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TECHNICAL PAPER

Development and optimal design of a HDD spindle motor with pulling magnet to reduce electrical loss

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Abstract A conventional hard disk drive (HDD) spindle motor has a pulling plate to generate the axial magnetic force. However, the pulling plate consumes significant amount of iron loss due to the alternating magnetic field on the pulling plate. We propose the new design of a HDD spindle motor with pulling magnet to generate the pre-load as well as to eliminate the iron loss of the pulling plate. We also develop an optimal design methodology to minimize iron and copper losses from the spindle motor of a computer HDD while maintaining the same level of torque ripple and pulling force. The new design is optimized by the developed optimal design methodology. A metamodel is constructed from the three-dimensional finite element analysis of the magnetic field and the meta-modeling techniques, and the accuracies of the metamodels are discussed. The proposed optimal design problem is solved by the progressive quadratic approximation method. The proposed design reduces the electrical loss of the HDD spindle motor by 30.42 % while maintaining the same level of torque ripple and pulling force.

1 Introduction

Efficiency and torque ripple are important design considerations of a spindle motor of a hard disk drive (HDD) in electromagnetic design point of view. A HDD spindle motor is one of the significant sinks of the electrical power in a computer, and it consumes the electrical input power through windage, bearing and electrical losses. Electrical loss is approximately 1/3 of total power consumption, and it is composed of copper and iron losses. Reduction of electrical loss is one of the obstacles to develop a highly efficient spindle motor, and it always affect torque ripple. It is generated from the cogging torque and current switching, and it is also a dominant source of vibration and noise. Reduction of vibration and noise of a HDD cannot be achieved without reducing torque ripple. Another important electromagnetic design consideration is pulling force, which is applied to the fluid dynamic bearings (FDBs) in order to increase the axial stiffness of a HDD system. Most electromagnetic design variables are not independent each other. For example, pulling plate of a HDD spindle motor in Fig. 1a generates the pulling force, but it consumes significant amount of iron loss due to the alternating magnetic field on the pulling plate. Another example is the magnet overhang of the spindle motor of a HDD such as that shown in Fig. 1a. The height of the permanent magnet is greater than that of stator core to increase the torque constant and efficiency and to generate the pulling force, but magnet overhang generally increases the torque ripple, and excessive magnet overhang increases the iron loss by increasing the magnetic saturation in the top and bottom laminations of the stator.

Many researchers have investigated the reduction of electrical loss, the reduction of torque ripple and the maintenance of pulling force of BLDC motors separately. Zhu et al. (2010) proposed the optimal design parameters to reduce the cogging torque by the Taguchi Method. And Wang and Kang (2000) found an optimum teeth shape that give the minimum system energy variation according to the rotor position by using the three-dimensional finite element method. Yao et al. (1998) studied a spindle motor with high efficiency and low cogging torque by changing the teeth

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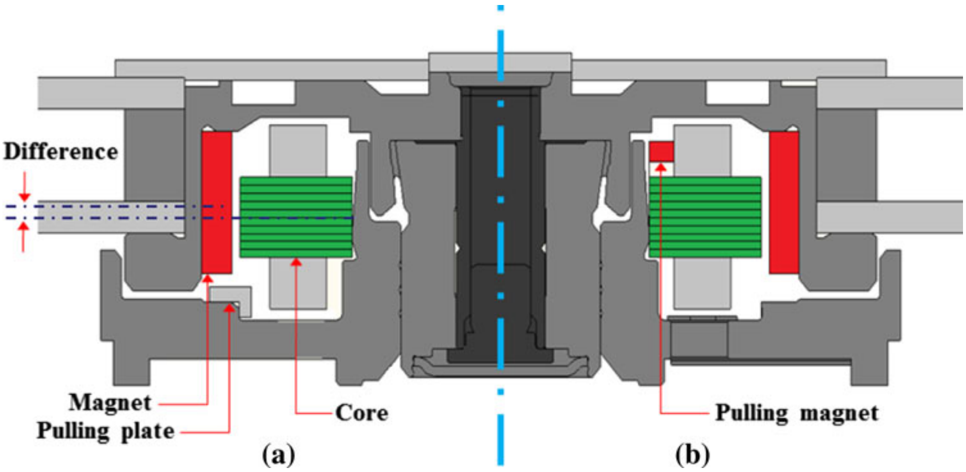

Fig. 1 Mechanical and electromagnetic structure of HDD spindle motors **a** with a pulling plate and **b** with a pulling magnet

shape. Several researchers have proposed the optimal control method to reduce the torque ripple and to increase the efficiency of BLDC motors (e.g. Hung and Ding 1993; Jang and Kim 2006; Park et al. 2000). However, prior researchers did not propose an optimal mechanical and electromagnetic design of BLDC motors including the torque ripple, pulling force and electrical loss.

We investigate a conventional HDD spindle motor in Fig. 1a by developing a three-dimensional finite element model of a HDD spindle motor to analyze the magnetic field, torque ripple, pulling force, torque constant and electrical loss. We propose the new design of a HDD spindle motor in Fig. 1b, which has a ring shape of pulling magnet to eliminate the iron loss of the pulling plate. The thickness of pulling magnet is 1 mm. It is axially magnetized and its residual flux density is 0.7 mT. We formulate an optimal design problem to minimize the iron and copper losses of the HDD spindle motor while maintaining same level of torque ripple and pulling force. The metamodel for the optimal design is constructed, and is solved by using a commercial process integration and design optimization (PIDO) software called PIAnO (FRAMAX 2011). The optimal solution from the metamodel is verified by a three-dimensional finite element analysis of an optimal HDD model, and the comparison of electromagnetic parameters between the conventional and optimal models was discussed.

2 Three dimensional finite element analysis

The conventional HDD spindle motor in this research supports two 2.5" disks at the operating speed of 7,200 rpm. The pulling plate in Fig. 1a motor generates the pulling force. We analyze the electrical loss, torque ripple and pulling force of the HDD spindle motor at that operating speed. We develop a three-dimensional finite element model with a periodic boundary condition, which is one-third of the HDD spindle motor with 12 poles and 9 slots in Fig. 2. It has approximately 1,000,000 tetrahedron elements with four nodes. Finite element analysis is performed at every 1.0° as the rotor rotates 60°. The torque and the pulling force are determined

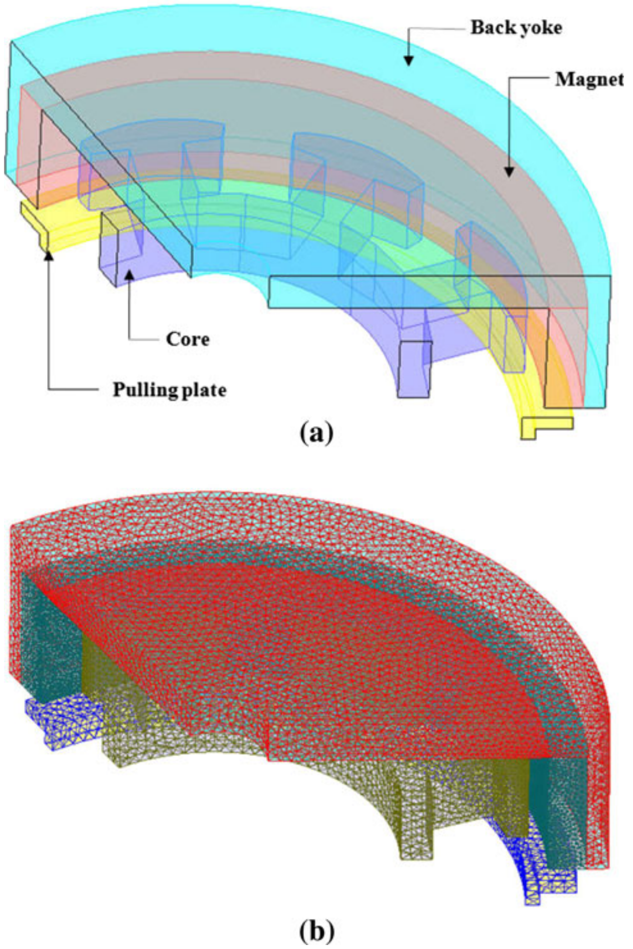

Fig. 2 **a** Analysis model and **b** three-dimensional finite element model of a HDD spindle motor

Table 1 Comparison of performances between conventional and proposed models

	Conventional model	Pulling magnet model
Torque constant (mNm/A)	5.56	5.77
Copper loss (mW)	50.72	48.81
Core loss (mW)	59.58	72.35
Pulling plate loss (mW)	37.62	0
Electrical loss (mW)	147.93	121.16
Torque ripple (mNm)	0.022	0.026
Pulling force (N)	0.93	0.81

by using the Maxwell stress tensor method. The copper loss is determined by multiplying the square of the current and the resistance of coil winding. The iron loss is determined by integrating the following equation for the stator core and pulling plate of the three-dimensional finite element model (Bertotti et al. 1991).

$$P_{core} = k_h B_m^2 f + \frac{\pi^2 \sigma d^2}{6}(B_m f)^2 + 8.67 \cdot k_e (B_m f)^{3/2} \tag{1}$$

where k_h, f, σ, d, B_m and k_e the coefficient of hysteresis loss, frequency, conductivity of material, lamination thickness, peak value of magnetic flux density, and coefficient of excess losses, respectively. The performance of the conventional HDD spindle motor is listed in Table 1. The pulling plate of the conventional HDD spindle motor consumes significant amount of iron loss, which is occupied by 25.43 % of total electrical loss.

3 A spindle motor with pulling magnet

This research proposes an axially magnetized pulling magnet on the stator in Fig. 1b to generate the pre-load and to eliminate the iron loss of the pulling plate. Table 1 shows the comparison of performances between conventional and the proposed models. The iron loss in pulling plate is 37.62 mW, but the proposed design with pulling magnet does not reduce the same amount of iron loss because iron loss of the stator increases magnetic saturation by the pulling magnet.

4 Design optimization

4.1 Formulation of design optimization

A design optimization problem of the HDD spindle motor to minimize the electrical loss while maintaining same level of torque ripple and pulling force of the conventional model can be formulated as follows:

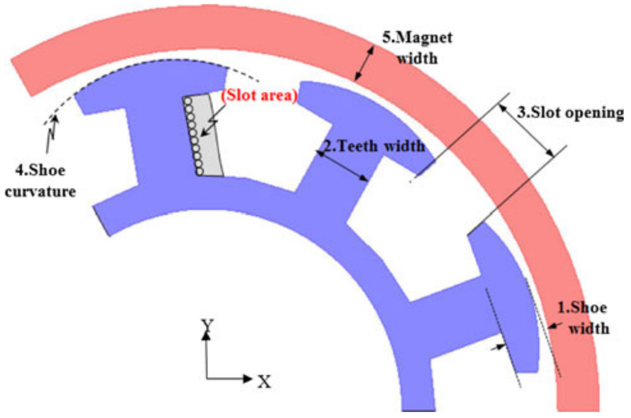

Fig. 3 Five design variables to solve the optimal problem

$$\begin{aligned}
&\text{Minimize } P(X_i) = P_{\text{copper}} + w \times P_{\text{iron}},\\
&\text{subject to } T(X_i) \le T(X_{i0}),\\
&\qquad 0.9\, F_{\text{pulling}}(X_{i0}) \le F_{\text{pulling}}(X_i) \le 1.1\, F_{\text{pulling}}(X_{i0}),\\
&\qquad (X_i)_{\text{lowerlimit}} \le X_i \le (X_i)_{\text{upperlimit}}.
\end{aligned}$$

where $P(X_i)$ is an objective function representing the electrical loss of the HDD spindle motors. It is composed of copper P_{copper} and iron P_{iron} losses. $T(X_i)$ and $F_{\text{pulling}}(X_i)$ are the constraints of torque ripple and pulling force, respectively. The weighting factor w is applied to compensate for the difference between experiment and analysis due to the PWM switching of the applied current. (X_i) is the i-th design variable of the HDD spindle motor. Figure 3 shows five design variables chosen in this research, and the lower and upper limits are determined by considering manufacturability.

4.2 Analysis procedure

Figure 4 shows the analysis procedure developed to calculate the electrical loss, torque ripple and pulling force.

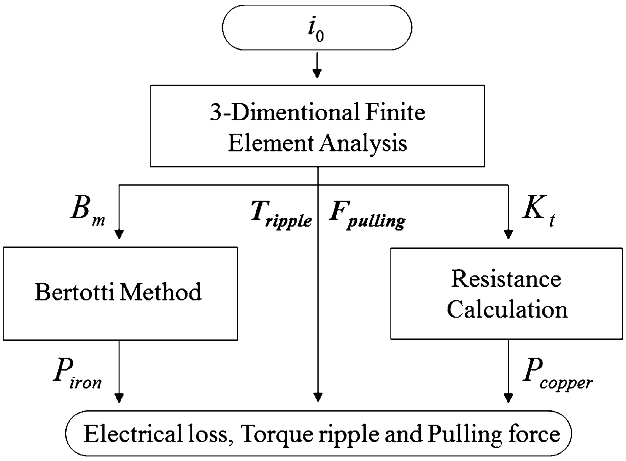

Fig. 4 Analysis procedure to calculate the electrical loss, torque ripple and pulling force

Table 2 Predicted R^2 values of metamodels

Meta-model type	Torque ripple	Torque constant	Pulling force	Iron loss
KR (constant)	0.612	0.729	0.755	0.780
KR (linear)	0.868 (best)	0.770 (best)	0.852 (best)	0.921 (best)
KR (simple quadratic)	0.813	0.760	0.770	0.882
KR (full quadratic)	0.701	0.682	0.713	0.772
KR (simple cubic)	0.637	0.670	0.683	0.738

First, the torque constant, torque ripple and pulling force are determined by the applied current which is experimentally measured for the conventional HDD spindle motor. Second, the iron loss is determined by Eq. (1). Third, the copper loss is determined. If the torque constant increases according to the change of design variables, the motor cannot operate at the rated operating speed since the back electromotive force increases. The number of coil turns of the current model is then determined by the linear relation of the torque constant and the number of coil turns as follows:

$$N = \left[N_0 \frac{K_t}{K_{t0}} \right] \tag{2}$$

where N_0 is the number of coil turns of the conventional model, and K_t and K_{t0} are the torque constants of the current simulated model and the conventional model, respectively. The number of coil turns is determined as an integer by Gauss' notation. The diameter of the coil is selected enough to wind the calculated turns of coil in the slot space, which also changes according to the change of design variables. The copper loss is determined with the following equation:

$$P_{\text{copper}} = \left(\frac{T_{\text{load}}}{K_t} \right)^2 \frac{\rho L}{A} \tag{3}$$

where T_{load} is the measured load torque when the conventional HDD spindle motor with two disks operates at rated speed, and K_t is the torque constant determined by the calculated number of coil turns. ρ, L, and A are the resistivity, total length, and cross-sectional area of the coil, respectively. Finally, the electrical loss is calculated by the summation of the copper and iron losses.

4.3 Metamodel-based design optimization

It takes around 6 h to calculate the magnetic field of a three-dimensional finite element model using a computer with a CPU of 2.93 GHz and 16 GB RAM. We improve computational efficiency in solving the design optimization problem by using the metamodel-based design optimization technique (e.g. Wang and Shan 2007; Simpson et al. 2008). Metamodels for torque ripple, torque constant, pulling force and iron loss are constructed from their values obtained by the three-dimensional finite element analysis (described in the previous section), which is performed at the experimental points specified by an orthogonal Latin-hypercube design (OLHD) as a design of experiments (DOE) technique (Butler 2001). In order to generate metamodels as accurately as possible, we construct five types KR models, which are constructed by employing constant, linear, simple quadratic, full quadratic and simple cubic global models with a general exponential correlation function (Sacks et al. 1989). Table 2 shows predicted R^2 values of the five metamodels for torque ripple, torque constant, pulling force and iron loss. The metamodel with a predicted R^2 value closest to one is the most accurate (Wang 2009). Metamodels of linear Kriging models KR are chosen for torque ripple, torque constant, pulling force and iron loss. To find the optimal solution, the progressive quadratic response surface method (PQRSM) is used as an optimization method (Hong et al. 2000).

5 Results and discussion

We carry out design optimization to minimize the electrical loss with five geometric design variables while satisfying the torque ripple and pulling force constraints. Table 3 shows the comparison of design variables between conventional and optimal designs. Table 4 shows the comparison of electromagnetic parameters between conventional and optimal models, and also shows that the metamodel of the optimal design matches well with the three-dimensional finite element model. Table 4 also shows that the electrical loss of the optimal model is decreased by 30.42 % from that of the conventional model, in which the iron and copper losses are decreased by 39.65 and 12.73 %, respectively. The circumferential arc of the

Table 3 Comparison of design variables between conventional and optimal models

Design variable	Lower limit	Conventional model	Upper limit	Optimal model
Shoe width (mm)	0.95	0.95	1.25	1.1
Teeth width (mm)	0.7	0.7	1	1
Slot opening (mm)	0.3	0.45	0.45	0.35
Shoe curvature (1/mm)	1/4	1/4	1/8.25	1/4.25
Magnet width (mm)	0.5	1	1	0.65

Table 4 Comparison of electromagnetic parameters between conventional and optimal models

	Conventional model	Optimal model		Difference (%)
		Metamodel	3-D analysis model	
Coil turns (EA)	57	54	54	−5.26
Coil diameter (mm)	0.15	0.19	0.19	26.66
Resistance (Ω)	3.60	3.16	3.16	−12.22
Copper loss (mW)	50.72	44.31	44.26	−12.73
Iron loss (mW)	97.20	56.99	58.66	−39.65
Electrical loss (mW)	147.93	101.30	102.92	−30.42
Torque constant (mNm/A)	5.56	5.58	5.58	0.35
Torque ripple (mNm)	0.0216	0.0160	0.0188	−12.96
Pulling force (N)	0.93	0.84	0.85	−8.60

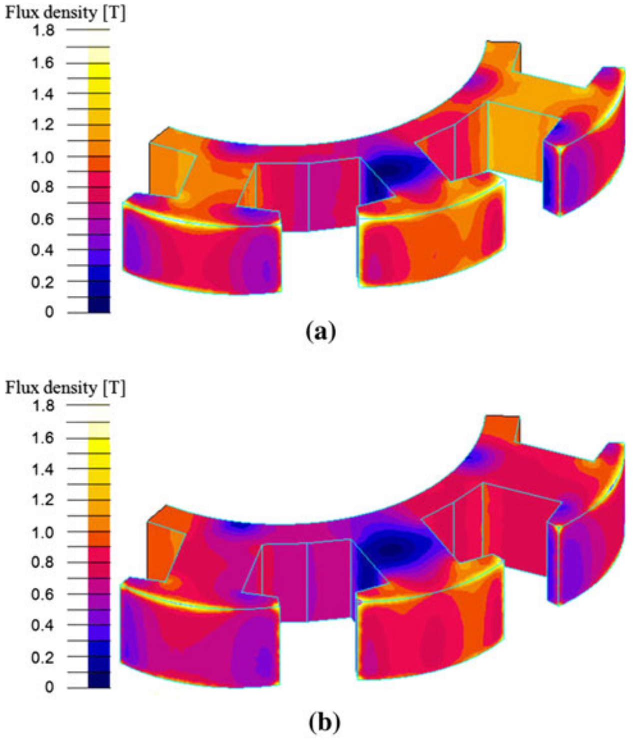

Fig. 5 Flux density distributions in stator core of **a** conventional model and **b** optimal model

teeth of the optimal model is larger than that of the conventional model, and the magnet thickness of the optimal model is smaller than that of the conventional model. The teeth shape and the magnet thickness decreased the magnetic saturation and the iron loss from Eq. (1). Figure 5 shows the magnetic flux density of the conventional and optimal stator cores, and it shows that the optimal core has less magnetic saturation than the conventional model. This results in the reduction of iron loss. The optimal model has small turns of coil with thick diameters, which results in the reduction of copper loss by decreasing the resistance of coil winding.

6 Conclusions

This paper proposes the new design of a HDD spindle motor with pulling magnet to eliminate the iron loss as well as to generate the pre-load. This paper also develops an optimal design methodology of a HDD spindle motor in such a way to minimize the iron and copper losses while maintaining the same level of torque ripple and pulling force. It shows that the proposed optimal design methodology is effective to decrease the electrical loss. The proposed HDD spindle motor and the optimal design methodology can be effectively applied to reduce the electrical loss of a brushless DC motor.

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