

Characteristics of a Rotor Vibration in an IPM Motor by Using Magnetic and Structural Analyses

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Abstract—This research presents a method to analyze magnetically induced vibration of a rotor in an IPM motor considering excitation of radial, tangential, and axial magnetic forces and gyroscopic effect. The magnetic forces are calculated by using the Maxwell stress tensor method, and the vibrations of a rotor excited by the magnetic forces acting on rotor poles are numerically analyzed by using the mode superposition method. Also, this research shows that the magnetic forces on rotor poles are multiples of both slot harmonics and half of slot harmonics due to winding pattern. This research introduces the characteristics of magnetic forces acting on a rotor pole and the concrete methodology to analyze magnetically induced vibration of a rotor excited by magnetic forces.

Index Terms—Vibrations, Electromagnetic analysis, Magnetic forces, Spinning machines, Finite element methods

I. INTRODUCTION

Permanent Magnet (PM) brushless DC motors have been widely used in various industrial applications because of their high efficiency and easy controllability over wide range of speed. Various structures of electric motors have been applied in industry. For example, the application area of electric vehicle or washing machine requires a motor with high torque in a limited space of large diameter and low height. However, the resonance of a rotor can cause serious vibration and acoustic noise as the bending stiffness of a rotor is weakened by the increase of the ratio of diameter to height. Many researchers investigate the characteristics of magnetic forces and magnetically-induced vibration of a rotor. Kim *et al.* investigated the unbalanced magnetic force (UMF) and dynamic response of a rotor [1]. They investigated the orbit of a rotor including shaft and roller-bearings, not the vibrations of a rotor itself due to magnetic forces. However, they did not consider the gyroscopic effect which is important to rotor dynamics. Yim *et al.* investigated the reaction force at the ball-bearings of a rotor due to magnetic forces [2]. However, they modeled the radial magnetic forces acting on rotor poles as the reaction of radial magnetic forces acting on stator teeth. Also, they considered only the radial magnetic forces without including the tangential force which results in torque ripple. Prior researchers did not investigate the characteristics of magnetic forces acting on rotor poles and the vibrations of a rotor itself considering all of radial, tangential, and axial magnetic forces on rotor poles and the gyroscopic effect simultaneously.

This research investigates the analysis method for magnetically induced vibration of a rotor. The magnetic flux densities were analyzed by using finite element method (FEM) with FLUX3D software, and magnetic forces were calculated by using the Maxwell stress tensor method. In addition, the

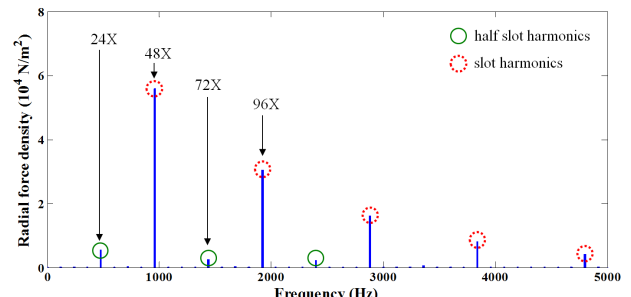


Fig. 1. Frequency spectrum of radial magnetic force on edge of a rotor pole.

characteristic of magnetic forces acting on rotor poles was investigated according to the variation of winding pattern. The structural finite element (FE) model includes the friction forces which prevent the divergence of the angular velocity of a rotor. The magnetically induced vibration of a rotor considering gyroscopic effect was analyzed by using the mode superposition method of ANSYS software.

II. ANALYSIS METHOD OF VIBRATIONS

A. Magnetic force

A three-dimensional magnetic FE model of an interior magnet permanent (IPM) motor with 56 poles and 48 slots was developed to simulate magnetic forces, and it consists of 829,920 brick elements. The magnetic forces acting on rotor poles in a rotating coordinate are calculated from the air-gap magnetic flux densities and the following Maxwell stress tensor [3]:

$$\sigma_{ij} = \frac{1}{\mu_0} \left(B_i B_j - \frac{1}{2} \delta_{ij} B_k B_k \right) \quad (1)$$

where μ_0 , B , and δ_{ij} are permeability of air, magnetic flux density, and Kronecker-delta function, respectively. Fig. 1 shows the frequency spectrum of the radial magnetic force on edge of a rotor pole of a motor running at 1,200 RPM with the applied current of 2.51 A and the both static and dynamic eccentricity of 25 μm . The magnetic forces acting on stator teeth have dominant components of pole harmonics [4], [5]. However, the magnetic forces acting on rotor poles have dominant components of slot harmonics. Also, this motor has the winding patterns of $A+A-B-B+C+C-$. The phase difference of magnetic flux between a PM and winding of $A+$ and $A-$ generates the magnetic forces of the half slot harmonics as shown in Fig. 1.

B. Rotor model and vibration analysis of a rotor

A three-dimensional structural FE model with 400,891 brick and tetrahedral elements was developed to numerically

analyze the vibrations of a rotor due to magnetic forces. The rotor model for vibration analysis is shown in Fig. 2. The stiffness of a ball-bearing is modeled by using matrix 27 element in ANSYS, and it has 5 degrees of freedom except a rotational degree of a rotor. In this research, we assumed that the load torque is mainly caused by the friction on ball-bearings because the operating speed is low and a pre-load on ball-bearings is very high. The load torque was calculated from the following equation of motion of a rotor in rotating degree of freedom:

$$T - T_L = J \frac{d\omega}{dt} \quad (2)$$

where T , T_L , J , and ω are driving torque, load torque, moment of inertia for a rotor, and angular velocity, respectively. The load torque is identical to driving torque when a motor operates at constant speed. And, the first term in (2) is eliminated once a motor is powered off, so that the friction force can be calculated from the following equation:

$$f_{fr} = -\frac{J}{n \cdot r} \frac{\Delta\omega}{\Delta t} \quad (3)$$

where n and r are a number of balls and a radius to the inner race of ball bearing, respectively. The $\Delta\omega$ and Δt were measured from the experiment of spin-down test. The friction force shown in Fig. 2 must be considered to prevent the divergence of the angular velocity of a rotor if the tangential magnetic forces are included in FE model. If not, the angular velocity of the motor in the simulation increases continuously by the driving torque. The magnetically induced vibrations of a rotor considering gyroscopic effect and friction force were determined from the following equation:

$$[M]\{\ddot{x}\} + ([C] + [G])\{\dot{x}\} + [K]\{x\} = \{F_{eq}\} + \{F_{fr}\} \quad (4)$$

where $[M]$, $[C]$, $[G]$, $[K]$, $\{x\}$, $\{F_{eq}\}$, and $\{F_{fr}\}$ are mass matrix, damping matrix, Coriolis matrix, stiffness matrix, nodal displacement vector, equivalent nodal magnetic force vector, and friction force vector, respectively. The damping matrix was determined from damping ratios via the modal testing for a rotor. Also, the mode superposition method was used to analyze the vibration. The number of superposed modes was fifty modes. Fig. 3(a) shows the frequency response of axial vibration at point A shown in Fig. 2(a). The dominant vibrations are caused by the magnetic forces of 48X on rotor poles and UMF of 84X which is originated from the harmonics of applied currents. An experiment was conducted to measure the vibration of a rotor by using both a slip-ring and an

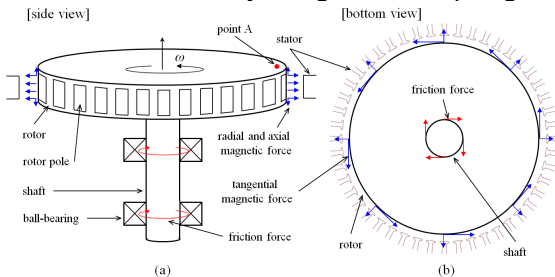


Fig. 2. Analysis model of a rotor including friction forces: (a) side view and (b) bottom view.

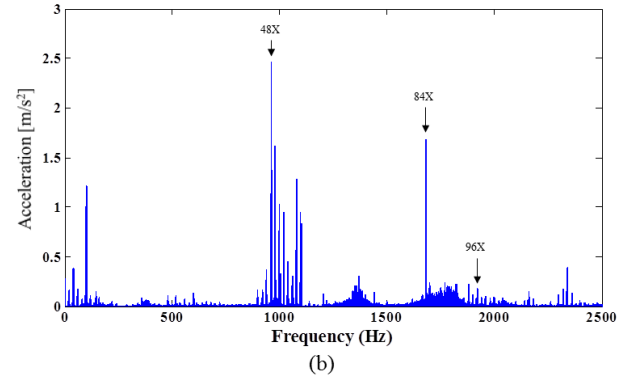
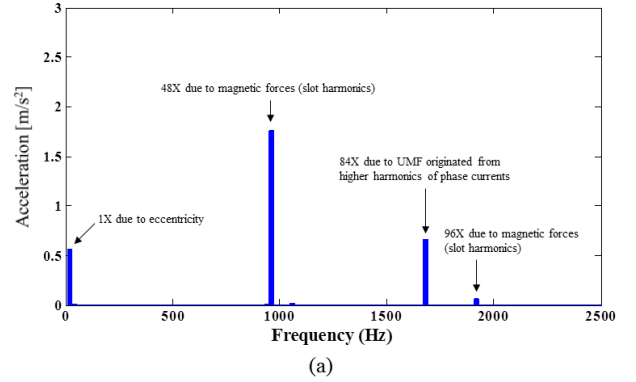


Fig. 3. Vibrations of a rotor due to magnetic forces at point A: (a) simulated vibration and (b) measured vibration.

accelerometer. The simulated vibration in Fig. 3(a) matches well with the measured one in Fig. 3(b). The analysis method for vibrations of a rotor considering all of the magnetic forces and gyroscopic effect was validated by comparing with the experimental results.

III. CONCLUSION

This research introduces the analysis method for vibrations of a rotor by considering excitation of radial, tangential and axial magnetic forces and gyroscopic effect simultaneously. Also, it shows that magnetic forces on rotor poles and vibrations in a rotor of IPM motor are mostly determined by the multiples of slot harmonics. This research will contribute to the reduction of vibration of a rotor of electric motors.

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