반응표면법을 이용한 초전도 전동기의 마그넷 형상 최적화

Shape Optimization of the Magnet for Superconducting Motor by Using RSM

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Abstract: This paper presents the optimization for shape design of a field coil used High Temperature Superconducting Motor (HTSM). In materials of HTSM, critical current Ic is more sensitive to magnetic fields directed along the axis of the unit cell ($B_\perp$). Thus, in the shape design of the HTS magnet, the maximum $B_\perp$ should be reduced to limit Ic. In order to reduce the maximum $B_\perp$, the shape optimization of the magnet, which is used for the field coil of HTSM, is necessary. It can be accomplished by using Response Surface Methodology (RSM). Finally, the result of RSM is verified by comparison with these experimental results.

Key Words: optimization, response surface method, Superconducting Motor.

1. Introduction

Solving design problems is a natural process in an optimization for requirements. Most optimization problems, however, involve the difficulties to create the function of the objective and constrain condition related to a desired performance. Moreover, it is difficult to optimize some shapes for many design variables because of interaction of the variables.

Therefore, RSM is recently received attention for modeling the performance of electromagnetic devices by using statistical fitting method because the RSM has been well adapted to make an analytical model for the complicated problem [1], [2]. With this analytical model, an objective function with constrains can be easily created, and computation time can be saved.

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In this paper, we present the shape design of the HTS magnet and the optimization procedure toreduce the maximum $B_\perp$ considering stress and optimization procedure, the RSM is employed. Thus, strain condition of Ag-sheathed Bi-2223 37-filament HTS tape [3], [4]. In order to attain this the analytical model for the maximum $B_\perp$, which is obtained from the RSM, is used as the object function to reduce one. In addition, optimal solution of the problem is accomplished by using the Sequential Quadratic Programming (SQP) [5].

2. Concept of the Statistical Fitting Method

2.1. Concept of Response Surface Methodology

The RSM seeks for the relationship between design variable and response through statistical fitting method. A polynomial approximation model is commonly used for a second-order fitted response and can be written as follow [1], [2], [6]:

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

β: regression coefficients, ε : random error

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

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

$$\hat{\mathbf{u}}=\mathbf{X}\hat{\boldsymbol{\beta}} \quad --- \quad (3)$$

(^): estimated values, $\mathbf{X}$: matrix of model terms should be evaluated at the data points, $\hat{\boldsymbol{\beta}}$: vector of the unknown coefficients which are usually estimated to minimize the sum of the squares of the error term

2.2. Design of Experiments

In order to determine the equations of the response surface, several experimental designs have been developed to establish the approximate equation using the smallest number of experiments [6]. The most preferred classes of experimental designs are the orthogonal first-order design and the central composite design. The first-order design is treated separately to develop the first-order response surface model. The first order model is achieved from a 2^k full factorial or fractional design. The 2^k design is where each of the k factors has two levels.

In this paper, the second-order fitted model of the maximum $B_\perp$ is used as the objection function. Experimental designs for fitting the second-order response surface must involve at least three levels of each variable because only two levels can't sense change of curved response surface. Therefore, for building the second-order fitted model, the Central Composite Design (CCD) is used. CCD is frequently used for fitting second-order response model and CCD involving four factors is required to conduct 25 experiments. In this paper, axial points on the axis of four design variables at a distance from the design center choose 2 for an orthogonal experiment design. The observed data is simulated using Biot-Savart law, which is described as following chapter.

3. Application Model and Field Analysis Method

In the cross section of the electromagnetic part as shown in Fig. 1, each pair of L1-L2, L3-L4, and L5-L6 is double-pancake coil for each position. The excitation system consists of four racetrack HTS magnets as field coils. Except magnetic shield, the other structures of HTSM including damper, nitrogen tank, vacuum vessel, field core, and armature core etc. are nonmagnetic materials. Inner diameters of field coils (banding diameter) are 31 mm and 42 mm as shown in Fig.1, respectively. The armature winding method is full pitch, and the specifications of armature winding include Y connection, double layer winding, (full pitch) and 2 slots per pole per phase. The magnet consists of the HTS coil with 3 mm width, 0.25 mm thickness and 467 turns per pole. In the paper, the design variables for designing to reduce the maximum $B_\perp$ are defined by x_1, x_2, x_3, x_4, which are the outer widths of field coils as Fig. 1. Analysis of the magnetic field can be derived from the Biot-Savart law as following [4], [7]:

$$d\vec{B} = \frac{\mu_0 I}{4\pi}\left(\frac{d\vec{l'} \times \vec{R}}{R^3}\right) \quad --- \quad (4)$$

$d\vec{B}$: magnetic flux density due to a current element $Id\vec{l'}$ estimated values, $\vec{R}$: distance vector directed from the source point to the field point, μ_0: permeability of free space

In the winding of the magnet, the maximum $B_\perp$ occurs at the layer of L1 and L6 in *x-y* plan respectively, whose magnitude determines Ic, a principal factor in the sense of stability and performance. Therefore, the shape design of field coil should be optimized as following conditions that its maximum $B_\perp$ is decreased at the layer of L1 and L6.

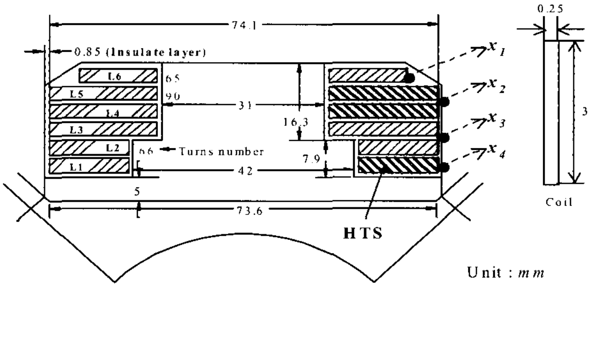


Fig. 1. Design variables of the magnet & HTSM's dimension

4. Numerical Optimization Result

The optimization design of the magnet shape based on the statistical fitting method is executed to reduce the maximum $B_\perp$ by using RSM [3]. The analytical model $\hat{y}_{B\perp}$ obtained from the RSM is used as an objective function. The CCD involving four factors is required to conduct 25 experiments. The Biot-Savart law is used to acquire the samples. Therefore, on the conventional optimization procedure, the objective functions and constraints are defined as following and a schematic depiction Fig. 2 describes the optimization procedure by using RSM.

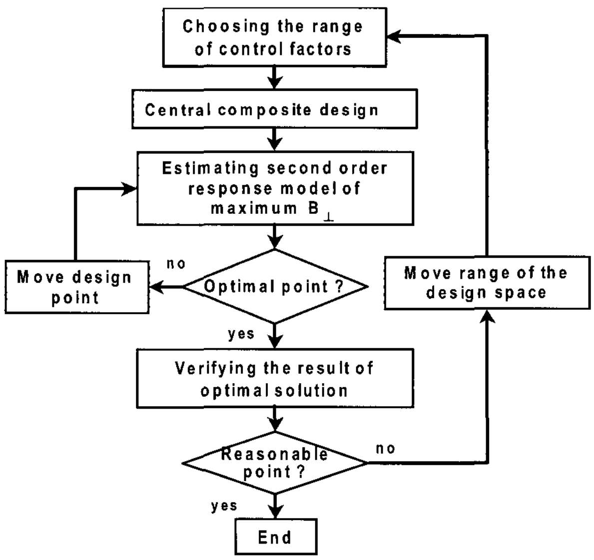


Fig. 2. Procedure of the optimization

Minimize:

$$f(x) = \hat{y}_{B_\perp} \quad (\mathrm{N\cdot m})$$
$$= -166.83 + 13.802x_1 + 2.364x_2 + 2.381x_3 + 1.551x_4 - 0.398x_1^2 - 0.096x_2^2 - 0.067x_3^2 - 0.026x_4^2 + 0.193x_1x_2 + 0.131x_1x_3 + 0.033x_1x_4 + 0.041x_2x_3 + 0.008x_2x_4 + 0.006x_3x_4 \quad \text{--- (5)}$$

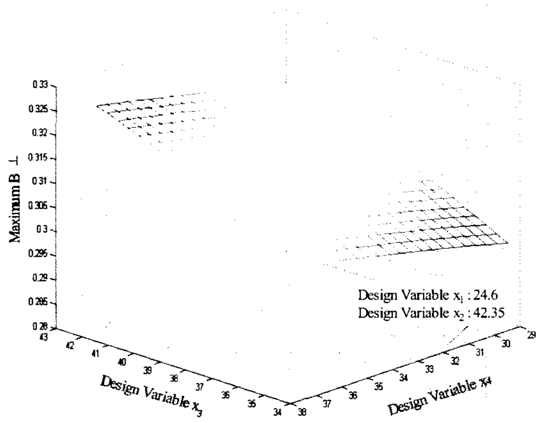
Subject to:

$$h(x) = \frac{x_1 + 2x_2 + 2x_3 + x_4 - 109.1}{0.25} - 467 \quad \text{--- (6)}$$

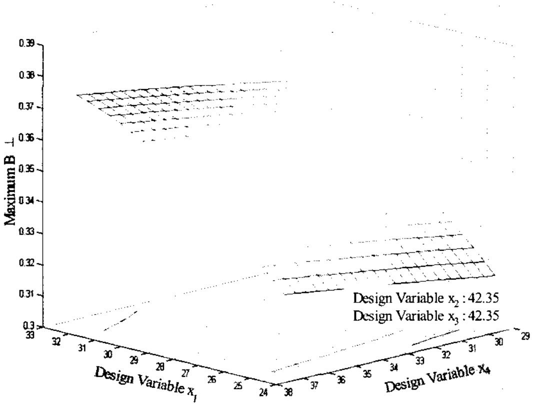
$$24.6 \le x_1 \le 32.6,\ 34.35 \le x_2 \le 42.5,\ 34.35 \le x_3 \le 42.5,\ 29.1 \le x_4 \le 37.1 \quad \text{--- (7)}$$

$h(x)$: equality constraint according to the limitation on the total number of turns per pole, and the range of design variables are limited to their lower and upper bounds

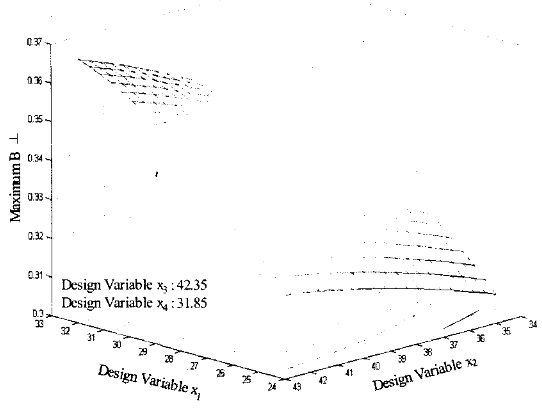
Fig. 3 shows the predicted response surfaces versus design variables. The RSM offers a systematic and efficient approach to study the effect of design variables and overall perspective of the system response according to the variation of design variables within a design space.



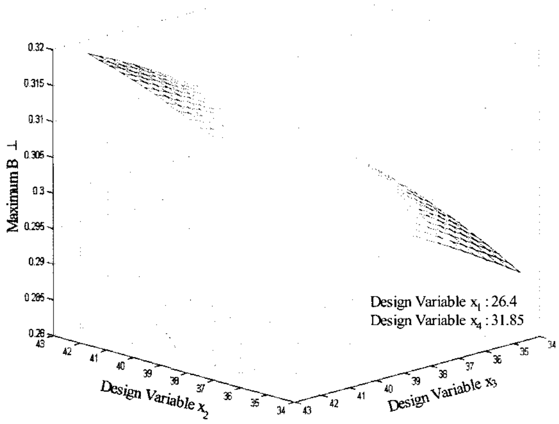
(a) according to variation between x_3 and x_4



(b) according to variation between x_1 and x_4



(c) according to variation between x_1 and x_2



(d) according to variation between x_2 and x_3

Fig. 3. Response surface versus design variables

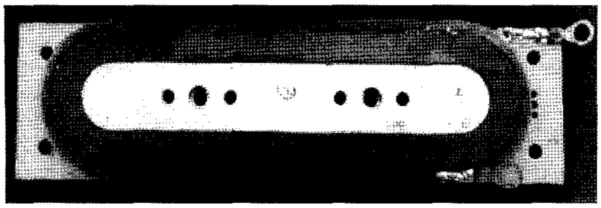
Table 1 shows the numerical optimization result, Fig. 4 shows the photographs of the initial design and the optimized design of the magnet, and Fig. 5 shows experimental results of the Ic (critical current) at the pair layer L5-L6.

4. Conclusions

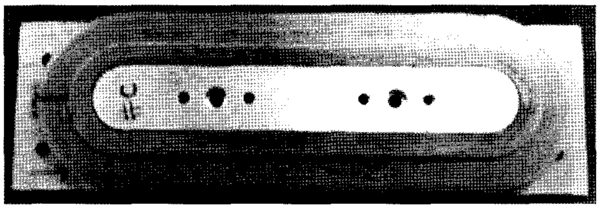
The main point in this paper is the optimization design of the magnet shape in order to reduce the maximum $B_\perp$. The deterministic Response Surface Method is used as the optimization technique. The Response Surface Methodology was well adapted to make the analytical model of the

Table 1. Results of the numerical optimization

Section	x_1 (L6)	x_2 (L4-L5)	x_3 (L2-L3)	x_4 (L1)	Maximum $B_\perp$
Initial design	33.1	39.35	39.35	39.35	0.360
Optimum design	24.6	42.35	42.35	31.85	0.325



(a) Initial magnet



(b) Optimized magnet

Fig. 4. Initial and optimized shape of the magnet

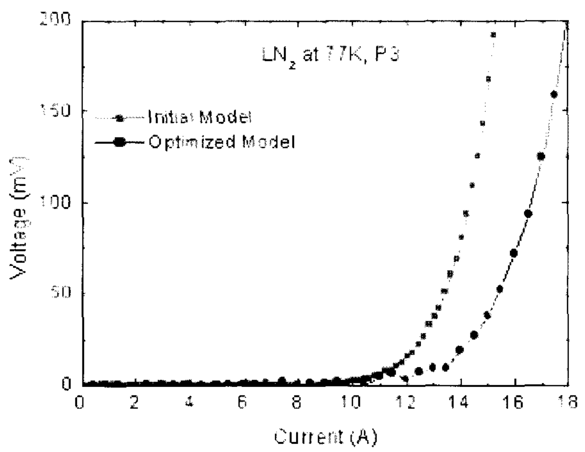


Fig. 5. Compare Ic between initial and optimized magnet at the layer L6-L5

maximum $B_{\perp}$, and enables the objective function to be easily createdand a great deal of the time in computation to be saved. Therefore, it is expectedthat the proposed optimization procedure using the Response Surface Methodology can be easily utilized to solve the optimization problem of electric machines

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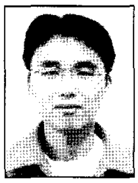

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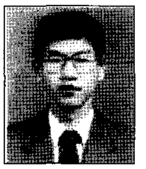

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