

Vibration Reduction in Motors for the SPORT HYBRID SH-AWD

Manabu Yazaki
Honda R&D Co., Ltd.

ABSTRACT

A new motor has been developed that combines the goals of greater compactness, increased power and a quiet drive. This motor is an interior permanent magnet synchronous motor (IPM motor) that combines an interior permanent magnet rotor and a stator with concentrated windings.

In addition, development of the motor focused on the slot combination, the shape of the magnetic circuits and the control method all designed to reduce motor noise and vibration.

An 8-pole rotor, 12-slot stator combination was employed, and a gradually enlarged air gap configuration was used in the magnetic circuits. The gradually enlarged air gap brings the centers of the rotor and the stator out of alignment, changing the curvature, and continually changing the amount of air gap as the rotor rotates. The use of the gradually enlarged air gap brings torque degradation to a minimum, and significantly reduces torque fluctuation and iron loss of rotor and stator.

A superposed harmonic current is used as the control method for the motor. This control method reduces torque fluctuation by adding a harmonic current component on the motor drive control in order to cancel the peaks of the torque waveform.

The application of the newly developed three motors in the SPORT HYBRID SH-AWD reduced cogging torque by 50% and torque fluctuation by 50% at an average torque of 5 Nm. The noise and vibration were reduced by at least 12 dB. This technology made it possible to realize quiet motor operation.

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1. INTRODUCTION

The need to expand applications of hybrid electric vehicles (HEV) into new configurations has increased rapidly. New applications of hybrid electric vehicles range from compact to large cars and from sedans to sport utility vehicles. A beneficial feature of HEV systems is that they can drive using their electric motor alone (1), (2), (3), (4), and due to the lack of engine noise and vibration there is considerable need for motor quietness.

Consequently, responses for HEV and electric vehicles (EV) that focus on the relatedness of vehicle sensitivity, vibration transfer path (1),(2),(5) and gear noise reduction have been proposed (6).

One approach that is frequently taken to reduce motor vibration and noise is to adopt distributed windings for the stator in the drive motor as an effective way of reducing torque fluctuation (7). However, distributed windings make the coil-end larger, thus limiting the

available locations in which it can be mounted. Also using distributed windings make the coil-end more compact and introduce complications in structure and manufacturing methods (7).

Meanwhile, concentrated windings are one way of making the coil-end more compact (8). If concentrated windings can achieve the same reduction in torque fluctuation as distributed windings, then that approach would be effective for the drive motor. Attention was focused on the shape of the magnetic circuits as a method for reducing motor vibration. Methods for reducing torque fluctuation connected with the electric angle 6th order are known (9). Methods of design that limit radial excitation force by the shape of the magnetic circuits have also been proposed (10), (11), (12), (13), (14), (15). Additionally, methods of reduction using control have also been reported (16),(17).

This paper will report on how a stator with concentrated windings and interior permanent magnet (IPM) rotor were combined in an AC synchronous motor (IPM motor) that achieves greater compactness and higher torque. Reduced vibration and noise were achieved by optimizing the magnetic circuit design and control technology.

The report will describe the technology for reducing vibration and noise during motor operation that was adopted in order to install this developed motor as the drive motor in the SPORT HYBRID Super Handling - All Wheel Drive (SPORT HYBRID SH-AWD).

2. OVERVIEW OF SYSTEM AND MOTOR

2.1. Sport Hybrid SH-AWD

The SPORT HYBRID Super Handling - All Wheel Drive (SPORT HYBRID SH-AWD) system in which the developed motor was used is a high-efficiency hybrid AWD system (18),(19) that is equipped with three motors. Figure 1 shows the overall configuration of the system, and Table 1 shows the system specifications. The front wheels are driven by a V6 3.5-L direct-injection engine and a motor integrated into the transmission, or dual-clutch transmission motor (DCT motor). These are mounted in the engine compartment at the front of the vehicle. The rear wheels are driven by the Twin Motor Unit (TMU).

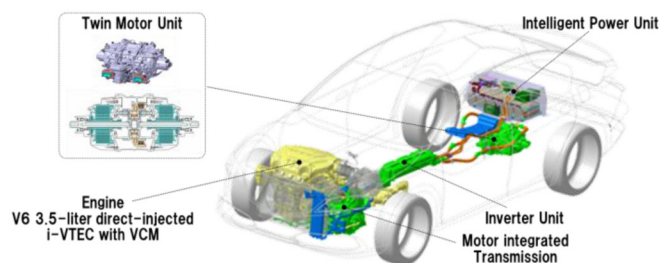


Figure 1. SPORT HYBRID SH-AWD

Table 1. System Specifications

System power [kW]		281
Engine	Type	V6 3.5 L, Direct injection, SOHC, VTEC 24-valve
	Power [kW]	231 at 6,500 [rpm]
	Torque [Nm]	371 at 4,700 [rpm]
DCT Motor	Type	Interior Permanent Magnet Synchronous Motor
	Power [kW]	35 at 3,000 [rpm]
	Torque [Nm]	148 at 500 to 2,000 [rpm]
TMU Motor	Type	Interior Permanent Magnet Synchronous Motor
	Power [kW]	27 at 4,000 [rpm] (x2)
	Torque [Nm]	73 at 0 to 2,000 [rpm] (x2)
Battery	Type	Li-ion
	Voltage [V]	260

2.2. Driving Modes

Figure 2 shows the four driving modes of this system: (1) EV launch and EV cruising mode, driven by the TMU; (2) engine drive and engine cruising mode, in which the front wheels are driven by the engine; (3) power acceleration mode, in which the engine is assisted by the TMU; and (4) all-wheel drive (AWD) mode, driven by the engine and TMU. These modes are selected by driver demand or according to road surface conditions. The electric power required by the TMU is supplied from power generated by the DCT motor. Therefore, the TMU can perform regardless of the charge state of the battery.

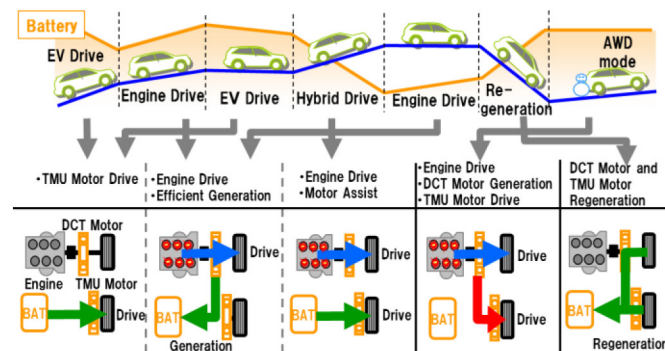


Figure 2. Driving Modes of the SPORT HYBRID SH-AWD

2.3. Active Torque Transfer

Figure 3 illustrates torque vectoring during cornering, whereby drive power is distributed to the left and right wheels in AWD. The two independent motors located at the left and right rear wheels are used to apply positive and negative torque differentially according to the acceleration or deceleration state of the vehicle. Depending on the acceleration or deceleration state, positive torque may be applied to the outside wheel and negative torque to the inside wheel. Rear wheel torque can be controlled freely in this way without being dependent on engine power output. This AWD system also recovers energy generated by the inside wheel and supplies it to the outside wheel. With this ability to produce by itself the power required for turning, the system is highly energy efficient.

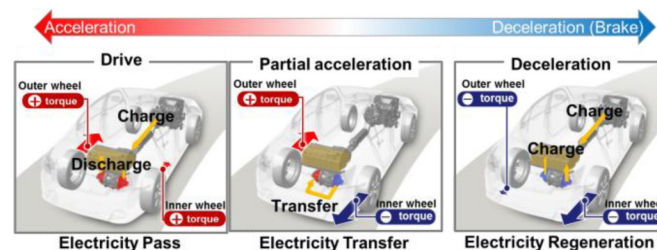


Figure 3. Concept of Torque Vectoring

2.4. Motor Structure

2.4.1. Twin Motor Unit

Figure 4 shows the external appearance of the TMU. The TMU is made up of two motors, one on the left and one on the right, a deceleration mechanism, and a disconnect mechanism(20).

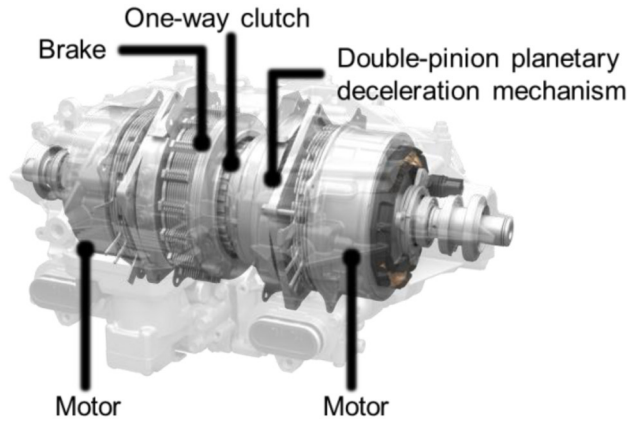


Figure 4. External view of Twin Motor Unit

Figure 5 shows a single TMU motor. The type of motor adopted for the unit is an interior permanent magnet motor (IPM motor) that combines a concentrated winding stator with an interior permanent magnet (IPM) rotor. An arrangement of 8 poles and 12 slots (8p12s) (19) was adopted as the combination in order to keep the resonance of the stator ring deformation and the excitation force of the motor from coinciding. Concentrated windings were used in order to make the TMU motors more compact.

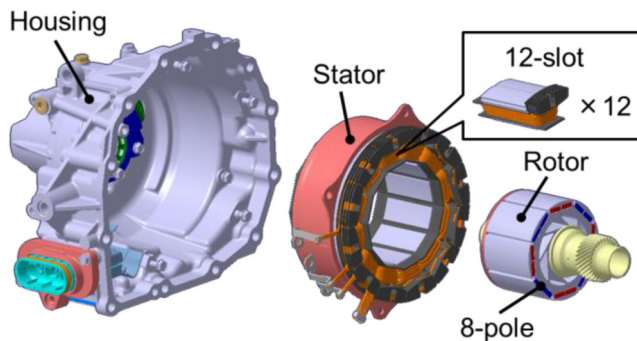


Figure 5. Configuration of Motor for Twin Motor Unit

2.4.2. DCT Motor

Figure 6 shows the DCT motor. This motor generates electric power during front wheel drive mode driven by the engine, all-wheel drive (AWD) mode, and deceleration regeneration mode. The type of motor adopted is an interior permanent magnet motor (IPM motor) combining an interior permanent magnet rotor and a concentrated winding stator. An arrangement of 12 poles and 18 slots (12p18s) was used as the combination.

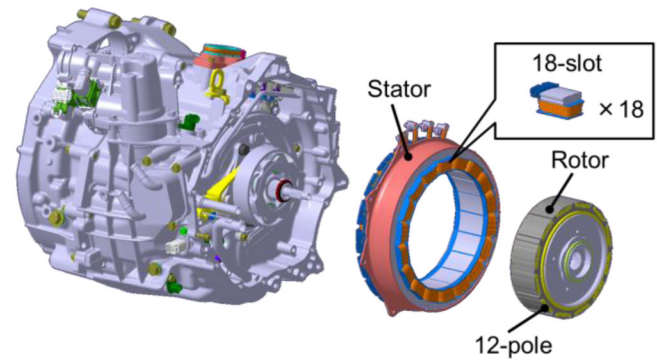


Figure 6. Configuration of Motor Integrated Transmission

3. TMU MOTOR VIBRATION AND NOISE

3.1. TMU Motor Operating Range

The explanation of vibration and noise in the TMU motors will start with an explanation of the TMU motor operating range. Figure 7 shows operation points that are typical for TMU motors during system operation. The horizontal axis shows motor speed and the vertical axis shows torque. The solid line in the graph marks the motor operating range. With regard to speed or torque, the TMU motors are used so operation ranges are low-speed, high-torque zone during EV launch, medium-torque zone during EV cruising, and maximum motor power output during AWD. It is therefore necessary to reduce motor vibration and noise throughout this entire range.

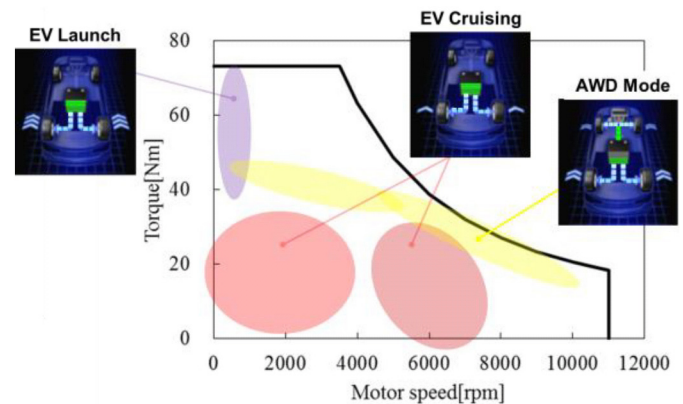


Figure 7. Operating Range of TMU Motor

3.2. Vibration and Noise of the electric angle 6th order

3.2.1. Vehicle Cabin Noise of TMU

Figure 8 shows a typical example of noise in the vehicle cabin during operation. The horizontal axis shows the vehicle speed and the vertical axis shows the frequency. Noise at the frequency corresponding to the electric angle 6th order of the TMU motor is conspicuous by comparison with other components and is therefore an issue. Figure 9 shows cabin noise of the electric angle 6th order component. This exceeds the cabin noise target value by 13 dB.