Analysis of Interior Permanent Magnet Synchronous Motor on Electromagnetic Vibration

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Abstract — Using a numerical process, this paper analyzes the vibration of interior permanent magnet synchronous motor (IPMSM) due to the electromagnetic force. This process includes calculation of local force in electromagnetic finite element analysis (FEA), and estimation of natural frequency and deformation in mechanical structural analysis. The effect of local force on the vibration will be investigated according to the analysis results. Two IPMSM models which have the same characteristics but different stator structures will be studied. The calculated results will be validated by an experiment.

I. INTRODUCTION

Interior permanent magnet synchronous motor (IPMSM) has been employed in various devices, such as wash machine, air conditioner, electric scooter, and hybrid electric vehicle. These devices surrounding people has highly demanding requirement on the vibration, because that the vibration does not only cause the vibro-noise, but also reduce the useful life of the devices.

In the electric motor, the vibration is mainly excited by the electromagnetic force which is consists of the tangential component and radial component. Many literatures proposed the estimation methods for the vibration of electric motor by analyzing the electromagnetic force. These methods generally can be divided into the total force analysis method and the local force analysis method. In the total force analysis method [1]-[2], the tangential component of electromagnetic force is ignored, and only the radial component of electromagnetic force in the air gap of motor is calculated. By using the harmonic analysis, e.g. Fast Fourier Transform (FFT) analysis, the harmonic order and amplitude of the radial force then is obtained. Due to the calculation in the air gap, the total force can not be used to the structural analysis. Therefore, the total force analysis method usually studies if there is the frequency of the radial force is close to one of the natural frequencies of the stator when the force order is the same as the circumferential vibrational mode of the stator. It is obvious that the total force analysis method only considers the worst condition of vibration but can not give the specific value.

In order estimate the vibration of motor, both the tangential component and radial component of electromagnetic force acting on each stator tooth should be calculated, i.e. the local force analysis. Vandevelde *et al.* [3] compared equivalent magnetization method and virtual work on the force calculation in a switched reluctance motor, and demonstrated that the validity of the equivalent magnetization method on the deformation analysis. But only the force calculation was discussed rather than the vibration characteristics. Using the Maxwell stress tensor method and equivalent magnetization method, Chen *et al.* [4] and Lee *et al.* [5] calculated the local force and successfully estimated the vibration in the permanent magnet synchronous motor, respectively. However, the relationship between the local force and the vibration was not revealed. Additionally, due to the special rotor structure, there is no analytical model which can accurately calculate total force or local force in IPMSM model.

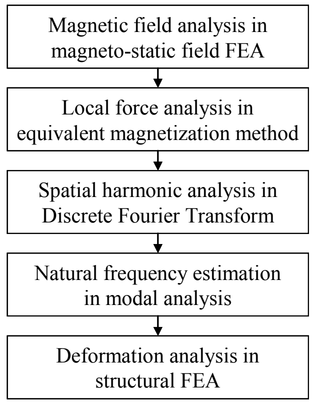


Fig. 1. Process for vibration estimation.

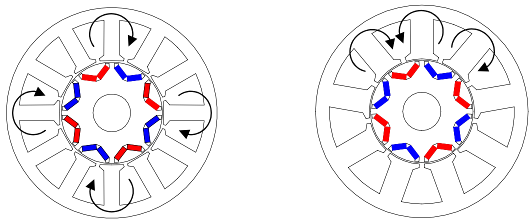
Based on this background, this paper analyzes the vibration of IPMSM due to the electromagnetic force by using a numerical process. As shown in Fig. 1, this process includes the electromagnetic finite element analysis (FEA), local force calculation, modal analysis, and deformation analysis. According to the analysis results, this paper will investigate the effect of local force on the vibration. Two IPMSM models which have the same characteristics but different stator structures are studied by this process. Finally, the calculated results will be verified by an experiment.

II. STUDY MODELS

The cross-sections of two IPMSMs are shown in Fig. 2. They have the identical rotor structure but different stator. The combination of pole and slot of one model is 8/12, while the other has the 8/9 combination of pole and slot. The specifications of these two models are listed in Table I.

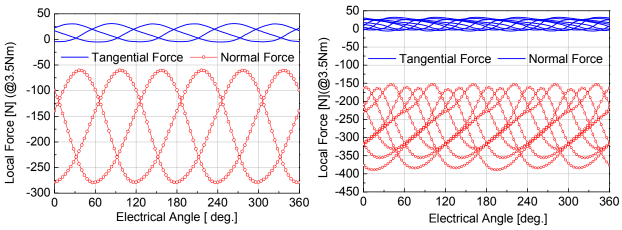
III. ELECTROMAGNETIC FORCE CALCULATION

In this paper, the equivalent magnetizing current method (EMC) is used to calculate the local force because it is effective to calculate the force distribution acting on the tooth. The tangential component and normal component of the local force acting on the edge of tooth and air gap can be described in (1) and (2), respectively.



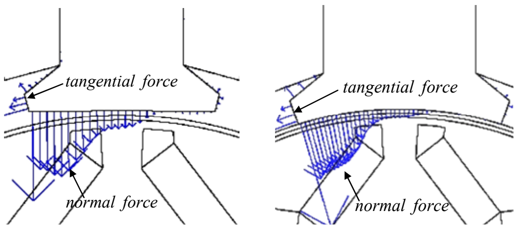
(a) (b)

Fig. 2. Cross-sections of the study IPMSM models: (a) 8-pole/12-slot model; (b) 8-pole/9-slot model.



(a) (b)

Fig. 3. Calculated local forces of the study models: (a) 8-pole/12-slot model; (b) 8-pole/9-slot model.



(a) (b)

Fig. 4 Vector of the calculated local forces: (a) 8-pole/12-slot model; (b) 8-pole/9-slot model.

$$f_t = H_{1t}B_{1n} - H_{2t}B_{2n} \quad (1)$$

$$f_n = \frac{1}{2}(H_{1n}B_{1n} - H_{1t}B_{1t}) - \frac{1}{2}(H_{2n}B_{2n} - H_{2t}B_{2t}) \quad (2)$$

In practice calculation, however, the second parts of (1) and (2) can produce the error in the ferromagnetic material. In the compensation calculation procedure proposed in [6], this error can be eliminated by substrate (3) and (4) from (1) and (2), respectively.

$$f_t' = -J_m{}' B_n^0 \quad (3)$$

$$f_n' = J_m{}' B_t^0 \quad (4)$$

Fig. 3 shows the calculated local forces of the studied models. And Fig. 4 shows the local force vectors acting on the tooth. In the extended paper, these local forces will be analyzed with the vibration estimation results.

IV. Modal Analysis and Deformation Analysis

Based on the principle of Hamilton, the modal analysis can be descriped in (3) with considering the undamping system and external force free

$$[M]\{\ddot{x}\} + [K]\{x\} = 0 \quad (3)$$

where x is the vector of the displacement, $[M]$ is the mass matrix, and $[K]$ is the stiffness matrix. When estimate the vibration, the deformation analysis requires to consider both the damping and applied force vector. Thus, the mechanical system is expressed as (4).

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\} \quad (4)$$

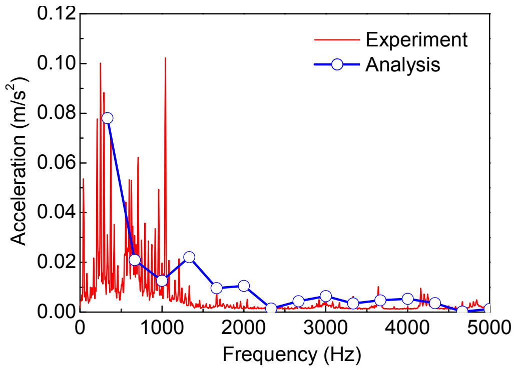


Fig. 5. Comparison of analysis and experiment results on the vibration 8-pole and 12-slot model

V. Analysis Results and Conclusion

Fig. 5 shows the comparison between the analysis results and experiment results on the vibration of 8/12 model at 2500rpm, 3.5Nm. More analysis and experiment results, and experiment set up will be presented in the extended paper. In addition, the local force, natural frequency, and vibration mode will be discussed and studied deeply.

TABLE I
SPECIFICATION OF STUDY MODELS

Item	Value	
	8/12 model	8/9 model
Rated power [kW]	2	
DC link voltage [V]	42	
Rated current [A_{rms}]	52	58
Maximum torque [Nm]	5.5	
Stator/rotor outer diameter [mm]	100.4 / 48.4	
Stack length / air gap [mm]	95 / 0.6	

VI. References

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