Comparison of Vibration Sources between Symmetric and Asymmetric HDD Spindle Motors with Rotor Eccentricity

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Abstract - The permanent magnet motor is often the most important element in hard disk drive (HDD) spindles and also a frequent source of vibration and acoustic noise. The eccentricity between stator and rotor is inevitably introduced during manufacturing process, such as mass unbalance, shaft bow and bearing tolerances. This paper analytically discusses effects of rotor eccentricity on motor performances for symmetric and asymmetric motors, such as local traction, unbalanced force, cogging torque, back EMF, phase current and torque ripple. An asymmetric motor, mostly chosen to reduce the cogging torque, shows a worse effect on cogging torque and unbalanced force when the eccentricity exists. It also adversely affects the flux linkage and introduces variation of the phase back EMF depending on winding and rotating eccentricity, thus yielding increased mutual torque ripple.

I. INTRODUCTION

For precision spindle motors, such as HDD spindle motors, vibration is one of the most important performance characteristics to be considered in design process. Due to the manufacturing imprecision such as unbalanced mass, shaft bow and bearing tolerances, rotor eccentricity is inevitably introduced mechanically. The mechanical vibration sources are usually coupled with magnetic vibration sources such as unbalanced forces, cogging torque and torque ripple to yield worse dynamic characteristics. For example, mechanical vibration sources induce variation of airgap due to rotor whirl, which again adversely affects magnetic vibration sources. For previous research, Jang [1] calculated torque and unbalanced forces in an asymmetric brushless DC (BLDC) motor without eccentricity. Kim [2], [3] analyzed magnetic field distribution of an eccentric rotor, without mentioning on various vibration sources. In this paper, symmetric(12-pole, 9-slot) and asymmetric(8-pole, 9-slot) motors, which are widely employed in HDD spindle motors, are analyzed to compare various sources of vibration and acoustic noise when rotor eccentricity exists.

II. UNBALANCED RADIAL FORCES

The unbalanced radial forces which are the resultants of uneven magnetic field distribution and rotor eccentricity, are one of the major sources of spindle runout, ball bearing wear and acoustic noise problem. Fig. 1 shows the prototype symmetric and asymmetric BLDC motors to be analyzed, which are popularly used.
due to high average torque and low cogging torque in HDD spindle motors. Design parameters of the prototype motors are listed in Table I. The magnetic field distribution associated with rotor eccentricity is modeled by a perturbation of the corresponding Maxwell equations and boundary conditions. Fig. 2 shows a geometric configuration of the BLDC motor with rotor eccentricity. In order to simplify the analysis, the permeability of the stator and the rotor back iron is assumed to be infinite. For radial force analysis, the armature reaction field can be neglected for surface mounted permanent magnet motors. The analytic solutions for the magnetic flux density distribution can be found from the previous work [3].

![Fig. 2. A schematic of an eccentric rotor](image)

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>DESIGN PARAMETERS OF THE MOTORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Parameter</td>
<td>Value (Unit)</td>
</tr>
<tr>
<td>Stator radius</td>
<td>9.725 (mm)</td>
</tr>
<tr>
<td>Magnet thickness</td>
<td>1.0 (mm)</td>
</tr>
<tr>
<td>Airgap length</td>
<td>0.25 (mm)</td>
</tr>
<tr>
<td>Slot opening angle</td>
<td>5 (degree)</td>
</tr>
<tr>
<td>Magnet remanence</td>
<td>0.71 (T)</td>
</tr>
<tr>
<td>Relative permeance</td>
<td>1.26</td>
</tr>
</tbody>
</table>

ratio (eccentricity / airgap length) of 0.5 and compared with FEM result. The discrepancy at slotting area and pole transition come from the inexact prediction of permeance function and the first order approximation of perturbation method. Since \( \mu_{\text{iron}} \) is infinite, the magnetic local traction acting on the stator surface can be determined using Maxwell stress tensor:

\[
f_r = \frac{1}{2\mu_0} (B_r^2 - B_0^2)
\]

(1)

\[
f_\theta = \frac{1}{\mu_0} B_r B_\theta
\]

(2)

where \( f_r \) and \( f_\theta \) denote the radial and the tangential traction and \( \mu_0 \) is the permeability of the air. Using Cartesian coordinates, the corresponding traction can be expressed as:

\[
f_x = f_r \cdot \cos \theta - f_\theta \cdot \sin \theta
\]

(3)

\[
f_y = f_r \cdot \sin \theta + f_\theta \cdot \cos \theta
\]

(4)

The unbalanced forces acting on the stator center can be determined by integrating the corresponding tractions over the stator surface and are given as:

\[
F_{x,\text{mag}} = \int_0^{2\pi} f_x \cdot r \cdot d\theta
\]

\[
F_{y,\text{mag}} = \int_0^{2\pi} f_y \cdot r \cdot d\theta
\]

(5)

\[
F_{x,\text{mag}} = \sqrt{(F_{x,\text{mag}})^2 + (F_{y,\text{mag}})^2}
\]

(6)

Fig. 4 shows the radial local traction with and without

![Fig. 3. Radial flux density (ee=0.5)](image)
eccentricity of 0.5 for the 8-pole, 9-slot motor. With the rotor eccentricity, it can be seen that the magnetic traction is stronger in the narrow airgap region and the direction of the magnetic forces should be towards narrow airgap region. Fig. 5 shows the maximum magnitude of the radial unbalanced magnetic forces for symmetric and asymmetric motors with various eccentricity. For an asymmetric motor, the unbalanced force always exists regardless of eccentricity since the stator structure is not symmetrical to the rotor. It should be noted that eccentricity has a bigger effect on unbalanced forces compared to symmetric motors. Fig. 6 shows x- and y-components of the unbalanced magnetic forces for symmetric and asymmetric motors with respect to the rotor position and Fig. 7 shows the corresponding loci of the radial unbalanced magnetic forces with the eccentricity ratio of 0.5. For a symmetric motor, it can be seen that the frequency of the unbalanced forces is the same as the rotor rotating frequency, \( \omega_{\text{rot}} \) and the magnitude of them are almost invariant to the rotating eccentricity. For an asymmetric motor, however, additional 8-th harmonic of the rotating frequency is introduced in the unbalanced magnetic forces due to asymmetric structure between stator and permanent magnets. Therefore, the unbalanced magnetic forces vary with the rotating eccentricity and have the exciting frequencies of \( \omega_{\text{rot}} \), \( 8\omega_{\text{rot}} \) and higher harmonics of \( 8\omega_{\text{rot}} \) and they can be expressed as:

\[
\begin{align*}
F_{x,\text{mag}} &= \sum_{n} F_{x}^{n} \cos(8n\omega_{\text{rot}}t) + \epsilon F_{x}^{1} \cos(\omega_{\text{rot}}t + \phi) \\
F_{y,\text{mag}} &= \sum_{n} F_{y}^{n} \sin(8n\omega_{\text{rot}}t) + \epsilon F_{y}^{1} \sin(\omega_{\text{rot}}t + \phi)
\end{align*}
\]  

(7)
For symmetric motors, it should be noted that $F_x^0$ and $F_y^0$ vanish for due to structural symmetry.

III. COGGING TORQUE

Cogging torque is generated due to the permanent magnet and the geometry of tooth. It has the tendency to move the rotor to the equilibrium position whose number is the twice of the least common multiple of pole and teeth. Cogging torque is calculated using Maxwell stress method as shown in (8) with the analytic magnetic field distribution;

$$T(\theta) = \frac{1}{\mu_0} \int \mathbf{r} \cdot \mathbf{B}_r \cdot d\Gamma = \sum_{n=1}^{\infty} A_n \sin(n\theta + \Psi_n)$$  \hspace{1cm} (8)

where $\mu_0$, $\Gamma$, $r$, $A_n$ and $\Psi_n$ are the permeability of air, integration contour, radius, the amplitude of Fourier series coefficient and the corresponding phase shift, respectively. Fig. 8 shows results of cogging torque for symmetric and asymmetric motors without eccentricity and Fig. 9 shows effects of eccentricity on the cogging torque for the given motors. Even if an asymmetric motor produces reduced cogging torque without eccentricity, it is greatly affected as the eccentricity exists. Also, it should be noted that the cogging torque does not significantly change with the eccentricity for a symmetric motor since the integration of local force density as in (8) averages out the effect of airgap variation.

IV. TORQUE RIPPLE

For a 6-step bridge inverter, phase current can be simulated by solving voltage equations as in (9);

$$V_j = R_ji_j(\theta) + \frac{d\lambda_j(\theta)}{dt}, \hspace{1cm} j = a, b, c$$  \hspace{1cm} (9)

where $V$, $R$, $i$ and $\lambda$ are terminal voltage, phase resistance, phase current, and flux linkage respectively. Flux linkage and back EMF for corresponding rotor position are calculated using (10) and (11).

$$\psi = \frac{a_{1/2}}{}$$

$$\psi = \int B(\alpha, \theta)R_{eq} d\alpha$$

$$c = -N \frac{d\psi}{dt}$$

where, $a$, $R$, $l_e$ and $N$ are the winding pitch angle, the radius of stator bore, the effective axial length and number of turns respectively. Once phase current and back EMF are calculated, mutual torque ripple can be determined using (12).

$$T = \sum_{j} c_j i_j / \omega_m$$  \hspace{1cm} (12)

Fig. 10 shows back EMF waveforms for symmetric and asymmetric motors with the rotating speed of 5400rpm. Even if the back EMF for a symmetric motor is not changed by the eccentricity due to average effect of the integration, that for an asymmetric motor is greatly

![Fig. 8. Cogging torque without eccentricity](image1)

![Fig. 9. Cogging torque with eccentricity](image2)
affected by the eccentricity. It should be noted that the phase back EMF in Fig. 10 is the phase that faces with the smallest airgap. Fig. 11 shows phase current waveforms for symmetric and asymmetric motors with rotor eccentricity. A distortion of phase current is also observed for an asymmetric motor. The mutual torque ripple can be determined by phase current and back EMF waveforms as in (12) and is shown in Fig. 12 with and without eccentricity. Fig. 13 shows the corresponding frequency spectra of the torque ripple for symmetric and asymmetric motor. Due to the variation of the back EMF and phase current for eccentric rotor, an asymmetric motor introduces additional exciting harmonics in torque ripple which are harmful for motor resonances.

V. CONCLUSION

Vibration sources for symmetric and asymmetric motors are analytically determined for comparison. An asymmetric motor is sometimes a design alternative for HDD spindle motors to reduce cogging torque. However, it shows a worse effect in both unbalanced force and cogging torque when eccentricity exists. It also introduces distortion of back EMF and phase current waveform due to the eccentricity, thus yielding increased mutual torque ripple. For this reason, application of asymmetric motors for HDD spindle needs to be limited.

REFERENCES

