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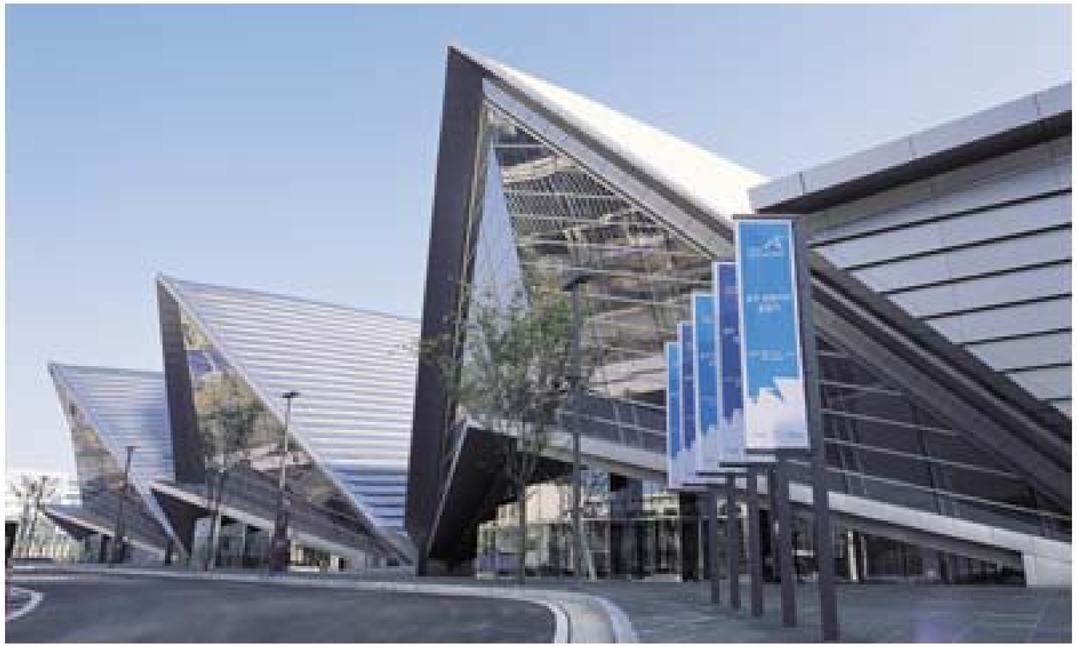

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Evaluation and Improved Design about Acoustic Noise and Vibration in IPMSM

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Abstract — This paper presents evaluation and analysis of acoustic noise and vibration in interior permanent magnet synchronous motor (IPMSM).

Acoustic noise and vibration have a close relationship. Acoustic noise is generated by vibration of the motor stator due to the magnetic force. It is called local force that is composed of normal force and tangential force. Harmonics of normal force associated with resonant frequency of structure are mainly cause of acoustic noise and vibration.

In this paper, the vibration of proto-model and improved model caused by normal force is evaluated using FEM. And experimental evaluations of improved model's acoustic noise and vibration are presented. The experimental results will be compared with simulation results.

I. Introduction

These days, not only basic characteristics of motor such as torque and power but also acoustic noise and vibration are being increasingly perceived as an important factor. For acoustic noise and vibration are very sensitive factor to people using products included motor.

Acoustic noise and vibration have a close relationship because acoustic noise is mainly affected by vibration of structure. Acoustic noise is generated by vibration of the stator of motor due to the magnetic force called local force that is composed of normal force and tangential force.

Some papers propose reduction of cogging torque and torque ripple generated by tangential force is effective to reduce acoustic noise and vibration [1]. However, the normal force's harmonic magnitude is so bigger than tangential force's. So the harmonics of normal force relative to resonant frequency of motor are more important factors at acoustic noise and vibration in electric machines of high power density such as IPMSM [2].

There are two methods to reduce the vibration and noise. One is improving the stiffness of stator and the other is reduction of electromagnetic exciting force (local force) [3]–[4]. Improvement of stiffness is utilized effectively to reduce acoustic noise and vibration. However, this mechanical solution brings an increase in motor size. Therefore, improvement design of reducing local force is more reasonable method to decrease acoustic noise and vibration level. [5]

In this paper, the vibration of proto-model and improved model caused by normal force is evaluated using FEM. And experimental evaluations of improved model's acoustic noise and vibration are presented. Also, the experimental results will be compared with simulation results.

II. Theory

A. Magnetic-Force Calculation

Fig. 1 shows the magnetizing current between two materials. As one of the methods of magnetic-force calculation, magnetizing current which exists on element boundary is used as equivalent-magnetizing-current (EMC) method and it can directly calculate the electromagnetic force which affects the surface of the structure. The current I_m on the line forming element e_1 and e_2 is written as

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

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

$$\overrightarrow{B} = \mu_0 \overrightarrow{H} + \overrightarrow{M} \qquad (2)$$

The relationship in (2) holds for all materials, whether they are linear or not [1]. Substituting (2) into (1) yields

$$I_m = \frac{1}{\mu_0}(B_{1t} - B_{2t})l_{ij} \qquad (3)$$

where B1t and B2t are the tangential component of the flux density in each material.

The electromagnetic force on the element boundary is written as

$$\vec{f}_{ij} = \vec{I}_{ij} \times \vec{B}_{ext} \qquad (4)$$

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

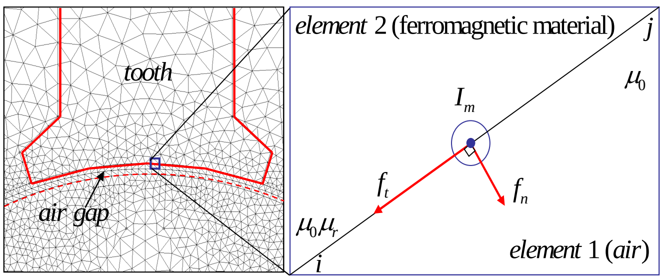

Fig. 1. Equivalent magnetizing current in the boundary line.

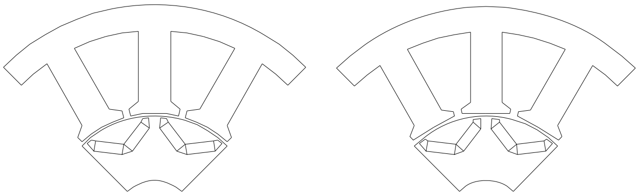

Fig. 2. Shape of motors
(a) Proto-model (b) Improved model

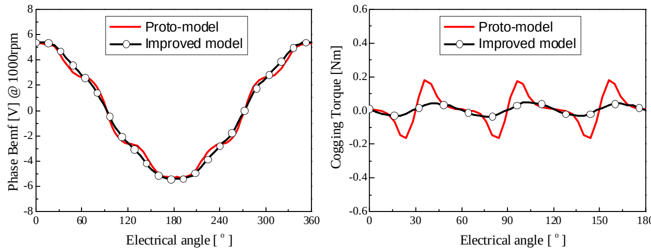

Fig. 3. Phase back EMF and cogging torque of two motors

TABLE I
MOTOR SPECIFICATIONS

Pole / Slots	8 / 12
Br [T]	1.16
Core material	S18
Stator diameter [mm]	100.4
Rotor diameter [mm]	48.4
Stack length [mm]	95
Air gap distance [mm]	0.6
Current [A] / Phase angle [°]	56.6 / 15.5

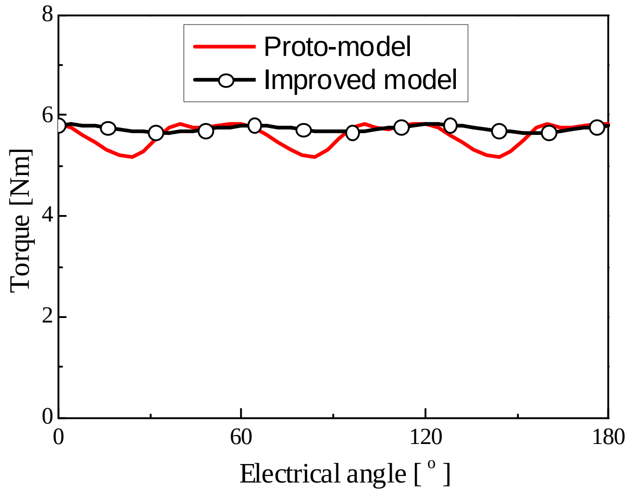

Fig. 4. Torque of two motors

III. CHARACTERISTICS OF TWO MODELS

Fig. 2. shows shapes of 8pole 12slots IPM motors used at compressors. Fig. 2. (a) is a proto-model and (b) is a improved model designed to reduce noise and vibration. Response surface methodology (RSM) is applied as an optimization method. Objective functions are reduction of torque ripple and normal force that are main factors of noise and vibration.

Fig. 3. and Fig. 4. show comparison results of two motors' main characteristics that are back EMF, cogging torque and torque. Fig.5. shows graphs of normal force. Upper graph is the normal force at a tooth moving on the 1-pole. And lower graphs shows harmonic components of normal force.

Optimization results show factors causing noise and vibration are reduced. Characteristics of two motors are presented in Table II.

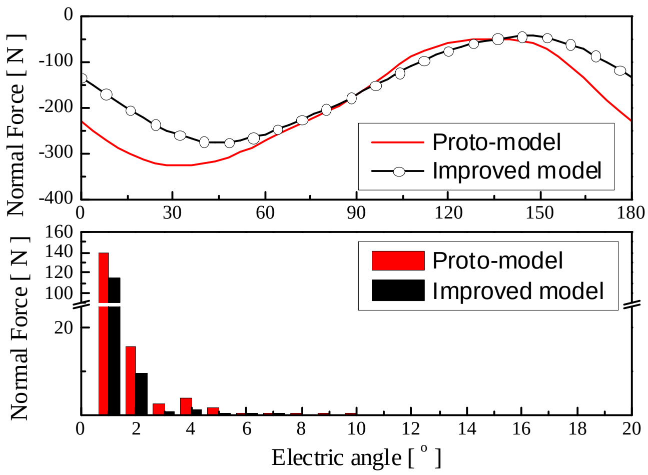

Fig. 5. Normal force of two motors

TABLE II
CHARACTERISTICS OF TWO MOTORS

	Proto-model	Improved model
Cogging torque (Nm)	0.34	0.08
Torque (Nm)	5.6	5.7
Torque ripple (Nm)	0.7	0.2
Fundamental harmonic amplitude of Normal force (N)	140	114
Total harmonic distortion(THD) of normal force (%)	11.8	8.3

IV. EVALUATION OF ACOUSTIC NOISE AND VIBRATION

A. FEM simulation

FEM simulation to compare noise and vibration of proto-model with improved model is calculating deformations at points of stator outer surface using normal force. Normal force is applied to all of the teeth considering phase angle, and deformations are calculated. Deformations according to harmonic components of normal force are analyzed on harmonic response simulation.

Fig. 6. shows mode shapes of natural frequency. Proto–model has 2^{nd} mode and 3^{rd} mode at frequencies of 1332Hz and 3312Hz. Improved model has at frequencies of 1338Hz and 3366Hz. Because Rotor shapes of two motors are very similar, natural frequencies are almost the same.

Fig. 7. is the FEM stator model applied normal force at all the teeth. And Fig. 8. shows the result of deformations by normal force in log scale. Not only deformations caused by fundamental component of normal force but also deformations caused by harmonic components are smaller at improved model.

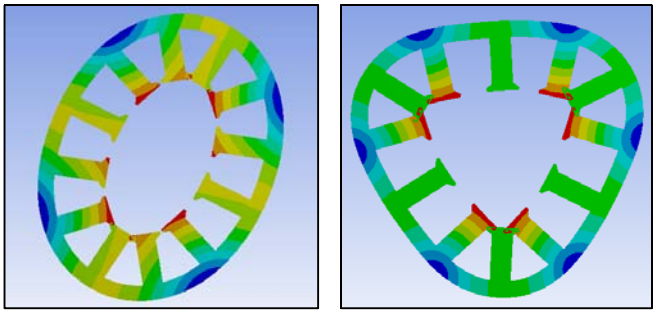

Fig. 6. Shapes of 2nd Mode and 3rd mode

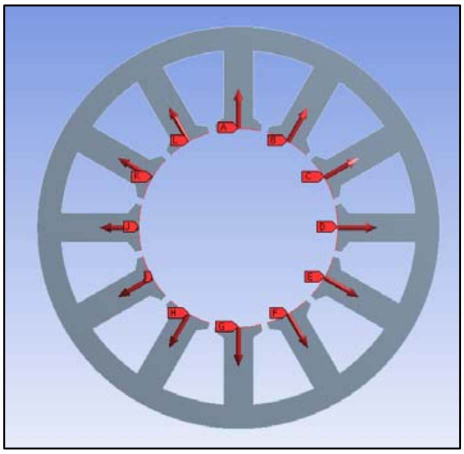

Fig. 7. Stator model applied normal force at all the teeth

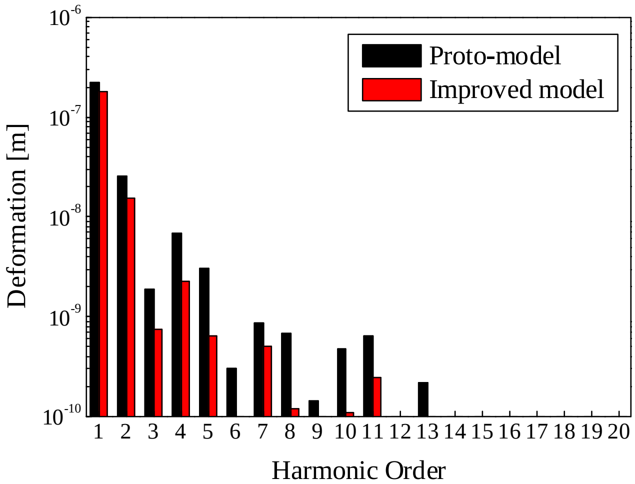

Fig. 8. Result of deformation of two motors

B. *Experimental evaluation of acoustic noise and vibration*

A manufactured motor of the improved model is used for the test to evaluate noise and vibration. Fig. 9. shows equipments and the motor for the experiment. The test is performed in anechoic room and equipments except for the motor are blocked by sound absorption material in order to measure noise of motor only. Acoustic noise is measured at distance of 1m using a microphone, and vibration is measured by acceleration sensors.

The overall noise corresponding to the various velocity of the motor is shown in Fig. 10. Under the constant load, the noise becomes larger as the velocity increasing.

Fig. 11. shows the result of noise experiment measured by 1/3 Octave band applied A-weighting. It shows that Acoustic pressure near the 600Hz and 1kHz are high.

Fig. 12. shows the result of vibration experiment measured by Narrow band. Peaks of acceleration at 333Hz, 666Hz and 999Hz are very high.

This motor has 8 poles and has electric frequency of 167Hz at 2500rpm. Therefore local force of the motor has frequency of 333Hz, 2nd harmonic and 3rd harmonic component each has frequency of 666Hz and 999Hz. Noise and vibration are high at Frequency band of local force's harmonic component.

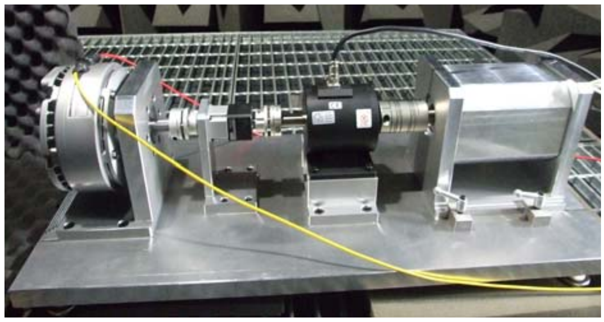

Fig. 9. Experiment equipments

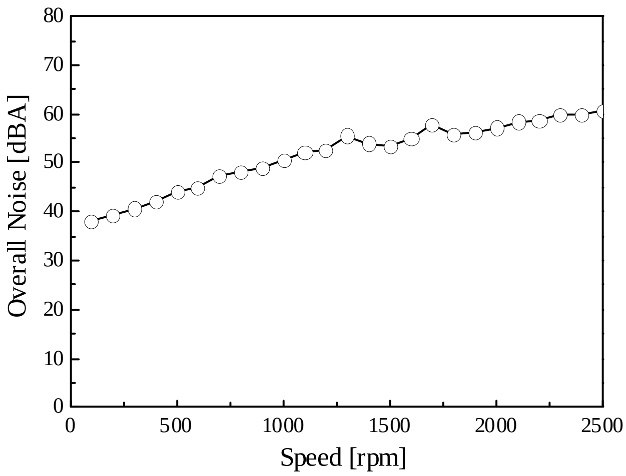

Fig. 10. Overall noise of two motors

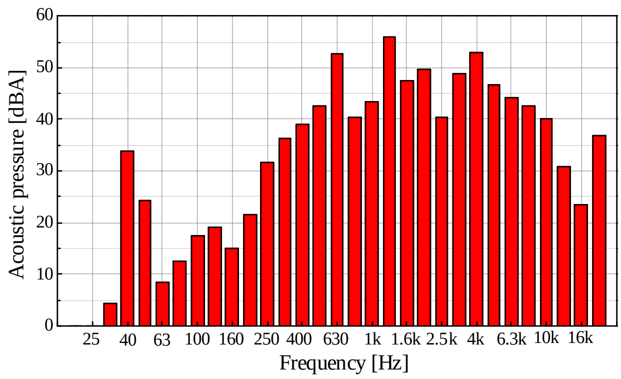

Fig. 11. The result of noise experiment (1/3 Octave band)

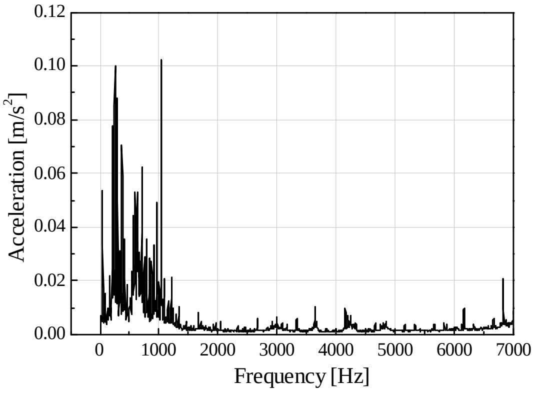

Fig. 12. The result of vibration experiment (Narrow band)

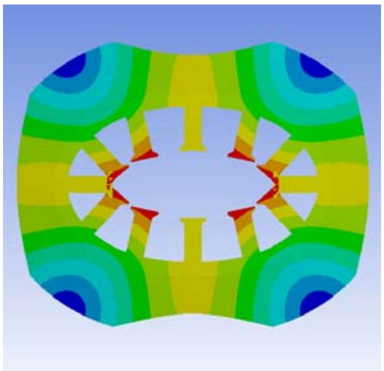

Fig. 13. . Shape of 2nd Mode of improved motor with housing

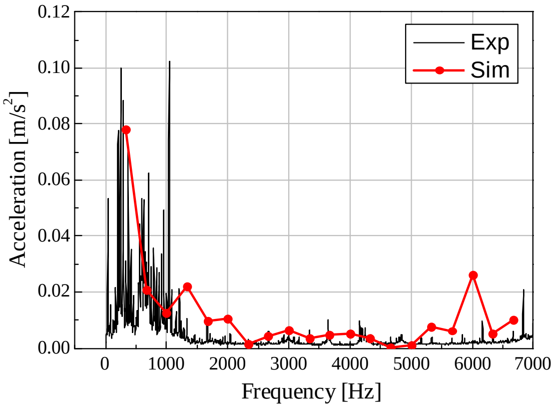

Fig. 14 . Comparison of acceleration

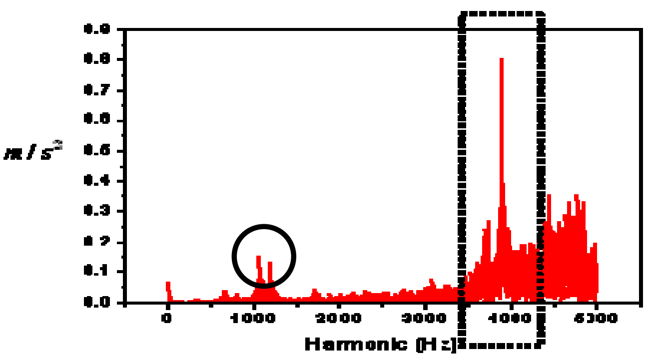

Fig. 15. Experimental modal test result

C. Comparison of simulation and experiment results

In order to compare simulation results with experimental results simulation model is remodeled. The stator housing structure is considered to simulation.

Fig. 13. shows the natural frequency of 2nd mode. The natural frequency is 3850Hz. It becomes higher comparing previous simulation results due to the effect of stator housing.

Fig. 14. shows the comparison of acceleration between experiments and simulation. In the most frequency region, simulation results agree well with experiments except 3rd harmonic's frequency of normal force.

Fig. 15. shows the experimental modal test result of motor showing 1kHz of natural frequency. The natural frequency is caused by stator and housing structure, and it causes resonance between 3rd harmonic of radial force and results in large vibration.

V. Conclusion

Causes of noise and vibration are reduced in the improved design, and design results are proved by simulation. In addition, noise and vibration of improved model is estimated by experiments, and it is confirmed that radial force is the main factor for noise and vibration.

In conclusion, in order to reduce noise and vibration, reduction of harmonics of radial force and separation between natural frequency and the frequency of radial force are very effective.

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