Magnetic Circuit Design of SPM Fractional-slot Motor for Vibration Reduction

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Abstract — This paper deals with the analysis of vibration and noise sources in modular-type SPM fractional-slot motor. To reduce cogging torque, torque ripple and unequal radial force, which are main cause of the electromagnetic vibration source, the optimal notch and magnet shape were designed.

I. INTRODUCTION

Recently, a new topology of fractional-slot motor, often referred to as "modular-type", has produced [1]. Fig. 1 shows a winding layout of modular-type SPM fractional-slot motor of which pole to slot ratio is 5:6. The back-EMF waveform of this modular-type motor is significantly more sinusoidal than that of the conventional PM motor and the cogging torque is smaller than that of the conventional PM motor.

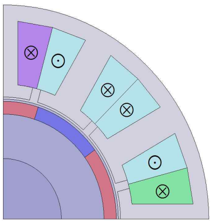


Fig. 1. Winding layout

However, the magnetic field of this winding has more space harmonics, which causes noise and vibration. In this paper, in order to reduce cogging torque and torque ripple, firstly, optimal notch was designed and the radial magnetic force was analyzed, then optimal magnet shape was designed for equal distribution of radial force.

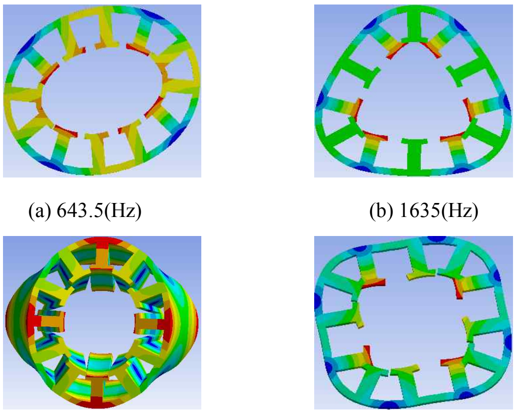
II. MAGNETIC CIRCUIT DESIGN FOR VIBRATION REDUCTION

A. Modal analysis

All of resonance frequencies and possible deformations of the structure can be computed with the modal analysis that depends only on the design parameters and the material properties. FEM (Finite Element Method) is used for the free vibration analysis and the vibration equation for an undamped system is as following.

$$[\mathbf{M}]\{\ddot{x}\}+[\mathbf{K}]\{x\}=0\,. \qquad (1)$$

where, [M] and [K] are the global mass matrix and stiffness matrix, $\{\ddot{x}\}$ and $\{x\}$ are the acceleration and the displacement at each points of the system. Fig. 2 shows mode shapes corresponding to natural frequencies.



(a) 643.5(Hz) (b) 1635(Hz)

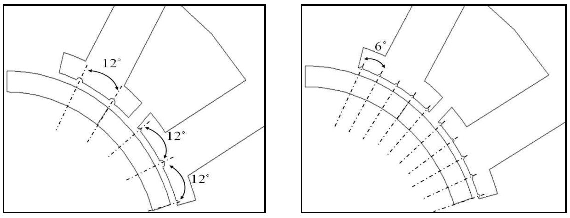
(c) 1909.4(Hz) (d) 2737.1(Hz)

Fig. 2. Mode shapes corresponding to natural frequencies

B. Reduction of vibration by reduced cogging torque

In order to reduce the cogging torque, the functions of cogging torque and dummy slot was found by using the Fourier series, and then notch design parameters were decided. Finally function of notch design is as following.

$$\cos\left(f_{Pn}\theta\right)+\frac{\sin\left(f_{Pn}r\right)}{\sin\left(f_{Pn}a\right)}\cdot\cos\left(f_{Pn}\left(\theta+x\right)\right)=0\,. \qquad (2)$$



(a) Notch 1 (b) Notch 2

Fig. 3. Position of notch

And the position and width of the notch are shown in a Fig. 3. In case of notch 1 model, as shown a Fig. 4, it can be seen that the fundamental harmonic of cogging torque was increased by 42.1 (%) compared with the basic model, which causes increment of torque ripple. Also it is predicted that amplitude of vibration is larger than that of the basic model because 600 (Hz) component of cogging torque and mode (a) of natural frequency resonate. However, in case of Notch 2 model, the fundamental harmonic of cogging torque was decreased by 57.9 (%) compared with the basic model, which causes the decrease of torque ripple. No

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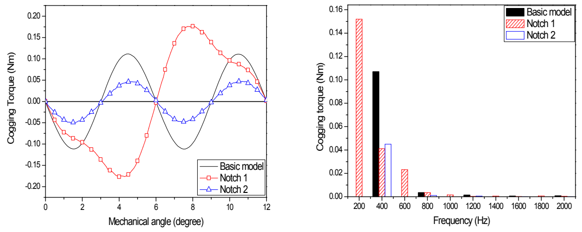
resonances can be occurred between the frequencies of cogging torque and natural frequencies.



(a) cogging torque (b) time harmonic distribution

Fig. 4. Characteristic of cogging torque

C. Reduction of vibration by equal distribution of radial force

The radial force density distribution on the stator surface, which results from the air-gap magnetic field under no-load and on-load conditions, is the main cause of electromagnetically noise and vibration source, and can be evaluated analytically by Maxwell`s stress tensor method. Thus,

$$F_{rad}(\theta_s,t)=\frac{1}{2\mu_0}[B_r^2(\theta_s,t)-B_\theta^2(\theta_s,t)]\,. \tag{3}$$

where, F_{rad} is the radial component of force density, B_r and B_θ are the radial and tangential components of the air-gap flux density, μ_0 is the permeability of free space, θ_s is the angular position at the stator and t is the time. The radial force density of basic model is shown in a Fig. 5. In case of the basic model, the distribution of radial force density is close to oval-shaped, so it is predicted that the amplitude of vibration is larger than that of the conventional PM motor.

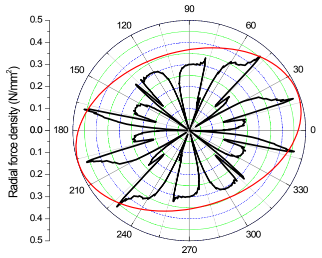


Fig. 5. Radial force density of the basic model

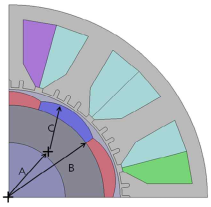


Fig. 6. Proposed model

To distribute radial force density equally, the optimal design of magnet shape and dummy slot were carried out as shown Fig. 6. FEM and DOE (Design of Experiment) are used for optimal design of magnet shape. Design parameters A, B, and C are 13.75 (mm), 23.98(mm) and 13.75(mm) respectively. In case of the proposed model, the harmonic components of radial force density were mostly decreased except 10th harmonic of radial force density compared with the basic model as shown a Fig. 7. And the radial force density of proposed model is shown in a Fig. 8. Due to distribution of radial force density equally, it is predicted that electromagnetic vibration source is reduced. However, the average output torque of the proposed model is a little smaller that than of the basic model because effective air-gap length is a little larger than that of the basic model. Nevertheless, in case of the proposed model, torque ripple was considerably improved to 1.16 (%), compared with that of the basic model, which was 6.18 (%).

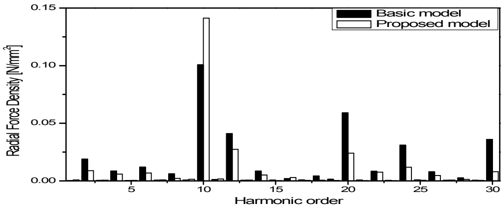


Fig. 7. Harmonic analysis of Radial force density

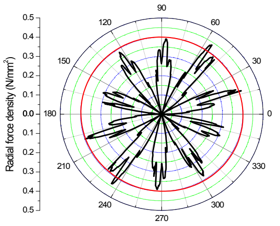


Fig. 8. Radial force density of the proposed model

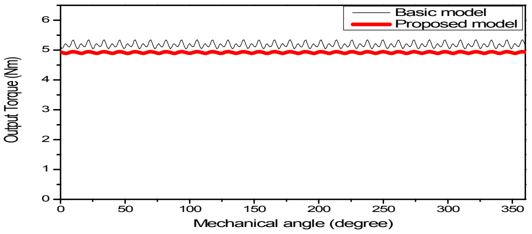


Fig. 9. Comparison of output torques

III. CONCLUSION

This study deals with the analysis of vibration sources and method of vibration reduction in modular-type SPM fractional-slot motor. By applying a new-type of notch and optimal design of magnet, it is expected that the amplitude of vibration electromagnetic vibration will be reduced as a result of decreased in cogging torque and equal distribution of radial force density. Afterwards, a prototype machine will be made and then comparison of experimental and analyzed values will be done to prove the validity of this research.

IV. REFERENCES

[1] Atallah, K., Wang, J and Howe, D., “Torque ripple minimization in modular permanent magnet brushless machines,” *IEEE Trans. on Industry Application.*, vol. 39, (6), pp. 1689-1695, 2003.