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[PS I] Poster Session I

Date : September 21, 2009 (Monday)
Time : 10:00 ~ 11:00
Room : Room C (Regency Room A)
Chair : Kokichi Ogawa (Oita Univ., Japan)

Optimal Design for Light Weight Mover of Moving Coil Type Linear Motor

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Topics: 11

1. Introduction

Considering development of factory automation technologies, high speed and high accuracy of linear moving systems are essential for mass production. Generally rotary type electric machines are widely used, however, applying rotary machines to linear system have limitations. When rotary machines are used for linear moving systems, additional mechanical losses due to gears, ball screw, and belts are inevitable, and the system become complex and inefficient. Therefore, various designs of linear motors are studied to overcome such limitations of rotary machines. When the linear motor is applied to linear systems, linear motion can be directly acquired without additional mechanical loss, noise, and vibration inevitable when rotary machine is used. Therefore, linear motor has the advantages in terms of efficiency and productivity.

The characteristics of acceleration and deceleration operation influence to system performance significantly, therefore, the weight of mover is one of the major design factors. This paper deals with the optimal design of core type linear motor to reduce the weight of mover part. Response surface methodology (RSM) is used for the optimal design of linear motor [1]. In order to reduce the weight of mover under maintained thrust, yoke thickness, tooth width, and permanent magnet thickness are chosen to be design parameters.

Finite element method (FEM) is used for the thrust analysis and results are compared to that of initial model. By combining voltage and mechanical equations, dynamic characteristics are estimated and compared.

2. Analysis theory

Using FEM and dynamic equations, steady and transient state characteristics are calculated. Thrust force constant, back electromotive force constant, and inductance are calculated by FEM at rated load condition and applied to dynamic equations [2].

2.1. Calculation of thrust force

By solving governing equation, magnetic vector potential is calculated, and then flux density in each element is calculated. Finally force is calculated using Maxwell stress tensor. Electromagnetic force can be expressed;

$$\vec{F}=\frac{1}{\mu_0}\left(\int_S \vec{B}(\vec{B}\cdot\vec{n})\,dS-\int_S \frac{1}{2}\overline{B^2}\cdot\vec{n}\,dS\right)=\oint_S \vec{P}\,dS \qquad (1)$$

$$P_x=\frac{1}{2\mu_0}\left\{\left(B_x^2-B_y^2\right)n_x+2n_y B_x B_y\right\}$$
$$P_y=\frac{1}{2\mu_0}\left\{\left(B_y^2-B_x^2\right)n_y+2n_x B_x B_y\right\} \qquad (2)$$

$$T=\int_l h P_x\, dl\,(N\cdot m) \qquad (3)$$

where, $\vec{P}$ is Maxwell stress tensor, S is the surface area of volume V, $\vec{n}$ is the unit vector perpendicular to S. x, y components of Maxwell stress tensor and thrust force along stack length h, and integral path l can be calculated;

2.2. Calculation of thrust force

RSM is applied to make appropriate response models of the average thrust and mover mass. 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 [3], [4], [5].

$$Y=\beta_0+\sum_{i=1}^{k}\beta_i x_i+\sum_{i=1}^{k}\beta_{ii}x_i^2+\sum_{i\neq j}^{k}\beta_{ij}x_i x_j+\varepsilon \qquad (4)$$

where, β is regression coefficient for design variables, and 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

$$\hat{\beta}=(X'Y)^{-1}X'Y \qquad (5)$$
$$\hat{Y}=X\hat{\beta} \qquad (6)$$

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

3. Specifications of analysis model

Fig. 1 shows the structure of single sided core type linear motor of MC-type. Stationary part consists of permanent magnet and core material, and mover parts consist of armature coil and core material. Since the length of armature coil is short, small leakage flux and copper loss are expected. However, additional supplying part is required since armature part is moving. Table 1 shows the specifications of initial model.

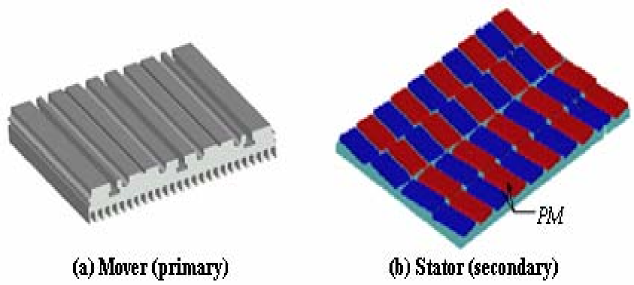


Figure 1: Structure of moving coil type linear motor.

Table 1 Specifications of linear motor.

		Items	Value	Unit
Mover		Pole/slot number	24/74	
		Conductor per slot/ Phase number	131/3	
		Stack length		mm
Stator	PM	type	Nd-Fe-B	
		Remnant flux density	1.33	T
		Width/ thickness/ length	24/5/50	mm
Air gap length			0.5	mm

4. Optimal design for light weight of mover

4.1. Design parameters

Figure 2 shows the size of initial model. Yoke thickness(x_1), tooth width(x_2), and permanent magnet thickness(x_3) are chosen to be design parameters for mover weight reduction under constraint of same average thrust force with initial model.

The relations between design parameter and mover weight is approximated by second order polynomial, and 6437Nm of average thrust force is used for constraint. In addition, sequential quadratic programming (SQP) is used to get the solution of optimization problem having constraints.

Objective function: $f(x) = f_{mass}(x)$

Subject to: $g_1(x) = f_{mean}(x) \geq 6,437$

$4.0 \leq x_1 \leq 8.0,\ 3.0 \leq x_2 \leq 4.0,\ 5.0 \leq x_3 \leq 6.0$

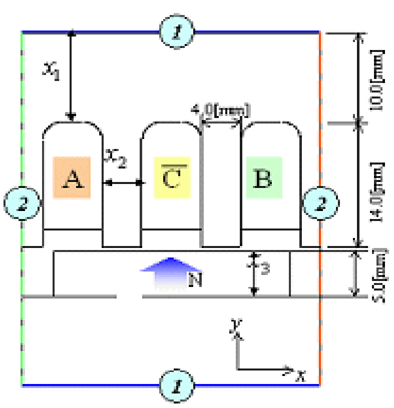


Figure 2: Initial model.

4.2. Optimal design result

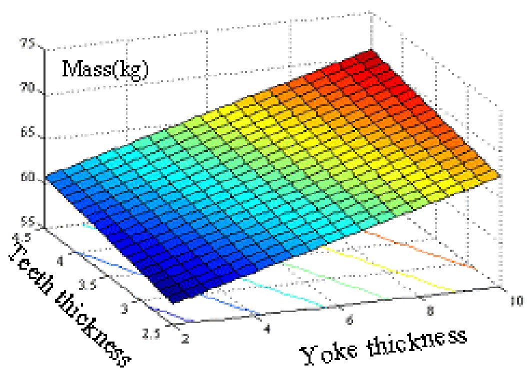
Table 2 shows the optimal design results. Figure 3 shows the response surface of average thrust force and mover mass according to the yoke thickness and tooth width. Using RSM, average thrust force is estimated according to yoke thickness and tooth width, and then optimal design values are determined. From the RSM results, yoke thickness decreased to 65% from initial design and permanent magnet thickness is increased to 27% from initial model to compensate the decreased average thrust force due to saturation. The weight of mover decreased to 35.3% from initial model. From the FEM results, the average thrust force of designed model is 6500Nm, which is 1% increased from initial model. In Figure 4, thrust forces of initial and optimal model are compared according to displacements.

4.3. FEM result of optimal model

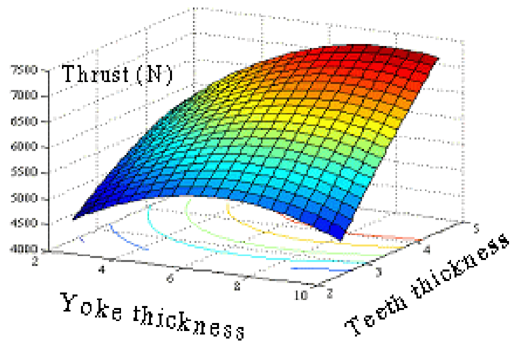
Figure 5 shows equi-potential line and flux density of initial model and optimal model at displacement 0(mm). As shown in the figure, flux saturation in teeth (C_1) and yoke (C_2) of optimal model is higher than initial model. Figure 5, 6 and 7 show flux density distribution in air-gap, teeth, and yoke respectively. Due to saturation effect, magnetic voltage drop in iron core of optimal model is higher than that of initial model. Nevertheless, both initial and optimal model present similar amplitude of flux density in iron core, because operating point of permanent magnet of two models are similar even though increased thickness of permanent magnet of optimal model.

Table 2: Optimal design results.

	Initial model	Optimal model	Improve ment
Yoke thickness($x1$) [mm]	10	4.5	65(%)↓
Tooth width ($x2$) [mm]	4	4	-
Permanent magnet thickness($x3$) [mm]	5	6.35	27(%)↑
Average thrust force[Nm]	6,437	6,500	1(%)↑
Mover weight [kg]	19.5	12.6	35.3(%)↓
Total mover part weight [kg]	70	63.1	10(%)↓
Average thrust force per weight [Nm/kg]	92	103	12(%)↑



(a) Response surface of mover mass



(b) Response surface of average thrust force

Figure 3: Response surface of average thrust force and mover mass according to the yoke thickness and tooth width.

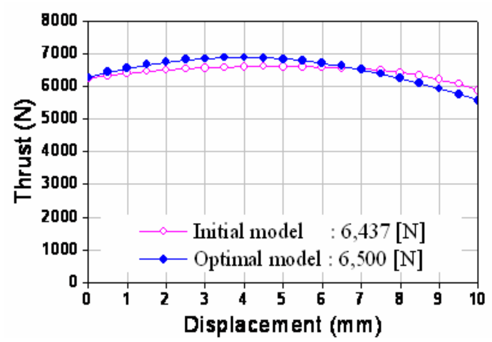


Figure 4: Thrust forces of initial and optimal model according to displacements

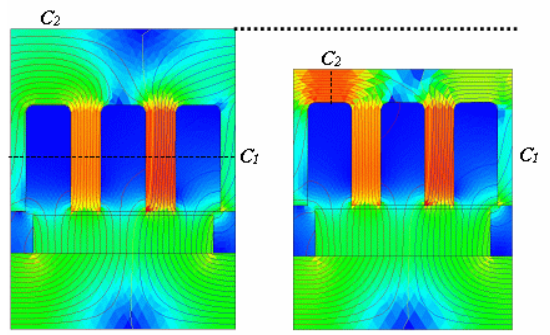


Figure 5: Comparison of equivalent potential line and flux density of initial model and optimal model at displacement 0(mm)

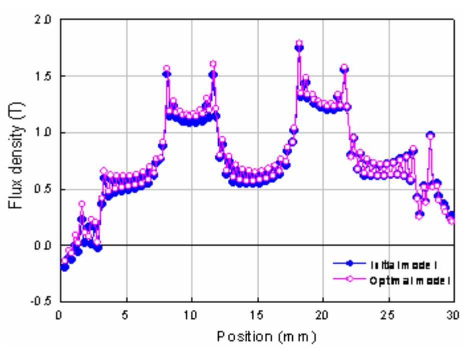


Figure 6: Flux density at air-gap (B_y component)

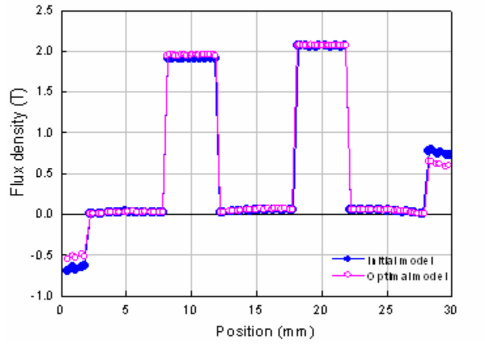


Figure 7: Flux density at teeth C_1 (B_y component)

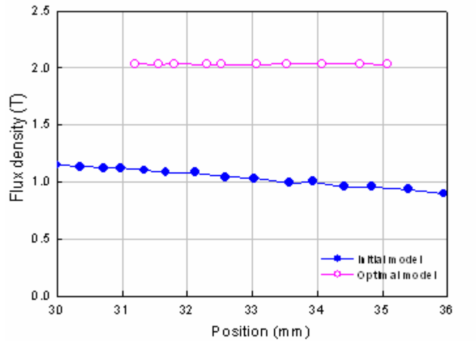


Figure 7: Flux density at yoke C_2 (B_x component)

5. Conclusion

This paper presents a magnet circuit design procedure to reduce mover weight of the MC-Type Linear Motor. The procedure of optimization is based on the FEM and RSM. The result of optimization is that the weight of mover in linear motor is reduced about 10% due to the reduction of yoke thickness about 65%. At the same time PM thickness is optimized to compensate reduced average thrust force.

References

[1] Sung-Il Kim, “Optimal Design of Slotless-Type PMLSM Considering Multiple Responses by Response Surface Methodology”, IEEE TRANSACTIONS ON MAGNETICS, vol. 42, pp.1219-1222, April 2006.

[2] J.-Y. Lee, “Computation of inductance and static thrust of a permanent-magnet-type transverse flux linear motor”, IEEE TRANSACTIONS ON MAGNETICS, vol. 42, pp.1566-1569, April 2006.

[3] D. C. Montgomery, Design and Analysis of Experiments. New York: Wiley, 2001.

[4] Y. K. Kim, J. P. Hong, G. H. Lee, and Y. S. Jo, “Application of response surface methodology to robust design for racetrack type high temperature superconducting magnet,” IEEE Trans. Appl. Supercond., vol. 12, no. 1, pp. 1434–1437, Mar. 2002.