Optimal Rotor Structure of Surface-mounted Permanent Magnet Motor for Vibration Reduction

Sunghoon Lim, Seungjae Min and Jung-Pyo Hong
Department of Automotive Engineering, Hanyang University
222 Wangsimni-ro, Seongdong-gu, Seoul, 133-791, KOREA
sleeplim82@hanmail.net, seungjae@hanyang.ac.kr (corresponding author), hongjp@hanyang.ac.kr

***Abstract*—This paper presents a new optimization method to design a rotor structure of surface-mounted permanent magnet (SPM) motor which can reduce the vibration. The optimization problem is formulated to minimize both the harmonic components of radial force and the torque fluctuation which are main factors of motor vibration. To obtain the optimal rotor shape consisting of permanent magnet and ferromagnetic material, a multiple level set model is employed to express the structural boundaries and magnetic properties of each material. The updating process of level set function based on the adjoint sensitivity and the time evolutional equation makes possible to obtain the novel rotor configuration of SPM motor. To verify the usefulness of the proposed method, the rotor design example of SPM motor for electric power steering (EPS) system is performed.**

***Index Terms*—Surface-mounted permanent magnet motor, vibration reduction, rotor design, harmonic elimination, torque ripple reduction**

I. INTRODUCTION

Since mechanical vibration is harmful to the robustness of an integration system and generates audible noise, which is a critical factor in human sensitivity, vibration reduction has become an important issue especially in motor design of automotive applications [1]-[2]. Many studies have noted that the main sources of motor vibration are harmonic components of magnetic force and the fluctuation of torque, and hence proposed several methods such as modification of motor shape [3]-[4] and pole-slot combination [5] to eliminate them. Especially in the surface-mounted permanent magnet (SPM) motor where the permanent magnet (PM) dominates the magnetic flux path, the shape change of the rotor is a key to vibration reduction [6]. However, it’s hard to design the detailed motor’s geometry for minimizing vibration by using previous approaches depends on the experimental data and engineering intuition.

In this paper, an optimization method with consideration of localized geometrical change [7] is introduced to get an innovative rotor design that guarantees a decrease in the motor vibration. The level set functions are employed to express the clear boundaries of the rotor and calculate the magnetic properties of PM and ferromagnetic material (FM). The optimization problem is formulated to minimize both the harmonic components of radial magnetic force and the torque ripple with maintaining the power density. The optimization is performed by solving the time evolutional equation which can lead to initial-independent results. The design example of a SPM motor is provided to investigate the effectiveness of the proposed method and achieve the optimum rotor design that promises reducing the vibration while the output torque is not deteriorated.

II. PROBLEM FORMULATION

A. Material Modeling and Analysis

To perform the magnetic analysis, two level set functions (ϕ_1, ϕ_2) which have a signed scalar value are introduced for representing the structural boundaries and material properties of PM and FM in the rotor [8]. Magnetic properties (p) such as the relative magnetic reluctivity (ν_r) and the remanent flux density (B_r) are defined by characteristic function as follows:

$$p(\chi_1, \chi_2) = \chi_1\left[p_{PM}\chi_2 + p_{FM}(1-\chi_2)\right] + p_{air}(1-\chi_1) \tag{1}$$

where χ_i is the characteristic function of which value is 1 or 0 according to the sign of each level set function. Fig. 1 shows how to separate each material domain and express its boundaries.

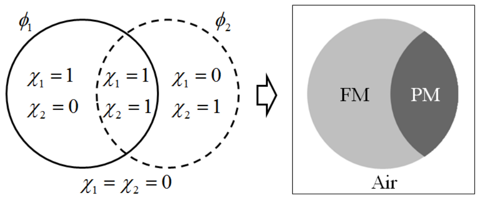


Fig. 1. Expression of multiple material domain

B. Optimization Problem Formulation

The optimization problem for vibration reduction can be formulated with the multi-objective function and the volume constraints as follows:

$$\begin{cases} \underset{\phi_1,\phi_2}{\text{Minimize}}\ F = F_f(\phi_1,\phi_2) + F_T(\phi_1,\phi_2) \\ \qquad = \left(\dfrac{f_r(\phi_1,\phi_2) - f_r^*}{f_0}\right)^2 + \left(\dfrac{T(\phi_1,\phi_2) - T_{\text{target}}}{T_{\text{target}}}\right)^2 \\ \text{subject to } G_1 = \int_\Omega \chi_1\chi_2\, d\Omega \Big/ \int_\Omega d\Omega \le \text{VF}_{\text{PM}} \\ \qquad\qquad G_2 = \int_\Omega \chi_1(1-\chi_2)\, d\Omega \Big/ \int_\Omega d\Omega \le \text{VF}_{\text{FM}} \end{cases} \tag{2}$$

where F_f is the objective function for fitting the fluctuation curve of radial force (f_r) on a single teeth to the modified waveform (f_r^*) that all harmonic components are removed except the fundamental wave (f_0). F_T indicates the amount of torque fluctuation from the target value (T_{target}). Hence, by minimizing F, we can reduce two main sources of motor’s vibration by maintaining the average torque, within the volume fraction (VF) of each material.

C. Optimization Process

In each design step, the design sensitivities of two objective functions calculated by the adjoint variable method for reducing the computational time are combined as follows:

$$\frac{\delta F}{\delta \phi_i} = w_f \frac{\delta F_f\left(\phi_1,\phi_2\right)}{\delta \phi_i} + w_T \frac{\delta F_T\left(\phi_1,\phi_2\right)}{\delta \phi_i},\ i = 1 \text{ or } 2 \qquad (3)$$

where w_f and w_T are the weighting factor for normalizing the effect of each objective function. Then the level set functions are updated by solving the time evolutional equation as follows:

$$\frac{\partial \phi_i}{\partial t} = -\left(\frac{\delta F}{\delta \phi_i} - \lambda_i\right),\ i = 1 \text{ or } 2 \qquad (4)$$

where t is the fictitious time interval for moving boundaries and λ_i is the Lagrange multiplier to satisfy the each volume constraint. These processes are continued until the convergence condition is satisfied.

III. NUMERICAL EXAMPLE

The proposed method is applied to the design optimization of 8-pole 12-slot SPM motor. The initial design illustrated in Fig. 2 is developed for the EPS system required to minimize the vibration. The average torque of the motor is 3.18 Nm and its torque ripple is 3.7 %. The optimization is performed in the upper side of the rotor (design domain), as shown in Fig. 2, with the target torque of 3.2 Nm. The same amounts of PM and FM of an initial design are applied to identity the different configuration.

Fig. 3 depicts the optimal rotor design consisting of PM and FM represented by the shaded color. The edge of PM is changed to smooth curve and the thickness of PM is varied along the rotor angle. It is noted that the air gap between the stator and rotor is not uniform due to the modified shape of PM.

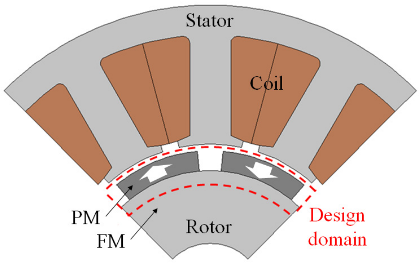


Fig. 2. Initial design and design domain of SPM motor

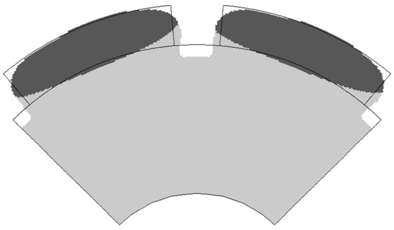
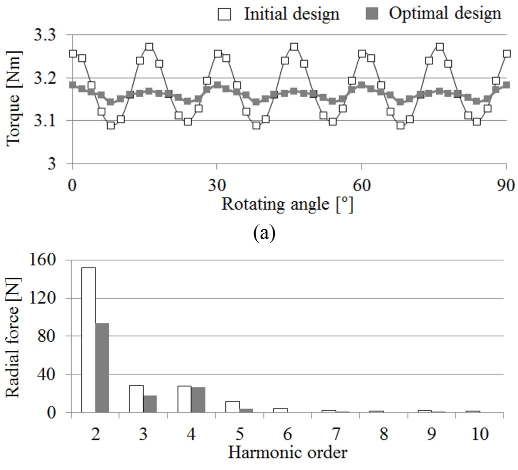


Fig. 3. Optimal rotor design of SPM motor



(a)

(b)

Fig. 4. Comparison between initial and optimal design: (a) torque profiles (b) harmonic components of radial force

Fig. 4 shows that the optimal design provides a decrease in the torque ripple from 3.7% to 0.5% and the harmonic components of radial force which create the mechanical resonance can be reduced.

ACKNOLEDGE

This research was supproted by the MKE(The Ministry of Knowledge Economy), Korea, under the CITRC(Convergence Information Technology Research Center) support program (NIPA-2012-H0401-12-2003) supervised by the NIPA(National IT Industry Promotion Agency).

REFERENCES

[1] W. Cai, P. Pillay, J. Tang and A. M. Omekanda, “Low-Vibration Design of Switched Reluctance Motors for Automotive Applications Using Modal analysis,” *IEEE Trans. on Magn.*, vol.39, no.4, pp. 971-977, 2003.

[2] S.-H. Lee, J.-P. Hong, S.-M. Hwang, W.-T. Lee, J.-Y. Lee and Y.-K. Kim, “Optimal Design for Noise Reduction in Interior Permanent-Magnet Motor,” *IEEE Trans. Ind. Appl.*, vol.45, no.6, pp. 1954-1960, 2009.

[3] T. Ishikawa, M. Yamada and N. Kurita, “Design of Magnet Arrangement in Interior Permanent Magnet Synchronous Motor by response Surface Methodology in Consideration of Torque and Vibration,” *IEEE Trans. on Magn.*, vol.47, no.5, pp. 1290-1293, 2011.

[4] J. Hur, J.-W. Reu, B.-W. Kim and G.-H. Kang, “Vibration Reduction of IPM-Type BLDC Motor Using Negative Third Harmonic Elimination Method of Air-Gap Flux Density,” *IEEE Trans. Ind. Appl.*, vol.47, no.3, pp. 1300-1309, 2011.

[5] T. Sun, J.-M. Kim, G.-H. Lee, J.-P. Hong and M.-R. Choi, “Effect of Pole and Slot Combination on Noise and Vibration in Permanent Magnet Synchronous Motor,” *IEEE Trans. on Magn.*, vol.47, no.5, pp. 1038-1041, 2011.

[6] S. Chaithongsuk, N. Takorabet and F. Meibody-Tabar, “On the Use of Pulse Width Modulation Method for the Elimination of Flux Density Harmonics in the Air-Gap of Surface PM Motor,” *IEEE Trans. on Magn.*, vol.45, no.3, pp. 1736-1739, 2009.

[7] T. Yamada, K. Izui, S. Nishiwaki and A. Takezawa, “A topology optimization method based on the level set method incorporating a fictitious interface energy,” *Comput. Methods Appl. Mech. Engrg*, vol. 199, pp. 2876-2891, 2010.

[8] S. Lim and S. Min, “Design Optimization of Permanent Magnet Actuator Using Multi-Phase Level-Set Model,” *IEEE Trans. on Magn.*, vol.48, no.4, pp. 1641-1644, 2012.