Design and Analysis of a BLDC motor with Halbach array magnets

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Background

As halbach array magnets are applied to make higher power density, the portion of electromagnetic vibration increases. In order to evaluate the vibration produced by motor, radial force has to be calculated. This paper presents vibration analysis on outer-rotor BLDC motor with two-segment halbach array magnets. The analytical model of radial force was developed. Mode shape and frequency of vibration source were determined and validated by comparing with FEM results.

I. Introduction

❖ Most studies on vibration produced by motor have yet been conducted on inner-rotor BLAC motor.
❖ This paper presents the analytical model of radial force including the current harmonic components of BLDC motor.

II. Analytical model of vibration source

❖ Magnetic field of two-segment halbach array

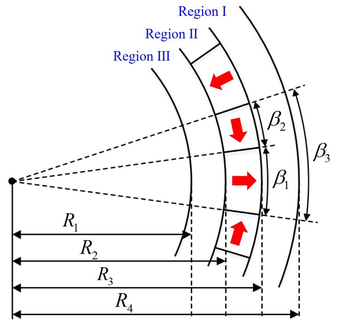

Fig.1. Typical shape of two-segment halbach array magnets

$$B_{rIII}(r,\theta_m)=\sum_{n=1,3,5\cdots}^{\infty}\mu_0 B_n\left[\left(\frac{r}{R_4}\right)^{np-1}+\left(\frac{R_1}{R_4}\right)^{2np}\left(\frac{R_3}{r}\right)^{np+1}\right]\cos(np\theta_m)$$

❖ Armature reaction field of BLDC motor

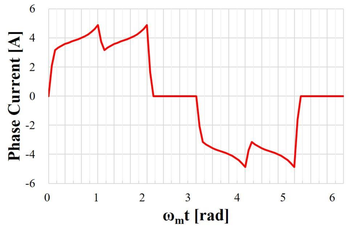

Fig.2. Current waveform of BLDC motor

$$B_s(\theta_m,t)=B_{sm}\sum_u I_u\sum_{n=1}^{\infty}\frac{1}{n}k_{dpn}(k_{sn})^2\cos(up\omega_m t-k_{sn}nT\theta_m+\theta_u)$$

III. Mode and frequency of vibration

❖ Radial force produced by motor

$$f(\theta_m,t)=\frac{1}{2\mu_0}\left[B^2(\theta_m,t)-B_t^2(\theta_m,t)\right]$$
$$\approx\frac{1}{2\mu_0}B^2(\theta_m,t)$$
$$=\sum_{r=0}^{\infty}\sum_{n=0}^{\infty}P_{rn}\cos(\omega_{rn}t\pm r\theta_m)$$

Table I. Vibration mode and frequency of radial force

Space harmonic			Source	Frequency	Mode
Stator	Rotor	Slot			
$6k\pm1$	$2k$-1	k	Stator	$(u\pm v)f_e$	$(n_s\pm m_s)T$
			Stator + Slot	$(u\pm v)f_e$	$(n_s\pm m_s)T\pm lQ$
			Rotor	$(n_r\pm m_r)f_e$	$(n_r\pm m_r)p$
			Rotor + Slot	$(n_r\pm m_r)f_e$	$(n_r\pm m_r)p\pm lQ$
			Stator + Rotor	$(n_r\pm u)f_e$	$n_r p\pm n_s T$
			Stator + Rotor +Slot	$(n_r\pm u)f_e$	$n_r p\pm n_s T\pm lQ$

IV. Example of vibration calculation

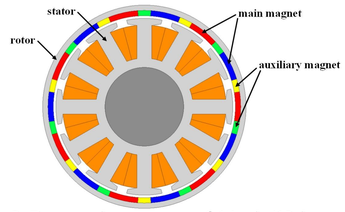

Fig. 3. Proposed prototype of 14pole/12slot

Table II. Specification of the prototype

Contents	Value	Unit
Pole ratio	0.7	-
Remanence of PM	1.2	T
Thickness of PM	0.6	mm
Outer diameter of rotor	23	mm
Outer diameter of stator	20	mm

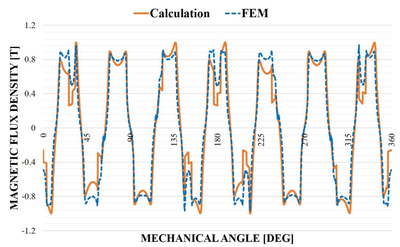

Fig. 4. Airgap magnetic field of analytical model and FEM

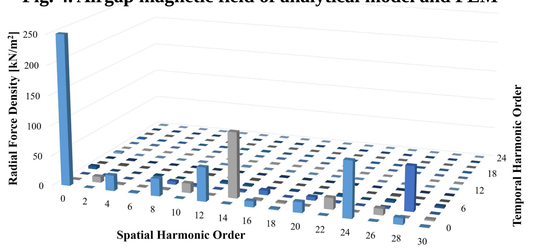

Fig. 6. Spatial and temporal harmonic components of radial force

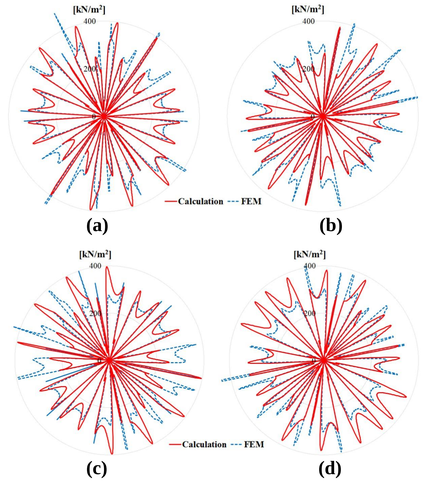

Fig.5. Radial force density at each time
(a) ωt=0 (b) ωt=π/4 (c) ωt=π/2 (d) ωt=3π/4

Table III. Mode numbers at twice the electrical frequency

Space harmonic			Source	Mode
Stator	Rotor	Slot		
1,5,7	1,3	*1*	Stator $(n_s\pm m_s)T$	(1+1)1=2
			Stator + Slot $(n_s\pm m_s)T\pm lQ$	(1-3)+12=10
			Rotor $(n_r\pm m_r)p$	(1+1)7=14
			Rotor + Slot $(n_r\pm m_r)p\pm lQ$	(3-1)7+12=26
			Stator + Rotor $n_r p\pm n_s T$	7+7=14
			Stator + Rotor +Slot $n_r p\pm n_s T\pm lQ$	7+7+12=26

V. Conclusion

❖ This paper presents vibration analysis of the BLDC motor with two-segment halbach array magnets.
❖ The result of the analytical model has been validated by FEM on the drone motor.

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