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Use of Experimental Design for Optimal Design of IPMSM by Response Surface Methodology

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Abstract *– This paper performs the optimization design to improve torque performance of an interior permanent magnet synchronous motor. Response surface methodology (RSM), as an optimization method, is applied in this paper. Moreover, full factorial design, one of the experimetnal designs, is used to raise the quality of the optimization and reduce the iteration of experiment in the application of RSM. In the end, the usefulness of RSM combined with FFD is verified by comparison with the result obtained from 2D fininte element analysis.*

Introduction

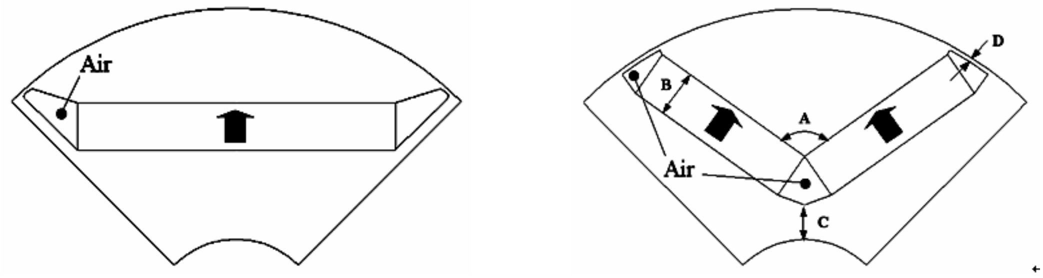
An interior permanent magnet synchronous motor (IPMSM) has high power density per motor volume because it can utilize both magnet and reluctance torque due to magnet saliency. Therefore, the IPMSM is one of the most attractive motors applied in compact system. However, torque ripple of the IPMSM is relatively large due to generation of reluctance torque and causes noise and vibration. The torque ripple generally depends on permanent magnet arrangement in the rotor of IPMSM. Accordingly, optimization design of the rotor shape is required to improve torque performance of the IPMSM [1].

Response surface methodology (RSM) is a set of statistical and mathematical techniques to find the "best fitted" response of the physical system through experiment or simulation. It has recently been recognized as an effective approach for modeling the performance of electrical devices. In RSM, a polynomial model, called a fitted model, is generally to be constructed to represent the relationship between the performance and design parameters. Thus, this model provides designers with an overall prospect of the performance according to the behavior of the parameters within a design space, and the design optimization be carried out with much ease. On the other hand, the quality of the fitted model depends on the size of the space in which the design parameters may vary. That is, as the size is small, the precision of the estimated polynomial model is higher [2], [3]. However, if the domain is narrow, optimal condition is not detected and guaranteed because the full design region is not explored. Therefore, this paper proposes full factorial design (FFD) to establish more reasonable and objective design area for RSM. It examines the responses according to the variation of each design parameter in the wide design area, and then the small region to apply RSM is set.

Analysis Model and Design parameters

Fig. 1 shows the rotor configurations of the two analysis models, prototype and V-type. The prototype is used for air-conditioning compressor of an automobile. The V-type is an improved type, applied in this paper, to obtain better the ratio between torque ripple and average operational torque (AOT) than the prototype. Analysis condition of the two models, based on finite element analysis (FEA), is the same except the arrangement and size of permanent magnet (NdFeB) in the rotor. Table 1 shows the condition.

The design parameters, from A to D, are described in Fig. 1. (b) : "A", Angle between two segment permanent magnets in the rotor; "B", thickness of permanent magnet; "C", distance from shaft, and "D", link width. Where link width fixes 0.4 [mm] to prevent leakage flux and consider fabrication difficulty.



(a) Prototype IPMSM (b) V-type IPMSM

Fig. 1 Rotor configurations of analysis models

Table 1 Specifications of analysis models

Items	Prototype IPMSM	V-type IPMSM
Pole / Slot number	4 / 24	
Air-gap [mm]	0.3	
Winding	Distributed winding	
Residual induction of PM [T]	1.2	
Height of PM [mm]	4	
Rated outpower [kW]	3.5	
Rated voltage [V]	42	
Rated current [A_{rms}]	100	
Length of PM [mm]	27	15

Optimization

Full Factorial Design (FFD)

Generally, the range of design variables for optimization is determined by past experimental data or designer's experience. However, that is apt to become a very restrictive and subjective design. 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. Thus, 2^3 FFD is applied to obtain more reasonable and objective design area for RSM. The advantages of FFD are written as follows [4]:

- All combinations of design parameters are investigated.
- All main and interaction effects are evaluated without confounding.

Table 2 shows the array of 2^3 FFD to examine the ratio between torque ripple and AOT of the prototype IPMSM. In Table 2, experiment No. 9 is added to estimate the curvature in the middle point of each design area because it is performed at only two levels. In this paper, the levels are called "low" and "high" and denoted "–1" and "+1" respectively.

Main and interaction effects of each parameter on the ratio are displayed in Fig. 2. The plot of main effect describes the difference between the average responses at the low and high level of each parameter, and a middle dotted line means total average of the every response. In the plot of interaction effect, if the difference in response between the levels of one factor is not the same at all levels of the other factors, there is an interaction between the factors.

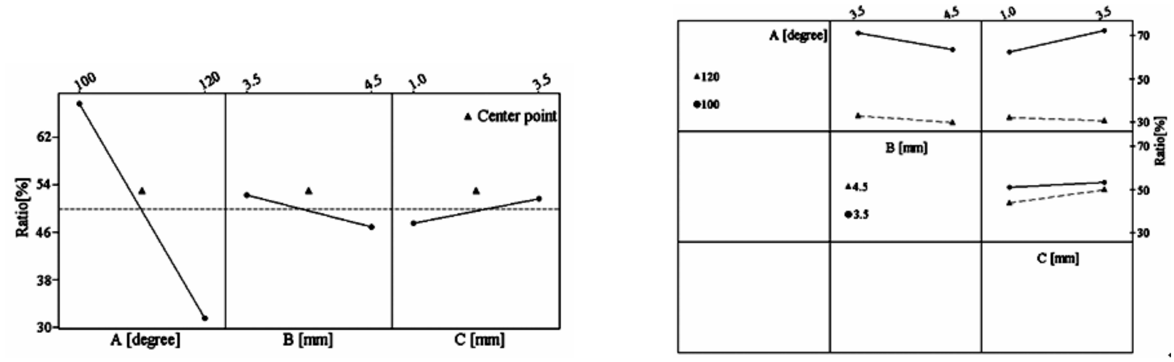
In conclusion, there is a little both the curvature response and the interaction effects between the parameters. Hence, the design area for RSM is mainly decided by the plots of main effects.

Response Surface Methodology (RSM)

RSM is applied to make appropriate response models of the average thrust and thrust ripple. A quadratic approximation function of the models is commonly used to construct the fitted response surface. In general, the response model can be written as follows [4], [5]:

Table 2 Array of 2^3 FFD

Experiment No.	**A(level)** [°]	**B(level)** [mm]	**C(level)** [mm]	**Ratio [%]**
1	100(-1)	3.5(-1)	1.0(-1)	70.0935
2	120(+1)	3.5(-1)	1.0(-1)	32.1670
3	100(-1)	4.5(+1)	1.0(-1)	55.2920
4	120(+1)	4.5(+1)	1.0(-1)	32.3206
5	100(-1)	3.5(-1)	3.5(+1)	72.7231
6	120(+1)	3.5(-1)	3.5(+1)	33.8917
7	100(-1)	4.5(+1)	3.5(+1)	72.3125
8	120(+1)	4.5(+1)	3.5(+1)	27.5542
9	110(0)	4.0(0)	2.25(0)	52.8305



(a) Main effect

(b) Interaction effect

Fig. 2 Main and interaction effects of each parameter on the ratio

$$\mathrm{Y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x^2_i + \sum_{i \neq j}^{k} \beta_{ij} x_i x_j + \varepsilon \tag{1}$$

where β is regression coefficients for design variables, ε is random error treated statistical error. the fitted coefficients and the fitted response model by using least square method which is used to estimate unknown coefficients, can be written as

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

$$\hat{\mathbf{Y}} = \boldsymbol{X}\hat{\beta} \tag{3}$$

where $\boldsymbol{X}$ is the matrix notation of the levels of the independent variables, $\boldsymbol{X}'$ is the transpose of the matrix $\boldsymbol{X}$, $\hat{\beta}$ is the matrix of fitted coefficients, and $\hat{\mathbf{Y}}$ is the vector of the observations.

In this paper, central composite design (CCD) is employed as the experimental design method to estimate the fitted model of the ratio response. CCD consists of three portions: a complete 2^k or fractional 2^{k-m} factorial design in which the factor levels are coded into –1 and 1; axial points at a distance α from the center point; one design center point [2], [5]. Table 3 displays the experimental area of CCD, and the area is set from the result of FFD performed to investigate the ratio between torque ripple and AOT of the prototype IPMSM. From the above process, the polynomial models of the responses are given by (4).

$$\hat{\mathrm{Y}} = 3152.5 - 41.9\mathrm{A} - 281.2\mathrm{B} - 36.9\mathrm{C} + 0.1\mathrm{A}^2 + 9.5\mathrm{B}^2 + 0.9\mathrm{C}^2 + 1.7\mathrm{AB} + 0.2\mathrm{AC} + 1.8\mathrm{BC} \tag{4}$$

Result and Discussion

Table 4 shows the results obtained by FEM and the fitted model in the optimal condition, and the values are alike. Moreover, R^2 and R_A^2 are very high as 0.994 and 0.99 respectively. It is the statistics index to evaluate the quality of the fitted model [2].

Although the whole volume of permanent magnet is increased 17.5[%], torque ripple is reduced 14.5[%] and AOT is increased 12[%]. The ratio between torque ripple and AOT is decreased 8.2[%]. In addition, RSM combined with FFD can find out the optimal point without iteration of experiment. Graphic performance comparison between the prototype and the optimized V-type is described in Fig. 3. The response surface and contour according to change of the parameters are shown in Fig. 4.

Table 3 CCD area for RSM

Design parameters	Level of design parameters				
	-α	-1.0	0	1.0	α
A [°]	114.64	116	118	120	121.36
B [mm]	4.23	4.3	4.4	4.5	4.57
C [mm]	0.32	1.0	2.0	3.0	3.68

Table 4 Result comparison at optimal point

Design parameters	Optimal point	Predictive ratio by RSM	Ratio by FEM
A [°]	117.75		
B [mm]	4.23	24.98 [%]	25.23 [%]
C [mm]	3.68		

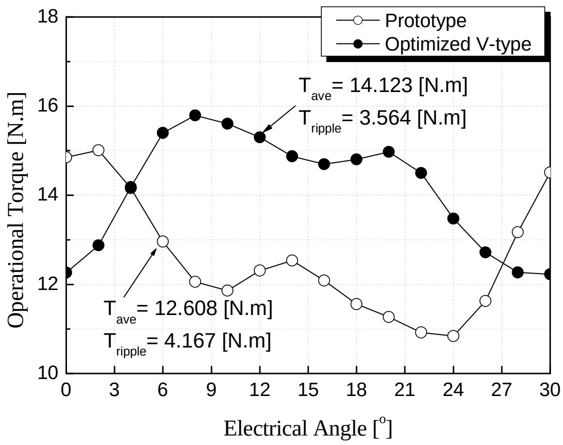
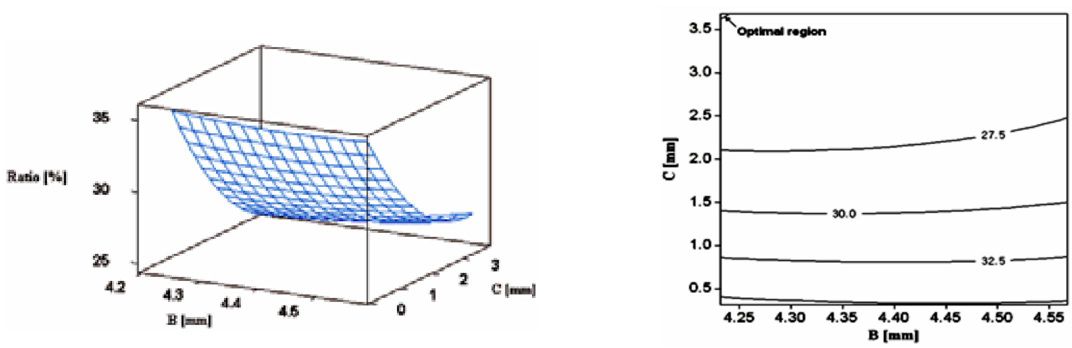


Fig. 3 Performance comparison between prototype and optimized IPMSM



(a) Response surface (A: 11.75 [°])

(b) Contour (A: 11.75 [°])

Fig. 4 Response surface and contour plot of the ratio

Conslusion

In order to increase performance of the prototype IPMSM, optimization design by RSM combined with FFD is performed in this paper. The performance of the optimized V-type IPMSM is improved as compared with that of the prototype IPMSM. Therefore, this proposed approach is very efficient to raise the quality of optimization and reduce the iteration of experiment in the optimization design by RSM.

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