Multi-component Layout Optimization Method for the Design of a Permanent Magnet Actuator

Sunghoon Lim[1], Seungmin Jung[2], and Seungjae Min[3]

Department of Automotive Engineering, Hanyang University, Seoul, Korea,
sleeplim82@hanmail.net[1], tidakss@naver.com[2], seungjae@hanyang.ac.kr[3]

This paper presents a multi-component layout optimization method that incorporates a parametric and topology optimization method to determine the optimal shape of a permanent magnet actuator (PMA). The optimal position and size of the rectangular-type permanent magnet (PM) are obtained by the design sensitivities of size parameters. The level set based topology optimization method, which can guarantee a high degree-of-freedom in geometrical change, is employed to obtain the optimal distribution of the ferromagnetic material (FM) that can affect the path of the magnetic flux. The optimization problem is formulated to maximize the magnetic force of the PMA under the fixed volume fraction constraint of each material. The magnetic properties of the PM and FM, such as the magnetic relative reluctivity and the direction of the remanent magnetic flux, are calculated by the geometric parameters and the sign of the level set function. To confirm the effectiveness of the proposed method, a design example of a simple C-core actuator is provided.

***Index Terms*—Design optimization, level set method, multi-component layout optimization method, parametric optimization, permanent magnet actuator (PMA)**

I. INTRODUCTION

SINCE THE driving performance of the permanent magnet actuator (PMA) is dominated by the shape and position of the magnetic material, the development of an effective optimization design method has been an important issue in computational magnetics. Thus, some researchers have proposed a design method to optimize the length, position, and angle of the magnetic material, such as the permanent magnet (PM) and ferromagnetic material (FM), for enhanced performance of PMA by using a few geometrical parameters [1]-[2]. However, the parametric design method is not suitable for the conceptual design stage because the optimal solutions strongly depend on the initial design and the number of design parameters. To overcome these limitations, the topology optimization method, which can guarantee a high degree-of-freedom in geometrical change, was applied to the magnetic design problem [3]-[4]. These previous studies provided an innovative optimal design that can improve the PMA's performance dramatically, but at the cost of producing a highly complicated shape [5].

This paper proposes a multi-component layout optimization method that incorporates parametric and topological design variables to find the optimal shape of a PMA. Since the complex boundaries of PM may cause a manufacturing problem, the parametric design method is employed to obtain the optimal size and position of PM with maintaining the rectangular shape. The optimal distribution of FM that has a great effect on the path of magnetic flux is determined by the topological derivative of the level set function. The optimization problem is formulated to maximize the magnetic force of PMA under the fixed volume fraction constraint of each material. The magnetic properties of PM and FM, such as the magnetic relative reluctivity and the direction of remanent magnetic flux, are calculated by the geometric parameters and the sign of the level set function. To improve an accuracy of magnetic analysis, an adoptive re-meshing technique is employed to express the outer surface of magnetic materials precisely. A design example will be provided to suggest the optimal layout of the high-efficient PMA and to verify the usefulness of the proposed method.

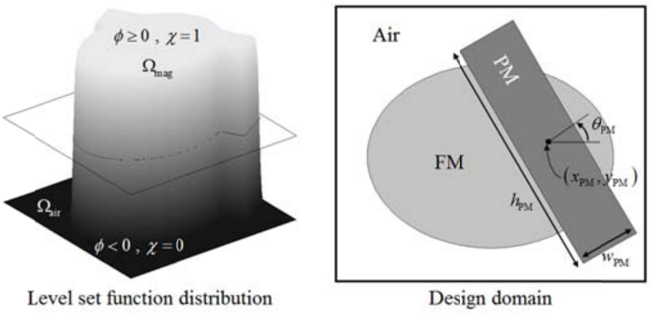
II. OPTIMIZATION PROBLEM FORMULATION

A. Design variables

To represent the shape of the multi-material and perform the magnetic analysis of the PMA, two types of design variables were introduced. First, the level set function (ϕ), which has a different sign according to the nodal coordinate ($\mathbf{x}$), was employed to represent the outer surface of the PMA. The material domain of the PM and FM (Ω_{mag}) can be determined by the positive sign of the level set function as follows:

$$\begin{cases} \phi(\mathbf{x}) \geq 0,\ \chi(\phi(\mathbf{x})) = 1 & \text{for } \mathbf{x} \in \Omega_{\mathrm{mag}} \\ \phi(\mathbf{x}) < 0,\ \chi(\phi(\mathbf{x})) = 0 & \text{for } \mathbf{x} \in \Omega_{\mathrm{air}} \end{cases} \tag{1}$$

where χ is the smooth step function and Ω_{air} is the non-material domain. In the material domain, the PM and FM can be distinguished by five simple parameters, as shown in Fig. 1.



Level set function distribution

Design domain

Fig. 1. Expression of the magnetic material

The shape of the PM is represented by two size parameters ($h_{\mathrm{PM}}, w_{\mathrm{PM}}$) for preventing complex geometrical change, and the PM's position is controlled by the central coordinate ($x_{\mathrm{PM}}, y_{\mathrm{PM}}$) and the rotating angle (θ_{PM}). It is noted that the value of the level set function on the PM region is needed for the continuity of the design sensitivity around the interfacial area between the PM and FM, not for the expression of the shape and property of the PM.

B. Optimization problem formulation

The optimization problem for maximizing the magnetic force (F) of a PMA can be formulated with the volume fraction constraints as follows:

$$\begin{aligned} &\text{minimize } F\left(\mathbf{s}_{\mathrm{PM}},\phi\right),\ \ \mathbf{s}_{\mathrm{PM}}=\left[x_{\mathrm{PM}},y_{\mathrm{PM}},\theta_{\mathrm{PM}},h_{\mathrm{PM}},w_{\mathrm{PM}}\right]^{T} \\ &\text{subject to } G_1\left(\phi\right)=\int_{\Omega}\chi\, d\Omega \Big/ \int_{\Omega} d\Omega \le \mathrm{VF}_{\mathrm{PM}}+\mathrm{VF}_{\mathrm{FM}} \\ &\qquad\qquad G_2\left(\phi\right)=h_{\mathrm{PM}}\cdot w_{\mathrm{PM}} \le \mathrm{VF}_{\mathrm{PM}} \end{aligned} \tag{2}$$

where $\mathrm{VF}_{\mathrm{PM}}$ and $\mathrm{VF}_{\mathrm{FM}}$ are the fixed volume fraction constraint of the PM and the FM. The design sensitivities for the PM's parameters ($\mathbf{s}_{\mathrm{PM}}$) can be calculated by the derivative for the objective function as follows:

$$\frac{\partial F\left(\mathbf{s}_{\mathrm{PM}},\phi\right)}{\partial s_{\mathrm{PM},i}}=\frac{F\left(\mathbf{s}_{\mathrm{PM}}+\Delta s_{\mathrm{PM},i},\phi\right)-F\left(\mathbf{s}_{\mathrm{PM}},\phi\right)}{\Delta s_{\mathrm{PM},i}} \tag{3}$$

where $\Delta s_{\mathrm{PM},i}$ is the variation of each design parameter of which the value can be changed for convergence of the optimization.

III. NUMERICAL EXAMPLE

The proposed method is applied to the design optimization of the C-core PMA. The initial design and design domain are illustrated in Fig. 2. The remanent flux of the PM ($\mathbf{B}_r$) is calculated by the angle parameter (θ_{PM}) as follows:

$$\mathbf{B}_r\left(\theta_{\mathrm{PM}}\right)=\left[B_r\cos\theta_{\mathrm{PM}}\ \ B_r\sin\theta_{\mathrm{PM}}\right]^{T} \tag{4}$$

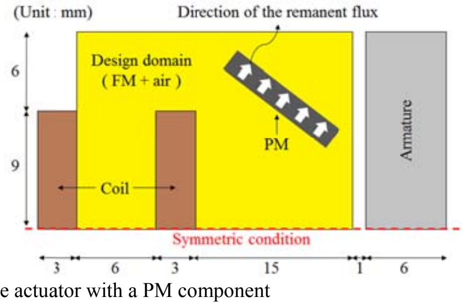


Fig. 2. C-core actuator with a PM component

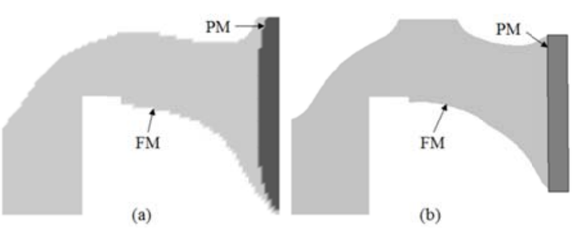


Fig. 3. Optimal shape of the c-core actuator: (a) level set method (b) proposed method

where B_r is the remanent flux density of the PM. The volume fraction constraints of the PM and FM are set to 0.05 and 0.45, respectively.

Fig. 3(a) shows the optimal shape of the C-core actuator in case only topological design variables are employed using multi-phase level set model [6]. Even if this design can concentrate the magnetic flux from the core to the armature and, hence, maximize the magnetic force significantly, the outer surface of the PM becomes a non-uniform curve, making it inappropriate for the manufacturing and magnetizing process. On the other hand, the optimal PM design from the proposed method maintains a rectangular shape while the size and position parameters are optimized, as illustrated in Fig. 3(b). The optimal distribution of FM, which was obtained by the level set function, can minimize the magnetic reluctance and the leakage flux inside the design domain. It is noted that the optimal layout of the PMA from the proposed method consists of clear boundaries because an adoptive re-meshing technique was applied to track the updated surface of each material precisely. Even though the magnetic force of the PMA decreased slightly compared with the previous level set method as summarized in Table 1, it permits the design of a practical PMA layout that can achieve both enhanced performance and manufacturability.

TABLE I
COMPARISON OF RESULTS ACCORDING TO THE OPTIMIZATION METHOD

Optimization method	Magnetic force [N/m]
Level set based topology	615.6
Proposed (parameter + level set based topology)	586.2 (4.8%↓)

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