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ABSTRACTS

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July 24, Wednesday	09:30-12:00	North Room/Poster

Session SF

MATERIALS FOR APPLICATIONS

(MOTORS,SENSORS, HIGH FREQUENCY, POWER, AND BIO/MEDICAL DEVICES)

Chair: Z.H. Wei(National Tsing Hua University)

OPTIMUM SHAPE DESIGN OF OUTER ROTOR TYPE BLDC MOTOR USING POLAR ANISOTROPIC FERRITE BONDED PM

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This paper deals with finding the optimal ratio of height and width of notch to reduce the torque ripple for outer rotor type Brushless DC motor using polar anisotropic ferrite bonded permanent magnet. In the proposed design method, the optimal notches are put on the inner stator face, which have an effect on the air gap flux density and shape. Through the space harmonic field analysis, the position and size of notches are found, in the case of polar anisotropic bonded PM orientation, due to the complicated magnetic field, the magnetizing direction cannot be determined by simple relational equations. Accordingly, for effective analysis, the characteristics of BLDC motor analyzed by using the finite element method (FEM) for unusual magnetic-field analysis coupled with optimal design methodology. In the optimal design, response surface method (RSM) is applied and considers the notches in the stator pole face as the only design factor. The validity of the proposed method is confirmed by experiments.

Index Terms—**Ferrite bonded magnet, magnetic field analysis, optimization, polar anisotropy, Response surface methodology.**

I. INTRODUCTION

Recently, bonded permanent magnets(PMs) have been widely used for many applications such as motors, sensors, and acoustic transducers [1]-[3]. In many cases, the bonded magnets are magnetized with a polar shape in order to increase magnetic flux and obtain flux density with a rectangular wave form.

The electric auxiliary water pump is a part of the heating system for hybrid electric vehicles. The motor of auxiliary water pump has a rotor combined with impeller. In addition, the material of them is the same as magnetic material. Because of these reason, it is not easy to magnetize this type of the motor. Thus, due to the complicated magnetic field in the case of polar anisotropic bonded PM orientation, the magnetizing direction cannot be determined by simple relational equations.

For effective analysis, we will propose a method in which the magnetic field distribution of the mold for anisotropic orientation is analyzed by using finite element method (FEM). As a result, the orientation of the polar anisotropic bonded magnet is determined by the magnetic flux direction.

Concerning the torque ripple reduction, numerous methods have been heavily published in the literature on PM motor. However, most of them used for reduction of pulsating torque based either on an adequate motor design [4]-[5] or on control techniques [6]. However, since there are few papers that research the torque ripple reduction of motor in terms of polar anisotropy, it is needed to suggest an optimization method considering it. Thus, this paper aims at presenting a technique to reduce the torque ripple without changing other properties while skew is not being used.

The characteristics of a BLDC motor analyzed by using the finite element method (FEM) for magnetic-field analysis coupled with optimal design methodology. In this optimal design, response surface method (RSM) is applied and considers the several notches in the stator pole face as the only design factor. RSM is well suited for making empirical models that relate the performance of motor to the design parameters.

The goal of this paper is to present a relatively simple and feasible design approach that will facilitate an improvement in the above mentioned characteristics without any sacrifice to other performance of the outer rotor type BLDC using the anisotropic PM.

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II. UNUSUAL MAGNETIZING PROCESS AND ANALYSIS

The motor of sub-water pump is a combination of the rotor and impeller. Besides, the material of those is the same as magnetic material. Due to these reason, this type of motor requires special care in magnetizing.

A. Unusual magnetizing process and analysis

When analyzing the characteristics of the BLDC using the polar anisotropic bonded PM, it is necessary to give the orientation of the magnet accurately. Moreover, the magnetizing direction cannot be determined by simple relational equations. For this reason, the orientation of the polar anisotropic bonded magnet is determined by FEM for unusual magnetic-field analysis. Fig.1 shows the process of the new magnetic field [7]. To be short, first, in order to find the accurate magnetic field strength for making a high-performance the polar anisotropic PM, the alignment behavior of the PM with a varying magnetic field strength has been investigated. Second, in order to validate the generated magnetic field intensity and distribution from a magnetizer, the structure of the mold is established and used for magnetic field analysis by FEM for unusual magnetic field analysis as shown in Fig. 2.

B. Analysis Method

The governing equation for analyzing the magnetic field distribution of the structure of the mold for this polar anisotropic bonded magnet is given by (1) [8]. Since the magnetic field inside the structure of the mold is produced by a permanent magnet, there is no forced current and no eddy current, and the analysis becomes a two dimensional static

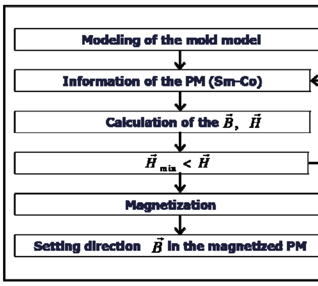


Fig. 1. The process of the new magnetic field analysis

magnetic field analysis.

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial x}\right)+\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial y}\right)=-\frac{1}{\mu_o}\left(\frac{\partial M_y}{\partial x}-\frac{\partial M_x}{\partial y}\right) \quad (1)$$

where A_z is the z-component of magnetic vector potential, $1/\mu$ is magnetic resistivity, $1/\mu_0$ is magnetic resistivity of vacuum, and M_x, M_y are the x- and y-direction component of magnetization M of the permanent magnets for orientation.

From the analysis of the magnetization model, the flux density vectors $B_x^{(e)}$, $B_y^{(e)}$ of each element in bonded magnet region are obtained. The magnetization directions of the anisotropic ferrite material are arranged to same directions as internal flux, so the magnetization directions, $\theta^{(e)}$, the orientation for every element can be determined as

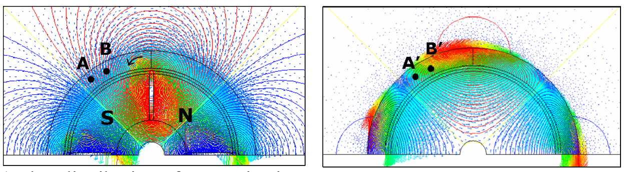
$$\theta^{(e)} = \tan^{-1}\frac{B_y^{(e)}}{B_x^{(e)}} \quad (2)$$

For the elements of part of the polar anisotropic magnet, the angles determined by Eq. (2) are output to a file as a database for the following magnetic field analysis.

III. DESIGN OPTIMIZATION

A. Analysis Model and Design parameters

The cross-section view of analysis model and the rotor fabricated for electric sub-water pump of hybrid vehicle is shown in Fig. 3. Rated power and rated speed are 12W and 3000rpm respectively.



(a) Flux distribution of magnetization
(b) Magnetization vector of the magnet after magnetized process
Fig. 2. The analysis result for magnetization procedure

(The *x*-coordinate of a point, The *y*-coordinate of a point)

Point A = (15.06, 16.24), angle : 206.30˚
Point B = (12.33, 16.45), angle : 137.01˚

➔ (The *x*-coordinate of a point, The *y*-coordinate of a point)

Point A = (15.07, 16.22), angle : 206.30˚
Point B = (12.30, 16.43), angle : 137.01˚

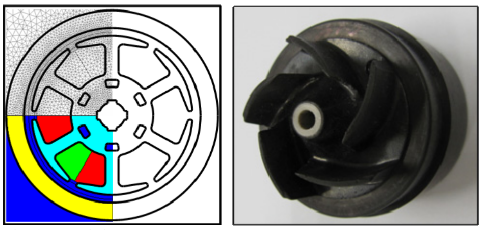


Fig. 3. Analysis model

TABLE I
SPECIFICATIONS OF THE ANALYSIS MODEL

List	Unit	Values
Number of Phases	-	3
Number of slots	-	6
Number of rotor	-	4
Stack length(Stator)	mm	15
Stack length(Rotor)	mm	17
Number of turn per phase	turn	118
Residual induction(Br)	T	0.267

The detail specifications of this motor are listed in Table I. This motor is driven by rectangular voltage waveforms coupled with the given rotor position.

In the initial model has not the notch, so we seek the optimal ratio of height and width of notch to reduce the torque ripple for outer rotor type Brushless DC motor using polar anisotropic ferrite bonded PM. As a result, the configuration of the stator and rotor should not be altered. Fig. 4 is the design variables. The proposed design process can be roughly classified as 2 steps; 1) screen activity to select main design parameters and 2) The application of RSM for Optimization.

B. Screen Activity to Select Main Factor

For the optimal design, sampling of experimental data should be conducted initially. In order to do that, design of experiment (DOE) is necessary for effective experiments. Moreover, if the space is established after investigating responses according to the variation of each parameter, a lot of modeling and analysis time is required, and it is difficult to predict the interaction between the parameters.

Among various DOEs, the full factorial design (FFD) design is used and approximation is constructed. The advantages of FFD are written as follows [9].

1) All combinations of design parameters are investigated
2) All main and interaction effects are evaluated without Confounding

Main and interaction effects of each parameter on the average torque and torque ripple are displayed in Fig. 5 and 6 separately. The plot of main effect describes the difference between the average responses at the low and high level of each parameter. In the plot of interaction effect, there is an interaction response between the factors.

In conclusion, there is little effect between the parameters on the average torque, and the width of notch has a large impact on the torque ripple. Additional, when the motor have 2 notches, torque ripple is a minimum value. Hence, the design area for RSM is decided by the torque ripple.

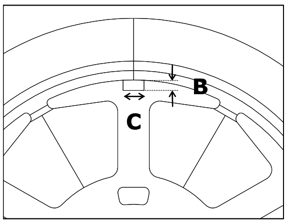


Fig. 4. Design variables of the initial model

C. The application of RSM for Optimization

The RSM seeks to find the relationship between the design variable and the response through the statistical fitting method, which is based on the observed data from the system. The response is generally obtained from real experiments or computer simulations. Therefore, FEM is performed to obtain the data of the outer rotor type Brushless DC motor using polar anisotropic ferrite bonded PM.

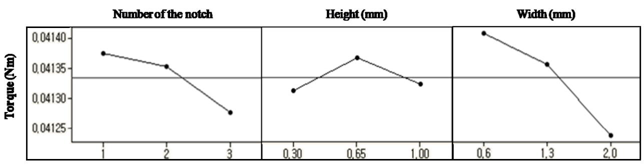
The RSM is applied to make appropriate response models of the average torque and torque ripple. Several types of functions can be used to generate the response surface approximation, such as linear, quadratic, cubic, and some other special functions. However, the polynomial approximation model F, called a fitted model, is commonly chosen to be a quadratic fitted response and can be written as follow [9].

$$F = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \beta_{ij} x_i x_j + \varepsilon \tag{3}$$

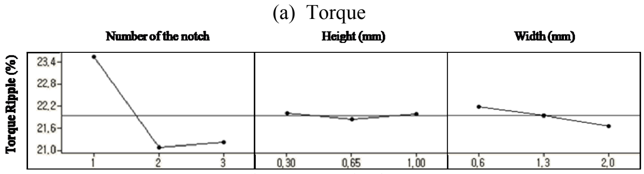
where $\beta_{0...ij}$ are regression coefficients for design variables, ε is a random error. In this paper, the least squares method is used to estimate unknown coefficients. The fitted coefficients and response model can be written as follow.

$$\mathbf{B}' = (\mathbf{X}'\mathbf{Y})^{-1}\mathbf{X}^{T}\mathbf{Y} \tag{4}$$

$$\mathbf{Y}' = \mathbf{X}\mathbf{B}' \tag{5}$$

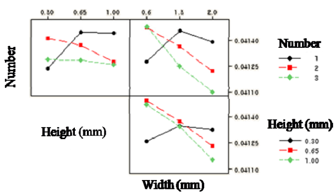


(a) Torque

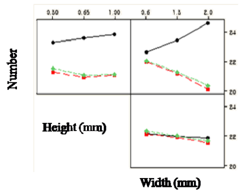


(b) Torque ripple

Fig. 5. Main effect of each parameter



(a) Torque



(b) Torque ripple

Fig. 6. Main effect of each parameter

where **X** is matrix notation for the levels of the independent variables, $\mathbf{X}^T$ is the transpose of the matrix **X**, and **Y** is the vector of the observation. The prime symbol (´) denotes estimated values.

Experimental designs for fitting the second order response surface must involve at least three levels of each variable. Therefore, for building the second order fitted model, the central composite design (CCD) is used. Table II displays the experimental area of CCD. From the above process, the polynomial models of the responses are given by (6) and (7), respectively

$$Y'_{Torque} = 0.041 - 1.18\times10^{-4}A - 1.98\times10^{-5}B + 2.78\times10^{-4}A^2 - 1.77\times10^{-5}B^2 - 1.94\times10^{-4}AB \tag{6}$$

$$Y'_{Torque\,Ripple} = 22.42 - 1.40A - 0.114B + 3.55A^2 - 0.0293B^2 - 2.14AB \tag{7}$$

Fig. 7 showing the change of the responses according to the dimension of notch is drawn by (6) and (7). The optimal design of height and width of notch was performed. The design objectives and constraints are as follows.

Design objective: $Y'_{Torque} \approx T_{initial}$

$$Y'_{Torque\,Ripple} \le TR_{initial}$$

TABLE II
CCD AREA FOR RSM

Design parameters	Level of design parameters				
	- α	-1	0	1	+ α
B [mm]	0.338	0.4	0.55	0.7	0.762
C [mm]	0.951	1.2	1.8	2.4	2.649

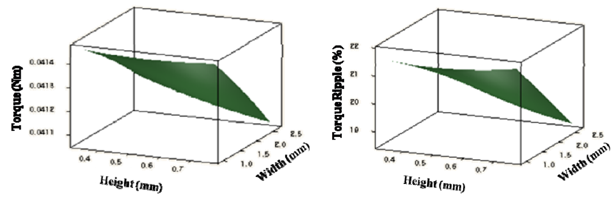


Fig. 7. Predicted response surface about torque and torque ripple

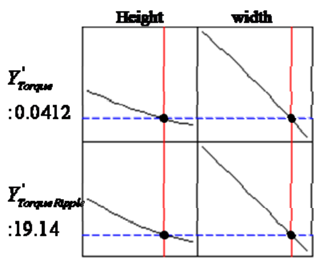


Fig. 8. Responses of each fitted model according to the design factos

TABLE III
RESULT OF THE OPTIMIZATION

Design objective	Initial model	Optimized model
Average torque [Nm]	0.0415	0.0412
Torque ripple [%]	22.35	19.14

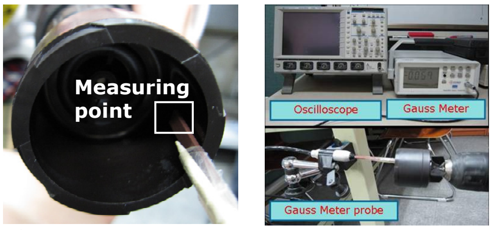


Fig. 9. Testing apparatus

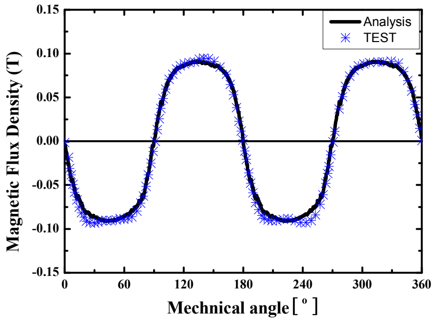


Fig. 10. The comparison of surface flux density

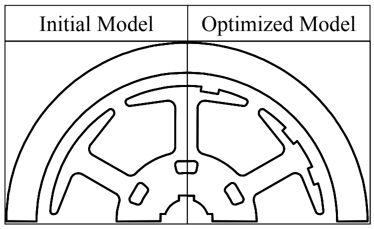


Fig. 11. Configuration s of optimized and initial model

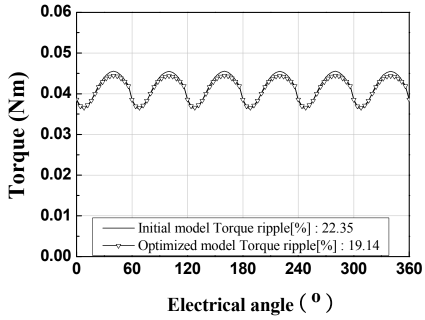


Fig. 12. Result of torque analysis

IV. Result and Discussion

The effectiveness of the analysis method is shown by comparing the analytical values and measured values of the surface flux density of the polar anisotropic bonded magnets itself. Fig. 9 shows the testing apparatus. The magnetic properties of the polar anisotropic bonded PM were measured by using a flux meter. Fig. 10 compares the measured values and the analytical values of the radial components of the surface flux densities of the magnet. Both agree very well and show that the orientation of the polar anisotropic bonded magnet determined by this analysis is appropriate.

Fig. 11 shows configurations of optimized and initial design. As shown in Fig.12, the torque ripple of optimized outer rotor type Brushless DC motor using polar anisotropic ferrite bonded permanent magnet is smaller than the initial model. Table III shows the results of the optimization in the optimal point. Additionally, R^2 and R_A^2 are applied to evaluate accuracy of the fitted model [9]; R^2 and R_A^2 are very high as 0.998 and 0.997 respectively. This result shows not only the accuracy of prediction by using RSM, but also successful optimization results in comparison with the initial value.

Therefore, in the design of the outer rotor type appropriate ratio of notch should be wide.

V. Conclusion

The optimal ratio of height and width of notch to reduce the torque ripple for outer rotor type BLDC motor using polar anisotropic bonded PM is determined in this paper.

In order to increase performance of the initial model, optimization design by RSM combined with FFD is performed in this paper. Moreover, because the magnetizing direction cannot be determined by simple relational equations in this model, the orientation of the polar anisotropic bonded magnet is determined by FEM for unusual magnetic-field analysis.

The validity of the analysis method is verified by comparing the analyzed results with measured ones. Therefore we confirm that out analysis method is useful for analysis and design of many electromagnetic machines.

Acknowledgment

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