Development of a High-Torque Motor with Superior Noise and Vibration Characteristics

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Summary: Recently the diversification of mobility has been started after the advent of IWM (In-Wheel-Motor), then small size and low-noise are requested as a Motor from the Market. [(1)] In this paper, Toothless Core was adopted as a technology of low-noise and Oriented Magnet was used to increase the Torque. As a result, the measurement of performance with actual sample proved these technologies are effective for coexistence of both market needs.

Keywords: Electric vehicle, power electronics, motor, power train, noise, vibration

1. Introduction

The diversification of the means of mobility has been started in recent years after the advent of IWM.[(2)] As shown in Fig. 1, IWMs are expected to increase the payload of MaaS vehicles and commercial vehicles by expanding their cabins and loading capacities. They also draw attention as a means of low-flooring. However, IWM are facing difficult challenges of miniaturization to install them inside wheels while providing extremely high levels of quietness. This paper discusses the low-noise technology without sacrificing their torque characteristics focusing on the noise reduction of motors.

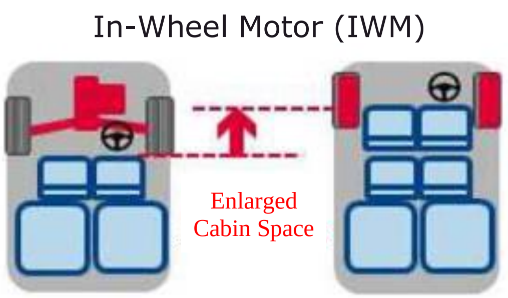

Figure 1: Advantages of an In-Wheel Motor

2. Noise Occurrence Mechanism

Motor noise arises from the vibration of the motor itself or the structural system on which the motor is installed, which is caused by the mechanical excitation force inside the motor. Generally, this problem arises when the frequency of the mechanical excitation force and the resonant frequency of the structural system are equal. Fig. 2 describes the mechanical excitation force by dividing it into the excitation force generation mechanism, vibrating part and noise generating part. Mechanical excitation forces are divided into two types, magnetic excitation forces and mechanical excitation forces. It follows that motor noise is roughly divided into magnetic noise and mechanical noise. Magnetic noise by magnetic excitation forces arises from the changes in the amount and direction of the magnetic field, which is caused when the magnet moves relatively against the slots of the stator core, and the changes in the magnetic flux which is generated by the changes in the current flowing through the stator coils. Magnetic excitation forces are further divided by the directions of the forces: the force in the direction of rotation, which is the torque fluctuation including torque ripples during operation and cogging torque while not operation, and the radial force caused by the changes in the magnetic attraction between the rotor poles and stator poles. In an IWM, the magnetic excitation force is dominant, which is one of the sources of in-vehicle noise. Torque ripples occur at the 2nd order of electrical angle × 3 phases = 6th order, and cogging torque arises at the least common multiple of the number of slots and the number of poles. Drive torque is determined by the magnetic flux and the input current, The magnetic excitation force causing vibration is also proportional to the magnetic flux and the input current. The magnetic flux density is raised since an IWM requires both miniaturization and increasing Torque, which results in the issue of reducing the magnetic excitation force.

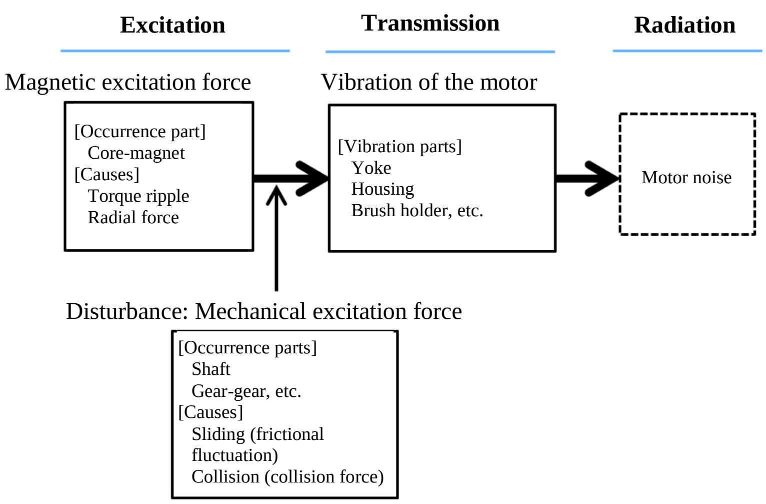

Figure 2: Noise Occurrence Mechanism

3. Noise Reduction Technology and High-Torque Density Technology

3.1. Low-Noise Technology

The previous chapter discussed the reduction of a motor's torque ripples and cogging torque which act as magnetic excitation forces. Cogging torque is generated by the changing of magnetic field energy with respect to rotor rotation angle which is shown in Formula A and B. Torque ripples are caused by the distortion of the voltage waveform induced by the magnetic saturation of the stator teeth and the distortion component of the core material. Therefore, in principle, removing the status teeth resolves the discontinuity of the magnetic flux, which also eliminates the effects of the magnetic saturation at the teeth and the distortion component of the core material, realizing the waveform of the induced voltage that is close to a sine wave. This paper reviewed a motor with a toothless core with the goal of minimizing the cogging torque and torque ripples. Fig. 3 shows the distortion of the induced voltages of a toothless core and a toothed core. The figure indicates that the toothless core has less distortion than that of the toothed core. In addition, a skewed rotor is sometimes used in reducing torque ripples. Considering that this method cancels out the pulsation by mixing torque waveforms with different phases, the fluctuation in the skew angle affects the reduction of torque ripples. This paper assumes a large-diameter and multiple-pole motor, which is significantly affected by the fluctuation in the skew angle during manufacturing, which limits the reduction by skewing. This is why a toothless core was used.

$$Tc = -\left(\frac{\partial W_N}{\partial \theta} + \frac{\partial W_S}{\partial \theta}\right) \quad \text{… Formula A}$$

Tc: Cogging Torque
W_N: Energy of N pole magnetic field
W_S: Energy of S pole magnetic field

$$W = W_N + W_S = \frac{l_g L_s r_g}{2\mu_0} \oint_N B_g^2 d\theta + \frac{l_g L_s r_g}{2\mu_0} \oint_S B_g^2 d\theta \quad \text{… Formula B}$$

l_g: Magnetic Gap Length、L_s: Core stuck length
r_g: Radius of Magnetic Gap、μ_0: Vacuum Permeability
B_g: Magnetic flux density of Magnetic Gap

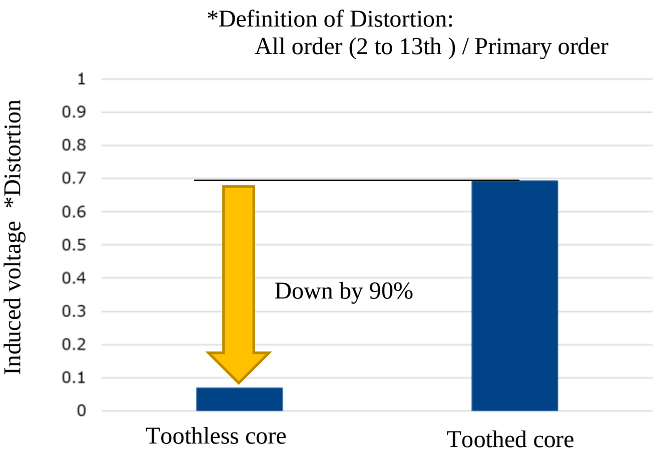

Figure 3: Comparison of Distortion

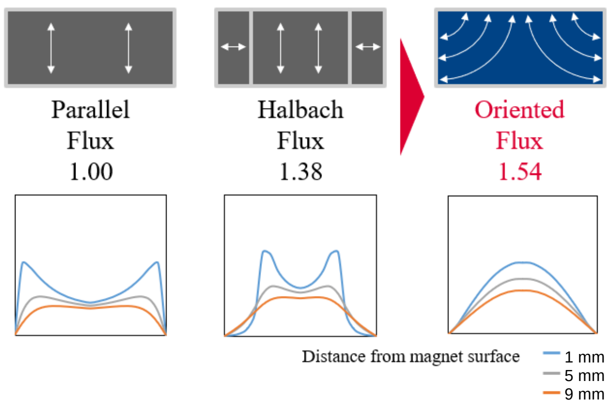

Figure 5: Comparison of the Magnetic Gap Flux [Wb]

3.2. High Torque Density Technology

Generally, a toothless motor eliminates teeth, which increases the magnetic GAP, as shown in Fig. 4, reducing the torque. In this paper, we increased the effective magnetic flux which generates the torque of a toothless motor using the technology for orienting sintered Nd-Fe-B magnets. Using a conventional technology for improving the effective magnetic flux of a magnet, a Halbach array magnet has a structure in which the main magnets polarized along the diameter and the auxiliary magnets polarized along the circumference are alternately arranged. The main magnet and auxiliary magnet of a Halbach array magnet need to be fixed to the rotor core, which requires a large number of man-hours, and the discontinuity in the direction of the flux makes it difficult to excite the rotor assembly. The array magnet is shown in Fig. 5 which enables a toothless motor to generate stronger magnetic flux by changing the axes that is easily magnetized from straight lines to arcs to solve the issues of the Halbach array magnet. In the surface magnetic flux waveform illustrated in Fig. 5, the oriented magnet allows a sine wave without distortion of the magnetic flux, which is also advantageous in reducing noise.

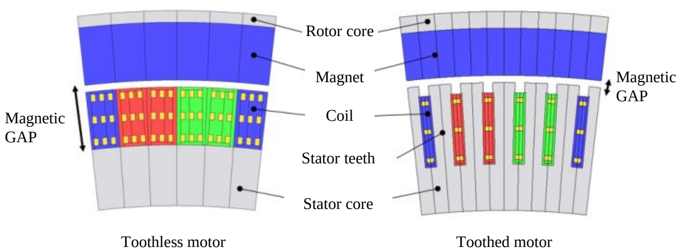

Figure 4: Structures of a Toothless Motor and a Toothed Motor

3.3. Magnetic Circuit Using a Toothless Core and an Oriented Magnet

Fig. 6 is a chart which was shown the demagnetization curve of the magnet and the stator demagnetization curve obtained from the magnetic resistance. The stator demagnetization curve indicates that the conventional toothed core has a critical point at a weaker magneto motive force as a result of the saturation at the area of tooth. On the other hand, the toothless core has no teeth which tends to cause saturation, and the critical point occurs at a stronger magneto motive force as compared to the toothed core. The cause of the generation of a critical point of a toothless core is the saturation of the core back. The intersection between the demagnetization curve of the magnet and the magnetic reluctance curve of the stator indicates the working point. Using an oriented magnet for the toothless core indicated magnetic flux at a working point is higher than the toothed motor.

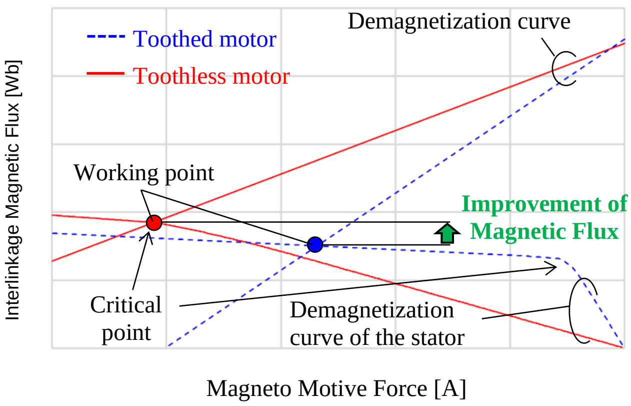

Figure 6: Magnet Demagnetization Curve and Stator Demagnetization Curve

3.4. Performance Verification by Simulation

The characteristics of a toothless motor and a toothed motor which use oriented magnets were compared by magnetic FEM analysis. Table 1 shows the result of comparison, and Fig.7 indicates the 2-dimensional cross section of the analytical model. They showed lower torque ripples, lower cogging torque, and lower radial force.

Table 1: Results of Comparison (Same Torque and diameter)

Item	Unit	Toothless Orientation (a)	Usual pole Tooth motor (b)
Ratio of Core stack length	-	0.69	1.00
Torque ripple ratio	%	1.0	5.4
Cogging torque	Nm	0.0	39.1
Radial excitation force pulsation (Total along the circumference)	N	13,182	68,707

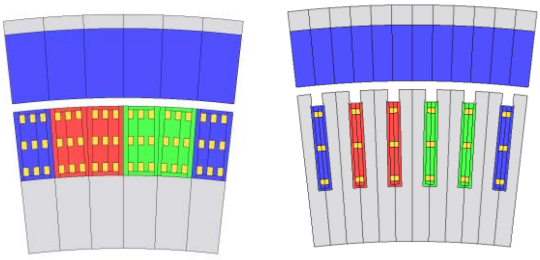

Figure 7: 2-Dimensional Cross-sectional View of the Analysis Model

Fig. 8 shows the reduction of ripples by expanding the Magnetic gap, which is the distance between the stator teeth and the magnet, and Fig. 9 indicates torque reduction as an example of reducing torque ripples of a toothed motor.

It is clear that widening the Magnetic gap reduces torque ripples. However, even the Magnetic gap is increased to 5 mm or more with an allowance of torque reduction by approximately 40%, the ripple ratio does not reach 1%, which is the level of toothless. Therefore, it is thought that a toothless core and an Oriented magnet are effective for reducing noise while maintaining the torque characteristics.

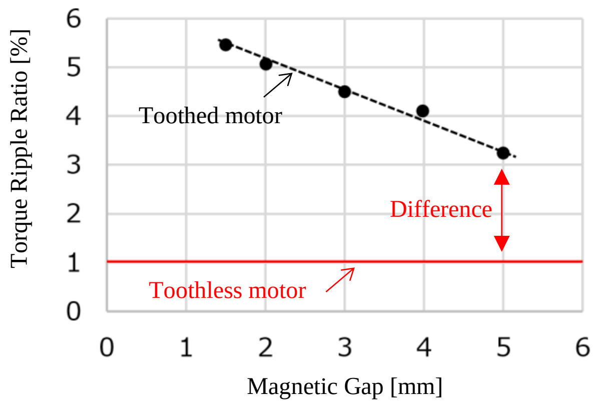

Figure 8: Relationship between the Magnetic Gap and Torque Ripples

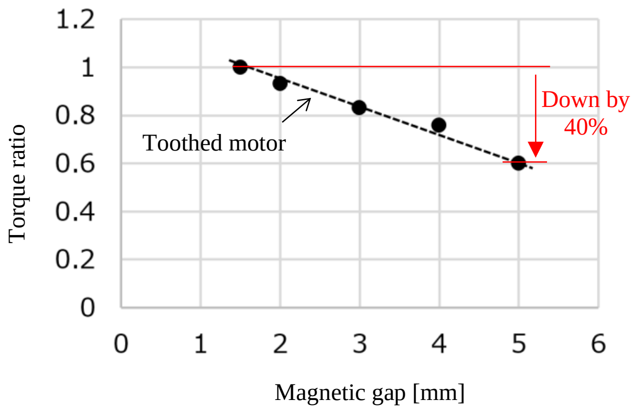

Figure 9: Relationship between the Magnetic Gap and Torque Ratio

3.5. Comparison between Results of the Measurement and Analysis value

Fig. 10 shows the toothless stator of the motor which was built and Fig. 11 the rotor using an Oriented magnet.

Fig. 12 illustrates the N-T curve of the motor which was built and Table 2 its conditions. The result of the measurement meets the analysis values which were obtained under the same conditions.

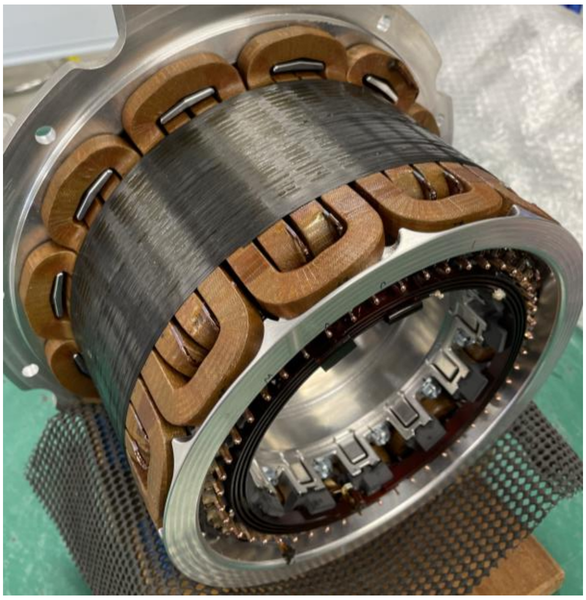

Figure 10: Toothless Stator

Figure 11: Rotor with an Array Magnet

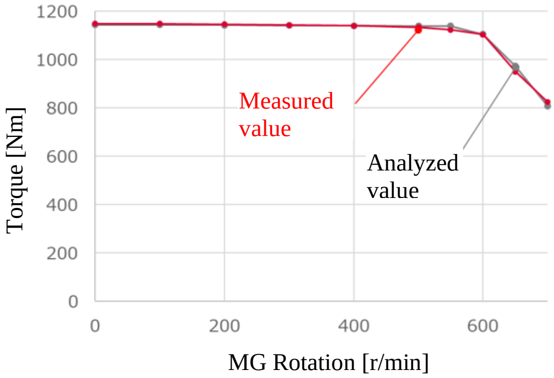

Figure 12: N-T Curve of the Motor

Table 2: Analysis/Mesurement Conditions

Item	Unit	Value
Motor Size	-	For 16 inch wheel
Voltage	V	350
Current	Arms	230
Maximum current density	Arms/mm2	30

Finally, Fig. 13 shows the evaluation environment in which IPM (type of Interior Magnet Rotor) and NV were compared, Fig. 14 the result of evaluation, and Table 3 the conditions for evaluation. The 6th order sound pressure which is main cause of Torque ripple were compared, and an NV reduction of approximately 18 dB against IPM was confirmed under the same torque conditions.

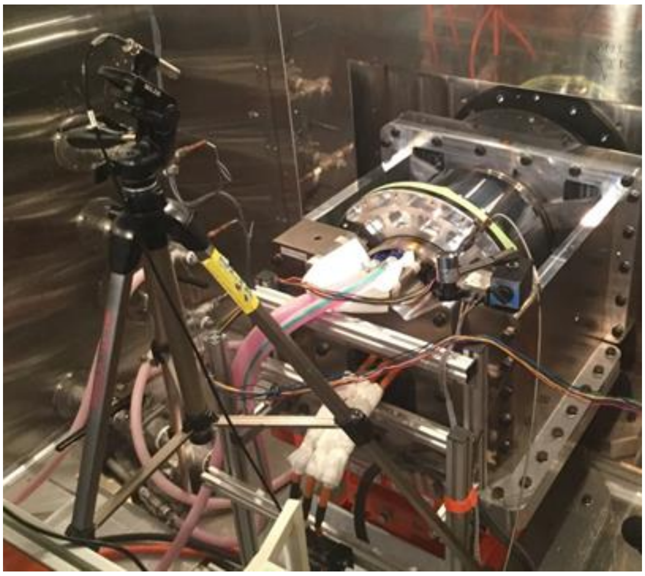

Figure 13: Evaluation Environment

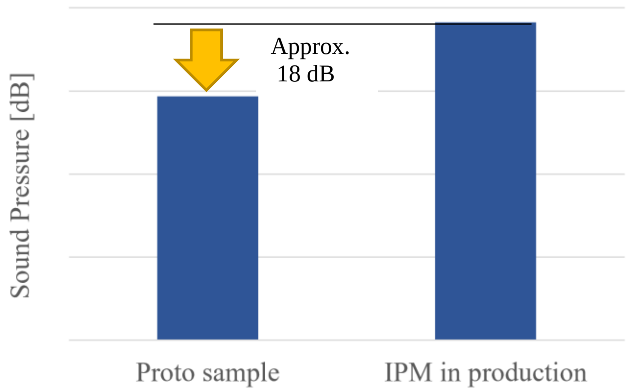

Figure 14: Results of Evaluation

Table 3: Conditions for Evaluation

Item	Unit	Prototype Prpduct	Our IPM
Measurement distance	cm	30	30
Torque	Nm	200	200
Rotation	rpm	150	2,000
Pole pairs	-	12	4
Comparison frequency	Hz	180	800

4. Summary

This paper has discussed the technology in reducing noise while maintaining the Motor size. Noise was reduced by approximately 18 dB by significantly decreasing torque ripples while providing a similar torque performance as compared to the conventional IPM. It is thought that a large cabin and low noise can be realized by applying this technology to IWM vehicles which have issues of mountability and noise. From now on, this technology is installed to vehicles and make efforts for further enhancement in reliability.

References

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