Mechanical Vibration and Stress Analysis of the Link of Interior Permanent Magnet type Synchronous Motor

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***Abstract* – This paper deal with stress analysis of the link and rotor vibration for Interior Permanent Magnet type Synchronous motor, which result from mechanical weakness coupled with electromagnetic forces. The electromagnetic force is calculated by using Equivalent Magnetizing Current (EMC). In addition, the natural frequency and mode shape of rotor are briefly analyzed through Transfer Matrix Method(TMM) and compared with experiments. Using the results of these stress and mechanical behavior analysis, mechanical safety in the link and critical speed are studied.**

***Index terms* – IPM, Equivalent Magnetizing Current, Transfer Matrix Method, Natural frequency, Stress, Electromagnetic force.**

I. INTRODUCTION

The source of noise and vibration can be classified into two groups: electromagnetic and mechanical sources. In case of the former, the electromagnetic force in electric machine results in torque of a motor and exciting force becomes radial force acting on stator and rotor, which produces a vibration. Especially, if the frequency of exciting force is close to the frequency band of natural frequency of a structure, a mechanical structure gets high vibration due to resonance. Hence it reduces lifetime of a motor and is transferred to objects in a near system. The noise with audible sound due to vibration has an unpleasant effect on human beings.

The increase of energy density gives rise to noise and vibration, so that the performance of a motor is deteriorated. Especially, the IPM has an advantage of high power per volume, but it has weakened mechanical structure in the link. Since the link of an IPM can contribute to the improvement of motor performance, such as reactance and torque, the strength of the link should be taken into account in a design stage. Therefore, this paper aims at calculating reliable exciting force and characteristics of mechanical structure in the link of IPM.

II. ANALYSIS PROCEDURE

A general method of force calculation is the Maxwell stress method that has different results of force according to the integral path. If the integral path of Maxwell stress is chosen very close to the iron-air surface, the error on force by elements is refined. However it is a tedious task and does not have reliability. The method based on EMC is able to obtain accurate magnetic force acting on surface of the rotor and is applied to the evaluation of the exciting force. In this method is that the existence of magnetic material can be replaced by distribution of EMC on the border line [1].

The periodic load of electromagnetic forces according to alteration of teeth and slot press on the link to continue. The bending stress and thermal stress action on the link is obtained by analytic method, and the stability is predicted by comparing with tensile strength of a measured peace of sample.

The resonance by means of natural frequency of rotor corresponding to exciting forces gives rise to the unbalance of air gap, and flux density of air gap caused by eccentric contains harmonics. Thus, whirling and bending vibration is produced by the unbalance of force and axial force as shown in Fig 1[2].

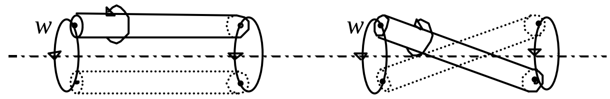

Fig .1 Whirling modes of a rigid rotor

The rotor vibration analysis of using 3D Finite Element Method takes a lot of time and expense. However, it's possible to make the model as a simple equivalent parameter model. After supposing that, it is easily analyzed by TMM. The result of natural frequency made by TMM is compared with the frequency of exciting force as well as that of experiment.

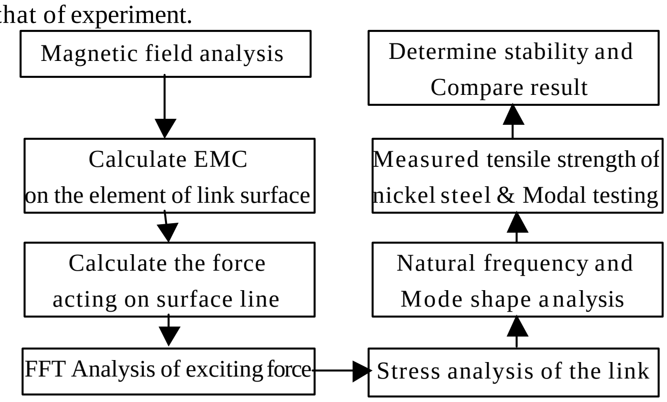

Fig. 2 The proceeding of the vibration and stress analysis

The procedure of the vibration calculation can be divided into eight steps as shown in Fig. 2.

III. ANALYSIS METHOD

A. Structure and analysis model

Figure 3(a) shows section of IPM, Fig. 3 (b) is the magnified structure of the link. The main specification is shown in Table 1. The permanent magnet is buried into the rotor. The link keeps permanent magnet from escaping rotor under operating

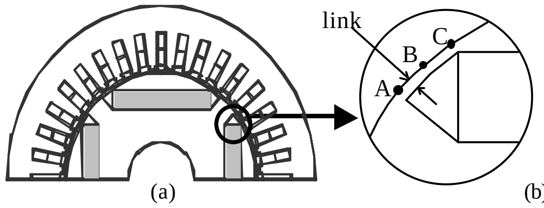

Fig. 3 Section of IPM and structure of the link

Table 1. Specification of analysis motor

Item	Value	Item	Value
Rate power	1.6.5 [kW]	Air gap	2 [mm]
Rate current	56.67 [A]	Outer stator diameter	184 [mm]
Phase/Pole number	3 / 4	Inner stator diameter	118 [mm]
Number of slots	36	Inner rotor diameter	40 [mm]
Residual flux density	1.2 [T]	Core length	114 [mm]

B. Magnetic Field Analysis

The magnetostatic field governing equation by field variable with vector potential is as follow [3]:

$$\frac{1}{m}\nabla^2\vec{A} = \vec{J} + \vec{J}_m \tag{1}$$

$$\vec{J}_m = \frac{1}{m_0}\nabla\times\vec{M} \tag{2}$$

where in $\vec{A}$ is a magnetic vector potential; $\vec{M}$ is the magnetization; m_0 is the magnetic permeability of vacuum; m is the magnetic permeability of core.

C. Magnetic Force Calculation

Each element shown in Fig.4 has different material. Magnetizing current exists on element borderline.

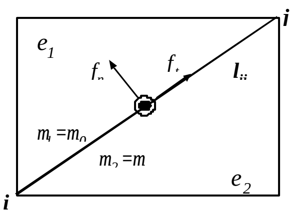

Fig. 4 Magnetizing current between two material

The interior magnetizing current in core is cancelled, so that magnetizing current only distributes on the element surface of different material. The current J_m on the line forming element e_1 and e_2 in Fig.4 can be expressed as follow [1]:

$$I_m = \frac{1}{m_0}\int \nabla\times\vec{M}\cdot d\vec{s} = \frac{1}{m_0}(M_{1t} - M_{2t}) \tag{3}$$

The equation (2) can be substitute into the equation (3), for simplicity. We obtain current I_m on the line i , j with length l_{ij} as shown in equation (5). Using equation (4):

$$\vec{B} = m_0\vec{H} + \vec{M} \tag{4}$$

$$I_m = \frac{1}{m_0}(B_{1t} - B_{2t})l_{ij} \tag{5}$$

The force on the length l_{ij} with current distribution by Lorenz's law is follow equation.

$$\vec{f}_{ij} = \vec{I}_{ij}\times\vec{B}_{ext} \tag{6}$$

Here the sum of the external field due to source and the self field due to the magnetizing current in core is B_{ext} . Flux density value of B_{ext} is given as the average value for each element.

D. Stress Analysis in the Link

The stress analysis model, which is a beam fixed at both ends, as shown in Fig .5. The electromagnetic force as uniformly distributed load w acts on surface of the link. We assume that the rotor core is a rigid body to expect the link and the load is in static state.

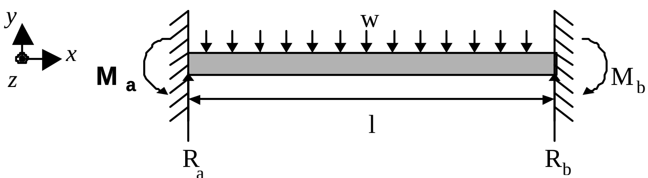

Fig. 5 Model for stress analysis in the link

The beam have unknown variables, such as bending moment and reaction forces at both ends. The unknown variables can be calculated by differential equation of elastic curve and area moment method. The bending stress and deflection according to displacement x has been calculated using equation (7) and (8)[4]:

$$s_m = \frac{M_x y}{I} = \frac{wl^2 y}{2I}\left(-\frac{1}{6} + \frac{x}{l} - \frac{x^2}{l^2}\right) \tag{7}$$

$$d_y = \frac{wl^4}{24EI}\left(\frac{x^2}{l^2} - \frac{2x^2}{l^3} + \frac{x^4}{l^4}\right) \tag{8}$$

where, w is uniformly distributed load due to electromagnetic force, M_x is bending moment, d_y deflection of the link, s_m is bending stress, and I is moment of inertia.

The interior temperature change of operating motor produces a change in length, so the stress due to the temperature change can be written as equation (10)

$$s_t = aE\Delta t = aE(t_2 - t_1) \tag{10}$$

where, a is coefficient of thermal expansion, E is Young's modulus, Dt is temperature change.

The total stress of the link equal to thermal stress adds to bending stress.

$$s_{link} = s_m + s_t \tag{11}$$

E. Calculation of Natural Frequency of Rotor

We model that each point are taken as discrete lumped mass which is replaced by distributed mass, and is connecting a field with stiffness as shown in Fig. 6. At the points of supported bearings, we only consider the stiffness of bearing and ignore the damping of bearing in this analysis.

Each point and field has the state vector containing the deflection w, angle deflection q, bending moment M_z, and shear forces V_y.

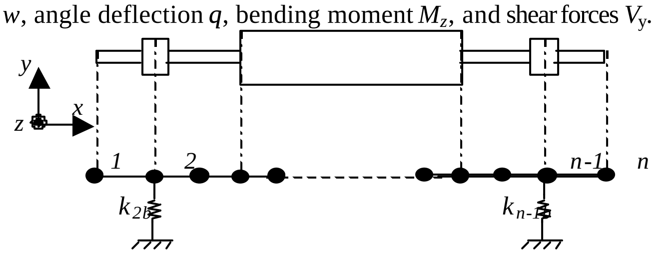

Fig. 6 Analysis model of rotor

- Point matrix: From the equilibrium relation for the mass at point I, we can directly write the following point transfer matrix..[2]

$$\begin{Bmatrix} w_i \\ q_i \\ V_{yi} \\ M_{zi} \end{Bmatrix}^R = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -ml^2 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} w_i \\ q_i \\ V_{yi} \\ M_{zi} \end{Bmatrix}^L \tag{12}$$

$$\{\mathbf{S}_i\}^R = [\mathbf{P}_i]\{\mathbf{S}_i\}^L \tag{13}$$

The point transfer matrix of node with bearing changes the element in third row and first column of matrix to $-mw^2 + k$.

-Field matrix: The governing differential equations of uniform beam segment connecting mass for ith are written in a transfer matrix.

$$\begin{Bmatrix} w_{i+1} \\ q_{i+1} \\ V_{yi+1} \\ M_{zi+1} \end{Bmatrix}^L = \begin{bmatrix} 1 & l & -\frac{l^3}{6EI} & \frac{l^2}{2EI} \\ 0 & 1 & -\frac{l^2}{2EI} & \frac{l}{EI} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -l & 1 \end{bmatrix} \begin{Bmatrix} w_i \\ q_i \\ V_{yi} \\ M_{zi} \end{Bmatrix}^R \tag{14}$$

$$\{\mathbf{S}\}_{i+1}^L = [\mathbf{F}_i]\{\mathbf{S}\}_i^R \tag{15}$$

-System transfer matrix: Defining the product of all element and point matrices in the order given by overall 4 by 4 transfer matrix [**T**].

$$\{\mathbf{S}\}_n^R = [\mathbf{P}]_n[\mathbf{F}]_{n-1}[\mathbf{P}]_{n-1}\cdots\cdots[\mathbf{P}]_1[\mathbf{F}]_1[\mathbf{P}]_1\{\mathbf{S}\}_1^L \tag{16}$$

$$\{\mathbf{S}\}_n^R = [\mathbf{T}]\{\mathbf{S}\}_1^L = [\mathbf{P}]_n \prod_{i=n-1}^{1} [\mathbf{F}][\mathbf{P}]_i \{\mathbf{S}\}_1^L \tag{17}$$

The natural frequency can be easily found and the corresponding mode shape can be determined by boundary condition at supported beam.

IV. DISCUSISON AND RESULT

In Fig. 7, there in show a set of time function of exciting force at 3 points described in Fig. 3(b). The reason why the radial force acts on maximum at point C is that the flux density of point C is maximum value due to nonlinearity in link. Thus point C illustrates maximum stress point. The distribution of banding stress (52.75[Gpa]) caused by electromagnetic excitation forces in the link is shown in Fig.8. The stress in both ends has larger amount than other place, so both ends of link are weaker than their center. Moreover, thermal stress is 115.25 [Gpa]. It means that the total stress given to both ends becomes 168[Gpa]. Comparing with a sheet of core tensile strength value 363[Gpa], the result safety factor of this result is only 2.115. Safety factor of mechanical construction must be at least 3, so that mechanical structure of the link is in unstable. It is necessary to make an analysis of vibration behavior, such as natural frequency and mode shape, and harmonics of exciting force. In order to verify the validity of the analysis result, rotor's modal testing will be done.

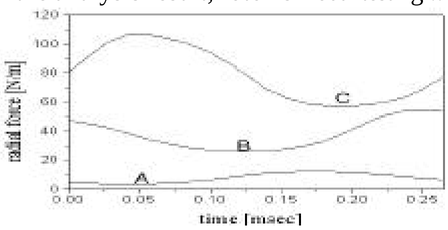

Fig. 7 Radial force in the link of IPM

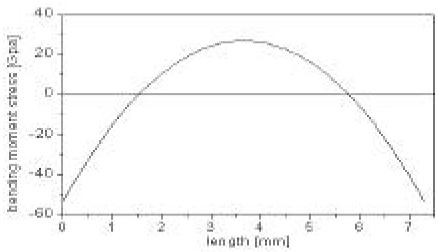

Fig. 8 Bending stress in the link

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