Sizing Optimization of a Switched Reluctance Motor for the Loudness Reduction

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In this paper, the response surface method to optimize a 6/4 switched reluctance motor for loudness reduction is conducted. By electromagnetic finite element analysis, torque profile and local force distribution loading to stator inner surface is calculated. After that structural and acoustic finite element analysis are performed to obtain the loudness of switched reluctance motor operating at 3000rpm. We set the objective functions concluding the torque and the loudness values in time domain. Also we set radius of rotor slot and the width of rotor poles as design variables and we obtain the design experiment table at each design variables design to make response surface. Finally, we get the optimal design to reduce the loudness of switched reluctance motor.

***Index Terms*—Switched reluctance motor, sound quality, response surface method, sizing optimization, and response surface method**

I. INTRODUCTION

SWITCHED RELUCTANCE MOTOR (SRM) is simple and robust in its structure, and reliable in high speed of its operation. Also, above all, it has strong advantages, that is, high torque/inertia ratio, and high efficiency although it does not use any permanent magnet. Thanks to these good points, SRM is suitable for various industrial applications, especially including electric vehicles.

By contrast, SRM needs to be improved because its stator and rotor have salient pole structures. These salient pole of SRM structure causes not only large torque ripple but also loud acoustic noise. Until now, many research have been studied to obtain optimal structure designs of SRM to reduce torque ripple or the sound pressure level which are generated from SRM [1], [2].

However, the design to reduce the torque ripple or sound pressure level is not effective to satisfy human growing demands against loudness, because it does not consider human hearing characteristics. Thus, we need the study to design the structure of SRM which takes human hearing characteristics into account by improving sound quality.

In this paper, we suggest the method to obtain the design of 6/4 SRM to reduce the loudness, one of the most important sound quality metrics.

First, we starts from electromagnetic finite element analysis (FEA) of 6/4 SRM to get the torque profile, and local force distribution applied to the stator inner surface. Next, through structural-acoustic finite element analysis in time domain, we calculate the sound pressure level, and loudness generated from 6/4 SRM. At the last, we obtain the optimal design to reduce the loudness of switched reluctance motor.

II. ELECTROMAGNETIC FEA OF 6/4 SRM

A. Torque Profile

The initial model of 6/4 SRM is shown in Fig. 1. The Magnetostatic problem is solved using FEA from rotor angle 0 to 45. It is enough that FEA is carried at those rotor angles which are closely spaced from the unaligned position to the aligned position [1]. Then we can calculate the segment inductance l_i at the rotor angle θ_i, as in (1).

$$l_i = \frac{1}{i^2}\int_{all\_space}\frac{1}{\mu}B^2 dA \tag{1}$$

where i is the current on the coil, μ is the magnetic permeability, B is the magnetic flux density, A is the finite element area.

The piecewise line segment connecting the inductance at θ_i and θ_{i+1} is given by (2).

$$L_{(line)\,j}(\theta) = \left(\frac{l_{j+1}-l_j}{\theta_{j+1}-\theta_j}\right)\theta + \left(l_j - \frac{l_{j+1}-l_j}{\theta_{j+1}-\theta_j}\theta_j\right) \tag{2}$$

The cosine Fourier series of the inductance is given by (3)

$$\begin{aligned} L(\theta) = {} & \frac{1}{2\pi/P_r}\sum_{i=1}^{m}\Big(\big(l_{i+1}+l_j\big)\big(\theta_{i+1}-\theta_i\big)\Big) + \\ & \sum_{n=1}^{NF}\frac{2}{n\pi}\sum_{i=1}^{m}\left[\begin{array}{l}(l_{i+1})\bullet\left(\sin(nP_r\theta_{i+1}) + \dfrac{\cos(nP_r\theta_{i+1})-\cos(nP_r\theta_i)}{nP_r\left(\theta_{i+1}-\theta_i\right)}\right) \\ -(l_i)\bullet\left(\sin(nP_r\theta_i) + \dfrac{\cos(nP_r\theta_{i+1})-\cos(nP_r\theta_i)}{nP_r\left(\theta_{i+1}-\theta_i\right)}\right)\end{array}\right]\cos(nP_r\theta) \end{aligned} \tag{3}$$

where n is the Fourier series terms, m is the number of piecewise line segments, NF is the number of Fourier series terms and P_r is the number of rotor poles.

The phase current curve using single-pulse voltage waveform is expressed as

$$i(\theta) = \begin{cases} \dfrac{V_0(\theta-\theta_{on})}{\omega\left(L_0 + \sum_{n=1}^{NF} L_n\cos(nP_r\theta)\right)} & (\theta_{on} \le \theta < \theta_{mid}) \\ \dfrac{V_0(\theta_{off}-\theta)}{\omega\left(L_0 + \sum_{n=1}^{NF} L_n\cos(nP_r\theta)\right)} & (\theta_{mid} \le \theta < \theta_{off}) \\ 0 & (\theta < \theta_{on}, \theta > \theta_{off}) \end{cases} \tag{4}$$

where V_0 is the voltage maximum voltage of single-pulse voltage waveform, ω is the angular velocity, θ_{on} is the voltage start angle, θ_{mid} is the phase change angle of voltage, θ_{off} is the voltage end angle, and L_n is the coefficients of n-th Fourier series term. Then the torque is given as

$$\text{Torque} = \frac{1}{2} i^2(\theta) \frac{dL(\theta)}{d\theta} \tag{5}$$

After that we obtain the torque profile of the initial 6/4 SRM model as shown in Fig. 2.

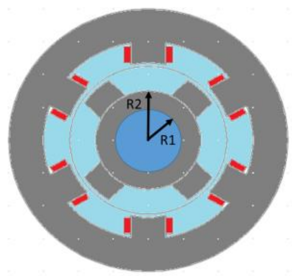

Fig. 1. Initial model of 6/4 SRM

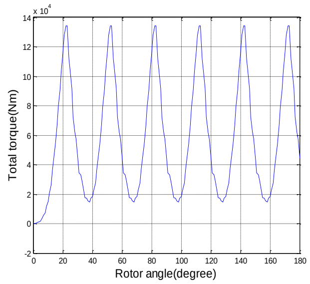

Fig. 2. Torque profile of 6/4 SRM

B. *Local Force Distribution*

The local force distribution using local virtual work method can be calculated by the derivative of the magnetic energy with respect to the position at constant flux linkage [3]. The local force F_j at a node j in δ_j direction is derived as

$$F_j = \frac{1}{2\mu} A^T \frac{\partial K}{\partial \delta_j} A_z \tag{6}$$

$$K = \int \begin{pmatrix} \frac{\partial N}{\partial s} \\ \frac{\partial N}{\partial t} \end{pmatrix}^T \left(\mathbf{J}^{-1}\right)^T \mathbf{J}^{-1} \begin{pmatrix} \frac{\partial N}{\partial s} \\ \frac{\partial N}{\partial t} \end{pmatrix} |\mathbf{J}| \, ds dt \tag{7}$$

where A is the magnetic vector potential, K is the stiffness matrix, $\mathbf{J}$ is the Jacobian matrix, and s, t are the local coordinates of x and y direction, especially.

III. Structural-Acoustic FEA of a Stator

2D Navier's equations are used in FEA to obtain the transient responses of the outer surface of the stator. We assume the problem is the 2D plane strain problem as (8) ~ (11),

$$\begin{aligned} &\rho \frac{\partial^2 u}{\partial t^2} + C_p \frac{\partial u}{\partial t} + \frac{\partial}{\partial x}\left((2G+\mu)\frac{\partial u}{\partial x}\right) \\ &- \frac{\partial}{\partial y}\left(G\frac{\partial u}{\partial y}\right) - \frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial y}\right) - \frac{\partial}{\partial y}\left(G\frac{\partial v}{\partial x}\right) = F_x \end{aligned} \tag{8}$$

$$\begin{aligned} &\rho \frac{\partial^2 v}{\partial t^2} + C_p \frac{\partial u}{\partial t} - \frac{\partial}{\partial y}\left((2G+\mu)\frac{\partial v}{\partial y}\right) \\ &- \frac{\partial}{\partial x}\left(G\frac{\partial v}{\partial x}\right) - \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial x}\right) - \frac{\partial}{\partial x}\left(G\frac{\partial u}{\partial y}\right) = F_y \end{aligned} \tag{9}$$

$$G = \frac{E}{2(1+\upsilon)} \tag{10}$$

$$\mu = \frac{2\upsilon}{1-2\upsilon} G \tag{11}$$

where ρ is the mass density, C_p is the proportional damping, u and v are the displacement in x and y direction, E is the young's modulus, and υ is the Poisson's ratio, F_x and F_y are the volume forces in x and y directions.

The solutions of the structure problem apply to the outer surface of the stator, and 2D acoustic problem is solved by using transient acoustic FEA. we obtain the time variant sound pressure at the 1m outside of outer surface of the stator. The governing equation of 2D transient acoustic problem is as (12)

$$\frac{1}{{c_s}^2} \frac{\partial^2 p}{\partial t^2} - \nabla^2 p = 0 \tag{12}$$

where c_s is the speed of sound, and p is the acoustic pressure.

From the calculated time variant acoustic pressures, we can obtain the Zwicker's loudness using LMS Test.Lab [4].

IV. Optimal Design using Response Surface Method

A. *Optimization problem definition*

The rotor inner radius R1, and rotor radius R2 are set as design variables as shown in Fig. 1. To get the response surface model, we make the design of experiment table using the central composite design (CCD) for R1 and R2.

In case of motor optimization, the average torque value is important to evaluate the motor performance. So, in this work, the average torque and the loudness are considered as objective functions. The multi-objective optimization is defined as follow,

$$\mathit{Minimize} \quad \alpha \times \frac{1}{T}\int_0^T \text{Torque}dt + \beta \times \mathit{Loudness} \tag{13}$$

$$s.t. \quad 0.1 \le R1 \le 0.2 \quad 0.3 \le R1 \le 0.35 \tag{14}$$

where T is the last time iteration number, α and β are weights.

We approximate the objective function according to the design variables using the least square method, which is called response surface method [5]. At the last, the optimal design to reduce the loudness of switched reluctance motor.

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