Numerical Modeling and Performance Analysis of a Disk Drive Spindle Motor using Circuit-Field Coupled Systems

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Abstract-- **This paper presents the modeling, simulation and performance analysis of the disk drive spindle motor using numerical methods. In the numerical model, nonlinear electromagnetic field, circuit and the rotor motion equations are formulated in time domain and solved simultaneously at each time steps. The proposed model is validated and used to investigate the steady state and transient analysis of the motor.**

Index Terms-- **Spindle motor, time-stepping finite element method, coupled system.**

I. INTRODUCTION

The spindle motor is one of the most important components in HDD and in many ways determines the drive capacity and reliability. Various methods of analysis have been employed to model the motor and to predict their performance accurately at the design stage. Due to the complexity of the motor geometries, control techniques and eddy current phenomena, the numerical simulation becomes a more appropriate engineering tool for the motor optimal design. Among these, finite element method is by far the most efficient and popular technique and widely used in electrical machine design and performance evaluation [1].

Most of the spindle motors are outer rotor type brushless PMDC motors and cannot work without the electronic controllers (Fig.1). The phase windings of the motor are energized in sequence by the switching elements in the inverter which are controlled by shaft position sensors or sensorless control techniques. The characteristic of the electromagnetic field is time variant and non linear. Therefore, in order to simulate the performances of the motor precisely, the behaviour of the time varying electromagnetic field, characteristic of the inverter circuit and its control loop feature should be considered together as a coupled system. In this work, time stepping FEM is used to analyze the non-linear time variant electromagnetic field which takes into account the effect of rotor rotation and non-linear electric circuit of the stator phase. A new approach to couple the time stepping FEM with feedback control loop feature is implemented. Due to the direct coupling of the field, circuit, motion and closed loop feedback control feature, the solutions can take into account the complexity of the geometric model, non-linearity of the electromagnetic field, induced eddy currents, the material saturation, the rotor rotational effect and characteristic of non-linear semiconductor devices which are very difficult to consider using analytical methods and traditional FEM [2].

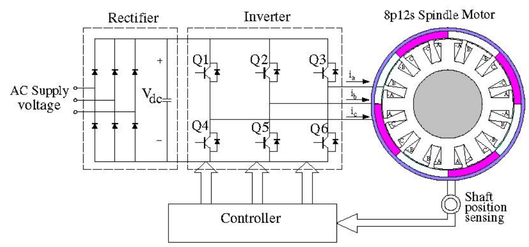

Fig.1 Spindle motor configuration and drive system

II. NUMERICAL MODEL OF THE MOTOR

The time dependent nonlinear electromagnetic field of the prototype spindle motor can be represented by the Maxwell's equation in the form of a magnetic vector potential A as

$$\nabla \times (\nu \nabla \times A) = J \qquad (1)$$

In the current carrying region (stator conductor region), $\nabla \times (\nu \nabla \times A) + \frac{i_s}{S} = 0$ (2)

In the solid rotor iron core where eddy current cannot be ignored, $\nabla \times (\nu \nabla \times A) + \sigma \frac{\partial A}{\partial t} = 0$ (3)

The permanent magnet can be represented an equivalent current source as

$$\nabla \times (\nu \nabla \times A) = \nabla \times (\nu B_r) \qquad (4)$$

in equations (1)-(4) i_s stator phase current, S the total cross-section area of the one turn one coil side, σ is the conductivity of the material and B_r is the remanent flux density of the permanent magnet.

The stator phase circuit equation can be expressed in general form as given by

$$V_s = Ri_s + L_\sigma \frac{di_s}{dt} + e \tag{5}$$

where R is the armature winding resistance, V_s is the supply voltage, L_σ is the ending winding inductances and e is the induced voltage (back emf). Rotor motion governed by the mechanical equation ,

$$J\frac{d\omega}{dt} = T_e - T_L + B\omega \tag{6}$$

Partial differential equations of field, circuit and motion are solved by Finite element method using Galerkin's formulation. In the solution procedure, Backward Euler method is used to discretize the time dependent equations (equ. (3), (5) and (6)). Newton Raphson method combine with ICCG algorithm is used to solve the global system of equations. From the numerical model, the magnetic vector potential A and stator phase current i_s are calculated directly. Electromagnetic torque is calculated by using Maxwell Stress Tensor method at each time step and from which the speed and rotor position can be determined. These parameters are subsequently used in the feedback signals for control loop.

Coupling with the Control Loop

In the hard disk drive system, fast and accurate control of disk spinning speed is vital for error free read/write operations. This requires a sophisticated controller for the purpose of rapid response [3]. In this model, a simple cascaded speed and current control structure is used to couple the time stepping FEM model. Detailed control system block diagram is shown in Fig.3.

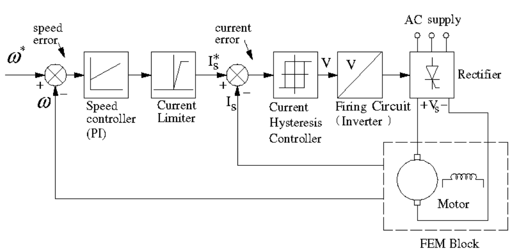

Fig. 3 Control system block diagram for spindle motor drive

III. PEFORMANCE ANALYSIS OF THE MOTOR

The proposed model is used to investigate the steady state and transient behaviours of the spindle motor drive system. Fig. 3 shows the simulated transient response at motor starting condition where the motor speed is limited to its rated speed 7200 rpm by the speed loop control. One of the important steady state parameters to analyze the spindle motor is cogging torque which is the key components of torque pulsations. Fig. 4 shows the results of computed cogging torque profiles with various magnet strengths.

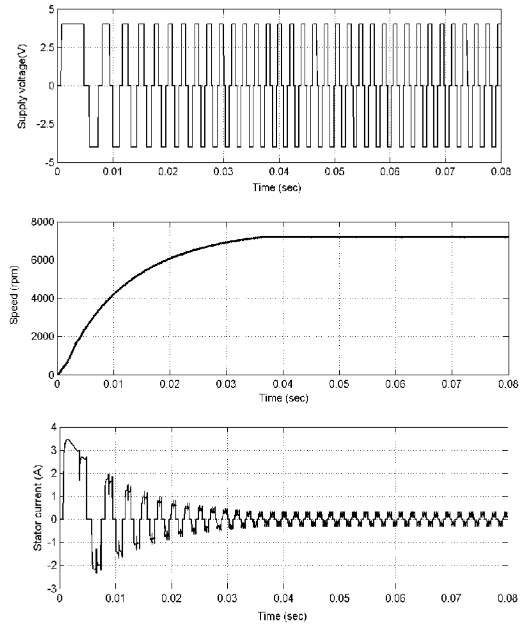

Fig.3 Simulated motor transient at starting condition

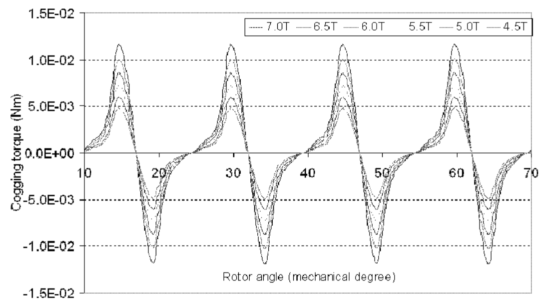

Fig.4 Simulated motor cogging torque

III. CONCLUSIONS

Numerical modeling of the spindle motor drive system in time domain was presented. Coupling of feedback loop control with the time stepping FEM block was implemented. Results show that proposed numerical models worked satisfactorily when used in simulation for steady state and transient conditions.

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