Modelling and Torque Analysis of Permanent Magnet Spindle Motor for Disk Drive Systems

Z. J. Liu, C. Bi, H. C. Tan and T-S. Low
Magnetics Technology Centre, National University of Singapore, Singapore 0511

***Abstract*— This paper discusses the modelling of magnetic field distributions in disk drive spindle motors using a combined finite element and analytical approach. The torque analysis of a spindle motor having NdFeB magnet poles is also presented. It is shown that the proposed method provides an effective tool for reliable torque computation in contrast to conventional finite element schemes.**

I. Introduction

The development of small format factor disk drives in recent years has led to a significant reduction in the size of spindle motors with increased saturation level in iron components. As a result, design constraints, in vibrational and acoustic aspects for example, become more demanding, necessitating a detailed analysis of magnetic field problems in spindle motors to predict accurately the machine performance and loss generation in order to achieve efficient utilization of materials. In current disk drive industry, permanent magnet (PM) brushless motors with slotted laminations are widely used as spindle motors. The use of rear-earth permanent magnets with high energy products, such as various grades of NdFeB magnets, in this type of machine may amplify the undesirable cogging effects which exist in slotted machines and contribute to vibration and noise. It is well known that the reliability of torque and force computations using conventional finite-element methods is problematic [1-3]. An accurate torque prediction for a PM electric machine is even more difficult if the cogging effects are to be accounted for. Existing analytical and numerical approaches to solving this problem appear to be limited to linear cases, e.g. [4,5].

This paper describes a numerical technique based on a combination of finite-element and analytical methods for magnetic field modelling and dynamic torque prediction for PM spindle motors, taking into account the effects of non-linear characteristics of soft magnet materials. An analytical expression is first derived for the region of the air gap and the magnet poles, using the information of the potential distribution on the boundary of the region. The expression is then used to obtain a finite element formulation for the linear region and to establish the set of describing equations for the total field problem.

The technique is applied to the magnetic field analysis and torque prediction for a disk drive spindle motor having polymer-bonded NdFeB magnet poles. The torque computations obtained from the proposed method appear to be more reliable compared to those obtained from a conventional finite element methods (FEM).

Manuscript received April 4, 1994.

II. Method of Analysis

Fig. 1 shows the geometry of an external rotor machine and the definitions of symbols to be used in the following discussion. The domain in which the field solution is required may be divided into two separate regions in one of which the magnetic field solution can be described analytically by the potentials at the nodes on the boundary of the region.

In PM electric machines, permanent magnets are usually designed to work in the linear regime of its demagnetization characteristics under normal operating conditions. Therefore the field problem may be solved by a pure analytical approach for the region of magnet poles and the air gap. In addition, the region in which an analytical technique is to be applied can also involve the rotor back iron, if it is not saturated or if the effect of the variation in rotor position on the average saturation level in the rotor back iron is not significant. The rest of the domain which involves the stator laminations with non-linear characteristics is to be formulated by a conventional finite element method.

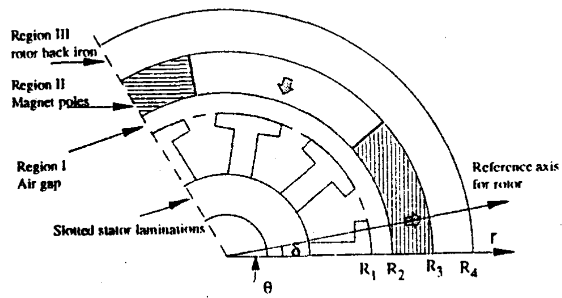

Fig. 1 Illustration of external rotor machine and regions

The region Ω that involves the machine air gap, magnet poles and rotor back iron, i.e. Regions I, II and III, as shown in Fig. 1, can be described, using vector potentials in the polar coordinates, in the following equations:

$$\frac{\partial}{r\partial r}\left(r\frac{\partial A_k}{\partial r}\right)+\frac{1}{r^2}\frac{\partial A_k{}^2}{\partial \theta^2}=J_k \qquad (1)$$

where $k=$ *I*, *II* and *III*, indicating Regions I, II and III,

0018-9464/94$4.00 © 1994 IEEE

respectively. The source term J_k is zero for Region I and III. In Region II, if the magnetization distribution in the radial direction is described by M(θ), J_k represents the effect of magnet poles, i.e. $(1/r)(\partial M/\partial\theta)$, which can be expressed in Fourier expansion with respect to θ :

$$\frac{1}{r}\frac{\partial M(\theta)}{\partial\theta}=\sum_{N}^{\infty} a_N \cos n(\theta-\delta) \quad (2)$$

where N=1,3,5,..., p is the number of pole pairs, $n = Np$, and

$$a_N=\begin{cases}4pB_r/\pi n & when \quad N=1,3,5,... \\ 0 & otherwise\end{cases} \quad (3)$$

In the above equation, B_r represents the remanance of magnets.

By referring to Fig. 1, the boundary conditions for the problem can be stated as follows:

$$\text{at } r=R_1 \quad A_I(r,\theta)\big|_{r=R_1}=\sum_{N}^{\infty}[\Psi_N \cos n\theta+\Phi_N \sin n\theta] \quad (4)$$

$$\text{at } r=R_4 \quad \frac{\partial A_{III}}{\partial\theta}(r,\theta)\big|_{r=R_4}=0 \quad (5)$$

and the usual boundary conditions for the radial and tangential components of the magnetic flux density apply to the interfaces between the regions, at $r = R_2$ and $r = R_3$.

In equation (4) Ψ_N and Φ_N are derived from the vector potential distribution, A_i, at boundary r = R_1, which is the interface between the region Ω and the region of stator laminations.

As given in (4), a Fourier expansion of the vector potential distribution based on A_i at boundary, r = R_1 and $\theta=\theta_i$ (i = 1, 2, ..., m) (m is the total number of nodes at the boundary) can be found, and Ψ_N and Φ_N may be expressed as follows:

$$\Psi_N=\sum_{i=1}^{m}\varsigma_{Ni}A_i \qquad \text{and} \qquad \Phi_N=\sum_{i=1}^{m}\xi_{Ni}A_i$$

where the Fourier coefficients ς_{Ni} and ξ_{Ni} are functions of θ_i.

The boundary value problem described by (1)-(5) is analytically solvable and the general solution may be expressed as:

$$A_k(r,\theta)=\sum_{i=1}^{m}v_{ki}A_i+\sum_{N=1}^{\infty}a_N\left[f_{kN}r^n+g_{kN}r^{-n}+b_{kN}r/(1-n^2)\right]\cos n(\theta-\delta) \quad (6)$$

$$\text{and} \quad v_{ki}=\frac{1}{2}\frac{\ln r}{\ln R_1}\varsigma_{0i}+\sum_{N=1}^{\infty}(\alpha_{kN}r^n+\beta_{kN}r^{-n})(\varsigma_{Ni}\cos n\theta+\xi_{Ni}\sin n\theta) \quad (7)$$

In (6) and (7), the coefficients, α_{kN}, β_{kN}, f_{kN}, g_{kN} and b_{kN} are determined from the boundary conditions and are dependent on the parameters R_1, R_2, R_3 and R_4, and the permeability for each region.

The Galerkin method [6] is used to obtain the finite element formulation for the region Ω, based on the analytical expressions (6) and (7). For the problem discussed here, the statement of Galerkin method can be expressed by the follow equation :

$$\int_\Omega \frac{1}{\mu_k}\left(\frac{\partial w_k}{\partial r}\frac{\partial A_k}{\partial r}+\frac{1}{r}\frac{\partial w_k}{\partial\theta}\frac{1}{r}\frac{\partial A_k}{\partial\theta}-w_kJ_k\right)d\Omega-\oint_\Gamma\frac{1}{\mu_k}w_k\frac{\partial A_k}{\partial n}d\Gamma=0 \quad (8)$$

where w_k is the prescribed function. If using v_{ki}, i.e. $w_k = \sum v_{ki}$, for the purpose of weighting, a set of independent equations can be obtained from (6), (7) and (8), such that

$$[s_{ij}]_\Omega[A_i]=[q_i]_\Omega \quad (9)$$

where $[s_{ij}]_\Omega$ is the stiffness matrix for the region Ω and $[q_i]_\Omega$ represents the effects of field sources in this region.

The combination of (9) and the finite element formulations for the region of stator laminations gives a set of equation describing the field problem for the whole domain and can be solved numerically.

Based on the Maxwell tensor theory, the electromagnetic torque, T, can be calculated by:

$$T=\frac{1}{\mu_0}\int_0^{2\pi}R^2\left(\frac{\partial A_I}{\partial r}\right)\left(\frac{1}{r}\frac{\partial A_I}{\partial\theta}\right)d\theta \quad (10)$$

for a given radius, R, in the air gap region. Substituting (6) and (7) into (10) leads to:

$$T=\sum_{i=1}^{m}\sum_{N}^{\infty}a_N(\beta_{1N}f_{1N}-\alpha_{1N}g_{1N})(\varsigma_{Ni}\cos n\delta+\xi_{Ni}\sin n\delta)A_i \quad (11)$$

for the torque computation. It can be seen from (11) that the torque is now directly related to the potentials instead of the flux densities computed by using finite element method, and therefore will become less sensitive to the errors of potentials that will inevitably occur in the finite element modelling.

III. Computational Results

The method described above is applied to a PM spindle motor with 6 poles and 9slots. The dimensions of the motor is given in Table I. Due to the periodicity of the field, an annular segment of two poles, i.e. $\theta_m-\theta_1=120°$, is used as the domain for the field analysis. The information about the mesh used in the computation is given in Table II.

Fig. 2 and 3 illustrate the equi-potential lines in the region of the laminations calculated using the proposed method at the rotor positions δ = 0 and δ = 7.5°, respectively.

A comparison of computational predictions of cogging torque obtained from the proposed method and the finite element method based on the first order triangular element, is shown in Fig. 4. Two different meshes were used for the finite element analyses. The information on the meshes used finite element analyses. The information on the meshes used in calculations is given in TABLE II. The curve represents the computed results obtained from the proposed method, the triangles are obtained from FEM using discretization scheme MESH B as described in TABLE II. In MESH B, the discretization of the lamination region is the same as that used for the proposed method. The Maxwell tensor method is used in the finite element analysis for torque calculations. The dotted curve shows the computed results obtained from FEM using MESH C which has a much higher mesh density level than MESH B. The sensitivity of the computed torque prediction obtained from FEM to the mesh distribution and mesh density level can be clearly observed. The proposed method on other hand is effective in capturing the peak value of the cogging torque with a relatively small number of elements.

TABLE I DIMENSIONS AND PARAMETERS OF THE MOTOR

Outer radius of machine	R4	11.75mm
Outer radius of magnet poles	R3	10.75mm
Inner radius of magnet poles	R2	9.5 mm
Outer radius of stator	R1	9.22 mm
Length of lamination		8.0 mm
Ratio of tooth tip arc to tooth slot pitch		0.78

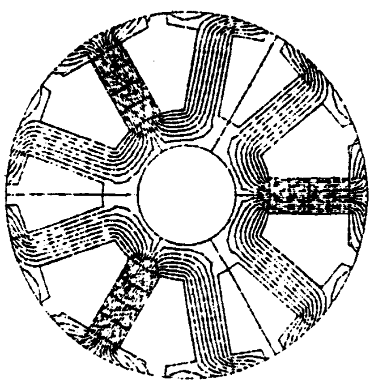

Fig. 2 Equi-potential lines in region of stator at rotor position $\delta = 0°$

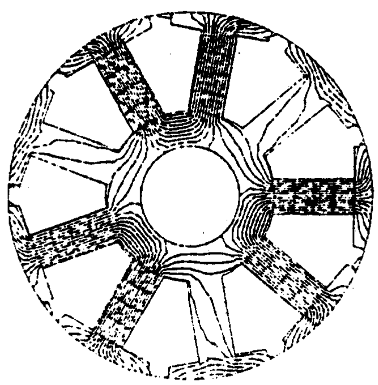

Fig. 3 Equi-potential lines in region of stator at rotor position $\delta = 7.5°$

TABLE II DETAILS OF MESHES USED IN ANALYSIS

	MESH A (used for the proposed method)	MESH B (used for conventional finite element method)	MESH C
Total number of element	726	1676	2066
Total number of nodes	401	883	1080
Number of nodes at r = R1	43	43	61

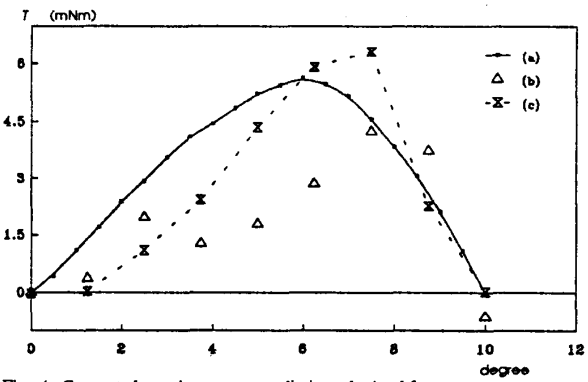

Fig. 4 Computed cogging torque prediction obtained from
(a) the proposed method using MESH A
(b) finite element method using MESH B
(c) finite element method using MESH C

IV. CONCLUSIONS

A new method based on the combination of analytical and finite element techniques is shown to be an useful tool for modelling PM spindle motors used in disk drive systems. The method allows a reliable torque computation to be easily made using the information on distribution of the potential rather than its derivative calculated using FEM. It will be noted that the proposed method can also be applied to the field analysis and torque computation problems for PM motors having an external rotor when the effects of saturation in the rotor back iron also need to be accounted for.

REFERENCES

[1] D. Howe and Z. Q. Zhu, "The influence of finite element discretization on the prediction of cogging torque in permanent magnet excited motors", *IEEE Trans. Magn.*, vol. 28, 2, pp 3771-3774, 1992.
[2] J. Mizia, K. Adamiak, A. R. Eastham and G. E. Dawson, "Finite element force calculation: comparison of methods for electrical machines", *IEEE Trans. Magn.*, vol. 24, pp 447-450, 1988.
[3] A. A. Abdel-Razek, J. L. Coulomb, M. Feliachi and J. C. Sabonnadiere, "Concept of an air-gap element for the dynamic analysis of the electromagnetic field in electric machines", *IEEE Trans. Magn.*, vol. 18, 2, pp 655-659, 1982.
[4] D. Howe and Z. Q. Zhu, "Analytical prediction of cogging torque in radial-field PM Brushless motors", *IEEE Trans. Magn.*, vol. 28, 2, pp 371-1374, 1992.
[5] E. S. Hamdi, A. F. L-Nogueira and P. P. Silvester, "Torque computation by mean and difference potentials", *IEE Proc.* vol. 140, 2, pp 151- 154, 1993.
[6] O. C. Zienkiewicz, "The finite element method", McGraw-Hill, 1987.