Effects Of Unbalanced Magnetic Pull In Spindle Motors

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Abstract - **This paper analyzes the effects of the unbalanced-magnetic-pull developed in spindle motors for hard disk drives. An analytical technique is used in the investigation which is based on magnetic circuit and field theory. Computational results show that the UMP development is closely related to the magnetic structure, armature winding and armature current of the spindle motors.**

I. INTRODUCTION

Although there has been intensive study on the Unbalanced-Magnetic-Pull (UMP) and its effects in certain type of electric machines, e.g., induction motors [1,2], the way by which UMP affects the performance of permanent magnet (PM) spindle motors still needs to be explored further. A thorough understanding of the UMP development is necessary for motor designers to identify the real causes of the run-out and acoustics noise in spindle motors. Since modern HDDs demand highly precise spinning motion and the requirements become more and more stringent, the UMP development and its effects on the performance of the spindle motors began to attract attention of researchers [e.g., 3-4].

In this paper, the UMP is defined as the global magnetic pull acting on the rotor. This force, as its name means, is caused by the unbalanced magnetic field in the airgap of the machine. There are many factors causing the unbalanced field, for example, the eccentricity of the rotor centre to the stator centre, the unbalance of the permanent magnets, and unbalanced armature current distribution due to the unbalanced armature windings. These factors lead the airgap flux density is increased in some regions, but reduced in some other regions. The unbalanced pull is thus produced.

The factors causing the unbalanced magnetic field may result from the quality of the machine components, problems taken place in machine assembling process, or unreasonable designs [1,2]. The focal point of the analysis presented in the paper will be on the effects of the magnetic structure, armature winding and current of the motors. The analysis results reveal some factors causing acoustic noise and run-out of the rotor, which are not commonly accounted for in the design and performance analysis of spindle motors.

II. UMP DEVELOPED IN THE PM SPINDLE MOTORS

The magnetic energy stored in the airgap of the PM motors, W_e, can be described by using F_r, the MMF produced by the magnets on the rotor, and F_s, the MMF produced by the armature current on the stator,

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$$W_e(\gamma,\alpha,e)=\frac{RL}{2}\int_0^{2\pi}\Lambda(\theta,\gamma,e)\,[F_s(\theta)+F_r(\theta,\alpha)]^2 d\theta \quad (1)$$

where, L is the effective length of the stator core, R is the average value of the equivalent outer and inner radii of the airgap, $\Lambda(\theta)$ is the permeance of the airgap in which the effects of rotor eccentricity and slotting are included, e and γ are the value and position of the eccentricity, $F_s(\theta)$ and $F_r(\theta,\alpha)$ represent the MMFs produced by the armature current on the stator and magnets on the rotor respectively, and α is the position difference between F_s and F_r.

From field energy point, the UMP, $P=(P_x, P_y)$, can be derived from W_e by using the following equations,

$$\begin{cases} P_x(\gamma,\alpha,e) = dW_e/dx \\ P_y(\gamma,\alpha,e) = dW_e/dy \end{cases} \quad (2)$$

and the following equations can thus be deduced,

$$P_x=\frac{RL\Lambda_0}{2}\int_0^{2\pi}[1+\sum_{n=1}\lambda_n\cos(nZ_s\theta)]\,F_\Sigma(\theta,\alpha,\gamma,e)\cdot\left[\frac{F_\Sigma(\theta,\alpha,\gamma,e)\cos(\theta)}{\delta_0}-\frac{2\sin(\theta)}{R}\frac{dF_r(\theta,\alpha)}{d\theta}\right]d\theta \quad (3)$$

$$P_y=\frac{RL\Lambda_0}{2}\int_0^{2\pi}[1+\sum_{n=1}\lambda_n\cos(nZ_s\theta)]\,F_\Sigma(\theta,\alpha,\gamma,e)\cdot\left[\frac{F_\Sigma(\theta,\alpha,\gamma,e)\sin(\theta)}{\delta_0}+\frac{2\cos(\theta)}{R}\frac{dF_r(\theta,\alpha)}{d\theta}\right]d\theta \quad (4)$$

where, Λ_0 and λ_n are the DC and *nth* harmonic components of Λ respectively, Z_s is the stator tooth number, δ_0 is the effective length of the airgap, and

$$F_\Sigma(\theta,\alpha,\gamma,e)=\frac{F_s(\theta)+F_r(\theta,\alpha)}{1-e\cdot\cos(\theta-\gamma)} \quad (5)$$

Equations (3) to (5) show clearly that, the UMP results from the following sources:

(1). the eccentricity of the rotor e;
(2). the unreasonable magnetic structure which produces unreasonable harmonics in F_r;
(3). the unreasonable armature windings which produces unreasonable harmonics in F_s.

From these equations, the influence of above sources on the UMP is complicated. Actually, even in the cases where the eccentricity of the rotor centre to the stator centre, e, is zero, the UMP could still be produced in the operation.

Using (3) to (5), it is not difficult to estimate the UMP

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performance when the magnetic structure and armature windings have been given.

In the following analysis, the discussion will just around the cases where e is zero. In these cases, the computations of (3) and (4) are simplified, and it can also give such a result that, ***for the spindle motor with even number of stator teeth and magnetic pole-pairs, if the fundamental pole-pairs of armature winding is even, no UMP is produced in the motor operation.*** For other kind of motors, examples will be used to analyze the UMP developed in the motor operation.

III. Computational Results

In this section, two spindle motors are used to show the influence of the magnetic structure, armature winding and armature current on the UMP.

A. Motor-1

The structure of the spindle motor is shown in Fig.1. This is a typical 3-phase 4 pole-pairs brushless DC motor designed for HDDs. The exterior rotor has a surface-mounted PM ring.

The major parameters of the motor are:

Outer diameter: 11.75 mm   Airgap length: 0.28 mm
Stator length : 7.3 mm   Tooth tip width: 5.02 mm

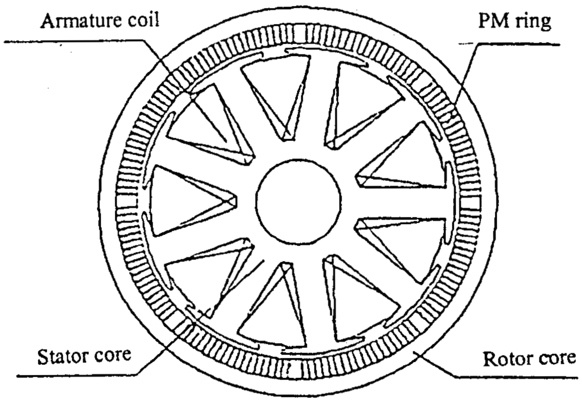

Fig.1 The structure of the motor with 9-slots

As the magnet on the rotor has 4 pole-pairs and stator has 9 slots, the fundamental harmonic of $F_r(\theta,\alpha)$ is 4, and Z_s is 9. In this case, the integration parts on the right sides of (3) and (4) cannot keep zero for all rotor position, therefore, the UMP exists in the motor operation. This phenomenon can also be explained from view point of electromagnetic (EM) field. Fig.2 shows the field distribution in the motor which was obtained by using finite element (FE) method. It is a unbalanced field which leads UMP inevitably.

Fig.3 shows the UMP generated under non-load operation which is obtained by using (3) and (4), and the curve is quite similar with the result obtained by using FE method [3].

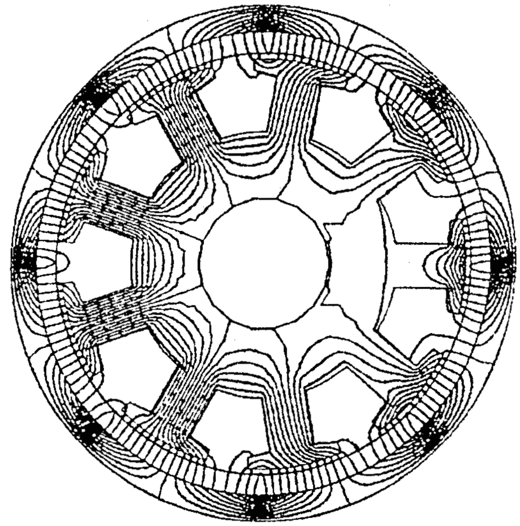

Fig.2 The field distribution in the motor with 9 slots

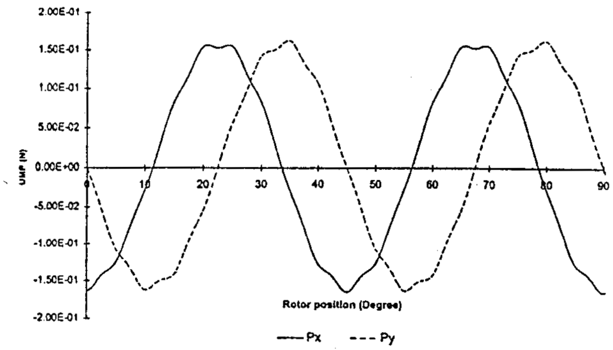

Fig.3 The UMP developed in the idle of the motor with 9-slots

For analyzing the UMP performance in the load operation, the results of the rated-load operation with Y-connected and Delta-connected armature windings are shown in Figs.4 and 5, respectively.

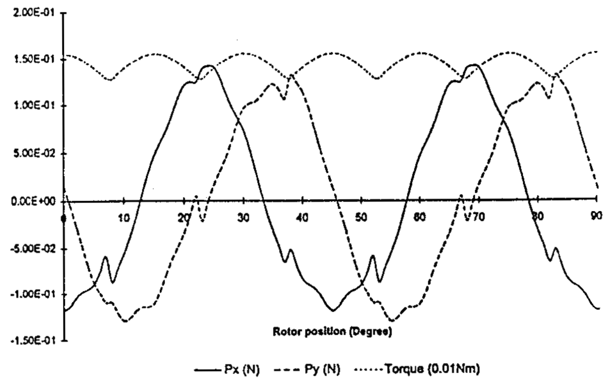

Fig.4 The UMP developed in the rated-load operation of the spindle motor with 9-slots (Y-connected armature winding)

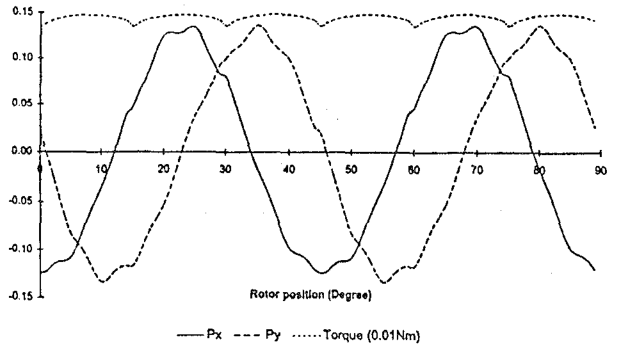

Fig.5 The UMP developed in the rated-load operation of the spindle motor with 9-slots (Δ-connected armature winding)

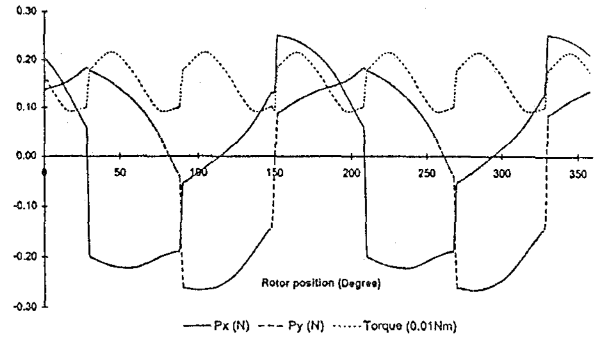

Fig.7 The UMP developed in the rated-load operation of the spindle motor with 6-slots (Δ-connected armature winding)

The cogging torque of the motor is also calculated in the analysis, and its amplitude is just about 0.1% of the rated torque. It is well known that low cogging torque is one of the advantages of this kind of PM motors which has 9-slots and 4 pole-pairs, but, there is pronounced UMP effects in this type of motor structure. HDDs demand precise spinning motion, and, Figs.3 to 5 show that, the effects of the UMP on the run-out, vibration and acoustic noise of the motor cannot be ignored in such precise spinning motion.

These figures show also that the way of the armature connection only has slight effects on UMP. However, different connections can affect the torque ripple a little.

B. Motor-2

This is a motor with 6 stator slots and the pole-pair of magnet is 1. All other parameters are same as *Motor-1*.

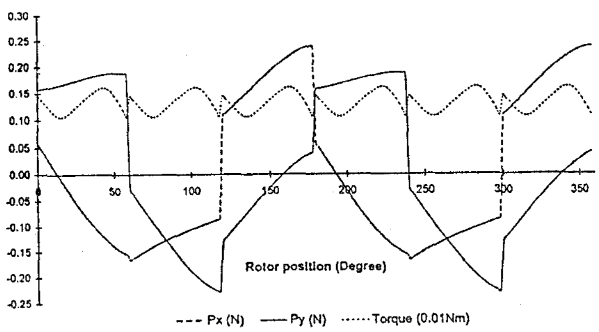

Fig.6 The UMP developed in the rated-load operation of the spindle motor with 6-slots (Y-connected armature winding)

As Z_s is 6 and the fundamental pole-pairs of F_r is 1, from (3) and (4), P_x and P_y are zero in the non-load operation. If the armature coils are formed by symmetric windings and the fundamental pole-pair is 1, F_r cannot produce even harmonics, the UMP is thus still zero in the load operation, and computational results also prove it. But, if the coils are formed by unsymetric windings, the UMP will appear in the load-operation, and the result is shown in Fig.6 where the windings are connected in Y connection. Fig.7 shows the results with Delta connection.

Comparing Figs.6 with 7, both Y and Delta connection can produce UMP, and their amplitudes are almost same, but, the torque ripple produced by Y connected motor is lower.

IV. CONCLUSIONS

In the design of spindle motors for HDDs, in addition to the cogging torque and torque ripple, the effects of UMP should also be carefully considered in order to avoid undesirable magnitudes of alternating EM force acting on the rotor. Analysis shows, UMP development is closely related with the stator tooth number, pole-pairs of the magnet and armature winding. For some motor structures, the UMP always exists in the motor operation, whether in the non-load operation, or load operation. For this kind of the motor, the UMP is determined mainly by the field produced by the magnet, and rated armature current can only affect UMP slightly. Some structure may not produce the UMP in the non-load operation, but can produce it in load operation. For this kind of motors, the UMP is closely related to the armature current and the way in which the armature windings are formed. Seeking for optimal structure in the motor design which can reduce not only low level of torque ripple, but also small UMP, is important for the spindle motors used in HDDs which require precise spinning motion.

In the paper, the analysis is just from the view point of EM field. However, the factors arising from the quality of the machine components, problems taken place in machine assembling process, can also lead the UMP development.

REFERENCES

[1] B. Heller, V. Hamata, Harmonic Field Effects In Induction Machines, Elsevier Scientific Public Company, Amsterdam Oxford, New York, 1977;

[2] P.L. Timar, Noise and Vibration of Electrical Machines, Elsevier, Amsterdam-Oxford, 1989;

[3] C. Bi, Z.J. Liu and T.S. low, "Analysis of unbalanced pulls in HDD spindle motors using a hybrid method", IEEE Trans. on Mag., Vol.32, No.5, Sept. 1996, pp.4308-4310;

[4] G.H. Jang, J.W. Yoon, N.Y. Park and S.M. Jang, "Torque and unbalanced magnetic force in rotational unsymetric brushless DC motor", IEEE Trans.on Mag., Vol.32, No.5, Sept., 1996, pp.5157-5159.