Optimal Design of Transverse Flux Rotary Motor using Response Surface Methodology to Reduce Cogging Torque

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Abstract. *This paper proposes an optimal design process and the optimized model for Transverse Flux Rotary Motor to reduce cogging torque remaining total main flux. Response surface methodology is used as the optimization method in design process after selecting main design parameters by screen activity. The utility of this method is verified through the comparison of the performances of initial model and the optimal one.*

Keywords: Cogging torque, Optimal Design, Response Surface Methodology (RSM), Transverse Flux Rotary Motor (TFRM)

1 Introduction

Permanent Magnet (PM) Transverse Flux Machines have been developed to apply to high power system, and the linear types have been introduced in many cases such as railway traction, electro-dynamic vibrator, free-piston generator, etc. [1, 2]. It is reported that its advantages are as follows; direct linear motion with high power density, mechanical simplicity, and robustness. On the other hand, it has disadvantages such as easy saturation in mover pole, and relatively high detent force or cogging torque. Morever, the peculiar coil winding method [2, 3] make it difficult to apply it as rotary type.

Therefore, these authors introduce a novel shaped rotary type, Transverse Flux Rotary Motor(TFRM), and an optimal design process to reduce cogging torque remaining total main flux.

Response surface methodology (RSM) is used as the optimization method after selecting main design variables by screen activity. Between several design variables such as stator pole width, rotor pole width, notch width and depth, etc., two or three variables mainly affecting the characteristics within the chose design area are selected and optimized. The cogging torque and flux of sample models are obtained by 3-dimensional finite element analysis (3D FEA).

The utility of this method is verified through the comparison of the performances of initial model and the optimal one.

2 Analysis Model

Fig. 1 shows the configuration of 2-phase TFRM, and the specifications for analysis are listed in Table 1. In each saperated stator core, there is one phase coil, and the phase difference is 90^o(electrical angle). When upper stator pole is aligned with rotor pole, lower stator pole is aligned with PM in the rotor. Fig. 2 shows the detailed configurtion of the alignment between stator and rotor poles. This partial model is the analysis model, and it presents magnetomotive force dirctions of current and PM, and flux path. This 3D flux path requires 3D analysis model, and therefore,3D FEA is used in this paper. The magnetic material characteristics are shown in Fig. 3. Eventhough the permeability of soft magnetic composit(SMC) core is lower than that of Si-laminated core, for example S23, SMC core is used in this research because it is useful to assembling.

Table 1: Specifications of 2-phase TFRM

Parameters	Values	Parameters	Values
No. of stator pole /phase	14	No. of rotor pole	64
Magnetic material	SMC (Somaloy500)	Permanent magnet	Br =0.38, μ_r =1.05

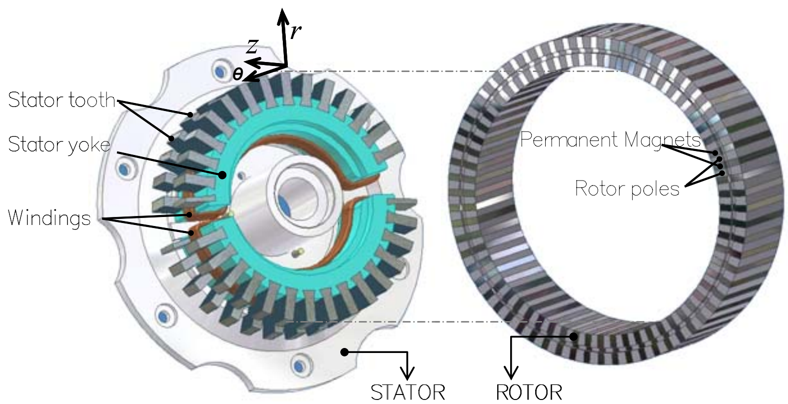

Fig. 1. Stator and rotor configurations of TFRM

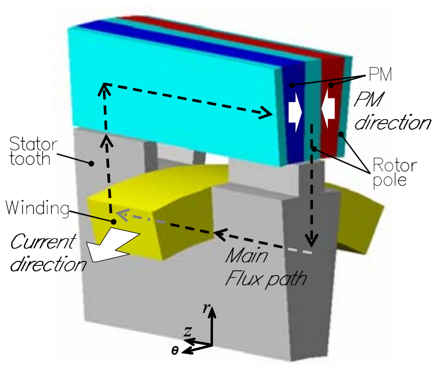

Fig. 2. Current and flux path in the 3D analysis model of TFRM

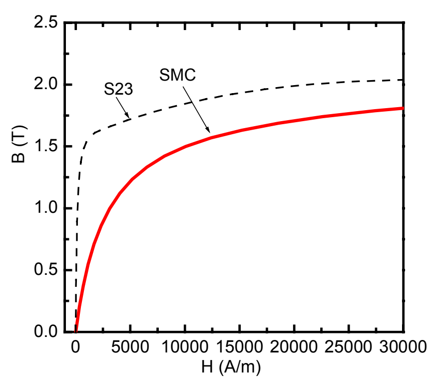

Fig. 3 B-H characteristics of SMC comparing with S23

3 Optimal Design Process

The optimal design of TFRM is executed to improve F_{obj} by using RSM based on the statistical fitting method. Fig. 4 shows the proposed design process, and it can be roughly classified as 2 steps: 1)screen activity to select main design parameters, and 2)optimization process.

A. Screen Activity to Select Main Factor

The geometries of TFRM can be defined by several variables, but in this paper five design variables are selected to reduce cogging torque as shown in Fig. 5. Except fixed specifications defined by requirement, all parameters can be the design variables, and be investigated if it has influence or not in motor characteristics.

If many parameters are defined as design variables, it takes large simulation time because of a large number of the required experiments even without taking into account the interactions of the high order between parameters. Therefore, it is necessary that the influence of significant parameters are investigated on the design results. Fractional factorial designs are suitable to solve this problem. When the number of design variables is n, only $2^{n\text{-m}}$ (m=1,2,3..) fractional factorial designs are needed. In this paper, 2^{n-1} fractional factorial is used [4].

B. Optimization Process

RSM seeks the relationship between design variables and response in interest area through statistical fitting method, which is based on the observed data from system. The response is generally obtained from real experiments or computer simulations. Thus, 3D FEA is used to analyze TFRM in this paper.

An approximation polynomial model is commonly used for a second-order fitted response and can be written as (1) [5]:

$$u = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i \neq j}^{k} \beta_{ij} x_i x_j + \varepsilon \quad (1)$$

where β is regression coefficients, ε denotes the random error.

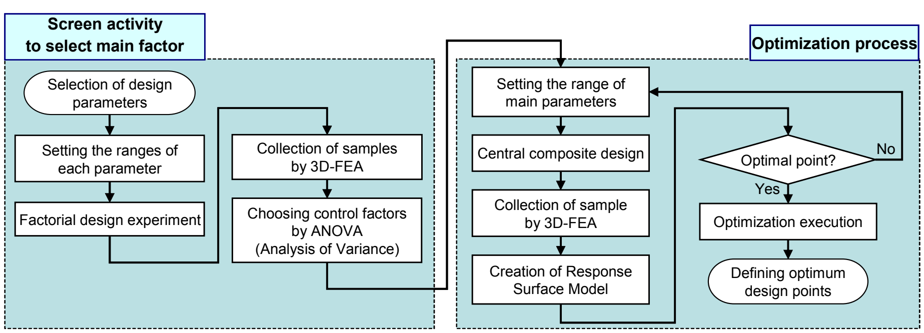

Fig. 4. Proposed design process using RSM

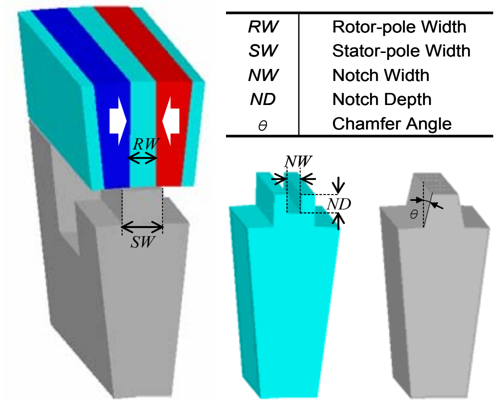

Fig. 5. Five design variables

The least squares method is used to estimate unknown coefficients. Matrix notations of the fitted coefficients and the fitted response model should be such as

$$\hat{\boldsymbol{\beta}} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{u}\ ,\ \hat{\mathbf{u}} = \mathbf{X}\hat{\boldsymbol{\beta}} \tag{2}$$

where the caret ($\hat{}$) denotes estimated values. **X** is the matrix notation of design parameters and the vector $\hat{\beta}$ contains the unknown coefficients which are usually estimated to minimize the sum of the squares of the error term, which is a process known as regression.

Experimental designs for fitting the second-order response surface must involve at least three levels of each variable. Therefore, to build the second-order fitted model, the central composite design (CCD) is used. CCD is frequently used for fitting second-order response model.

The observed data is also simulated using 3D FEA. In this paper, the second-order fitted model of F_{obj} is used as the object function. In order to reduce cogging torque remaining total flux to keep the output power, two object functions are adopted. F_{obj1} is peak to peak value of cogging torque, and F_{obj2} is average of absolute values of flux density distribution in air-gap instead of linkage flux.

4 Design Results

The 2-phase TFRM above mentioned in Fig.1 and Table I was fabricated in Korea Electrotechnology Research Institute. With the fabricated model as an initial model, five parameters are selected, and then the effects are investigated in the screen activity. As the results of screen activity with 16 experiments, the effects of design variables are shown in Fig. 6. The initial values of each parameter are the minimum values, and the maximum values are selected considering possible modeling with all combinations of the five variables. The most effective parameters are notch depth and width, however zero value of the two parameters makes F_{obj1} minimize. Therefore, except notch, three parameters are selected to be optimized, and the changed ranges are shown in Table 2.

With the three design parameters, CCD is required to conduct 15 experiments. After getting the experimental data by 3D FEA, the function to draw response surface is extracted. The purpose of this paper is to minimize the object function F_{obj1} maintaining F_{obj2}. The two fitted second-order polynomial of object functions for the three design variables are as follows.

$$\boldsymbol{F}_{obj1} = -82.42 + 29.40\boldsymbol{x}_1 + 3.23\boldsymbol{x}_2 - 0.34\,\boldsymbol{x}_3 - 2.17\boldsymbol{x}_1^{\,2} - 0.77\boldsymbol{x}_1\boldsymbol{x}_2 \tag{3}$$

$$\boldsymbol{F}_{obj2} = 0.06 + 0.05\boldsymbol{x}_1 + 0.12\boldsymbol{x}_2 - 0.005\boldsymbol{x}_3 - 0.003\boldsymbol{x}_1^{\,2} - 0.02\boldsymbol{x}_2^{\,2} - 0.001\boldsymbol{x}_1\boldsymbol{x}_2 \tag{4}$$

With these functions, six predicted response surfaces are drawn. Fig. 7 shows an optimal point and the contour lines including the point on each six response surface. In this case, the optimal point is searched to find the point of under 50% of initial value of F_{obj1}. The found optimal point is at the point in which SW is 8.3mm, RW is 3.9mm, and θ is 10^{o}. The values of object functions at predicted point are 1.65 and 0.369 denoted by V_{RSM} in Table 3, and the calculated values by 3D FEA are 1.62 and 0.364 denoted by V_{FEA}. The errors between V_{RSM} and V_{FEA} are under 2%. This result shows not only the accuracy of prediction by using RSM, but also successful optimization.

5 Conclusions

In this paper, a design process is introduced to design TFRM to reduce its cogging torque maintaining the total flux. A optimal design is performed considering unique characteristic of TFRM such as 3D flux path. The optimal design results satisfy the requirement very well.

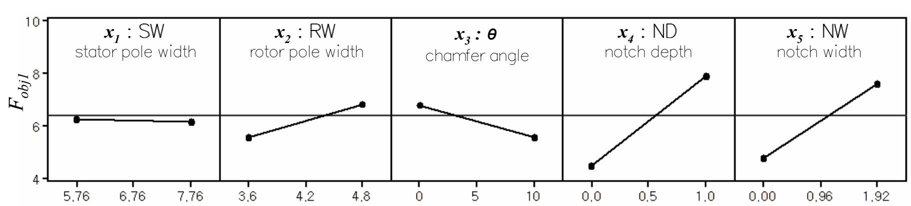

Fig. 6. Main effect plots of F_{obj1} , (cogging torque peak to peak) for five variables

Table 2: Design variables and area for optimization

Design variables		unit	Minimum value	Maximum value
x_1	SW	mm	4.3	8.3
x_2	RW	mm	2.4	5.4
x_3	θ	degree (^{o})	-6.8	26.8

Table 3: Comparison of design results

Parameters	Initial model	Optimized model	Parameters	Initial model	Optimized model	Error
SW	5.76mm	8.3mm	F_{obj1}	3.89 (100%)	V_{RSM}=1.65 V_{FEA}=1.62 (41.6%)	1.8%
RW	3.6mm	3.9mm				
SW/RW	1.6	2.1	F_{obj2}	0.366 (100%)	V_{RSM} =0.369 V_{FEA} =0.364 (99.5%)	1.4%
θ	0°	10°				

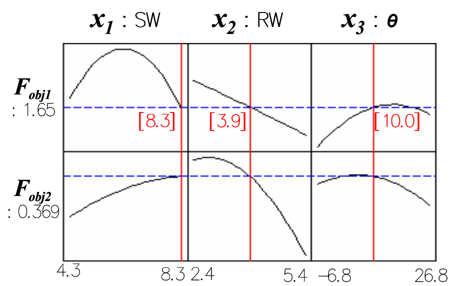

Fig. 7. The optimized point

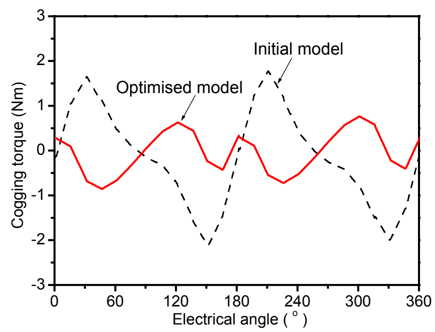

Fig. 8. The comparison of cogging to

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Programme

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Wednesday, October 12, 2005

Section B: Mechatronics and Robotics (Lecture Room C1-318)

Chairman: Prof. K. Oka

8:30–8:50	H. Kobayashi, H. Suzuki (Japan) *Development of a muscle suit for the upper body.*
8:50–9:10	N. Kubota, Y. Ito, M. Abe, H. Kojima (Japan) *Computational intelligence for natural communication of partner robots*
9:10–9:30	N. Kubota, K. Tomoda, T. Shimizu (Japan) *Computational intelligence toward educational partner robotics*
9:30–9:50	S.Y Lee, S.Y. Kwak, J.K. Kim, H.K. Jung, S.K. Hong, S.J. Han (Korea) *Finite element analysis of inductance variation for interior permanent magnet synchronous motor*
9:50–10:10	Y.M. Park, C.G. Heo, H.K. Jung , H.S. Kim (Korea) *Design of partial discharge sensor in rotating machines*
10:10–10:40	**Coffee Break**

Chairman: Prof. Nguyen Van Khang

10:40–11:00	J.Y. Lee, J.W. Jung, J.P. Hong, J.H. Jang, D.H. Kang (Korea) *Optimal design of transverse flux rotary motor using response surface methodology to reduce cogging torque*
11:00–11:20	M. Minami (Japan) *Avoidance ability of redundant mobile manipulator during hand trajectory tracking*
11:20–11:40	N.H. Minh, T. Takamori, S. Kobayashi (Japan) *Development of Carbon dioxide sensing system for searching victims in large scale disasters*
11:40–12:00	M. Sasaki, C.K. Ho, S. Ito (Japan) *Biped locomotion robot control using bio-potential signals*
12:00–13:30	**Lunch**