Shape Optimization of the SPM Motor for Noise Reduction Based on Magnetic-structural-acoustic Coupled Analysis

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This paper presents the topology optimization process of surface-mounted permanent magnet (SPM) motor for reducing the average sound pressure level (SPL) in the noisy frequency spectrum. In the time-frequency map of noise level, the loud noises due to harmonic magnetic forces occur in the noisy frequency spectrum on the wide range driving conditions. The sensitivities of the SPL with respect to harmonic magnetic forces are used on the whole driving conditions. A level set method is used to obtain the optimal shape of the rotor. To confirm reducing the noise level in the noisy frequency spectrum, magnetic-structural-acoustic coupled analysis is performed using the optimal shape of SPM motor.

***Index Terms*— Coupled analysis, level set method, noise reduction, rotor design, sound pressure level, topology optimization.**

I. Introduction

Noise reduction is an important design factor in the motor design process because the continuous noise generation adversely affects environment of human. Many papers have suggested the noise reduction techniques such as modification of the motor shape [1], change of pole-slot combination [2] and the reduction of exciting magnetic force [3]. However, it is difficult to predict or select design parameters affecting noise of the motor when using the previous methods. Topology optimization with a relatively high degree of freedom was employed to minimize the magnetic source of the motor vibration [4], however, an acoustic analysis to confirm noise level was not included for calculating the design sensitivity.

Since the loud noises of the motor generally occur in the resonance area, the reduction of the harmonic radial magnetic forces has an effect on reducing the noise of the motor. The noise levels have different value on the whole driving conditions, depending on the driving frequency of harmonic magnetic forces which pass through the resonance area. Therefore, the optimization process is performed using the sensitivities of the sound pressure level (SPL), with respect to harmonic magnetic forces, calculated over the whole driving conditions. The optimization problem is formulated to minimize average SPL in the noisy frequency spectrum, which can be obtained by the magnetic-structural-acoustic coupled analysis. Magneto-static finite element analysis (FEA) is performed to obtain the radial magnetic force, and the acoustic-structural FEA is performed to obtain the SPL. As the magneto-static FEA model including design variables and the acoustic-structural FEA model are different, the chain rule is employed to calculate the design sensitivity for reducing the SPL with respect to design variables. It is applied to the surface-mounted permanent magnet (SPM) motor to confirm usefulness to reduce noise.

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II. Problem Formulation

A. Magnetic-structural-acoustic Coupled Analysis

To calculate the radial magnetic force acting on the tooth of the stator which has a great influence on the noise of the motor, a nonlinear magneto-static FEA is performed. A level set function (ϕ) is employed to represent the shape of the rotor. The magnetic properties (ψ) such as the relative permeability (μ_r) and the remanent magnetic flux of the permanent magnet (PM) ($\mathbf{B}_r$) are described as below:

$$\psi(\phi) = \psi_{\mathrm{PM}}\chi(\phi) + \psi_{\mathrm{air}}\left[1-\chi(\phi)\right] \tag{1}$$

where χ is the characteristic function of which value is 0 or 1 according to the sign of the level set function.

The radial magnetic force can be obtained using the Maxwell stress tensor method. The harmonic magnetic forces, obtained by the fast Fourier transform (FFT) decomposition of the radial magnetic force, are applied to the teeth of the stator for the noise analysis in the frequency domain. Acoustic-structural FEA is performed by the following equation [5]:

$$\begin{bmatrix} \mathbf{M}_\mathrm{a} & \rho_\mathrm{a}\mathbf{L}_\mathrm{as} \\ \mathbf{0} & \mathbf{M}_\mathrm{s} \end{bmatrix}\begin{bmatrix} \ddot{\mathbf{p}} \\ \ddot{\mathbf{u}} \end{bmatrix} + \begin{bmatrix} \mathbf{K}_\mathrm{a} & \mathbf{0} \\ -\mathbf{L}_\mathrm{as}^\mathrm{T} & \mathbf{K}_\mathrm{s} \end{bmatrix}\begin{bmatrix} \mathbf{p} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} 0 \\ \mathbf{F} \end{bmatrix} \tag{2}$$

where $\mathbf{M}_\mathrm{a}$ and $\mathbf{K}_\mathrm{a}$ are the acoustic mass and stiffness matrices, respectively. $\mathbf{M}_\mathrm{s}$ and $\mathbf{K}_\mathrm{s}$ are the structural mass and stiffness matrices. $\mathbf{L}_\mathrm{as}$ is the acoustic-structural coupling matrix. $\mathbf{p}$ and $\mathbf{u}$ are the sound pressure vector of the acoustic domain and the displacement vector of the stator, respectively. ρ_a is the density of the air and $\mathbf{F}$ is the excitation force vector on the teeth of the stator. Using the sound pressure obtained from (2), the SPL at a specific point (j) can be calculated as follows:

$$\mathrm{SPL}_j = 10\log_{10}\left(p_{j,\mathrm{rms}}^2 / p_{\mathrm{ref}}^2\right) \tag{3}$$

where $p_{j,\mathrm{rms}}$ is the root-mean-square sound pressure at a specific point (j), and p_{ref} is the reference pressure of the air.

B. Optimization Problem

The optimization problem is formulated to minimize the sum of average SPL in the target frequency domains (SPL_{ω}) with the volume constraint of PM ($\mathrm{VF}_{\mathrm{PM}}$) and the requirement torque constraint.

$$\begin{aligned} &\underset{\phi}{\text{minimize}}\ F(\phi)=\mathrm{SPL}_{\omega} \\ &\text{subject to } G_1(\phi)=\int_{\Omega}\chi(\phi)\,d\Omega \Big/ \int_{\Omega} d\Omega-\mathrm{VF}_{\mathrm{PM}}\leq 0 \\ &\qquad\qquad G_2(\phi)=T_{\mathrm{avg,target}}-T_{\mathrm{avg}}(\phi)\leq 0 \end{aligned} \tag{4}$$

where Ω is the total design domain. T_{avg} and $T_{\mathrm{avg,\ target}}$ are the average axial torque and the requirement average axial torque, respectively.

The topology optimization process is illustrated in Fig. 1. The design sensitivity of SPL at a specific point with respect to design variables can be derived using chain rule as follows:

$$\frac{\partial \mathrm{SPL}_{\omega}}{\partial \phi}=\sum_{\omega_{\min}}^{\omega_{\max}}\sum_{k_{\min}}^{k_{\max}}\frac{1}{m}\sum_{j}^{m}\frac{\partial \mathrm{SPL}_{j}}{\partial f_k}\frac{\partial f_k}{\partial \phi} \tag{5}$$

where ω and k are the rotational speed of the motor and the harmonic order. m is the number of noise sampling points of the acoustic domain and f_k is the k th harmonic force of the radial magnetic force. The sensitivity of the harmonic magnetic force with respect to design variables can be obtained by using the FFT decomposition of the sensitivity of the radial magnetic force, and the sensitivity of the SPL with respect to the harmonic magnetic force can be obtained by the adjoint variable method using acoustic-structural FEA. Then, the level set function is updated by solving the reaction diffusion equation [6]. The optimization process is performed until the objective satisfies the convergence condition.

III. Design Example

The 8-pole 12-slot SPM motor developed for the EPS system is used in the proposed optimization process. The initial design

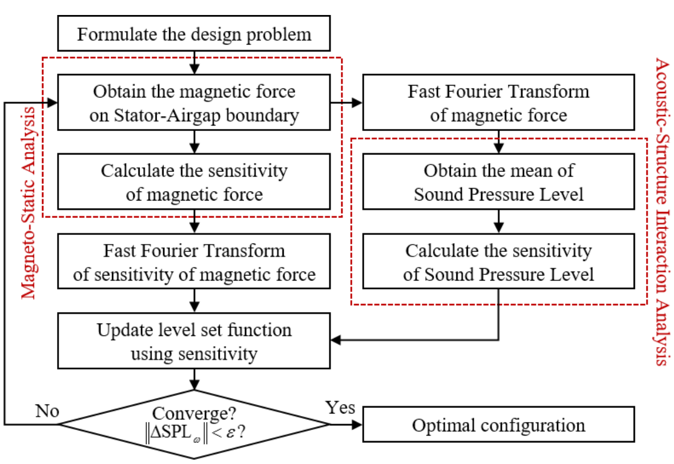

Fig. 1. Optimization process.

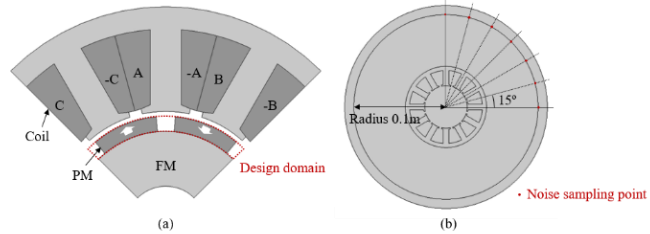

Fig. 2. SPM motor: (a) Initial configuration of the magneto-static analysis model (b) Acoustic-structural analysis model

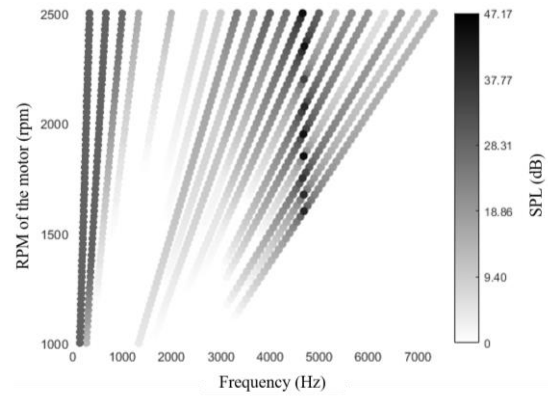

Fig. 3. Time-frequency map of noise level with 0.1 m radius from the SPM motor in frequency spectra of initial model.

of the SPM motor is illustrated in Fig. 2 and the design domain is defined as shape of permanent magnet in rotor. Fig. 3 indicates that the noise level in frequency spectra varying rotational speed of the SPM motor. The maximum acoustic noise is generated in the resonance area nearby natural frequency (4648.9 Hz) of the stator.

IV. Conclusion

This paper performs the noise analysis of the SPM motor through the coupled analysis and the topology optimization of which the objective function is the noise level. It is expected that this optimization process is suitable for the reduction of the motor noise, because the objective function defines the average SPL, which used as a measure of noise evaluation.

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