Optimization of Permanent magnetic Actuator for Minimizing Permanent Magnet Using Response Surface Method

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Abstract — This paper presents optimization of permanent magnetic actuator (PMA) for minimizing permanent magnet by response surface method (RSM). To verify dynamic characteristic, the initial model is manufactured and measured and then dynamic characteristics are compared with results of finite element analysis. Based on verified finite element analysis, the optimal model is obtained by RSM.

I. INTRODUCTION

Circuit breakers using SF6 gas have been mainly used in the electric power system. Recently, the electric power industry is in the spotlight as green growth for eco-friendly. Thus a research that gas circuit breaker (GCB) is replaced by vacuum circuit breaker (VCB) is needed [1]. The operation mechanism of VCB is spring operated mechanism and PMA mechanism [2]. Spring operated mechanism has drawbacks such as the complicated structure and periodic maintenance. Nowadays, however, PMA is widely used in driving mechanism of VCB. PMA has advantages such as simple structure, improved operating time, easy motion control as well as high reliability compared with spring operated mechanism. The structure of PMA is shown in Fig. 1. PMA is held its position by permanent magnets without electrical and mechanical energy and changed its holding force as per permanent magnet [3]-[4].

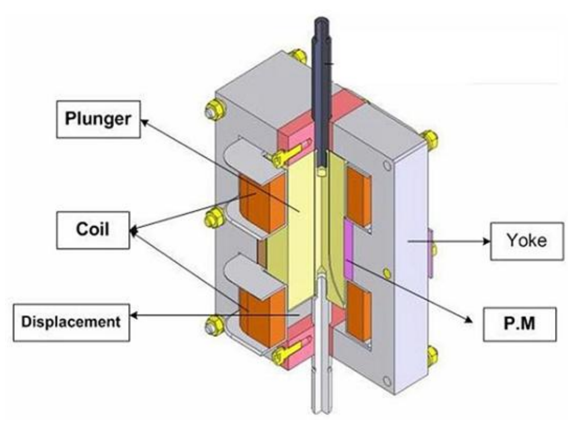


Fig. 1. Structure of Permanent Magnetic Actuator

RSM is the technique which accomplishes optimization. This method can make an approximate response surface model from analysis values to express mathematical formula between design variables and response variables [5].

This paper applies RSM effective design of electrical machines and then performs optimization to minimize permanent magnet of PMA. Finally, we verify comparing with dynamic characteristic analysis using finite element method as holing force, exciting current, and operating time [6].

II. NUMERICAL ANALYSIS

PMA has transient response during operation. In coupled electromagnetic-mechanical analysis, governing equation consists of electric circuit, magnetic field, and motion equation.

A. Electric Circuit Equation

To analyze the performance of PMA model, the electric circuit equation should be coupled with magnetic field equation. When the source voltage is applied to an exciting coil, the electric circuit equation is given as:

$$V = R \cdot i + L\frac{di}{dt} + \frac{d\lambda}{dt}\,. \tag{1}$$

B. Magnetic Field Equation

PMA operates with the magnetic field which occurs by current at permanent magnet and an exciting coil. The magnetic field equation which considers the change of time is formulated as follows:

$$\nabla \times \left(\frac{1}{\mu}\nabla \times \vec{A}\right) + \frac{\partial \vec{A}}{\partial t} + \sigma\nabla V = \vec{J}_0 + \nabla \times \vec{H}_c\,. \tag{2}$$

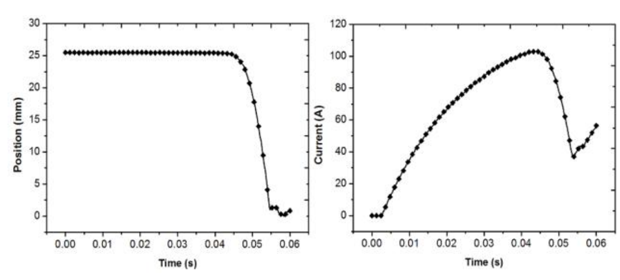
C. Motion Equation

Mechanical operation of PMA can calculate by motion equation of plunger. The motion equation of the plunger is expressed as:

$$m\frac{d^2 z}{dt^2} = F_{mag} + F_{load}\,. \tag{3}$$

III. NO LOAD CHARACTERISTIC TEST

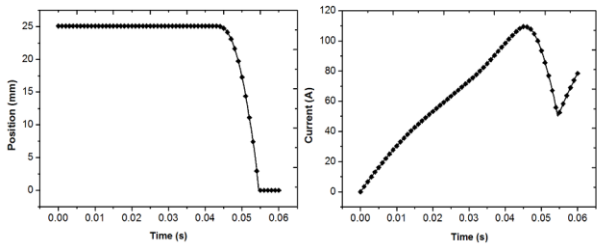
The dynamic characteristics of holding force, exciting current, and operating time must be considered in PMA. In this paper, no load characteristics of PMA the manufactured model are tested. Fig. 2 is operating time and exciting current obtained no load test.



(a) Operating time (b) Exciting current

Fig. 2. Dynamic characteristics of no load test

Fig. 3 is operating time and exciting current calculated by finite element analysis.



(a) Operating time (b) Exciting current

Fig. 3. Dynamic characteristics calculated by finite element analysis

We compared with the simulation model using finite element method and the manufactured model. Dynamic characteristic is got the error 5%, 6% respectively because an actual test is arose friction and structural characteristic at link.

IV. APPLICATION OF RESPONSE SURFACE METHOD

RSM express correlation between design variables and response variables by a mathematical formula. This method is statistical method that makes an approximate response variable model. A response y to the number of k design variables is expressed as:

$$y = f\left(x_1, x_2, \cdots, x_k\right). \tag{4}$$

When a secondary regression model is used by the function approximation, the equation between the response function f and the function approximation y is formulated as follows:

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i \neq j}^{k} \beta_{ij} x_i x_j + \varepsilon \ . \tag{5}$$

Fig. 4 shows the design variables of PMA model. And design variables are chose width of permanent magnet (x1), height of permanent magnet (x2) and width of yoke tip. Response variables are chosen holding force of PMA, operating time and peak value of exciting current.

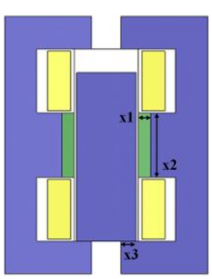


Fig. 4. Design variables of PMA

V. COMPARING DYNAMIC CHARACTERISTICS

Application result of RSM to minimize permanent magnet shows in Table I. Permanent magnet of the optimal model reduced about 8% as compared with permanent magnet of the initial model.

TABLE I
RESULTS OF RESPONSE SURFACE METHOD

Division		Initial Model	Optimal Model
Design Variables	x1 (mm)	10.0	9.2
	x2 (mm)	54.2	54.1
	x3 (mm)	17.0	17.2
Axial Depth of PM (mm)		125.0	125.0
Volume of PM (mm^3)		67750	62215

Table II is value compared the initial model with the optimal model. In the result, the operating time was reduced and the peak value of exciting current was similar also holding force was increased. Thus dynamic characteristic of the optimal model is better than the initial model.

TABLE II
RESULTS OF RESPONSE SURFACE METHOD

Division	Initial Model	Optimal Model	Error (%)
Holding Force (N)	7710.0	7916.1	3
Peak Value of Current (A)	109.3	108.7	1
Operating Time (ms)	55.0	54.5	1

VI. CONCLUSIONS

This paper proposed the shape of PMA which improves to minimize permanent magnet. Dynamic characteristics such as holding force, exciting current, and operating time of the initial PMA model are analyzed by finite element method and shows good agreement with the results obtained from no load test. Width of permanent magnet, height of permanent magnet, and width of yoke tip are predefined for the minimized permanent magnet of PMA and optimized using RSM. In result, permanent magnet was decreased 8% for comparing with the initial and the optimal model. Therefore the optimal design technique using RSM can be extended to reduce the size of permanent magnet.

VII. REFERENCES

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