Analysis of Iron Loss in Hard Disk Drive Spindle Motors

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Abstract— **The paper presents analysis of iron loss in permanent magnet spindle motors used for hard disk drives. The analysis is based on finite element method and uses the information on local flux density variation in the motor components. The iron loss distribution and the effect of the stator dimensions on the total iron loss are discussed.**

I. INTRODUCTION

The trend of hard disk drive (HDD) technology towards miniaturization and high spindle speed operation continues unabated. However, the increase in the recording speed tends to increase the power consumption, and the downsize of the disk drive spindle motor also raises the concern about the power loss distribution. Therefore the need for accurate prediction of power loss in design stage arises. This paper discusses analysis of iron losses in permanent magnet brushless motors, the underlying objective being to investigate the iron losses in spindles motors, which may be supported by fluid film bearings for high speed recording.

As well known, it is a difficult task if the accuracy of iron loss prediction is of concern. Firstly, accurate iron loss analysis relies on the information about local flux density in the stator core having non-linear property. Therefore analytical or lumped parameter model [1] is not adequate in most of the cases. Secondly, the local iron loss rate depends also on the shape of the locus formed due to rotation of the local magnetic field vector. The study presented in this paper uses finite element analysis (FEA) to obtain the field distributions and the loci of the local flux density vectors, by performing a series of FEA calculations at different rotor positions for a complete cycle of field variation. With the use of this iron loss model, the local iron loss density in different motor components, and effects of stator dimensions on the iron losses can be analyzed as shown by the computational examples in the paper. Iron losses in various spindle motors with different slot numbers are also examined by using the method.

II. IRON LOSS ANALYSIS

The distribution of the iron losses depends on the variation of the local field vector. More specifically, the iron loss induced by field variation, whether it is pulsating or rotating, can be related to the shape of the locus formed by the variation of the field vector for a complete cycle. A lock-step mesh generation scheme is used in the analysis of the magnetic field in spindle motors. In each step, the rotor is at first rotated with respect to its previous position, and the mesh is re-generated automatically before the FEA calculation is performed. Between two sequential steps the rotor moves a fixed angle corresponding to the arc between two nodes at the inner rotor diameter. The mesh regeneration scheme can be easily implemented in motor design packages. Although an adaptive mesh generation scheme may be ideal for accurate flux density prediction, its demand for computer time consumption is very high. The effect of rotational fields has been taken into account in the model in addition to the normal eddy current and hysteresis losses due to pulsating fields. The effect of the change in the flux density during excursion around the minor loop of ferromagnetic material characteristics is also included.

In calculation of the hysteresis loss due to local field variation, the flux density is first expanded into Fourier series to obtain the series of the elliptical harmonics having the major axis flux density B_{kmajor} and the minor axis flux density B_{kminor} of kth order. The total hysteresis loss density, p_h, can then be calculated based on the rotational and pulsating losses:

$$p_h = \sum_{k=0}^{\infty}[\beta_k p_{rh} + (1-\beta_k)^2 p_{ph}], \qquad (1)$$

where β_k is the ellpticity of the harmonic component of field vector of the kth order, p_{rh} rotating loss, and p_{ph} the pulsating loss. Then, the total iron loss in the ferromagnetic materials due to flux density variation is the sum of the hysteresis, eddy current and anomalous losses such that [2-4]:

$$P_p = p_h + p_e + p_x. \qquad (2)$$

In the above equation, the expression for the classical eddy current loss p_e is well established,

$$p_e = \frac{\sigma d^2}{12\rho}\frac{1}{T}\int_0^T B(\tau)^2 d\tau, \qquad (3)$$

and the anomalous loss [2], p_x due to pulsating or rotating fields can be described as a function of the time derivative of the flux density:

$$p_x = \frac{k_x}{T}\int_0^T \left|\frac{dB}{d\tau}\right|^{3/2} d\tau, \qquad (4)$$

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where k_x is the anomalous loss coefficient, and can be obtained experimentally.

The hysteresis loss due to pulsating fields, p_{ph} in Eq. (1), depends on the maximum value of the local flux density, B_m, and it can be determined by

$$p_{ph} = k_h f B_m{}^{\alpha}, \qquad (5)$$

where f is the frequency of the flux density variation, constant k_h and the power α are determined experimentally. If the flux density waveform causes considerable minor loops the above expression should be modified such that [5]:

$$p_{ph} = k_h k_{mh}(B_m) f B_m{}^{\alpha}, \qquad (6)$$

where $k_{mh}(B_m) = 1 + \frac{k_\delta}{B_m}\sum_{i=1}^{n}\Delta B_i$ is an empirical correction coefficient with k_δ in a range of 0.6~0.7, ΔB_i is the flux density variation during the excursion along the minor loops.

As shown in Eq. (1), the hysteresis loss may be divided into two components: pulsating hysteresis loss p_{ph}, and rotational hysteresis loss, p_{rh}. The hysteresis loss due to rotating fields can be evaluated using the following equation

$$p_{rh} = k_h k_{rh}(B_m) f B_m{}^{\alpha'}, \qquad (7)$$

where k_{rh} is an empirical coefficient [6] and the power $\alpha' = 1$.

III. Computational Results and Discussion

The above iron loss model was applied to the brushless dc type of disk drive spindle motor having plastic bonded NdFeB magnet. Three motors, all with 8 poles but different number of slots, Motor A (8-poles 6-slots), Motor B (8-poles 9-slots) and Motor C (8-poles 12-slots), are examined. The main parameters of the motors are given in TABLE I as below.

TABLE I
DIMENSIONS OF MOTORS UNDER INVESTIGATION

Outer radius of motor	11.7mm
Outer radius of magnet poles	10.9mm
Inner radius of magnet poles	9.6mm
Outer radius of stator	9.4mm
Inner radius of motor	3.5mm
Length of lamination	4.5mm
Stator yoke height	1.1mm

The wedge angle (See inset in Fig. 3 for definition) for the motors is 90°. The values for the tooth tip height are 1.74mm for Motor A, 0.76mm for Motor B, and 0.54mm for Motor C, respectively. The average air gap flux density and the tooth flux density for the three motors are designed to be at the similar level. All the motors use 0.35mm M-15 steel sheets for the lamination stacks.

Fig. 1 shows the predicted iron loss in the 8-pole 9-slot motor as a function of the motor speed. The eddy current and hysteresis losses are also illustrated. It can be seen that as the speed reaches 12500 rpm, the iron loss is 2.6 W, which is the same order as the total power loss of the 3600 rpm spindle motor used for HDDs. This is mainly due to the sharp increase in the eddy current loss. The total iron loss predictions for Motors A, B and C are compared in Fig. 2 where it can be observed that the iron loss tends to be larger with larger number of slots. The analysis of the iron loss distribution shows that there is high level of concentration of the eddy current loss in the tooth tip areas. There is strong correlation between total iron loss and tooth tip dimensions. Besides, the ellipticity $\beta_k = B_{kminor} / B_{kmajor}$ for the magnetic field in the tooth tip area tends to be larger when the number of the slots increases. It may be conjectured as the other factor leading to higher iron loss in motors with large number of slots, although its effect may be less significant.

With the use of the FEA based iron loss model, the local iron loss density in different motor components, and effects of stator dimensions on the iron losses can also be analyzed. The sensitivity of the iron loss to the tooth tip dimensions is illustrated in Fig. 3 which plots the iron loss against the tooth wedge angle. It will be noted that the question of optimizing the tooth tip dimensions to minimize iron losses is sensible as they should be designed under the constraint for keeping sufficient space for the stator windings.

It should be noted that the lock-step mesh regeneration scheme is also suitable for analyzing the electromagnetic forces, e.g. cogging torque and radial forces, developed in spindle motors. Though, for these purposes the angular range over which the field evaluation is to be performed is much smaller, and the step must be much refined to capture the actual picture of the force fluctuation. Fig. 4 illustrates the computed distribution of the radial component of the Maxwell tensor $T_n = B_r^2 - B_t^2$ computed during the field evaluation process for an 8-pole 12-slot motor. An accurate prediction of this quantity is essential for radial force calculation and the determination of the mechanical stresses.

The iron loss analysis presented above concerns only with the loss in the stator since it is reasonable to assume that the eddy current loss in the rotor due to the magnetic field energized by the stator windings is negligibly small for spindle speeds currently adopted in HDD industry. However it should be recognized that this type of loss exists because of the high frequency commutation and the relatively high conductivity of the permanent magnet materials, especially NdFeB magnets, and it rises rapidly when the spindle speed increases. The eddy current loss in the rotor of Motor C was estimated and shown in Fig. 5 for two different types of magnet, i.e. polymer bonded NdFeB and sintered NdFeB magnets, respectively. The latter has a much higher value of conductivity. An analytical approach presented in Ref. [7] was used in the analysis. It can be seen that while it may still be true to assume an negligible rotor iron loss if polymer bonded NdFeB magnet is used, the commutation induced

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field variation can generate a significant amount of eddy current loss in rotor magnet and yoke for high spindle speeds.

IV. Conclusions

The iron losses in the stator of HDD spindle motors are investigated by using a lock step mesh regeneration scheme. The iron loss model accounts for the losses due to both pulsating and rotating fields. Various spindle motor structures are analyzed using the model. It is shown how rapidly the increase in the iron loss in PM spindle motors may accelerate for high speed operation. In order for the designers to decide appropriate safety margin for the design parameters of high speed spindle motors, an accurate prediction of the iron losses is needed. With the use of the FEA based modeling, the details of the loss density, such as the sensitivity of the iron loss to the motor parameters, can be studied. In addition, the effects of eddy current loss in the rotor is also discussed, and it is shown the use of certain type of sintered NdFeB magnet having high conductivity can be problematic for high speed operation.

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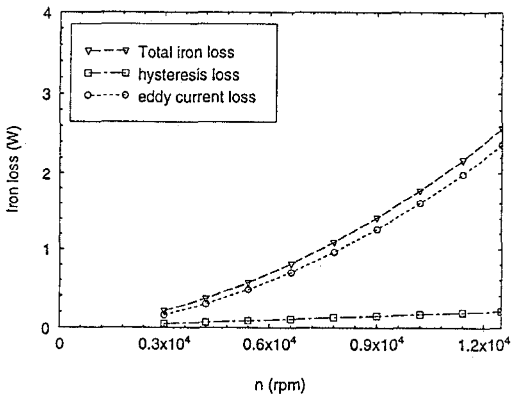

Fig. 1 Iron loss in 8-pole 9-slot spindle motor

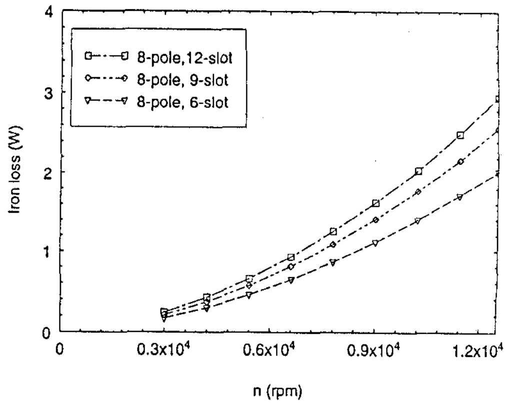

Fig. 2 Iron loss in Motor A, Motor B, and Motor C

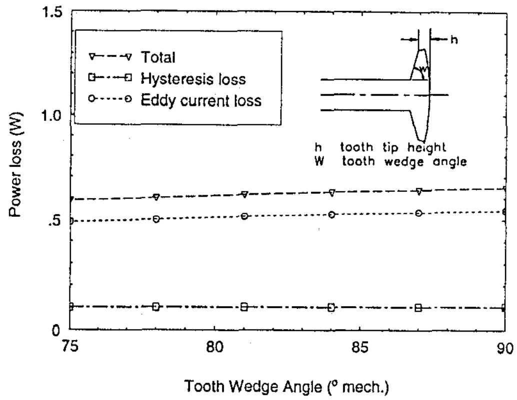

Fig. 3 Effect of wedge angle on iron loss in Motor C at 5400 rpm

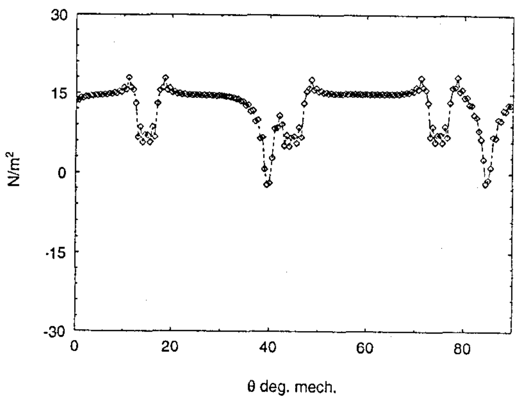

Fig. 4 Maxwell tensor vs. θ for Motor C

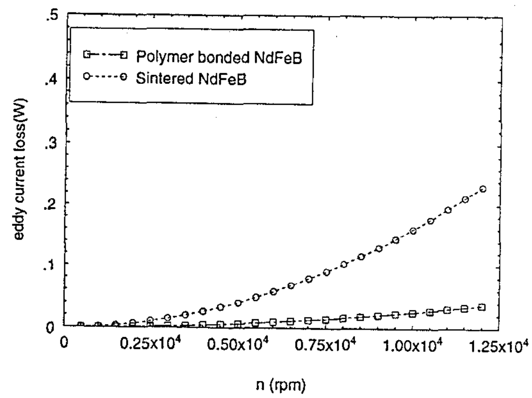

Fig. 5 Predicted eddy current loss in rotor
resistivity (polymer bonded NdFeB) 56 μΩm
resistivity (sintered NdFeB) 1.6 μΩm

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