

Vibration Reduction of Two Motors of Rear Wheel Drive for SPORT HYBRID SH-AWD

Manabu YAZAKI*

Tadanobu AOKI*

ABSTRACT

The two motors employed to drive the rear wheels in the SPORT HYBRID SH-AWD system were developed to balance compactness, high power, high torque, and quietness. Stators employing concentrated windings were used to reduce the size of the motors, and development focused on the combination of slot number and pole number, the magnetic circuits, and control methods in an attempt to satisfy one of the development goals, the reduction of torque fluctuation, which is a cause of vibration and cabin noise.

A Gradually Enlarged Air Gap was adopted for the magnetic circuits. The Gradually Enlarged Air Gapshape offsets the centers and modifies the curvature of the rotor and the stator, producing continuous change in the air gaps with the rotation of the rotor. The application of the Gradually Enlarged Air Gap method made it possible to reduce torque fluctuation while also controlling decline in torque. Superposition of higher harmonics was applied as a control method. This control method reduces torque fluctuation by superposing high-frequency components on the motor traction control current in order to cancel the torque waveform peak.

The newly developed motors realize a 50% reduction in cogging torque and torque ripple in comparison to the previous specifications, and motor vibration has been reduced by 10 dB and cabin noise by more than 13 dB.

1. Introduction

Today's increasing demand for environmental performance from automobiles is driving a rapid expansion in the application of several types of hybrid electric vehicle (HEV)⁽¹⁾. While environmental performance has traditionally been the priority in HEV, in the past several years demand has been increasing for the vehicles to offer other forms of added value, including dynamic performance and quietness. With regard to quietness, some HEV systems able to operate on motor drive alone, and which consequently are not affected by engine vibration or noise, have been brought into practical use⁽²⁾⁻⁽⁴⁾. This trend is not limited to HEV; in order to maximize the benefit of quietness, developments are being conducted that focus on vehicle sensitivity and vibration transfer paths in electric vehicles (EV) and other automobiles employing electric drive⁽⁵⁾⁻⁽⁸⁾.

Generally, traction motors utilize distributed windings in a stator, and reduce vibration and noise by reducing torque fluctuation⁽⁹⁾. However, this necessitates a considerable amount of space for vehicle fitting, because the coil ends of the distributed windings are large. A configuration that reduces the size of the coil ends by dividing and overlapping the coils has therefore been proposed⁽⁹⁾, but

this configuration necessitates multi-spot welds, making the manufacturing method complex.

The use of concentrated windings is available as a method of reducing size⁽¹⁰⁾. However, concentrated windings present the issue of producing a greater amount of torque fluctuations (cogging torque and torque ripples) during rotation than distributed windings.

The form of deformation of the stator has been focused on in order to develop methods of reducing vibration in motors using concentrated windings, and proposals have included the selection of basic frameworks that control deformation⁽¹¹⁾, the use of configurations in which the teeth of the core or the poles of the magnets are skewed^{(12), (13)}, the engineering of holes in the rotor⁽¹⁴⁾, and the adjustment of magnetic resistance by means of the shape of the stator⁽¹⁵⁾⁻⁽¹⁷⁾. Methods of reducing vibration through the application of control have also been reported^{(18), (19)}.

This paper will discuss the realization of compactness, high power and high torque in an interior permanent magnet synchronous motor (IPM motor) combining an IPM rotor and a stator using concentrated windings, while also reducing motor vibration and cabin noise. The paper will introduce newly developed magnetic circuit design and control technologies.

* Automobile R&D Center

2. Overview of System and Motor

2.1. SPORT HYBRID SH-AWD

Honda's SPORT HYBRID Super Handling All-Wheel Drive (SPORT HYBRID SH-AWD) is a high-efficiency hybrid all-wheel drive (AWD) system fitted with three motors^{(20), (21)}. Figure 1 shows the overall system configuration, and Table 1 shows the system specifications. The V6 3.5L direct injection engine and DCT motor that drive the front wheels and the transmission are positioned in the engine room at the front of the vehicle. The rear wheels are driven by two motors (TMU motors) fitted in a Twin Motor Unit (TMU).

2.2. Hybrid System Operation

Figure 2 shows the operation of the system. As an operating mode using motor power only, the system is provided with an EV drive mode offering takeoff and acceleration realized through TMU drive. It also features an engine drive mode, in which the front wheels are driven by the engine, and a hybrid drive mode, in which assist is provided by the TMU. In response to driver demands and road surface conditions, AWD control is applied, and drive is provided by the engine and the TMU.

2.3. Torque Vectoring

Figure 3 shows the operation of torque vectoring using AWD control. In response to the steering wheel angle and

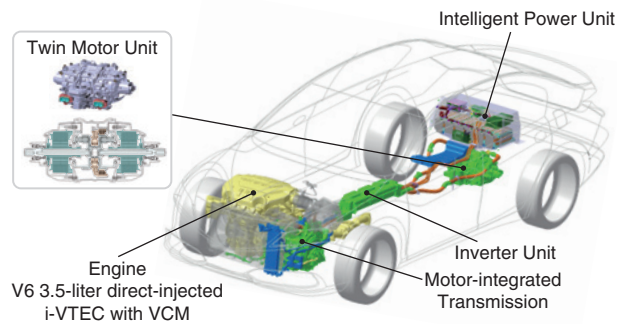


Fig. 1 SPORT HYBRID SH-AWD system

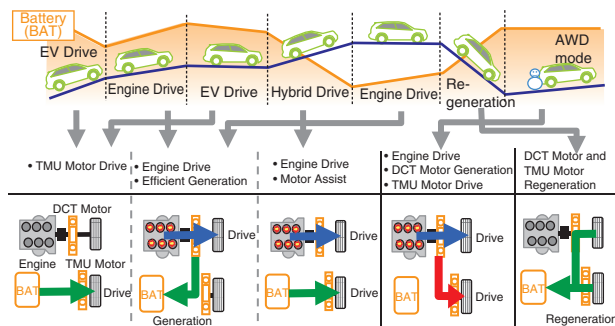


Fig. 2 Operation of SPORT HYBRID SH-AWD hybrid system

Table 1 System specifications

System power [kW]		281
Engine	Type	V6 3.5L, 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 (× 2)
	Torque [Nm]	73 at 0 to 2,000 rpm (× 2)
Battery	Type	Li-ion
	Voltage [V]	260

the state of acceleration or deceleration, the system is able to generate a difference between torque in the direction of drive and the direction of braking using the two independent motors for the left and right rear wheels, and allocate torque to the left and right rear wheels. This is a high-efficiency AWD system that is also able to electrically recover the energy produced by the inner wheels when the vehicle is turning and impart it to the outer wheels, thus generating the energy necessary for turning itself.

2.4. TMU and TMU Motor

Figure 4 shows an external view of the TMU. The TMU is made up of left and right motors, a deceleration mechanism, and a disconnect mechanism⁽²²⁾.

Figure 5 shows the TMU motor. The motor is an IPM motor with a stator using concentrated windings, and the combination of slot number and pole number is 8 poles and 12 slots (8p12s). Concentrated windings have been used in the TMU motor in order to reduce size⁽²¹⁾.

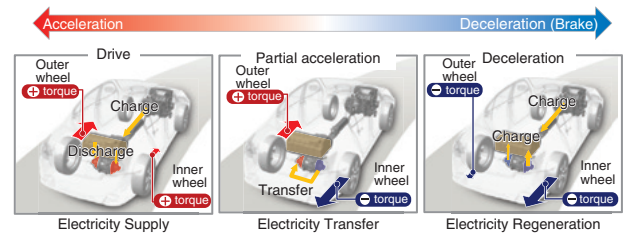


Fig. 3 Concept of torque vectoring

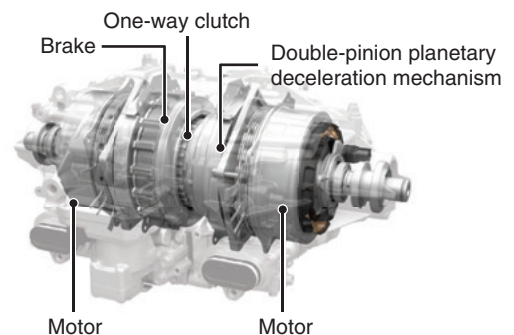


Fig. 4 External view of TMU

2.5. Range of Use of TMU Motor

Figure 6 shows representative operating points for the TMU motor in the hybrid system operation discussed in Sections 2.2 and 2.3. The horizontal axis shows motor speed and the vertical axis shows torque. The range bounded by the solid line in the graph is the motor operating range. Takeoff provided by EV drive mode uses the low-speed high-torque range; the medium-torque range is used in EV drive mode. AWD control uses a range that follows the line of maximum motor power, and the TMU motor can therefore be used irrespective of motor speed and torque.

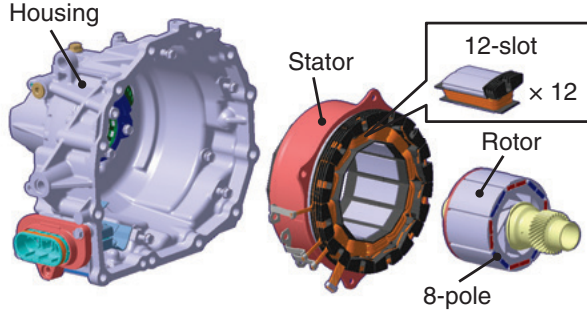


Fig. 5 Configuration of TMU motor

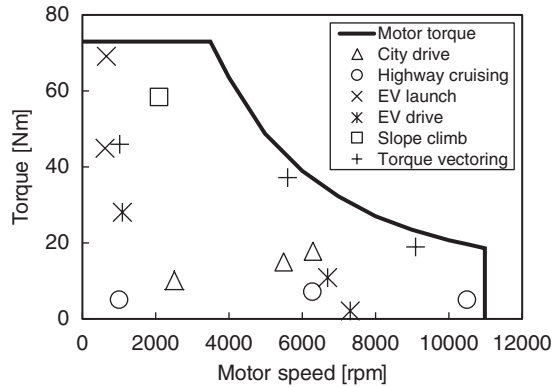


Fig. 6 Operating range of TMU motor

3. Motor Vibration and Cabin Noise

In motors using concentrated windings, annular deformation of the stator produced chiefly by excitation in the radial direction of the electric angle 2nd-order and 6th-order components is generally the factor in vibration and noise^{(11), (18), (19)}. Excitation in the radial direction of the electric angle 2nd-order components results in 4th-order annular deformation of the stator, and excitation in the radial direction of the electric angle 6th-order components results in 0th-order annular deformation of the stator^{(11), (18), (19)}. In addition, torsional vibration of the motor and the unit resulting from torque fluctuation and shaking of the body of the unit also produce vibration and noise. This chapter discusses measurements of cabin noise during vehicle operation following the application of concentrated

windings in the two rear wheel drive motors for the SPORT HYBRID SH-AWD system, making it possible to identify the vibration and noise that represented an issue.

3.1. Motor Vibration and Cabin Noise Due to Electric Angle 6th-Order Components

3.1.1. Order of cabin noise during vehicle operation

Figure 7 shows a representative example of cabin noise for the system when the vehicle is in operation. The horizontal axis shows vehicle speed and the vertical axis shows frequency. These results indicate that for this system, frequency components corresponding to the electric angle 6th order are more remarkable than other components, and represent an issue. Figure 8 shows the cabin noise generated by the electric angle 6th-order components at this time. Cabin noise is 13 dB in excess of the target value.

In order to reduce this type of cabin noise when the motor is in operation, conventionally the relationship between vehicle sensitivity, vibration transfer paths, and gear noise has been focused on and the resonance points of various parts have been set to help ensure that motor vibration does not excite resonance^{(5), (8)}, or a two-fold vibration-damping mount configuration has been adopted in order to extend the vibration-damping characteristic to the high-frequency range⁽⁶⁾. A method of combining the frequency characteristics of each component of the vehicle

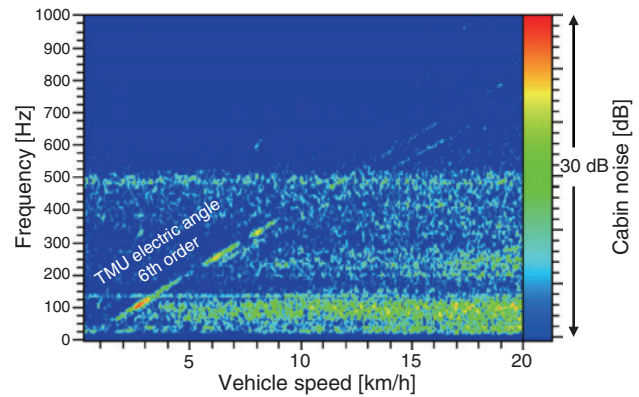


Fig. 7 3D map of TMU motor

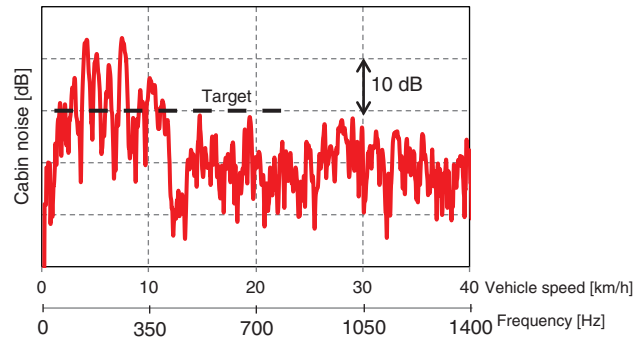


Fig. 8 Cabin noise of TMU motor (Electric angle 6th order)

body in order to develop bodies with low sensitivity to vibration has also been adopted⁽⁷⁾. In the case of the present system, however, vibration was reduced by redesigning the magnetic circuits of the motor and applying control, making it possible to employ SPORT HYBRID SH-AWD.

3.1.2. Factors in occurrence of cabin noise

The electric angle 6th-order components were most prominent in the cabin noise produced by the TMU motors during vehicle operation, as discussed above. This section will discuss the mechanism of production of this noise. Depending on vehicle speed, the frequencies corresponding to these frequency components cover a broader frequency range in a vehicle using a TMU system than in one fitted with a conventional engine. The frequency of the electric angle 6th-order components changes with vehicle speed, and at frequencies that match the natural vibration modes of each part of the vehicle, motor vibration increases⁽²³⁾. This vibration produced by the electric angle 6th-order components and the natural vibration modes of the vehicle body were focused on.

Figure 9 shows subframe and differential mounts with a TMU fitted. Figure 10 shows vibration data during actual vehicle operation at a subframe mounting point (Point B) in relation to the mounting point of a housing (Point A) fitted with the TMU (the vibration source) when the spring rate of the differential mount is changed. These results show that when the spring rate of the differential mount is low, vibration is suppressed across the entire range, but that when the spring rate of the differential mount is high, there is almost no suppression of vibration in the mount below 400 Hz. Balancing the use of a differential mount with a

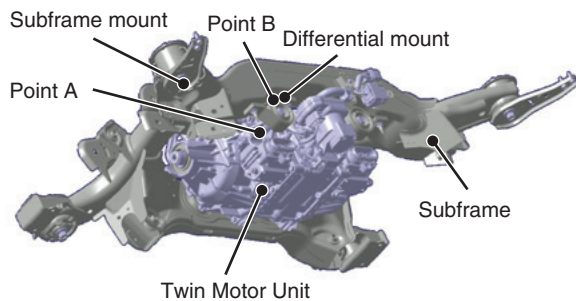


Fig. 9 Bottom view of TMU attached to subframe

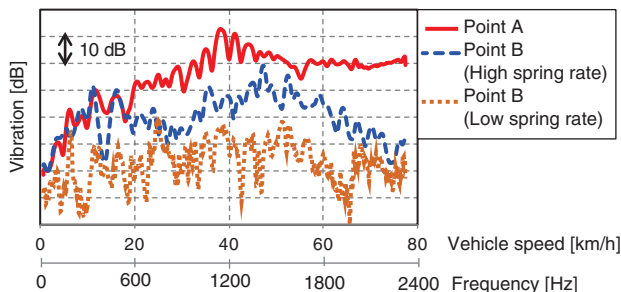


Fig. 10 Vibration of TMU and subframe mounting point

high spring rate in order to boost SPORT HYBRID SH-AWD handling stability with the suppression of vibration therefore represented an issue.

In addition, as Fig. 11 shows, the subframe itself resonates below 400 Hz, and motor vibration increases subframe vibration. For these reasons, motor noise is high in the low vehicle speed range, at takeoff and when the vehicle is about to stop.

As described above, motor vibration excites subframe resonance, producing audible cabin noise. In order to reconcile a high level of dynamic performance with quietness in the SPORT HYBRID SH-AWD system, it was necessary to reduce vibration and noise generated by the electric angle 6th-order components in the TMU motor characteristic.

3.2. Cabin Noise Generated by Torsional Vibration of the TMU

In addition to the vibration and noise generated by the electric angle 6th-order components, as discussed in Section 3.1, a 1.3 kHz noise also occurs. An investigation of the cause of this noise showed that a resonance existed at 1.3 kHz in the vibration mode of the TMU (Fig. 12). In addition, measurement of the deformation mode of the TMU showed that torsional resonance with an eigenvalue existed at 1.3 kHz. It was recognized that this was the noise produced at the vehicle speed corresponding to the resonance peak when the vehicle was operating using the TMU motors.

This cabin noise produced by torsional vibration was

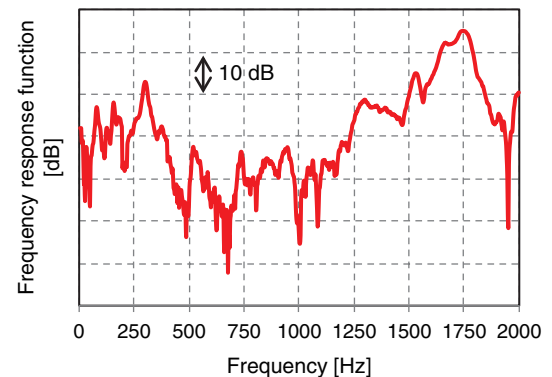


Fig. 11 Vibration of subframe

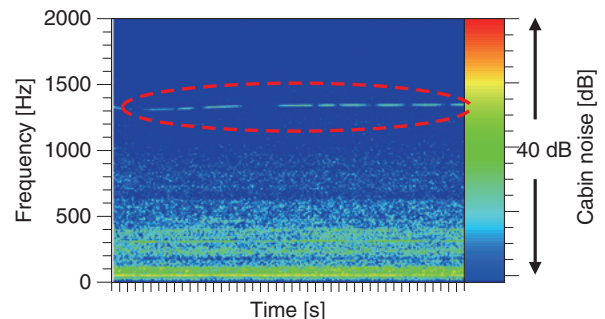


Fig. 12 3D map of TMU torsional vibration

therefore a structural phenomenon characteristic of the left-right two motor configuration.

As indicated in Sections 3.1 and 3.2, it was necessary to reduce vibration and noise across a wide frequency band for both the vehicle and the TMU. Vibration in the motors, the excitation source, was therefore reduced.

4. Reduction of Motor Vibration and Noise via Magnetic Circuits

4.1. Combination of Slot Number and Pole Number

The combination of slot number and pole number for the motor was selected with consideration of attempting to help ensure that the frequencies of the electric angle 2nd-order and 6th-order components, which are determined by the vehicle speed employed and the combination of slot number and pole number, did not correspond to the resonance points of annular deformation of the stator.

Figure 13 shows the results of an analysis of frequency and stator deformation against motor speed for the TMU motors. For a combination of 8p12s, there was no resonance between the electric angle 2nd-order components and 4th-order annular deformation of the stator and the electric angle 6th-order components and 0th-order annular deformation of the stator. Based on these results, 8p12s was selected as the combination of slot number and pole number for the TMU motors.

4.2. Optimization of Stator Shape

4.2.1. Gradually enlarged air gap

In order to reduce the electric angle 6th-order frequency components that were the main causes of cabin noise in the case of the present system, a new magnetic circuit shape was designed as a method of damping the fluctuations in magnetic flux density occurring when switching between U, V, and W phases.

Case 1 in Fig. 14 shows the conventional shape of the magnetic circuits. Partial modification of the shape of the stator or rotor in order to enlarge the air gaps and adjust magnetic resistance is known as a method of reducing motor vibration. Examples include the notched shape shown in Case 2 in Fig. 14⁽¹⁶⁾ and the enlarged air gaps at the tips of the teeth shown as Case 3 in Fig. 14⁽¹⁷⁾. However, while these shapes do reduce the electric angle 6th-order components, higher-order frequency components increase in proportion to the number of partially enlarged air gaps.

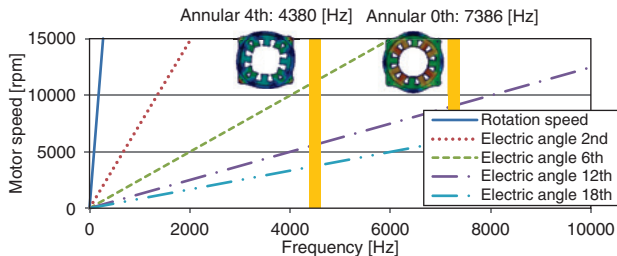


Fig. 13 Natural frequency of 8p12s motor

A method in which holes are introduced in sections of the rotor⁽¹⁴⁾ is also available, but it was decided not to change the shape of the rotor based on considerations of strength.

A method termed Gradually Enlarged Air Gap (GEAG) was therefore adopted for the motors under discussion. This magnetic circuit shape is shown as Case 4 in Fig. 14. The GEAG shape displaces the centers and modifies the curvature of the rotor and the stator.

Figure 15(b) compares the air gaps in relation to the electric angle for the conventional shape (Case 1) and the GEAG shape (Case 4). Case 4 is a shape that generates change in the air gaps along a curved trajectory, with the air gaps at their minimum at electric angles of 0, 120, and 240 deg. Figure 15(a) compares changes in magnetic flux density as determined by a magnetic field analysis for the conventional shape (Case 1) and the GEAG shape (Case 4). The application of the GEAG shape (Case 4) reduces change in magnetic flux density close to electric angles of 72, 192, and 312 deg. Figure 15(c) shows the results of applying FFT to fluctuations in magnetic flux density. High-frequency components (electric angle 2nd-order components and above) have been reduced. These results indicated that it had been possible to reduce the high-frequency components of magnetomotive force, and thus to reduce torque fluctuation and the high-frequency components of the excitation force.

4.2.2. Degree of change in air gaps and reduction of torque fluctuation

Figure 16 shows the reduction in torque fluctuation with the degree of change in the air gaps as a result of the GEAG shape, based on the results of a magnetic field analysis. As Fig. 16(a) shows, torque fluctuation was calculated by varying the degree of change in the air gaps

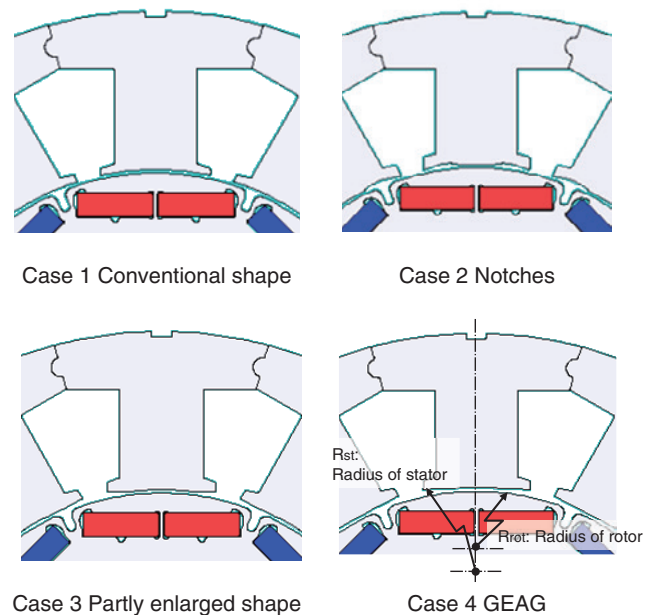


Fig. 14 Difference of magnetic circuits

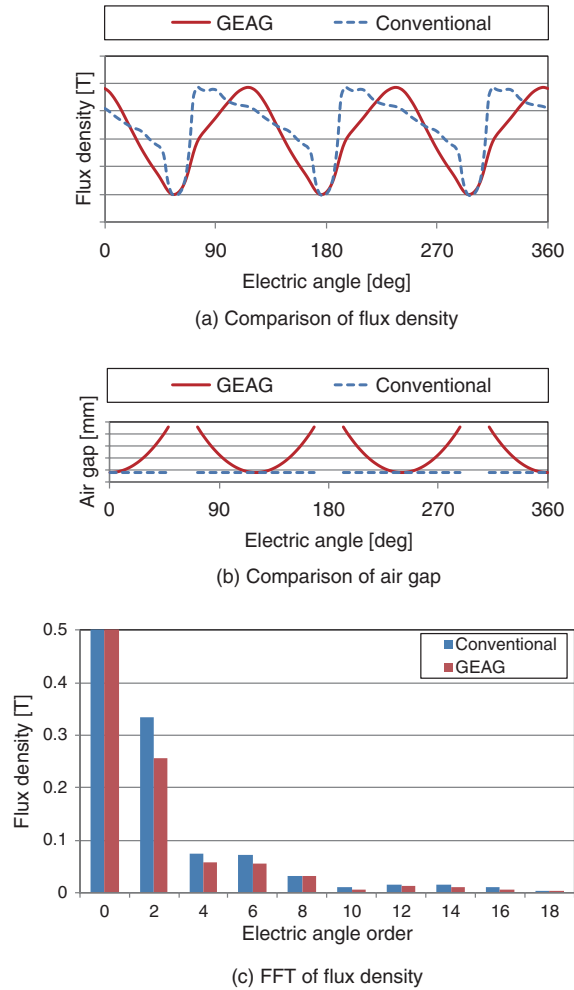


Fig. 15 Reduction of higher harmonic components of flux density fluctuation

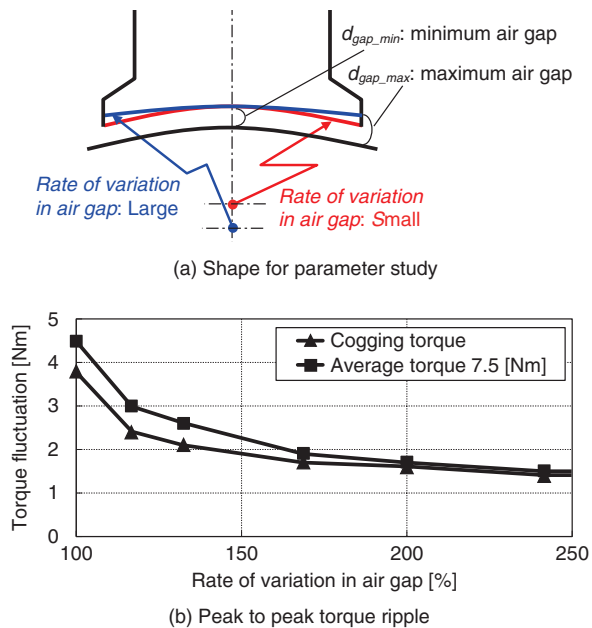


Fig. 16 Results of torque fluctuation parameter study

by changing the inner diameter of the stator. Figure 16(b) shows torque fluctuation against the rate of change in the air gaps between the center and the tips of the stator, as defined by Eq. (1). These results indicated that a degree of change in the air gaps of 200% (twice the air gap at the tips of the stator as at the center) or more would sufficiently reduce vibration, and the GEAG shape was therefore applied in the TMU motors.

$$\text{Rate of variation in air gap} = \frac{d_{\text{gap_max}}}{d_{\text{gap_min}}} \times 100[\%] \quad (1)$$

4.3. Results of Analysis of Torque Fluctuation and Radial Excitation Force

Figure 17(a) shows the results of an analysis of cogging torque for each of the magnetic circuit shapes shown as Cases 1 to 4. Figure 17(b) shows the results of an analysis of the electric angle 6th-order components of torque ripple for torque in Cases 1 to 4. These results indicated that the GEAG shape (Case 4) produced the greatest reduction in both cogging torque and torque ripple.

Figure 17(c) shows the results of an analysis of the electric angle 6th-order components of radial excitation

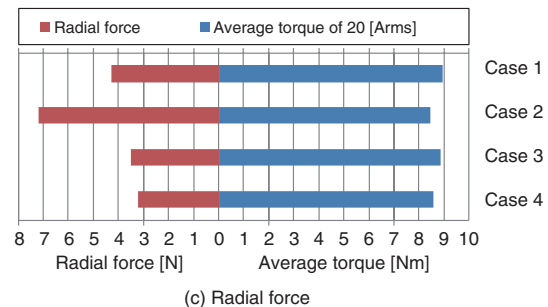
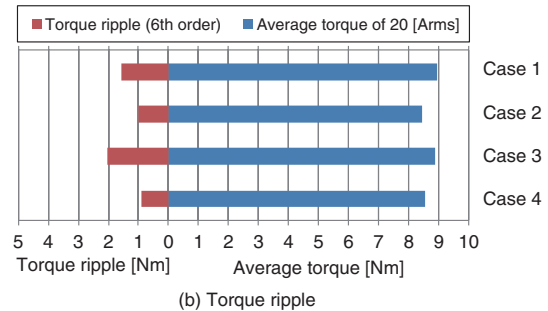
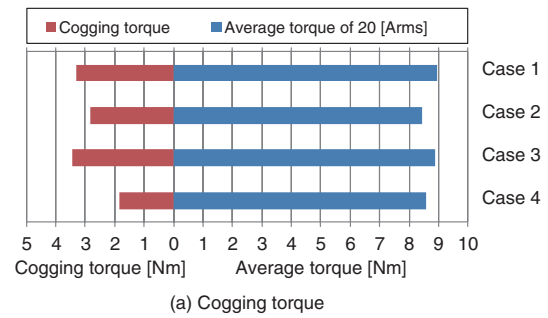


Fig. 17 Results of analysis of different stator shapes

force for torque in Cases 1 to 4. These results indicated that the GEAG shape (Case 4) also reduced radial excitation force. Taken together, the results shown in Figs. 17(a) and (b) show that the GEAG shape achieves reductions in both the circumferential and radial directions.

4.4. Results of Measurement of Torque Fluctuation

Figure 18 shows the reduction in cogging torque and torque ripple in the TMU motors realized through the application of the GEAG shape in the magnetic circuits. The results show a maximum reduction of 50% in overall cogging torque and torque ripple [Fig. 18(a)] and in the electric angle 6th-order components of cogging torque and torque ripple [Fig. 18(b)] in peak-to-peak measurements of torque fluctuation at a motor speed of 5 rpm.

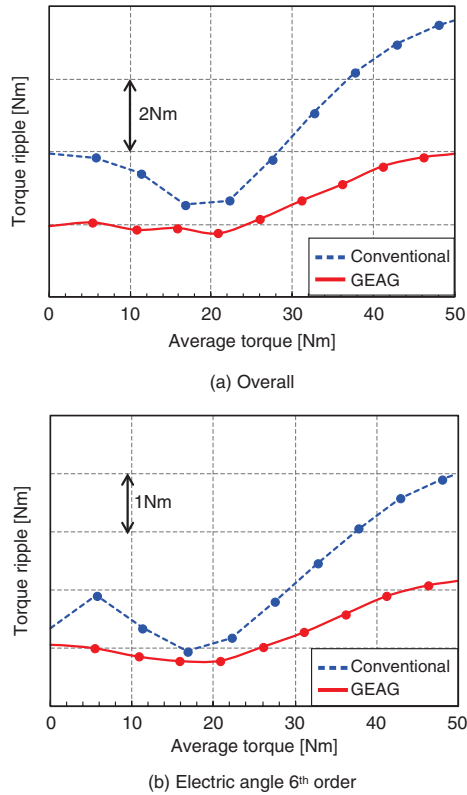


Fig. 18 Results for torque ripple

5. Reduction of Motor Vibration and Noise through Application of Control

5.1. Superposition of Higher Harmonics for Control

Figure 19 illustrates the concept of the Superposition of higher harmonics. With the basic frequency components of 3-phase alternating current as the benchmark, a high-order current of $6n \pm 1^{\text{th}}$ -order is superposed on the 3-phase alternating current. Because the superposed phase is the opposite phase to the target for damping, it cancels the target waveform. The superposed current is set as the minimum value of the torque ripple due to the electric angle 6th-order components, which is the target for damping. This makes it possible to reduce torque ripple resulting from magnetic excitation force (the electric angle 6th-order components). Figure 20 shows an overview of control using Superposition of higher harmonics. The control outputs a final motor torque value by overlaying a map

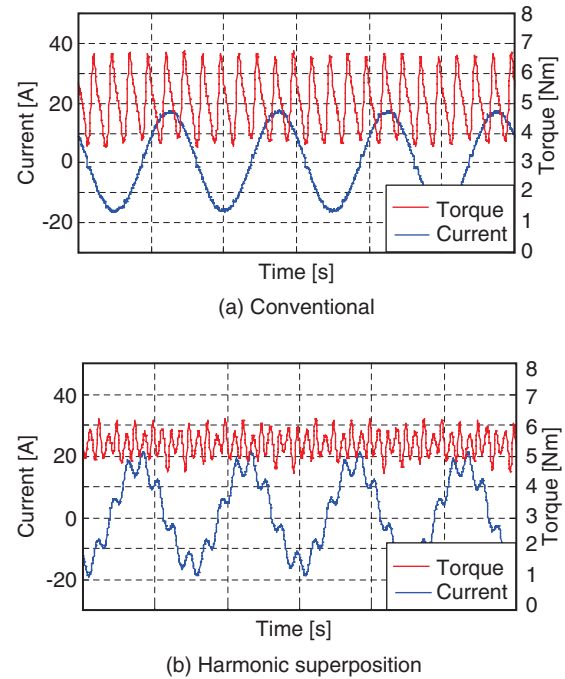


Fig. 19 Concept of superposition of harmonic current

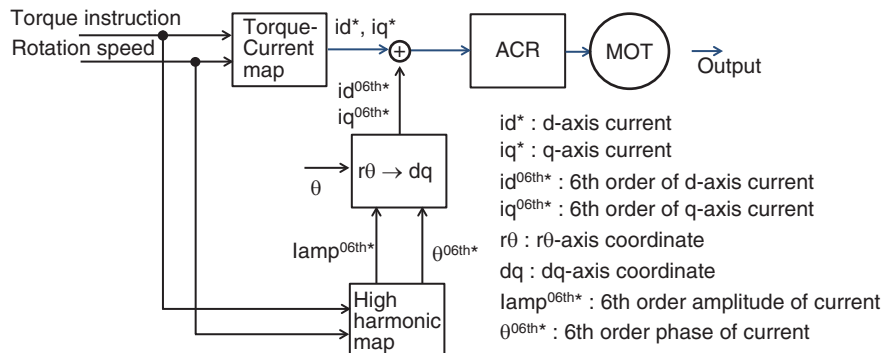
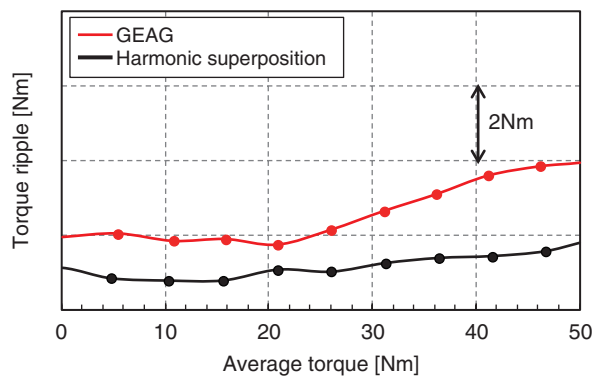


Fig. 20 Control diagram for superposition of harmonic current

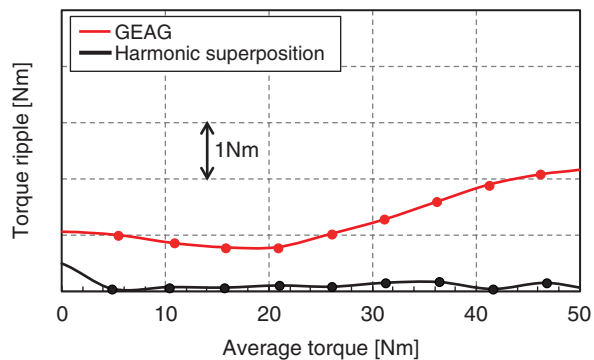
of the amplitude and phase of Superposition of higher harmonics organized around the axes of torque instructions and motor speed on a map of torque and current, similarly organized around axes of torque instructions and motor speed. This makes it possible to effectively impress high-order currents up to high motor speeds.

5.2. Results of Torque Fluctuation Measurements

Figure 21 shows the reduction in cogging torque and torque ripple realized through the application of higher harmonics Superposition control to TMU motors using GEAG magnetic circuits. As Fig. 21(a) shows, peak-to-peak measurements of torque fluctuations at a motor speed of 5 rpm show a maximum reduction of 50% in overall cogging torque and torque ripple. Figure 21(b) shows that the torque ripple due to the electric angle 6th-order components, the target of this control, is canceled by the application of the control, as indicated in Section 5.1.



(a) Overall



(b) Electric angle 6th order

Fig. 21 Results for torque ripple

6. Measurement Results

6.1. Results of Unit Measurements of Motor Vibration

Measurements were conducted using an actual motor in order to verify the effect of the combination of the GEAG

magnetic circuits and the higher harmonics superposition control discussed in Chapters 4 and 5. As Fig. 22 shows, vibration is reduced by 10 dB up to a speed corresponding to 1,000 Hz.

6.2. Results of Measurements of Cabin Noise

Figure 23 shows the results of measurements of cabin noise for TMU motors using the GEAG magnetic circuits and superposition of higher harmonics. The horizontal axis shows vehicle speed and the frequency of the electric angle 6th-order components, and the vertical axis shows cabin noise. The data was measured under relaxed acceleration. The use of the GEAG shape for the magnetic circuits in the TMU motors reduced cabin noise by 5 dB across the entire range against the conventional circuits. In addition, the application of superposition of higher harmonics reduced cabin noise by more than 13 dB. These measurements demonstrated that cabin noise targets had been achieved.

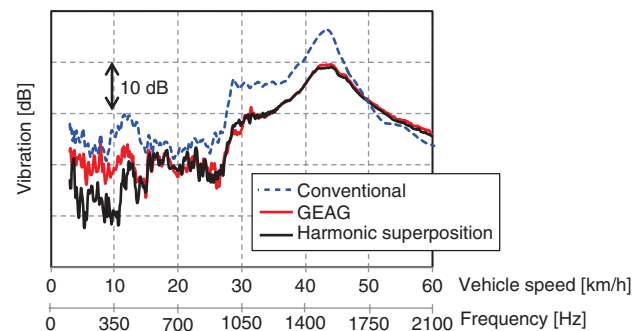


Fig. 22 Results for TMU vibration (Electric angle 6th order)

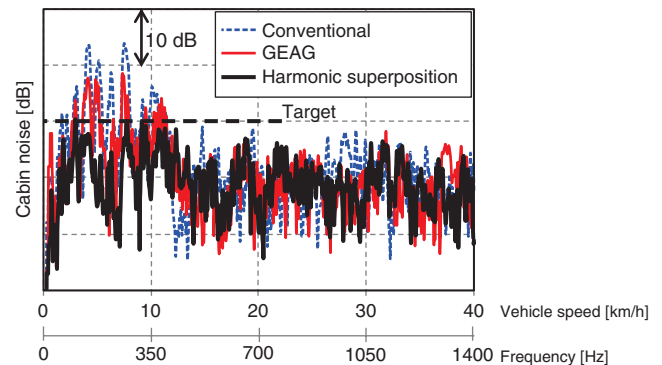


Fig. 23 Results for cabin noise of TMU motor (Electric angle 6th order)

7. Conclusion

The following technologies were developed for application in the two motors of rear wheel drive for SPORT HYBRID SH-AWD

(1) Newly designed GEAG magnetic circuits

Realizes a 50% reduction in peak-to-peak torque

fluctuation at a motor speed of 5 rpm and an average torque of 5 Nm.

(2) High-order current superposition control

In combination with the GEAG magnetic circuits, reduces vibration in a TMU motor by 10 dB.

The application of these technologies has made it possible to employ stators using concentrated windings, balancing a reduction in the size of the motors with reduced vibration and noise. The use of the developed motors in the SPORT HYBRID SH-AWD system has reduced cabin noise by more than 13 dB, making it possible to meet cabin noise reduction targets.

References

- (1) Kato, T., Miura, T.: Development of Twin Motor 4WD for OUTLANDER PHEV, JSAE Symposium Text, p. 46-50 (2013) (In Japanese)
- (2) Matsui, H., Hayasaki, K., Kan, S., Gunji, K., Ueno, M.: Evolution of One-motor Two-clutch Parallel Full Hybrid System, JSAE Annual Congress Proceedings, No. 57-13, p. 17-20 (2013) (In Japanese)
- (3) Ikegami, T., Yokoo, K., Saito, S., Shikata, S., Kanamori, I.: New One-Motor SPORT HYBRID System, JSAE Annual Congress Proceedings, No. 64-14, p. 17-20 (2014) (In Japanese)
- (4) Shikata, S., Kamata, T.: Development of New Motor for Hybrid Vehicle, JSAE Annual Congress Proceedings, No. 3-14, p. 9-12 (2014) (In Japanese)
- (5) Yamamoto, T., Kuriyama, Y., Floreintin, J., Durieux, F.: Steel Solution for Light weight and Quiet Electric Vehicle, JSAE Annual Congress Proceedings, No. 56-11, p. 9-14 (2011) (In Japanese)
- (6) Kamazuka, H., Kanuma, T., Mori, Y., Hogaki, S., Kuwata, T., Hatou, N.: Technical Development of Vehicle Quiet Performance for newly developed Electric Vehicle, JSAE Annual Congress Proceedings, No. 56-11, p. 5-8 (2011) (In Japanese)
- (7) Nagai, H., Nakagawa, T., Sakamaki, H., Hatou, N., Kuwata, T., Ochi, D.: Development of NV (Noise & Vibration) performance for FR vehicles with hybrid system (1-motor, 2-clutch system), JSAE Annual Congress Proceedings, No. 56-11, p. 23-25 (2011) (In Japanese)
- (8) Hamano, T., Hirano, Y., Kawakami, T., Yamamoto, K., Hatou, N., Kaminaga, S.: Technologies for Gear Noise Reduction in The Newly Developed Electric Vehicle, JSAE Annual Congress, No. 56-11, p. 1-4 (2011) (In Japanese)
- (9) Takasaki, A., Kamiya, M., Mizutani, T., Kaneiwa, H., Kato, M., Umeda, A.: Motor Stator for Small Hybrid Vehicle, JSAE Annual Congress Proceedings, No. 58-12, p. 5-8 (2012) (In Japanese)
- (10) Ogawa, H., Fukuda, K.: Development of the Motor for the CIVIC Hybrid, Honda R&D Technical Review, Vol. 14, No. 2, p. 25-30
- (11) Miyakawa, T., Enomoto, T., Komiya, H., Hatsuda, T., Tanimoto, T.: Vibration mechanism of the motor for EV by analysis and An example of the vibration reduction countermeasures, JSAE Transaction, Vol. 45, No. 1, p. 109-113 (2014) (In Japanese)
- (12) Ohnishi, K.: Cogging Torque Reduction in Permanent Magnet Brushless Motors, The transactions of IEEJ, Vol. 122-D, No. 4, p. 338-345 (2002) (In Japanese)
- (13) Takahata, R., Wakui, S., Miyata, K., Noma, K., Senoo, M.: Study on Reduction in Vibrations of Concentrated Winding Permanent Magnet Synchronous Motor by Skew Effects of Rotor, The transactions of IEEJ, Vol. 132-D, No. 2, p. 278-287 (2012) (In Japanese)
- (14) Kobayashi, T., Takeda, Y., Sanada, M., Morimoto, S.: Vibration Reduction of IPMSM with Concentrated Winding by Making Holes, The transactions of IEEJ, Vol. 124-D, No. 2, p. 202-207 (2004) (In Japanese)
- (15) Asano, Y., Honda, Y., Takeda, Y., Morimoto, S.: Reduction of Vibration on Concentrated Winding Permanent Magnet Synchronous Motors with Considering Radial Stress, The transactions of IEEJ, Vol. 121-D, No. 11, p. 1185-1191 (2001) (In Japanese)
- (16) Kobayashi, T., Ma, Lei, Sanada, M., Morimoto, S., Takeda, Y.: Improvement of Radial Force and Torque Ripple for IPMSM with Concentrated Winding, The papers of Technical Meeting on Rotating Machinery, IEEJ, RM-02, p. 41-51 (2002) (In Japanese)
- (17) Yamazaki, K., Kanou, Y., Fukushima, Y., Ohki, S., Nezu, A., Ikemi, T., Mizokami, R.: Development of Interior Permanent Magnet Motors with Concentrated Windings for Reducing Magnet Eddy Current Loss, The transactions of IEEJ, Vol. 129-D, No. 11, p. 1022-1029 (2009) (In Japanese)
- (18) Yashiro, H., Takada, H.: Reduction of a Radial Electromagnetic Oscillating Force of an Electrical Motor by Superposing a High Order Current, transactions of JSME, Vol. 72-C, No. 715, p. 723-728 (2006) (In Japanese)
- (19) Kanematsu, M., Miyajima, T., Fujimoto, H., Hori, Y., Enomoto, T., Kondou, M., Komiya, H., Yoshimoto, K., Miyakawa, T.: Proposal of Simultaneous Suppression Control of 6th Radial Force and 6th Torque Ripple for IPMSM Based on Flux Linkage: Verification on No-Load Condition, The papers of Technical Meeting on Vehicle Technology, IEEJ, VT-13-018, p. 19-24 (2013) (In Japanese)
- (20) <http://world.honda.com/automobile-technology/SH-AWD2/>
- (21) Yazaki, M., Nakamura, T., Tsuyoshi, T.: New Motors of SPORT HYBRID SH-AWD, JSAE Annual Congress Proceedings, No. 3-14, p. 13-18 (2014) (In Japanese)
- (22) Hiramatsu, N., Suzuki, T., Ueda, M.: Twin Motor Unit for SPORT HYBRID SH-AWD, JSAE Annual Congress Proceedings, No. 113-14 (2014) (In Japanese)

- (23) Hojo, H., Yamamoto, K., Hirano, Y., Kondo, M.:
Motor noise reduction technologies of newly developed
electric vehicle considering higher frequency modes,
JSAE Annual Congress Proceedings, No. 108-12, p.
31-34 (2012)

■ Author ■



Manabu YAZAKI



Tadanobu AOKI