The Acoustic Noise Reduction in Interior Permanent Magnet Motor by Structural and Electromagnetic Design

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***Abstract*—This paper presents methods to reduce acoustic noise in interior permanent magnet (IPM) motor with concentrated windings. Mechanical and magnetic sources are considered to reduce noise of the machine, and structural and electromagnetic designs are performed. In the structural design to reduce mechanical source, the structural resonances are moved to higher frequency for enhancement of stiffness. Then, the electromagnetic design to reduce magnetic source, the amplitudes of magnetic force harmonics are reduced by using objective function of response surface methodology (RSM). The validity of the design process and objective functions is confirmed with calculated and experimental results.**

***Index Terms*—Acoustic noise, equivalent magnetizing current, normal force, stiffness.**

I. Introduction

Noise sources in electric machines are broadly categorized as magnetic, mechanical, electronic, and aerodynamic sources [1]. Generally, the mechanical and magnetic sources are considered as main noise sources of electric motors [2-4] because the interaction between the harmonic of magnetic forces and the resonant frequency of mechanical structure is the major cause of vibration which produces the noise. Although torque pulsations and tangential components of magnetic force also contribute to vibration and magnetic noise, normal components are larger than the tangential one in general.

Concentrated windings types of brushless DC (BLDC) interior permanent magnet (IPM) motors have more advantages such as short end windings, low copper loss and effective high-volume automated manufacturing than distributed winding types [2]. However, back electromotive force (BEMF) and current have many harmonic, because flux in concentrated winding types concentrates on stator pole. In addition, cogging torque and torque fluctuation are relatively high compared with distributed winding types.

In this paper, optimal design performs to reduce acoustic noise in IPM motor through structural and electromagnetic design. Especially, response surface methodology (RSM) is firstly applied in electromagnetic design and second optimization to reduce torque ripple is performed. Accordingly, the validity of the design methodology to reduce noise is verified by comparison with calculated and experimental results.

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II. Theory

A. Resonant frequency

Calculation of resonant frequencies of the stator is essential in the vibration analysis of electric machine. The resonant frequency of the stator system of the *m*th circumferential vibration mode can be expressed as:

$$f_m = \frac{1}{2\pi}\sqrt{\frac{K_m}{M_m}} \tag{1}$$

where K_m is the lumped stiffness (*N/m*) and M_m is the lumped mass (*kg*) of the stator system.

As the result of the vibration, the surface of the stator yoke displaces with frequencies corresponding to the frequencies of magnetic forces [5].

B. Force calculation

As one of the method of magnetic force calculation, equivalent magnetizing current (EMC) method uses magnetizing current which exists on element boundary and it can directly calculate the magnetic force which affects the surface of structure. The current I_m on the line forming element e_1 and e_2 is written as eq. (2)

$$I_m = \frac{1}{\mu_0}\int \nabla \times \overrightarrow{M} \cdot d\vec{s} = \frac{1}{\mu_0}(M_{1t} - M_{2t})l_{ij} \tag{2}$$

where M_{1t} and M_{2t} are the tangential components of magnetization on element boundary, l_{ij} is the distance on element boundary.

$$\vec{B} = \mu_0 \overrightarrow{H} + \overrightarrow{M} \tag{3}$$

The relationship in eq. (3) holds for all materials whether they are linear or not [6]. Substituting eq. (3) into eq. (2) yields

$$I_m = \frac{1}{\mu_0}(B_{1t} - B_{2t})l_{ij} \tag{4}$$

where B_{1t} and B_{2t} are the tangential component of flux density in each material.

The electromagnetic force on the element boundary is written as

$$\overrightarrow{f_{ij}} = \overrightarrow{I_{ij}} \times \overrightarrow{B}_{ext} \quad (5)$$

Flux density value of $\vec{B}_{ext}$ is given as the average value for each element.

C. Objective function

The harmonic of normal force which is calculated by EMC are used as objective function of DOE and RSM. The objective function takes A-weighting in frequency curves into consideration because the ear is relatively insensitive to very low and very high frequencies [7]. In addition, add the weighting factor around the resonant frequency of stator. As the constraint condition of objective function (H), average torque produced by experiments should be greater than rated torque.

$$H = 10 \log \sum 10^{\frac{F}{10}} \quad (6)$$

where F is the harmonic of normal force considering the A-weighting in frequency weighting curves and weighting factor around resonant frequency of stator.

III. Characteristics of Prototype Model

The specifications of prototype which is operated by 6-step are listed in Table I.

Fig. 2 shows the configuration of noise experiment in the anechoic room where background noise is 41dBA and measured 1m away from the motor by microphone. As a load of IPM motor, generator coupled with IPM motor produces the active power at the resistance.

The result of noise experiment prototype under 3000 rpm and 8 Nm is shown in Fig. 3. The noise spectra occur mostly four times of driving frequency and it corresponds with the harmonic component of normal force which affects stator pole.

TABLE I.
Specifications of Prototype

Contents	Values
Number of poles and slots	4/6
Stack length (mm)	80.0
Rated current (A_{rms})	13.0
Number of turns per phase (turns)	65
Rated speed (rpm)	3000
Rated torque (Nm)	8.0
PWM frequency (kHz)	4.0

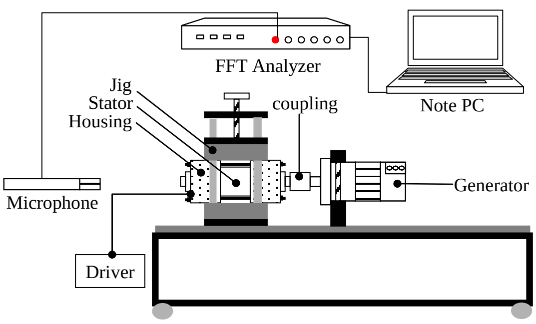

Fig. 1. The configuration of noise experiment.

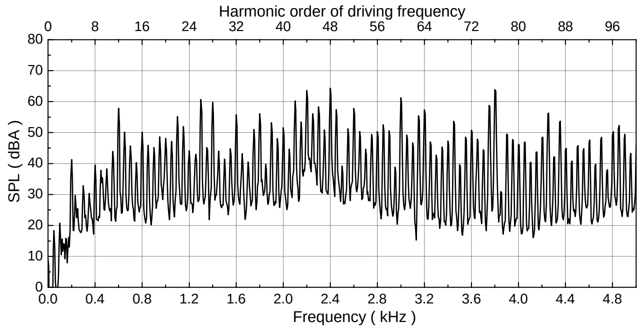

Fig. 2. Noise spectra of prototype (@ 3000 rpm, 8 Nm)

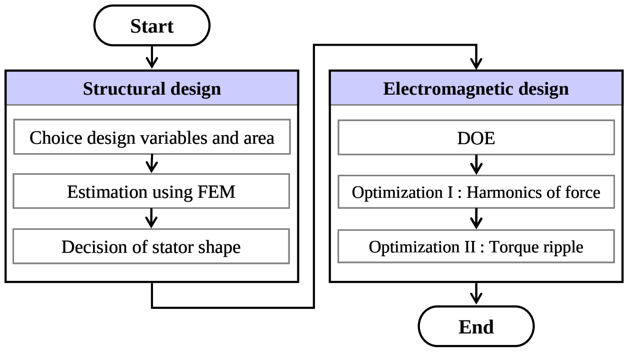

Fig. 3. Configuration of noise experiment.

IV. Design Process

The normal force affecting stator pole has many harmonic components because the main flux concentrates on stator pole. Therefore, design process to reduce the harmonic of normal force which is related with resonant frequency of stator is necessary.

The design process which is shown in Fig. 3 consists of structural and electromagnetic design. First, structural design focuses on the reduction of the vibration quantity by enhancing stiffness of stator. Second, electromagnetic design concentrates on the harmonic reduction of normal force which is calculated by EMC.

A. Structural design

Fig. 4 shows the design variables in structural design, which are tooth width (TW), tooth angle (TA), tooth height (TH), link thickness (LT), and yoke thickness (YT). According to change for each design variables, resonant frequencies of stator using modal analysis compared with prototype. As the main effective design variables, resonant frequency of stator is increased by LT and YT.

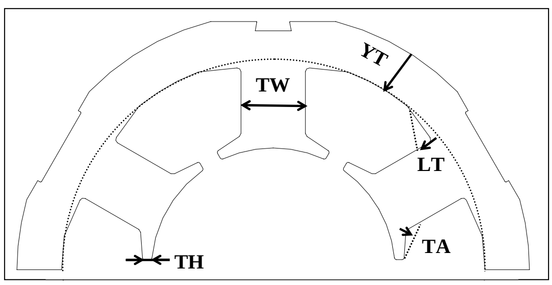

Fig. 4. Design variables in structural design.

TABLE II.
THE COMPARISON OF RESONANT FREQUENCY

	Resonant frequency (Hz)	
	Prototype	Structural design
1st	1550	1888
2nd	1558	1896
3rd	3449	4164
4th	4642	5814

LT and YT are used to find the optimal point, which is the increase in the resonant frequency of first circumferential vibrational mode to enhance the stiffness. As the constraint condition, the values of fill factor are between 35% and 40% to get the same turn number per phase of prototype. In addition, the external diameter of stator is constant.

Resonant frequencies of stator which results from structural design compared with prototype are listed in Table II. To reduce vibration which is related with noise, resonant frequencies is increased through enhancement of the stiffness.

B. Electromagnetic design

The design procedures of electromagnetic design are presented in Fig. 5. To consider operating condition of motor, parameters such as BEMF and inductance are calculated through FEA. In addition, current considering PWM frequency is calculated by duty ratio.

Fig. 6 shows the design variables in electromagnetic design, which are bridge width (BW), pole arc (PA), slot open (SO), and tooth height (TH). Full factorial design (FFD), which is required experiments 17 including central point, is used to find the main factors and design areas are shown in Table III. Main and interaction effects of BW, PA, and SO are significantly expressed from the result of DOE. Among those design variables, effective degree of PA and SO is higher than BW, therefore, PA and SO are firstly selected to reduce the harmonic of normal force in RSM.

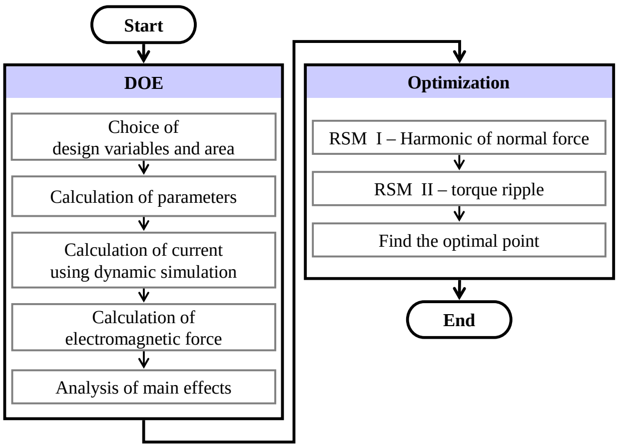

Fig.5. Design procedures in electromagnetic design.

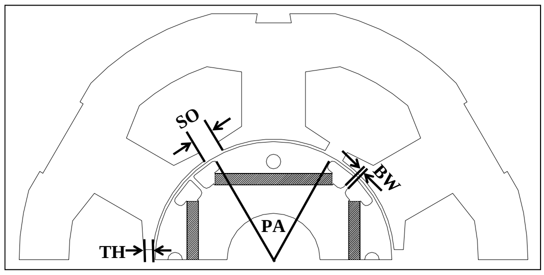

Fig. 6. Design variables in electromagnetic design.

Central composite design (CCD), which is required to conduct 9 experiments, is used to the response of each factor and design area of PA and SO based on the result of DOE shown in Table III. Initial optimal point considering constraint condition is shown in Fig. 7 and then PA and SO are 72 ^{o} and 4.3 mm, respectively.

Using the initial optimal point, second optimization to reduce torque ripple by changing BW is performed and then the values of objective function are also observed.

In the results by changing BW, the distribution and harmonic component of normal force which affects stator pole and torque are analyzed under having similar average torque. Although the distribution of normal force is similar, torque ripple is decreased from 68.0 to 54.0 % and average torque is increased from 7.5 to 8.1 Nm. Therefore, BW is chosen as 2.5 mm in second optimization.

V. EXPERIMENT RESULTS

Fig. 8 shows the noise experiment result measured by 1/3 octave band at the 3000 rpm and 8 Nm. Total SPLs of OPT(the result of structural and electromagnetic design) compared with prototype are entirely reduced and the values of prototype and OPT are 76.5 and 71.4 dBA, respectively. The noise of prototype around PWM frequency is higher than OPT because inductance of OPT is higher than prototype due to the reduction of magnetic saturation by increasing pole arc.

TABLE III.
DESIGN VAIRALBES AND AREA IN ELECTROMAGNETIC DESIGN

	Design variables	Coded values				
		-1.682	1	0	1	1.682
DOE	BW (mm)	-	0.5	2.5	4.5	-
	SO (mm)	-	4.0	5.5	7.0	-
	TH (mm)	-	1.5	2.5	3.5	-
	PA (^{0})	-	45.0	65.0	75.0	-
RSM	SO (mm)	3.89	4.35	5.45	6.55	7.00
	PA (^{0})	50.08	53.4	61.4	69.4	72.71

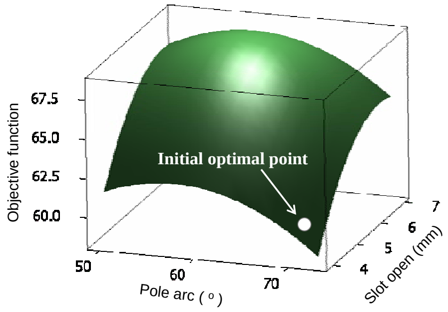

Fig. 7. Response surface of objective function.

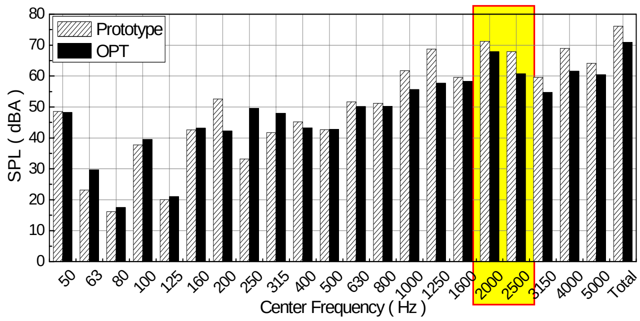

Fig. 8. Design variables in electromagnetic design.

VI. Conclusions

This paper deals with the reduction of acoustic noise in IPM motor by structural and electromagnetic design. In addition, objective function using the harmonic of normal force is applied to the electromagnetic design..

The structural design should focus on vibration reduction by increasing stiffness and stability of stator. In addition, the electromagnetic design should pay more attention to the harmonic reduction of normal force than one of tangential force in electric machine with high-power density such as IPM motor.

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