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Minimization of driving force ripple of linear motor for rope-less elevator using topology optimization technique

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Abstract

The reduction of the ripple of driving force is especially required for the practical utilization of linear synchronous motor for rope-less elevator. In this paper, the magnetic region of the linear motor is optimized by using topology optimization techniques (density method and ON/OFF method) in order to reduce the ripple of driving force. The optimal results of both methods are compared, and useful information for the optimal design of linear motor is obtained.

Keywords: Density method; ON/OFF method; Topology optimization; Core-less linear synchronous motor; Adjoint variable method

1. Introduction

In the conventional optimization problem, such as size and shape optimization [1], the outline of magnetic circuit should be given beforehand. The topology optimization based on the density method [2,3] does not need such an initial shape of magnetic circuit, and also the knowledge of experience. This method provides useful information for engineers in order to start the design of electromagnetic machines.

In the conventional density method [2,3], the material density is the design variable, which changes continuously from zero to unity. There occurs some gray scale elements (the medium value of material density) in the optimal topology obtained by the above-mentioned method. Then, an efficient method called as ON/OFF method, by which the continuous shape of magnetic material can be successfully obtained, is proposed [4,5] by utilizing the adjoint variable method [6].

A basic demand for an elevator system is the smoothness of motion of the permanent magnet synchronous motor. The controlling performance extremely drops because of the feedback of the oscillation of acceleration, velocity, and position by the ripple of driving force. Therefore, the design of lower ripple linear motor is needed for the practical utilization of rope-less elevator system.

In this paper, in order to reduce the ripple of the driving force, the optimal topology of magnet region is obtained by using the ON/OFF method [4,5], in which the existence of magnetic material in each element is decided by using the design sensitivity. The ON/OFF method is compared with the conventional density method [2,3] in order to illustrate the effectiveness of these methods from the viewpoint of convergence characteristic and practical utilization of obtained topology.

2. Topology optimization technique

2.1. Sensitivity analysis methods

The sensitivity is accurately calculated by using the adjoint variable method [6]. The equation for finite element method (FEM) is given as:

$$\boldsymbol{H}\boldsymbol{A} = \boldsymbol{G}, \tag{1}$$

where $\boldsymbol{H}$ is the coefficient matrix, $\boldsymbol{A}$ is the magnetic vector potential, and $\boldsymbol{G}$ is the right-hand vector. Taking the derivative of (1) with respect to the remanence B_r in an element k:

$$\frac{\partial \boldsymbol{A}}{\partial B_{\mathrm{r}k}} = \boldsymbol{H}^{-1}\left(\frac{\partial \boldsymbol{G}}{\partial B_{\mathrm{r}k}} - \frac{\partial \boldsymbol{H}}{\partial B_{\mathrm{r}k}}\tilde{\boldsymbol{A}}\right), \tag{2}$$

where $\tilde{\boldsymbol{A}}$ is obtained by solving (1). If the objective function is expressed as the function $W\,(B_{\mathrm{r}k}, \boldsymbol{A})$ of the permeability in design domain and the magnetic vector potential, the sensitivity with respect to the remanence $B_{\mathrm{r}k}$ is given by:

$$\frac{\mathrm{d}W}{\mathrm{d}B_{\mathrm{r}k}} = \frac{\partial W}{\partial B_{\mathrm{r}k}} + \frac{\partial W}{\partial \boldsymbol{A}}^{\mathrm{T}}\frac{\partial \boldsymbol{A}}{\partial B_{\mathrm{r}k}}, \tag{3}$$

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substituting (2) into (3):

$$\frac{\mathrm{d}W}{\mathrm{d}B_{\mathrm{r}k}}=\frac{\partial W}{\partial B_{\mathrm{r}k}}+\frac{\partial W}{\partial \boldsymbol{A}}^{\mathrm{T}}\boldsymbol{H}^{-1}\left(\frac{\partial \boldsymbol{G}}{\partial B_{\mathrm{r}k}}-\frac{\partial \boldsymbol{H}}{\partial B_{\mathrm{r}k}}\tilde{\boldsymbol{A}}\right). \tag{4}$$

In order to avoid the calculation of the inverse of $\boldsymbol{H}$, an adjoint vector λ is introduced. The adjoint equation is given by:

$$\boldsymbol{H}^{\mathrm{T}}\lambda=\frac{\partial W}{\partial \boldsymbol{A}}, \tag{5}$$

$\mathrm{d}W/\mathrm{d}B_{\mathrm{r}k}$ is calculated by substituting $\boldsymbol{\lambda}$ into (6).

$$\frac{\mathrm{d}W}{\mathrm{d}B_{\mathrm{r}k}}=\frac{\partial W}{\partial B_{\mathrm{r}k}}+\lambda^{\mathrm{T}}\left(\frac{\partial \boldsymbol{G}}{\partial B_{\mathrm{r}k}}-\frac{\partial \boldsymbol{H}}{\partial B_{\mathrm{r}k}}\tilde{\boldsymbol{A}}\right), \tag{6}$$

(6) means that only one extra solution for the adjoint vector is needed in order to determine the sensitivity to all parameters, rather than obtaining each value per parameter, providing a computationally fast method for deriving the gradients.

2.2. Density method

In the case of the calculation of the magnet topology, the relation of the material density ρ and remanence B_r in an element i is given by:

$$B_{\mathrm{r}i}=B_{\mathrm{r}0}{\rho_i}^n(0\le\rho\le 1), \tag{7}$$

where $B_{\mathrm{r}0}$ is the standard value of remanence, which is chosen as 1.2 T, and n, which is set as 2, is the exponent for the relationship. The normalized density ρ takes the value between 0 and 1. The design sensitivity of W with respect to ρ_i can be written as:

$$\frac{\mathrm{d}W}{\mathrm{d}\rho_i}=\frac{\partial W}{\partial B_{\mathrm{r}i}}\frac{\partial B_{\mathrm{r}i}}{\partial\rho_i}=nB_{\mathrm{r}0}\rho^{n-1}\frac{\partial W}{\partial B_{\mathrm{r}i}}, \tag{8}$$

where $\partial W/\partial B_{\mathrm{r}i}$ is calculated by (6). The calculated sensitivity is used to search the optimal distribution of the material density in magnet region. The steepest descent method is adopted as an optimization algorithm because there is no constraint on the volume of the magnet region. In the steepest descent method, ρ in the $(k+1)$-th iteration is updated by using the design sensitivity following (9):

$$\boldsymbol{\rho}^{(k+1)}=\boldsymbol{\rho}^{(k+1)}+\Delta\boldsymbol{\rho}^{(k)}, \tag{9}$$

where $\Delta\rho^{(k)}$ is the change vector. $\Delta\rho^{(k)}$ is given as:

$$\Delta\boldsymbol{\rho}^{(k)}=-\alpha^{(k)}\frac{\partial W^{(k)}}{\partial\boldsymbol{\rho}^{(k)}}, \tag{10}$$

where $\alpha^{(k)}$ is the step size. $\alpha^{(k)}$ is given as:

$$\alpha^{(k)}=W^{(k)}/||\partial W^{(k)}/\partial\rho^{(k)}||^2. \tag{11}$$

Then, $\rho^{(k+1)}$ is given by

$$\boldsymbol{\rho}^{(k+1)}=\boldsymbol{\rho}^{(k)}-\frac{W^{(k)}}{||\partial W^{(k)}/\partial\boldsymbol{\rho}^{(k)}||^2}\frac{\partial W^{(k)}}{\partial\boldsymbol{\rho}^{(k)}}. \tag{12}$$

When the change of the material density $|\Delta\rho|$ is less than 10^{-3} in each element, the topology optimization is terminated.

2.3. ON/OFF method

The gray scale element is generated by using the above density method. Then, the ON/OFF method [4,5], in which the existence of magnetic material in each element is decided by using the design sensitivity, is adopted because of no existence of gray scale element. The algorithm of the ON/OFF method is as follows:

Step 1: (initialization) The initial material location is decided. The initial material of the design domain is air.
Step 2: (forward analysis) The calculation of initial topology by using the finite element method (FEM).
Step 3: (sensitivity analysis) The calculation of design sensitivity by using the adjoint variable method.
Step 4: (modification of topology) The topology is modified using the design sensitivity. If $\partial \mathrm{W}/\partial \mathrm{B}_{\mathrm{r}i}$ is negative, the remanence in an element i should be increased. Therefore, the magnet is allocated in the element i. On the other hand, if the sensitivity $\partial \mathrm{W}/\partial \mathrm{B}_{\mathrm{r}i}$ is positive, the remanence in the element i should be decreased. Then, the air is allocated in the element i.
Step 5: (forward analysis) The magnetic field of the modified topology is calculated using FEM. If the objective function is improved, return to Step 3. Otherwise, go to Step 6.
Step 6: (annealing) If the objective function is not improved, the changeable element number N_{m} of material is relaxed by using the following Eq. (13):

$$N_{\mathrm{m}}=\gamma N_{\mathrm{m}}, \tag{13}$$

where γ is the annealing factor and chosen as 0.9. The obtained topology in this step is calculated by FEM. This step is continued until some improvement of the objective function is detected. If the objective function is improved, go to Step 3. Otherwise, the optimization is terminated.

3. Linear synchronous motor model

3.1. Analyzed model

The analyzed model of core-less type linear synchronous motor model is shown in Fig. 1. The analyzed region is chosen as the upper half region considering the axis-symmetry. The hybrid-type infinite element [7] is adopted in the outer region of air in order to reduce the calculation cost. The analyzed region is subdivided by the first order rectangular element. The amplitude of current density J_0 in three-phase system is 3.125×10^6 A/m^2.

The dimension of the analyzed model is shown in Fig. 2. The gap length between the magnet and the coil is 4 mm, the thickness of magnet is 8 mm. The number of elements nd in design domain is 6720, and the total number of elements is 45 600. The waveform of three-phase alternative current is shown in Fig. 3. One period is equal to the distance of the movement of 120 mm. The FEM calculation is performed at every 5 mm displacement of magnet region in two-dimensional magneto-