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IMPORTANT DATES

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- + Fuel Cells & Fuel Cell Systems
- + Electric Motors & Generators
- + Power Electronic Systems
- + Embedded Control Systems
- + Propulsion Systems & Subsystems
- + Charging & Infrastructure
- + Heating & Cooling Systems
- + Auxiliary Components

- + Electric Vehicles
- + Hybrid Electric Vehicles
- + Plug-In Hybrid Electric Vehicles
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- + Urban Electric Mobility

- + Public Policy & Promotion
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A Study to Determine Design Parameters with Statistical Methods Considering Cogging Torque of EPS Motors

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Abstract

Nowadays, the trend of automobile part is being electric/electronic. Thus, a vehicle steering system is replaced with Electric Power Steering (EPS) system that gain power from electric motors. In the electric motors of EPS system, reducing cogging torque is one of the most important part in designing the electric motors. It takes much cost to select proper design variables in designing the electric motors. In this paper, statistical methods that screen the design variables which affect on cogging torque are introduced. The impacts of design variables will be investigated by using full factorial design (FFD) and multiple regression. The performance of the electric motors will be checked by 2-D Finite Element Analysis (2-D FEA).

Keywords: list 3-5 keywords from the provided keyword list in 9.5pt italic, separated by commas

1 Introduction

Because of unstable oil price, global warming owing to air pollution, eco-friendly products are being a trend of this age. [2] Hybrid vehicles and electric vehicles lead the eco-friendly market of automotive industry also affected by the trend of eco-friendly. Thus, a vehicle steering system is replaced with Electric Power Steering (EPS) system that gain power from electric motors. The EPS system has better performance and mileage than oil pressure steering system and has less weight than the oil pressure steering system. [1]-[2] Because of many advantages like a high torque/volume ratio and a dynamic driving, an Interior Permanent Magnet Synchronous Motor (IPMSM) is used in the EPS system.

The most of the EPS system on the production stage is a column type which is that the motors are attached to a column of the steering wheel that transfers the drive torque to a gearbox. The motors used in the column type should reduce noise and vibration because the rotation characteristic is transferred to the users directly.

Especially, the steering wheel is the most frequently used device by drivers among the vehicle parts. Thus, continuous steering control is important part in steering system. But, the smooth steering control and low noise/vibration driving are disturbed by a cogging torque in electric motors.

The cogging torque is an irregular torque in the motor and the force of the tangential direction that moves to a location where the magnetic energy is minimal. [1] The cogging torque can be reduced by adjusting the shape parameters of the stator and rotor of the motors. But, it consumes a lot of computation time and cost to screening and optimizing these parameters. In this paper, the methods of reducing computation time and cost will be investigated by using two different statistical methods. The first method is full factorial design and the other method is multiple regression. The design points of the electric motors will be changed and the cogging torque will be checked by 2-D Finite Element Analysis (2-D FEA).

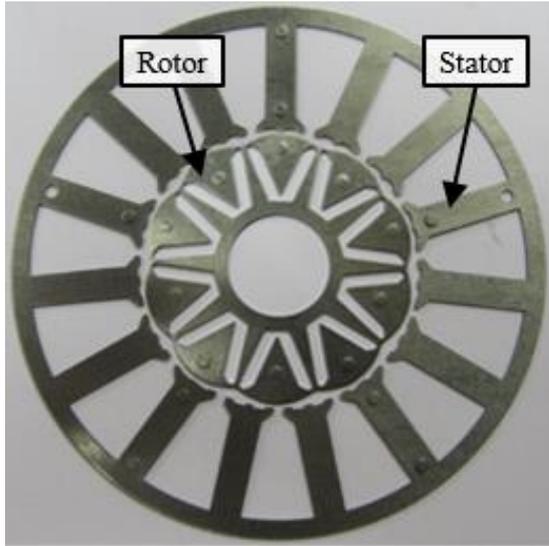


Figure 1: Prototype of IPMSM for EPS system

2 Model and Design Variables

2.1 Model of Prototype

The specifications of the prototype for the EPS system are shown in Table 1. The specifications are 10 poles, 15 slots, 12 (V_{DC}), 1000 (rpm), 84 (A_{rms}) for the current limitation and the stator outer diameter is 84 (mm), and the rotor outer diameter is 42.5 (mm) and the stack length is 47 (mm). The prototype for is shown in Figure 1.

2.2 Design Variables

In this paper, five design variables (eccentricity, pole angle, tooth tip, notch width, and notch height) are considered to reduce the cogging torque.

To obtain sinusoidal no-load air gap flux density, increasing the eccentricity and controlling the pole angle are pretty effective way. Eccentricity makes the air gap asymmetric and it makes no-load air gap flux density (air gap flux density) with sinusoidal distribution.

Table 1 : Specifications of Prototype

Parameters	Unit	Value
No. of pole/slot	-	10/15
DC linkage	[V_{DC}]	12
Stator outer diameter	[mm]	84
Rotor outer diameter	[mm]	42.5
Stack length	[mm]	47

Table 2 : Design variables and each level

	Design Variable	Unit	Level	
			1	2
x_1	eccentricity	[mm]	10.00	14.00
x_2	pole angle	[°]	28.00	32.00
x_3	tooth tip	[mm]	0.15	0.25
x_4	notch width	[mm]	2.20	2.40
x_5	notch height	[mm]	2.00	2.20

The wave form of the air gap flux density is concerned with the pole angle. The wide pole angle distributes magnetic flux to the air gap and it makes the air gap flux density sinusoidal. But, the back-electromotive force may be decreased by using the rotor with eccentricity and wide pole angle. If the stator has thin tooth tips, it is liable to saturate, and the slot ripple increases, and this in turn increases the cogging torque. The notch acts like slot open in stator and it affects to the period of the cogging torque and its amplitude. [3]

3 Methods of Screening the Design Variables

To check the impacts of the design variables, full factorial designs (FFD) and multiple regression will be conducted and compared. Five variables (eccentricity, pole angle, tooth tip, notch width, notch height) with two level is used in the analysis, and tendencies of the parameters to the objective function and the validity of each modeling will be analysed. The cogging torque of the electric motors will be the objective function in this paper. The design variables and each level are shown in Table 2. To compare the two methods, same combinations of design variables will be used in FFD and multiple regression.

3.1 Design of Experiments

FFD is one of the design of experiments in which all levels of every variables in an experiment are combined with all levels of every other variable. [4] The main effects and interaction of the combinations of each variable can be seen in FFD. It helps to find tendencies and optimum point among the every combinations of each variable. The most common type of factorial design is one that uses n variables, 2 levels When high order levels are used in factorial design, the number of data increases exponentially. Then 2^5 data should be selected so that they lie at each corner of a 5-dimensional hypercube. The design points of the FFD is shown in Table 3.

Table 3 : FFD in the case of five design variables

No. of experiment	Design Variables				
	Eccentricity	Pole angle	Tooth tip	Notch width	Notch height
1	1	1	1	1	1
2	1	1	1	1	2
⋮	⋮	⋮	⋮	⋮	⋮
16	1	2	2	2	2
17	2	1	1	1	1
⋮	⋮	⋮	⋮	⋮	⋮
31	2	2	2	2	1
32	2	2	2	2	2

3.2 Multiple Regression

Regression allows users to predict objective functions based on design variables. Multiple regression is a statistical method that makes

regression model using more than 2 design variables. Its linear model of the objective function can be written as

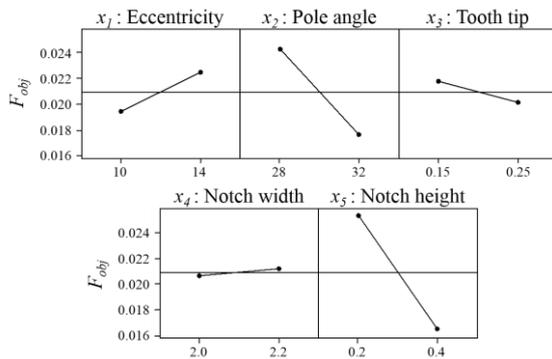


Figure 2 : Main effect plot of cogging torque [peak to peak], for five variables

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n \quad (1)$$

where α , β are coefficient of the regression model, x_n is the n th design variables, and y is the objective function.

R-squared is a statistical measure that represents the percentage of a consistence to an actual model. The definition of R-squared is written as

$$R^2 = 1 - \frac{SSR}{SSE} \quad (2)$$

$$SSE = \sum_{i=1}^n (y_i - \bar{y})^2, \quad SSR = \sum_{i=1}^n (y_i - (\alpha + \beta x_i))^2$$

where R is R-squared, SSE is a sum of squares due to error, and SSR is a sum of squares due to regression.

This linear regression model will help to find the tendencies of the parameters to objective function and screen the inefficient variables among the five design variables.

Table 4 : Analysis of variance, ANOVA

	Parameter Estimate	Standard Error	t- value	P-value
	0.0728	0.0187	3.89	0.001
x_1	0.000739	0.000347	2.13	0.043
x_2	-0.00165	0.000347	-4.77	0.000
x_3	-0.0163	0.0138	-1.18	0.250
x_4	0.00250	0.00694	0.36	0.721
x_5	-0.0438	0.00694	-6.31	0.000

4 Results and Analysis

The observed data is simulated by using 2-D FEA. 3-D FEA can show the precise data, but this paper aims to check the tendencies of the design variables, not to satisfy the performance of the machine. After getting the experimental data by 2-D FEA, FFD results and regression equation are extracted.

The regression model of screening the design variables by using multiple regression are obtained as

$$F_{obj} = 0.0728 + 0.000739x_1 - 0.00165x_2 - 0.0163x_3 + 0.00250x_4 - 0.0438x_5 \quad (3)$$

with these functions, the cogging torque can be predicted by these five design variables. In order to

check the variables that has low reliability, analysis of variance (ANOVA), shown in Table 4, was conducted. ANOVA is a statistical test for heterogeneity of means by analysis of group variances and it tests effects of each variable for response. In ANOVA results, the eccentricity, pole angle, notch height have effects on cogging torque and low p-value that do not exceed

the threshold p-value (0.05). The tooth tip and notch width are considered non-significant variables that exceed over threshold p-value (0.05). A R-square value of the model (2) is 0.725. This means that the model (2) consistent with 72.5% of the actual model.

As the results of screen activity with 32 experiments by using FFD, the main effects of design variables are shown in Figure 2. Among the five variables, the notch height, pole angle and eccentricity have large impacts on the cogging torque. The tooth tip and notch width have less impacts on cogging torque than other three variables. It is good for users to show us the graphic plot of the impacts on the objective function in FFD. However FFD doesn't consider the reliability of the variables, users can't screen the variables that have low reliability.

5 Conclusion

In this paper, screening the variables with FFD and multiple regression was conducted. The results of the analysis with using each method, the eccentricity, pole angle and the notch height have significant impacts on the cogging torque. The model that obtained by multiple regression has validity of 72.5%.

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