EVS26
Los Angeles, California, May 6-9, 2012

Direct-Drive In-Wheel Motor Realized High Performance and Comfortable Drive

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Abstract

We have been developing high performance EV motor. Its unique selling points are “direct drive” and “in-wheel”. Direct drive brings about high efficiency thanks to the lack of reduction gear or transmission, and in-wheel system brings about the free space for the cabin above the floor. This motor must however overwhelm two problems written in the followings. One problem to be solved is high torque constant because the motor is coupled directly to a wheel without a reduction gear. Another problem is cogging torque. We chose the innovative selection of magnet shape capable of solving this problem. Consequently the torque constant reached up to 1.8Nm/Arms, and 720Nm for 450Arms was obtained as the maximum torque.

In spite of this difficulty, We succeeded in depressing cogging torque taking 3D electromagnetic phenomenon into consideration.

The countermeasure to reduce cogging torque consists of two treatments. The first treatment is to adopt 4 layers rotor skew, and the second one is to insert 3 nonmagnetic rings between 4 layers, the function of which is to block the magnetic interaction between layers. The cogging torque was predicted to reduce to about a half compared with the case of no rings, and to become probably sufficient to comfortable driving. ~~And~~ As a result, the measured cogging torque was 65% (peak to peak).

Due to replacement of a part of rotor core with nonmagnetic rings, the total amount of flux is predicted to reduce. However, despite of this prediction, the torque constant didn’t decrease so much (8%).

Keywords: motor design permanent magnet motor, torque, wheel hub motor,

1 Introduction

Internal-combustion engine vehicles cause a lot of environmental problems such as global warming, oil supply crisis, air pollution and so on. For a long while EV has been remarked as a solution to such a problem. Moreover the Tohoku Earthquake revealed newly the more advantages of EV, for example chargeability from solar cell or wind power generator and emergent power supply to hospital and so on. Even now many companies in the world are developing EVs, however the EV

market is not so extremely big. It is till necessary to improve the technology of EV to expand the EV market more and more widely.
We have been developing high performance EV motor. Its unique selling points are “Direct Drive” and “In-Wheel (wheel hub motor)”. Direct Drive brings about high efficiency thanks to the lack of reduction gear or transmission, and In-Wheel system brings about the free space for the cabin above the floor.

2 Propositions

There are two problems to be solved in this paper. One problem is high torque constant. Direct Drive Motor needs to output higher torque than Reduction Drive Motor and to produce less copper loss ~~is~~ more effective than iron loss or mechanical loss in Direct Drive Motor as normal use or mileage test mode. To realise a lower copper loss and a higher torque constant, the coil resistance must be small. And it is effective for acceleration of the vehicle, that is inevitable to comfortable drive.
Another is cogging torque. Cogging torque is used to estimate the motor’s noise and vibration quantity that are harmful to EV’s comfort driving especially in case of direct drive system.
Generally speaking, it is very hard to increase torque constant and to decrease cogging torque at the same time.

3 Research Method

As a method of this research, highly precise electromagnetic simulation software JMAG-Studio was used. The traditional process of designing a motor consists of the following steps : 1st consideration and research, 2nd initial designing, 3rd electromagnetic analysis, 4th final designing, 5th manufacturing, 6th evaluation. Under constraints of term and cost, the above mentioned 2nd step must be omitted.
The accuracy of the computed value was over90% in comparison with the measured value, and is adequate as a research method.

4 Specifications of Basic Motor

This Direct Drive Motor is used for In-Wheel Drive. Table1 shows specifications of the basic motor having a conventional structure.

Table 1: Specification of the Basic Motor

Type	IPM
Magnet	Nd-Fe-B
Diameter of the Motor	300mm
Maximum Output	60kW
Maximum Torque	535Nm
Poles	12
Slots	18
Skew	4 layers

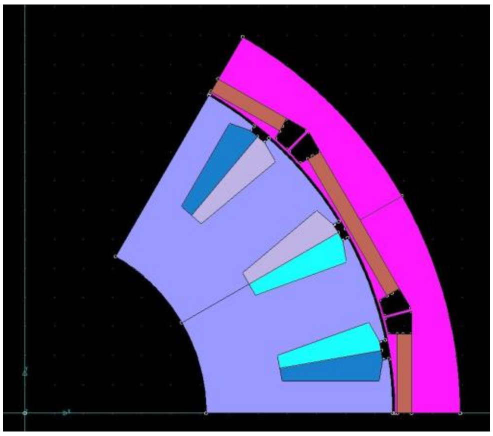

Figure 1: Cross-Section of Basic Motor

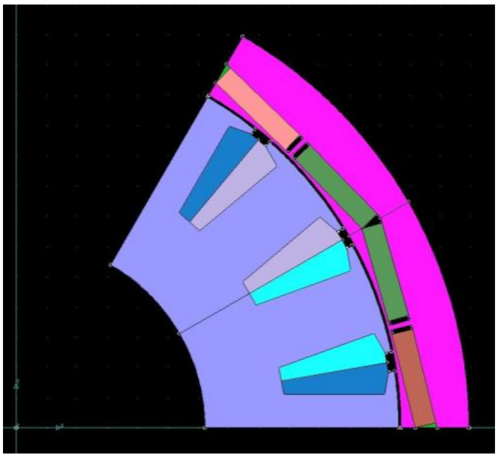

Figure 2: Cross-Section of A type
(1/6model)

5 High Torque Constant

In this chapter, method of design of magnets is shown.
The basic motor choose I-shaped magnet. I-shaped magnet is shown in Figure 1. And new motor that is named A type choose V-shaped magnet. V-shaped magnet is shown in Figure 1.

The basic motor’s performance is set as a standard, which is mentioned above.

Only placement of the magnets is changed to see the effect. This method of placement divides each magnet into two to form letter "V". The simulation was implemented by using the model which has a V-shaped placement with the same electrical angle of magnets as the ones of the basic motor.

5 models are designed for comparing the performances, the magnet electrical angles of which are 150°, 156°, 162°, 168° and 174°. A model of the magnet angles 180° as not simulated because the impossibility of producing the interpolar magnetic flux barriers.

The thickness of magnets is effective for increasing motor torque.
Thicker the magnets, higher the torque. However, if the magnet's thickness is too thick and saturates the core iron magnetically, the motor torque is saturated or decreased. Therefore, to optimizing the thickness is important to increase motor torque and necessary to design an efficient motor. By using V placement, the thicker magnets can be installed compared with the ones in case of I placement. To find the saturation point, 5 models with magnet thickness of 6.5mm, 7mm, 7.5mm, 8mm, and 9mm were simulated.
All the simulations were implemented in the same conditions; 450Arms, 600r/m.

5.2 Simulation results

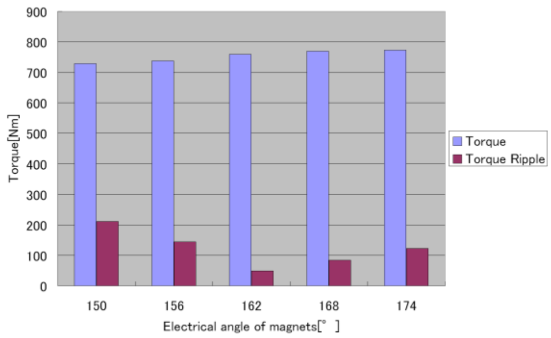

Figure 3 Torque Comparison (Angle)

If the electric angles of magnets are increased, the motor torque increases. However, there is only a little difference between 168° and 174° and the torque ripple increased.
The holes to prevent magnetic shunt increased the motor torque in this case.

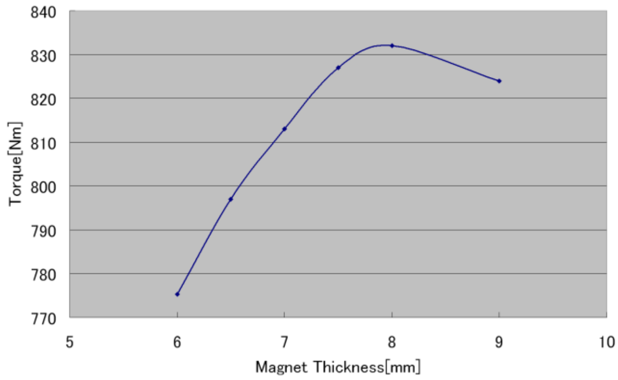

Figure 4 Torque Comparison(Magnet Thickness)

If the thickness of the magnets increases, the motor torque also increases, but for models with magnet thickness 7.5mm and over tends to be saturated. Also the torque ripple increases when the magnet thickness is increased.

The innovative selection of magnet shape can solve this problem. Consequently the torque constant reached up to 1.8Nm/Arms, and 720Nm for 440Arms was obtained as the maximum torque by actual measurement. So maximum torque is estimated 730Nm for 450Arms.

Figure 5 Torque for 440Arms(actual measurement)

Table 2: Specification of A type motor

Type	IPM
Magnet	Nd-Fe-B
Diameter of the Motor	300mm
Maximum Output	60kW
Maximum Torque	720Nm
Poles	12
Slots	18
Skew	4 layers

The reason why there is difference between analysis value and measurement value is skew. It is very difficult to calculate 3D model in short term. So 2D analysis is adopted for this case.

6 Low Cogging Torque

6.1 Cause of remaining cogging torque

High torque constant is realized. Instead of that, another problem, cogging torque, is revealed. Cogging torque isn't big problem when the motors are tested on the testing bench. However it causes sympathetic vibration on the vehicle. The testing bench has very high stiffness. It is not possible to make vehicles to have high stiffness like testing bench. So it is necessary to make the motor to have low cogging torque that cannot be felt by drivers or passengers during driving the vehicle.

This motor has four phase skews to reduce cogging torque. This countermeasure is valid but not enough. In theory, four layers skew can reduce most of cogging torque. Figure4 shows cogging torque estimated by only 2D magnetic field analysis.

Calculation of 4 layers skews estimation from 2D analysis data is below. (1)

$$Tc\theta = \frac{1}{4}Tc\theta + \frac{1}{4}Tc(\theta + \frac{\pi}{4S}) + \frac{1}{4}Tc(\theta + \frac{2\pi}{2S}) + \frac{1}{4}(Tc\theta + \frac{3\pi}{4S})$$

The last term is incorrect.

Tc:Cogging Torque
S:Number of Slots (1)

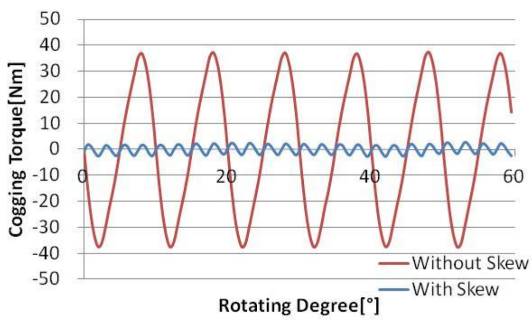

Figure 6 : Cogging Torque (2D analysis)

Cogging torque is caused by perrmeance distribution and air gap flux. 2D analysis cannot calculate flux leakage in an axial direction. Axially leakage flux is the main cause of remaining cogging torque.

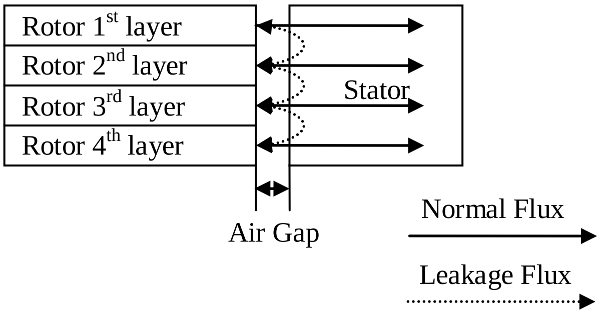

Figure 7 : Image of Leakage Flux

6.2 Provision for cogging torque

In new motor, non-magnetic rings are inserted among layers as flux barrier. The motor is named B type.

Figure 5 and Figure 6 shows the result of magnetic analysis.

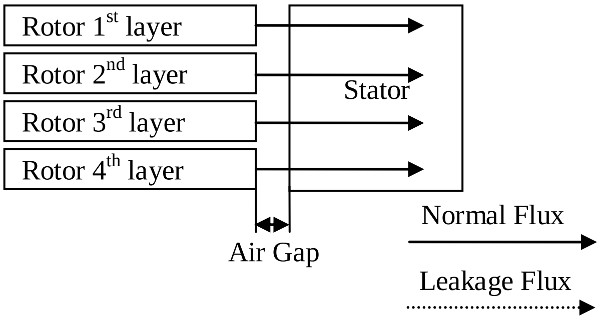

Figure 8: Image of Flux Barrier

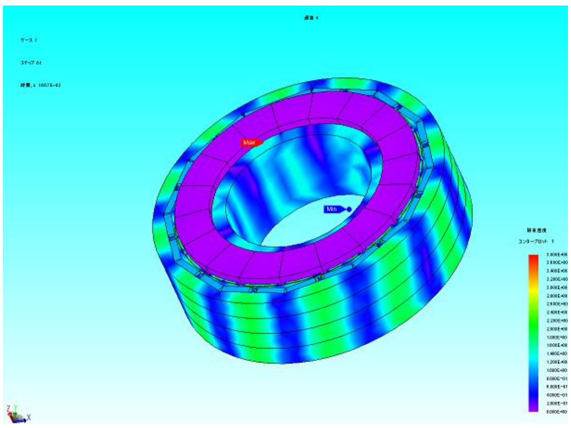

Figure 9: Flux Density (A type)

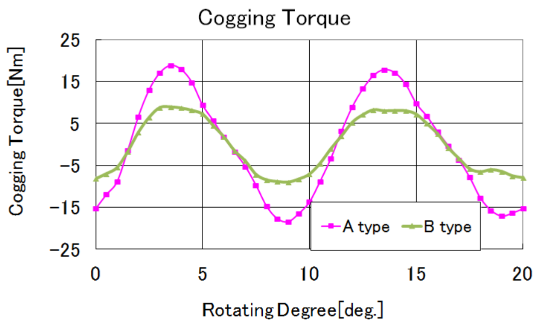

Figure 10: Cogging Torque (3D Analysis)

Figure 10 shows the cogging torque reduced to about 51% by magnetic field analysis.
It means that flux barrier is effective to decrease cogging torque.

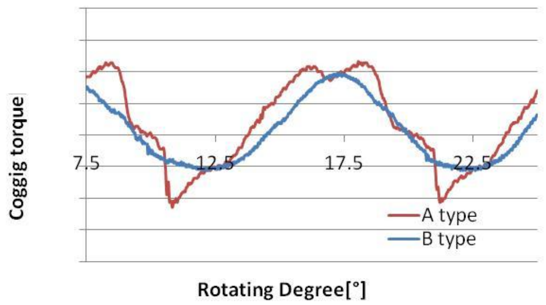

Figure 11: Cogging Torque (Actual Mesurement)

Figure 11 shows the cogging torque reduced to about 66% by actual measurement.
The discrepancy between magnetic field analysis and actual measurement is due to magnetic anisotropy of materials. Magnetic steel sheet has magnetic anisotropy. However the software used for analysis cannot take the magnetic anisotropy of the materials into consideration..

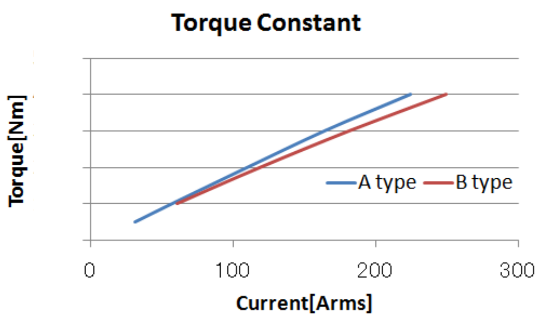

Fig. 12 Torque Constant (Measured Value)

Due to replacement of rotor core with nonmagnetic rings, the total amount of flux is considered to reduce. Despite of this prediction, the torque constant didn't decrease so much (8%) in spite of the the core length decrease (7%).

7 Conclusion

We succeeded in depressing cogging torque taking 3D electromagnetic phenomenon into consideration.
There is still a problem of excessive computing time to be spent for 3D analysis. For example, 3D-analysis of no-load condition spends 1 day even for linear analysis mode. It will take longer to analyze non-linear range. However it is expected to shorten these computing time using high quality computer in near future.
We have been developing high performance motor for EV. Its unique selling point is "Direct Drive" and "In-Wheel". Direct drive brings about high efficiency thanks to the lack of reduction gear or transmission.

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