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Hanbat National University, Korea, South (Republic of)

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1: Dong-A University, Korea, South (Republic of); 2: Korea Electrotechnology Research Institute, Korea, South (Republic of)

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1: New Product Development Group, Meidensha Corp., Tokyo, Japan; 2: Dept. of Electrical and Electronic Engineering, Saga Univ., Saga, Japan

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Prediction of conductor ratio for Tubular Linear Induction Motor using Finite Element Method and Response Surface Methodology

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In many countries demand of motor is rapidly increased. For equipment automation and reducing of energy motor is high efficiency machine, and this plays an important role about current energy crisis. But until today rotary machine has been studied in the various fields, however linear machine is not. Also Tubular Linear Induction Motor (TLIM) has been developed for use in the industry, but this machine is unknown for analyzing the characteristic. In this paper using the Finite Element Methodology (FEM), TLIM was examined the ratio of conductor thickness and back iron. For obtaining this result, Design of Experiment (DOE) and Response Surface Methodology were used. Also FEM is used the analysis, this method is efficient and powerful to analyze the TLIM under time harmonic field. TLIM is modeled to obtaining thrust force in the steady state. And using the DOE, conductor and back iron thickness is efficiently assigned. CCD that was introduced in this paper, used in various methods about DOE. As a result, ratio of conductor and back iron thickness is obtained optimum value. This ratio is helpful to design the TLIM about low voltage.

Index Terms— Design of experiment (DOE), finite element method (FEM), equivalent magnetic circuit network method, optimization, Tubular linear induction motor (TLIM), response surface methodology (RSM).

I. Introduction

In all modern industries, for improving productivity and reducing of the unit cost of production demand of the factory automation and energy saving is increasing. Especially the motor is used power source in mostly industrial settings. So the performance and characteristic of this machine is played an important a leading role of energy reducing and automation [1]. In generally a number of industrial machines are rotary type, but this machine is difficult of applying the linear motion system. If rotary type motor is used linear motion system, the loss of gear, ball screw and belt due to mechanical friction is generated. Also complex circuit composition and efficiency is not reasonable. So linear motion motor for generating the straight thrust force is developed machine. This machine is tubular linear induction motor and this application is diversified [2].

Design of experiment is application of statistics on purpose of designing efficient method and analyzing the result. In other word, in respect of resolution matter, DOE can be described plan of acting the experiment, getting the resulting data, and analyzing the data of resulting. Through this method, minimum number of experiment resulted in maximum information. DOE is advanced from agriculture in 1920, since than this is applied from agriculture experiment to medical science, engineering, experimental psychology, and sociology. In this paper, central composite design among is applied among the DOE.

Through the DOE, sampling points are obtained. And optimal solution result in using RSM about sampling points. Approximate polynomial equation of response of system about complex combination of parameters is effect of design parameter and response surface have the optimal design. DOE is a optimal combination of design parameter, RSM is a form of obtaining a mathematical relational expression about combination of design parameters.

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II. Analysis Model and Design Parameter

A. Analysis model

In this paper in the TLIM, analysis is performed about each power; 200W, 300W, 400W, 500W, 600W. Fundamental model is Fig. 1. The primary of a flat linear induction motor is rolled about an axis parallel to the direction of the traveling field. The field travels along the bore of the stator (or primary). The mover consists of a cylindrical ferromagnetic core having a conducting sleeve mounted over it. The main advantages of the TLIM are that it is rugged and easy to construct. TLIM are particularly suited for short-stroke applications [3], [4].

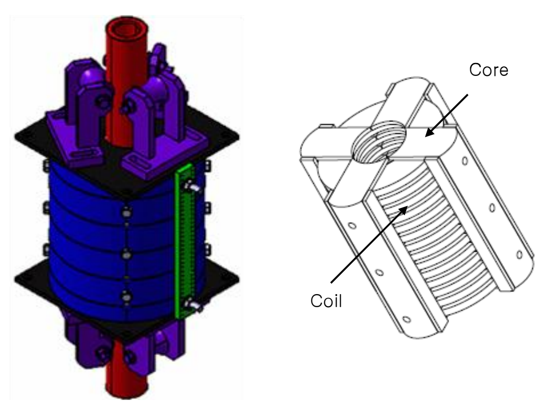


Fig. 1. Structure of TLIM

In this paper 2p/13s model is presented. The dimension of an initial model is shown Fig. 2, and specification of the TLIM is shown TABLE I.

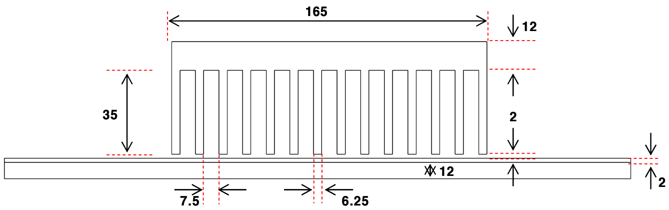


Fig. 2. Initial model

TABLE I
SPECIFICATION OF THE TLIM

	Value
Number of poles	2
Number of phases	3
Number of slots	13
Input voltage	220 V
Frequency	7 Hz
Conductor conductivity	3.12×10^7 S/m
Back iron conductivity	0.5×10^7 S/m
Mover material	S23

TLIM of introducing the paper is 2-pole machine, and winding configuration shows Fig. 3 [5].

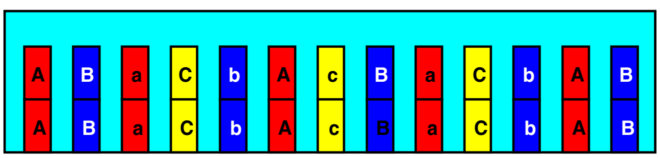


Fig. 3. Winding configuration

B. Design parameters

Parameters using the optimal design are conductor thickness, stator back iron, and tooth width. In linear motor minimum, conductor thickness and back iron thickness is required so as to obtain the maximum thrust force. Tooth width can be representable of various shapes.

Fig. 4 shows a variable for optimum design. Tooth width were determined by using equivalent magnetic circuit method, this is excluded in this optimal design.

III. ANALYSIS THEORY

In this section analysis theory shows the design of minimum reluctance about tooth width and the optimum design, and optimal design.

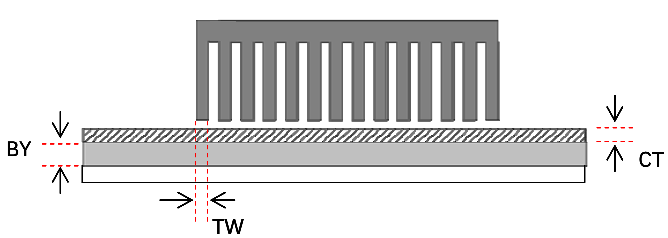


Fig. 4. Variable for optimal design

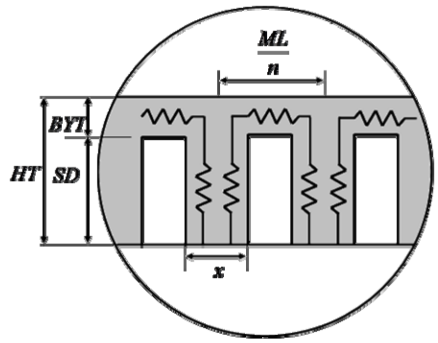


Fig. 5. Equivalent magnetic circuit of mover

A. Design of minimum reluctance

For obtaining the more output power, determine the tooth width and yoke width. In order to compute of this width, equivalent magnetic circuit is comprised of component that mover is divided. So tooth width and yoke width is determined of value that is minimum reluctance.

Fig. 5 shows the equivalent magnetic circuit of mover.

$$\begin{aligned} R_{total} &= R_{tooth} + R_{yoke} \\ &= 2 \times x \cdot L_{st} / \mu \left((HT + SD)/2 \right) \\ &\quad + \left((HT - SD) \cdot L_{st} / \mu \left((ML/n) - x \right) \right) \end{aligned} \tag{1}$$

$$SD = slot\ area / ((ML/n) - x) \tag{2}$$

where, R_{total} is the total reluctance, R_{tooth} is the tooth reluctance, R_{yoke} is the yoke reluctance, L_{st} is stack length, μ is the permeability, x is the tooth width.[6]

B. Optimum design

For performing the optimum design in target TLIM, DOE and RSM is used.

1) Design of experiment

In order to design of TLIM, DOE is applied before RSM. As the DOE is conducted, if various design parameter and high level is used, high efficiency may be obtained. But in this case, sampling point increase geometrically. So more cost and more effort is required by limited time about high level. To avoid this effort, DOE is needed. Result can be given the DOE through the efficient placement for minimum experiment.

DOE is concluded the number of undetermined coefficients of response shape and supposed approximate model. In case of applying the 2nd order polynomial regression model, n^k factorial design (FD), central composite design, and D-optimal design is generally used.

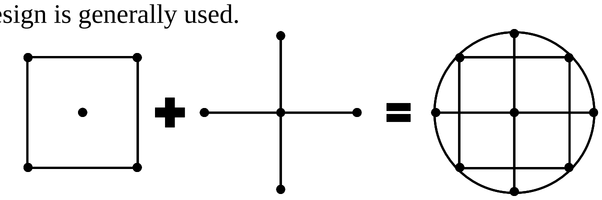


Fig. 6. Design of experiment-CCD

In this paper, between FD, CCD, D-optimal design, CCD is used. Complementing the demerit of FD and for increasing the efficiency, this method is shape that a n^k factorial design become with the central point and axial point. In n^k factorial design, the number of variable is k and lever is n. n^k factorial design is efficient of linear response. However curvature of response value is not detected. Practical utilization is limited. Also according to the number of design variable is increasing, this method is not efficiency because of increasing the experiment number [7], [8].

CCD is composed each variable of design that have 5 level, and sampling points are 9 at 2 variables. This explanation is presented Fig. 6. And this method has high level more than factorial design, so surface response is efficiently presented. Equation (3), (4) are presented the number of FD and CCD.

$$NS_{FD} = n^k \tag{3}$$

$$NS_{CCD} = 2^k + 2k + n_c \tag{4}$$

where, n_c is the number of central point that is more than one. If the number of design variable is three, sampling point of 3k factorial design is 27, but CCD is 15. So CCD is more efficient.

2) Response surface methodology

Experiment is conducted by sampling point of obtaining DOE. This result is applied RSM. RSM is the method that is function of relation between design variables and response. Through the result of DOE, outcome is conducted of approximating least square regression analysis about fist order or second order. And for analyzing of regression curve about accuracy, R^2 and adjust R^2 is used. This coefficient is error between exact value and estimation of regression curve [9]. R^2 and adjust R^2 shows equation (5), (6).

$$R^2 = \frac{SSR}{SST} \tag{5}$$

$$adjust\ R^2 = 1 - \frac{SSR/(N-k)}{SST/(N-1)} \tag{6}$$

where, N is total number of experiment, k is design variable number. SST, SSR, and SSE are following.

$$SST = \sum_{u=1}^{N} (y_u - \bar{y})^2 \tag{7}$$

$$SSR = \sum_{u=1}^{N} (\hat{y}_u - \bar{y})^2 \tag{8}$$

$$SSE = \sum_{u=1}^{N} (y_u - \hat{y})^2 \tag{9}$$

where, y is actual response, $\bar{y}$ is mean value of actual response, $\hat{y}$ is estimation value of regression curve [10]. Value of R^2 and adjust R^2 is between 0 and 1. And that value is nearer 1, approximation is good.

IV. Result & Discussion

According to each of output power, the regression curve is equation (10) ~ (14).

$$\begin{aligned} Y_{200W} &= 2.5414 - 3.8624A + 1.6871B - 3.6687C \\ &- 7.1468A^2 - 0.4254B^2 + 0.5106C^2 \\ &+ 0.2200AB + 4.8900AC + 0.0775BC \end{aligned} \tag{10}$$

$$\begin{aligned} Y_{300W} &= -127.069 + 13.5182A + 30.4581B + 20.1841C \\ &- 3.8086A^2 - 5.0940B^2 - 1.3332C^2 \\ &+ 3.0133AB - 0.8644AC + 0.5111BC \end{aligned} \tag{11}$$

$$\begin{aligned} Y_{400W} &= -5.03185 - 26.0310A + 15.8675B + 7.4655C \\ &- 4.6410A^2 - 0.7713B^2 - 0.5547C^2 \\ &+ 0.3987AB + 4.5381AC + -0.9943BC \end{aligned} \tag{12}$$

$$\begin{aligned} Y_{500W} &= 20.2838 + 13.0798A - 0.6742B - 1.7004C \\ &- 0.5972A^2 + 2.5446B^2 + 0.6460C^2 \\ &- 4.0296AB - 4.0296AC - 1.8988BC \end{aligned} \tag{13}$$

$$\begin{aligned} Y_{600W} &= 27.3360 + -0.9205A + 23.9074B - 12.4568C \\ &+ 1.4271A^2 - 1.3070B^2 + 0.6125C^2 \\ &+ 0.0817AB + 0.0819AC - 0.5197BC \end{aligned} \tag{14}$$

where, A is CT, B is TW, C is BY. R^2 is 0.89 and adjust R^2 is 0.80 @ 400W. This value is somewhat low.

Fig. 7 shows equi-potential distribution of TLIM under the rated condition of 400W. And Fig. 8 is fabricated TLIM.

Fig. 9 shows the optimum design of 400W. This response surface shows the three design variables that is a various combination of DOE. This three graphs show maximum thrust force response surface. Through the RSM, optimum design of each power shows TABLE II.

TABLE II
Result of Optimum Design

	A(mm)	B(mm)	C(mm)
200W	0.83	3.32	6.68
300W	1.50	3.75	7.79
400W	3.68	3.31	13.36
500W	4.60	4.14	16.70
600W	5.52	7.5	15.00

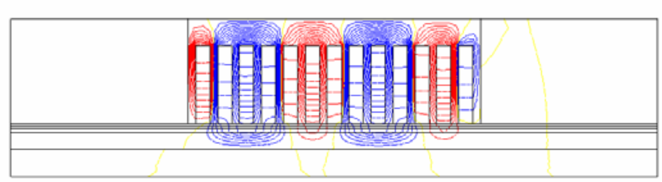
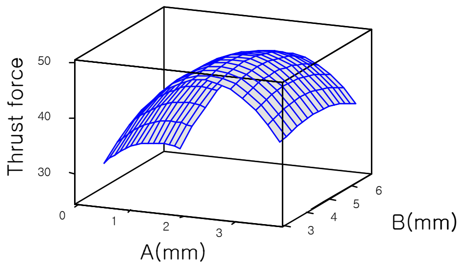
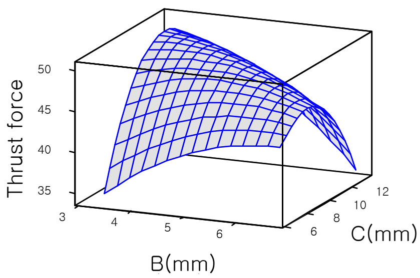


Fig. 7. Equi-potentials of 400W at rated condition (slip:0.5)

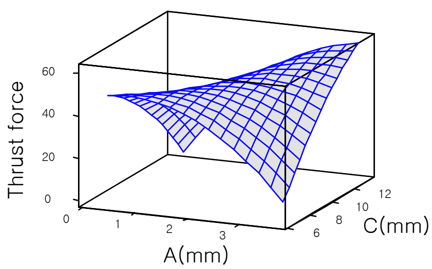
Fig. 8. Fabricated TLIM



(a) A combination of A and B



(b) A combination of B and C



(c) A combination of A and C

Fig. 9. Response surface model @ 400W

On analysis result, output power and ratio of conductor thickness and back iron is converged constant value, 2.8. If conductor thickness is constant, the more power capacity increases, the less back iron thickness. Finally this value converged to 2.8.

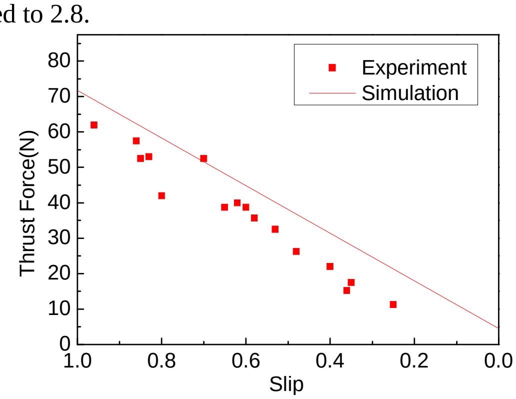


Fig. 10. Comparison of thrust force according to slip)

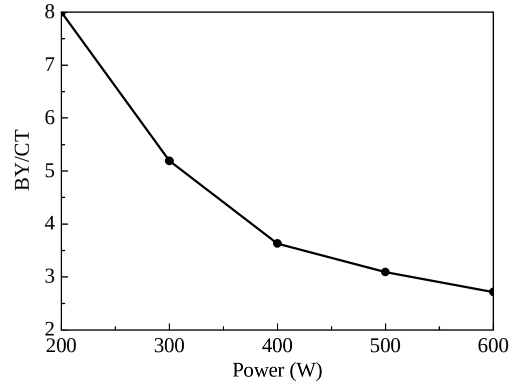


Fig. 11. Ratio of BY/CT according to power

Fig. 10 shows the thrust force comparison of experiment and simulation. Measurements are conducted with dc power supply calculated values follows the experiments well.

Fig. 11 shows this result. This result is reason that TLIM should perform a certain standard thrust force in a limited voltage.

V. Conclusion

In this paper the TLIMs are conducted optimum design by DOE and RSM.

Ratio of BY and CT of TLIMs according to power is examined in this paper. The result shows that power becomes larger, the ratio of BY and CT is converged 2.8. Although this result are constant voltage, this ratio is helpful by design of TLIM which of is low voltage.

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