to motor torque, a small torque but high speed motor can decrease overall motor size (See Figure 5).

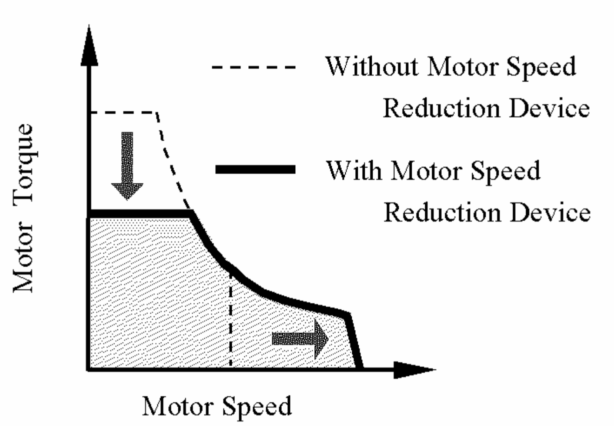

Figure 5: Downsizing of Motor

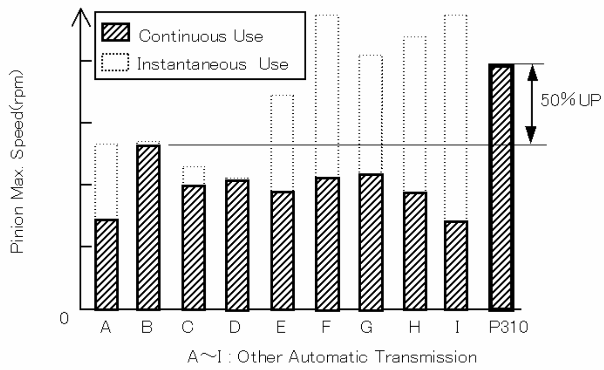

Figure 6: Comparison of Pinion Maximum Speed

With increasing of motor speed, rear planetary pinion maximum speed is 50% higher than conventional pinion maximum speed (See Figure 6). High speed causes flaking of pinion pin and pitting on gear face. In order to improve this planetary durability, the gear, carrier, and needle bearing shapes were modified and the lubrication was optimized (See Figure 7). A five-pinion type gear set has reduced gear load on a pinion in comparison with a four-pinion type gear set. Cage and roller type bearings were adopted in the pinion gear. Oil is supplied to each bearing via an oil groove (See Figure 8). Helix angle of pinion was optimized in consideration of both durability and gear noise.

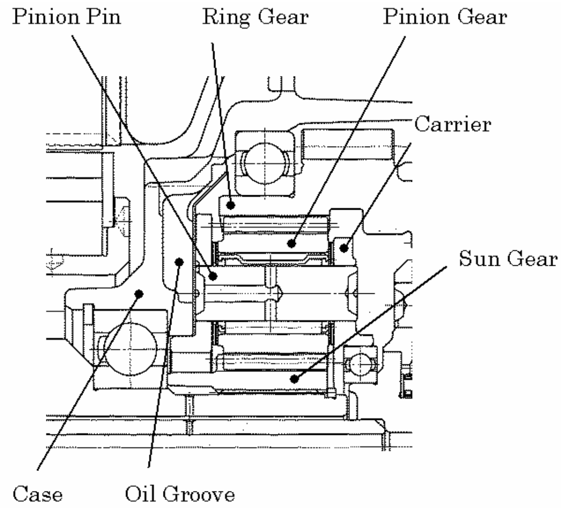

Figure 7: Structure of Five-Pinion Type Gear Set

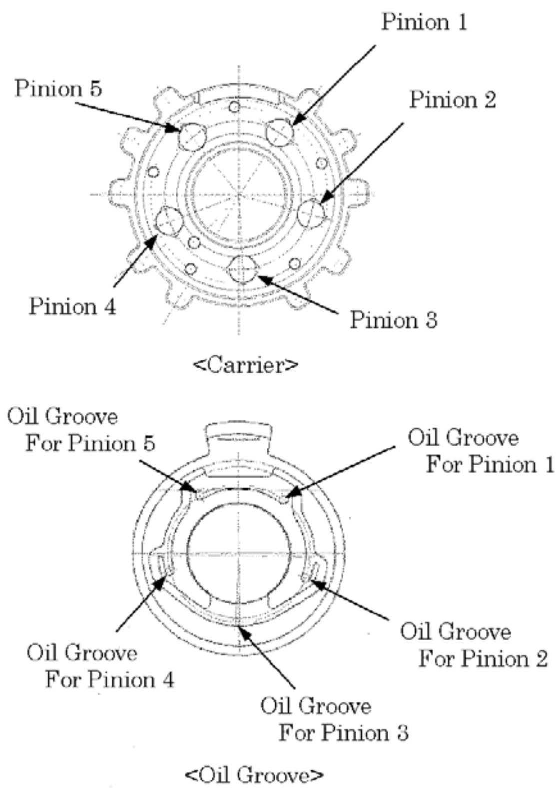

Figure 8: Shape of Oil Groove

5.2 COMPOUND GEAR

Compound gear consists of the front planetary ring gear, rear planetary ring gear, counter drive gear and parking gear. By integration of its 4 parts, the gear train remained very compact. At the same time by arranging large diameter bearings on the outside of planetary gear sets, there is no increase of length for its bearings. Since the compound gear is a large diameter and has a thin web, there is a fear of distortion during quenching. By optimizing the quenching and tempering treatment, distortion during quenching was prevented.

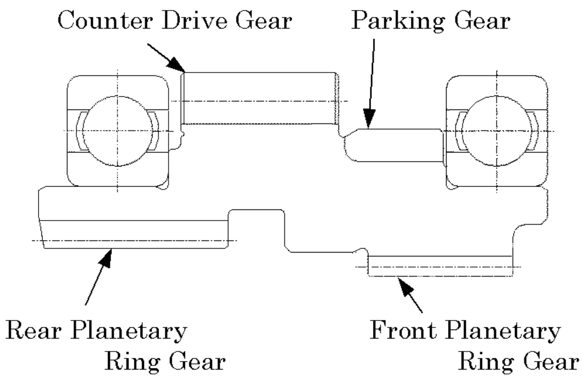

Figure 9: Structure of Compound Gear

6 IMPROVEMENT OF POWER PERFORMANCE AND FUEL ECONOMY

The conventional traction drive motor was thoroughly revised and has been downsized while providing high power performance and high efficiency. This section describes the outline of the technical items for the new downsized motor adopted to P310.

6.1 MOTOR SPEED, INCREASING

Figure 10 shows the frequency map of the traction drive motor in normal driving conditions and its feature is high frequency in low load area. The main motor loss is the copper loss which occurs in the coil as joule heat and the iron loss which occurs in the motor core. Iron loss reduction is important to improve fuel consumption in normal driving as it mainly accounts for the low load area (See Figure 11).

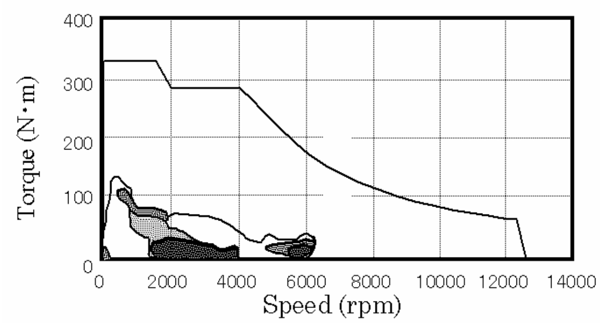

Figure 10: Frequency Map in Town Ride Condition

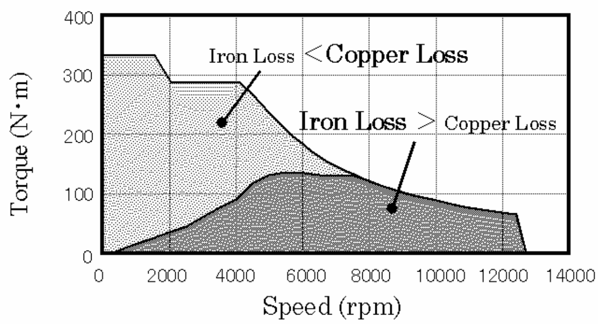

Figure 11: Motor Loss Rate

The feature in P310 is the downsized motor based on the adoption of the reduction gear which has more than double the reduction ratio compared with the conventional type; however, this reduction gear adoption requires more than double-speed motor operation. To achieve the high speed rotation, satisfying the mechanical condition such as the strength towards centrifugal force, and reducing the iron loss to avoid the insufficient fuel consumption is vital thought the iron loss increase is proportional to the square of the motor frequency.

Significant reduction of the iron loss has been achieved in P310 development by the design and material revision.

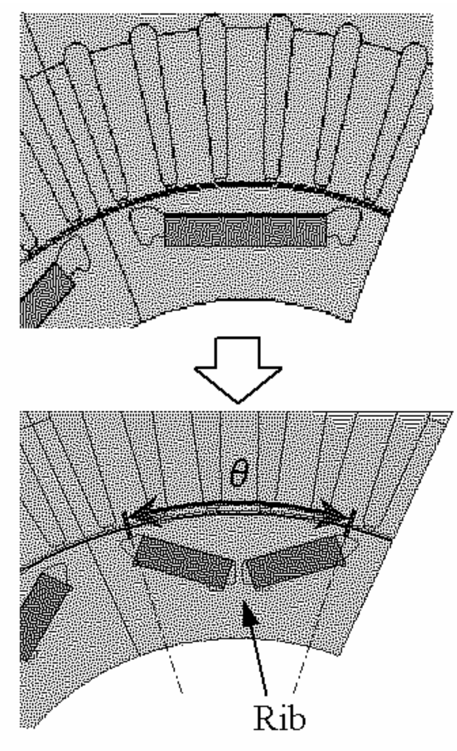

Figure 12: Rotor Permanent Magnet Layout

Regarding the design, reluctance torque has been remarkably increased by the layout change of the rotor permanent magnet to V-formation (See Figure 12), and it reduces the iron loss during the low load application. The rib is newly adapted to the center of the rotor to improve the strength, and these modifications have brought more than double-speed rotation compared with the conventional motor. Furthermore, the reduction of the harmonic components in magnetic flux due to the optimization of the open angle θ in the rotor magnet also contributes for the iron loss reduction. These are optimized based on the FEM including magnetic field and strength analysis.

Regarding the material, new silicon steel has been developed. It is thinner than the 0.35 mm silicon steel used in the Prius transmission (P112) and enables to reduce iron loss remarkably.

Other items related to the production process such as stack method for the silicon steel of stator were also revised and as the whole result of those improvements, iron loss has been remarkably reduced from the conventional type (P112).

6.2 HIGHER VOLTAGE, DOWNSIZING

Compared to the P112 higher voltage and reduced physical size of motor (coil-end) were achieved in the P310. Following is a description of the newly improved technologies. Phase voltage of P310 has increased from that of P112 by 30%. More than 20% of the voltage is increased at its peak while considering the surge caused by a switching of an inverter. We have designed insulating paper that would not develop Partial Discharge Inception Voltage (PDIV) at the peak. Also, the motor is designed to keep the distribution voltage low in a phase. We designed the new motor considering the fact that phase voltage and distribution voltage are influenced by the length of cable connecting an inverter and a motor and the fact that PDIV is influenced by surrounding conditions such as temperature and humidity. Insulating material with superior (Automatic Transmission Fluid) ATF resistance and hydrolysis resistance was adopted. Like P112, P310 is using ATF as a motor coolant; therefore, ATF resistant material is essential. Hydrolysis resistance must be considered because ATF contains a slight amount of moisture. In addition, P310's temperature range of operation is higher than P112's. ATF and hydrolysis resistance in higher temperature is required. Considering those points above an insulator with a three-layered structure was applied for P310.

P310 has achieved coil-end downsizing by 15% compared to P112. Considerations for downsizing coil-end are formation of insulating paper, choice of coiling material, and production technology. A decrease of dielectric strength voltage caused by damages and pinholes on a coil as well as partial discharge due to torn insulation paper may occur during a formation of a coil-end. Insulation quality during coil-end forming is achieved by contriving the shape of insulation paper, considering the smoothness of the surface and the hardness of a coil, and using a 0 type coil. Moreover, cutting back the amount of coil at the coil-end allowed us to accomplish further downsizing.

6.3 COOLING PERFORMANCE

As with P112, heat radiation for P310 is conducted through the motor case. A technology applied for P310 is a forced ATF cooling which circulates ATF to the stator in order to conduct heat away from the stator to the motor case. The same air-cooling system and water-cooling system as in P112 are used to radiate heat from the motor case. In order to improve the cooling efficiency some vehicles use an oil cooler to cool down ATF.

Heat radiation from the stator is conducted by two paths; one from a metal contact between the stator and the motor case and another from the motor case in contact with ATF. 30% to 50% of overall heat radiation is caused by the metal contact. The rest of the 50% to 70% of heat radiation is by conduction between ATF and the motor case. Cooling efficiency by ATF is much greater in P310. Including the air-cooling, we have achieved extensive upgrade of overall cooling performance (See Figure 13,14).

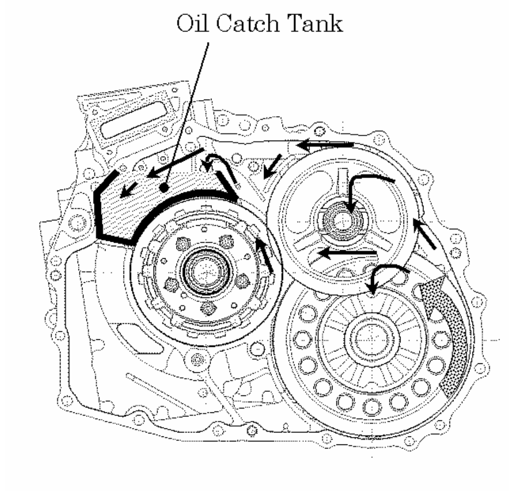

Figure 13: Imaginary Diagram of Oil Flow

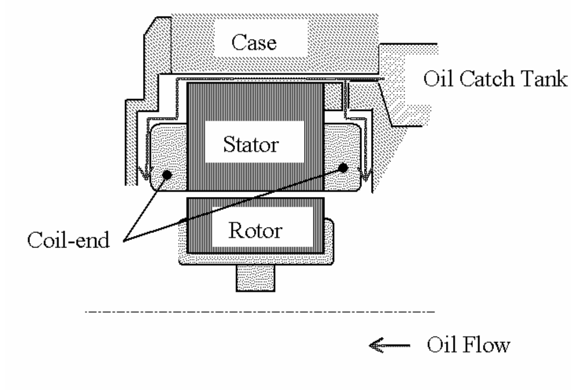

Figure 14: Imaginary Diagram of Motor Generator Cooling

7 CONCLUSION

This new hybrid transmission (P310) has been developed for FWD 3-liter engine class sports utility vehicles. It is compact, light weight and superior for power performance and fuel economy. The gearing, size reduction and enhanced efficiency technologies are expected to contribute greatly to enhancing the performance of this hybrid transmission.

REFERENCES

1. S. Abe, S. Sasaki, H. Matsui, K. Kubo. Development of Mass-produced Hybrid System for Passenger Vehicles: 975, pre-printed papers of the academic lecture meeting, Society of Automotive Engineers of Japan, Inc., Oct. 1997
2. S. Sasaki, T. Takaoka, H. Matsui, T. Kotani. Toyota's Newly Developed Electric-Gasoline Engine Hybrid Power Train System: EVS-14, Dec. 1997
3. K. Tanoue, H. Miyazaki, Y. Kawabata, T. Yamamoto, T. Hirose, G. Nakagawa. Production and Technical Development of EV and HV Units. Toyota Technical Review Vol. 47, No. 2
4. M. Matsui, K. Kondo, R. Ibaraki, H. Ito. Development of Trans-axle for Hybrid Vehicles. Journal of Society of Automotive Engineers of Japan, Vol. 52, Sept. 1998
5. K. Yoshimura, K. Ohshima, K. Kondo, S. Ashida, H, Watanabe, M.Kojima. Development of Trans-axle for Hybrid Vehicles to Reduce Fuel Consumption. Journal of Society of Automotive Engineers of Japan, Vol. 58, Sept. 2004