DESIGN OF LINK IN INTERIOR PERMANENT MAGNET TYPE SYNCHRONOUS MOTOR CONSIDERING MECHANICAL STRESS DUE TO ELECTROMAGNETIC FORCE

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Abstract: *This paper deals with the mechanical stress analysis due to electromagnetic force and the optimal design of the link that is a part of Interior Permanent Magnet type synchronous motor (IPM). The decrease of the link thickness serves to improve the torque, whereas this decreases the strength of link. Therefore, the effects of the mechanical stress caused by the electromagnetic force and the torque according to the link thickness are analyzed by the magnetic force coupled with the mechanical problem. In addition, this paper proposes an optimal geometry of the link with the strong strength against the stress and the high magnetic torque.*

Key words: *Mechanical stress, Electromagnetic force, Link and Optimal geometry.*

1. Introduction

The electromagnetic force in a electric machine results in torque of a motor and the its radial force component becomes a exciting 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, the mechanical structure gets high vibration due to resonance [1-2]. Hence, it reduces lifetime of a motor due to excessive stress and is transferred to objects in a near system. The audible noise 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. As a electric machine using permanent magnet, the IPM among the many Brushless permanent magnet motors widely used in industrial application has the advantage of high power per volume and high-speed operation through field weakening control [3]. The IPM has the link in its structure. The part of link in IPM has an effect on motor performance such as magnetic torque as well as mechanical strength.

Hence, it is important to determine the appropriate size of the link in IPM to improve the magnetic torque and to reduce the mechanical stress resulting from electromagnetic force. This paper studies on the optimal design of link in this relation.

2. Structural feature and analysis approach

The permanent magnet in the cross section of IPM is buried into the rotor as shown in Fig. 1. The link keeps permanent magnet from flying apart during rotation, as shown in Fig. 2, whereas it serves to a means of a pathway of leakage flux driven by the permanent magnet. The decrease of link thickness allows the magnetic flux path through the link to be saturated so that the flux of permanent magnet can be linkage with the stator. Thus, the decrease of link thickness is to improve the torque. In the mechanical stress point of view, as the magnetic force that is due to the slotting on the stator is acting on the surface of rotor, the thin structure of the link increases the mechanical stress and vibration [3]. At high-speed range, the link of IPM actually can be easily broken because of the magnetic force and centrifugal force.

Therefore, in the design stage of IPM, it is necessary to determine the appropriate dimension of link having the stable mechanical strength. The goal of this paper is to design the robust optimal link against the stress induced by magnetic force, together with always satisfying the resultant torque. The teeth width of stator to reduce the magnetic force acting on the link is determined and the effect of the torque and stress according to the change of link thickness is investigated.

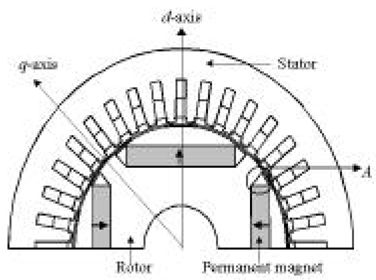


Fig. 1. Structure of IPM

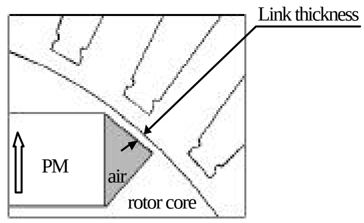


Fig. 2. Configuration of magnified link in A of Fig. 1

Table 1

Specification of analysis model for prototype

Item	Value	Item	Value
Phase/Pole	3 / 4	The number of slot	2(mm)
Air gap	2 (mm)	Residual flux density	1.2 (T)

The analysis procedure consists of three steps.

•Step I: the analysis of force in electric machines is important for the accurate prediction of motor vibration. Thus, the method based on Equivalent Magnetizing Current (EMC) is used to calculate the electromagnetic force distribution acting on surface of the rotor [4].

•Step II: the results of the electromagnetic force distribution are applied to the link and then the stress is calculated. For simplicity, the mechanical analysis model of the link is a beam fixed at both ends having the exact solution. The effects of the link thickness on the stress are investigated by the known solution.

•Step III: the design of the appropriate link thickness with fillet is conducted by using structural Finite Element Method (FEM) of a plan stress problem [5]. The improved model has the better torque and strength than the prototype model with link thickness 1 (mm).

3. Analysis method

A. Prototype motor

The specification is presented in Table I. Fig. 1 shows the cross section of IPM with 4 pole and 36 slot and the magnified structure of the link is shown in Fig. 2. For prototype IPM, the link length and its thickness are 7.5(mm) and 1(mm), respectively. This motor has the difference of magnetic reluctance between d-axis and q-axis so that the particular construction of this rotor produces a certain amount of reluctance torque.

B. Electromagnetic force calculation

The magnetic force acting on surface of the rotor is calculated by EMC. This method is that the existence of magnetic material can be replaced by distribution of EMC on the borderline, as shown in Fig. 3. The flux distribution is obtained by solving equation (1) with FEM. Each element shown in Fig. 3 has different materials. The magnetizing current exists on element borderline.

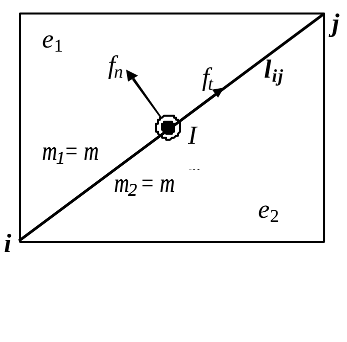


Fig. 3. Magnetizing current between two materials

The interior magnetizing current in core is cancelled, so that the magnetizing current distributes on only the element surface of different material. The magnetizing current I_m on the line forming element e_1 and e_2 in Fig.3 can be expressed as follows [4]:

$$I_m = \nu \int \nabla \times \vec{M} \cdot d\vec{s} = \nu (M_{1t} - M_{2t}) \quad (1)$$

In the above equation, magnetic materials have been replaced by the equivalent magnetizing current I_m for simplicity. We obtain current I_m on the line i , j with length l_{ij} as shown in equation (2).

$$I_m = \nu (B_{1t} - B_{2t}) l_{ij} \quad (2)$$

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

$$\vec{f}_{ij} = \vec{I}_{ij} \times \vec{B}_{ext} \quad (3)$$

where B_{ext} is the sum of the external field due to source and the self field due to the magnetizing current in core. Because the normal components on the element line are equal, flux density value of tangential component, B_{ext} is given as the average value for each element.

C. Stress Analysis by analytical solution

The stress analysis model for one sheet of core, a beam fixed at both ends, is shown in Fig. 4. The electromagnetic force as distributed load F acts on surface of the link. Assume that the rotor core is a rigid body to expect the link part and the material of beam is homogeneous that follows the Hook's law. The exact solution of the bending stress due to the load is founded by solving Newton's equilibrium equation and the principle of superposition.

The bending stress according to displacement x can be calculated by using equation (4) [5].

$$\sigma_m = \frac{Fl^2 y}{2I}\left(-\frac{1}{6} + \frac{x}{l} - \frac{x^2}{l^2}\right) \quad (4)$$

where, F is uniformly distributed load due to electromagnetic force, s_m is bending stress, I is moment of inertia and E is Young's modulus.

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

$$s_t = aE\Delta t = aE(t_2 - t_1) \quad (5)$$

where a is coefficient of thermal expansion and Δt is temperature change.

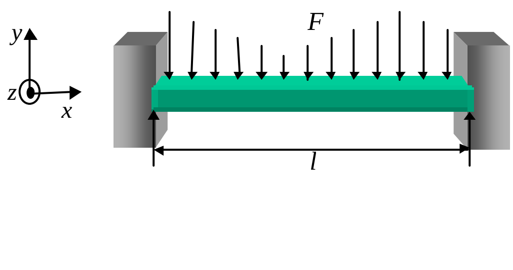


Fig. 4. Analysis model to analyze stress in the link

The total stress of the link σ_{link} is equal to the sum of thermal and bending stress.

$$\sigma_{link} = \sigma_m + \sigma_t \tag{6}$$

The stability is determined by comparing the tensile strength of a measured silicon steel plate with the analyzed total stress, which is called a factor of safety.

D. Optimal design of structural FEM

To analyze the link of a sheet of core using 2-dimensional FEM, the link is divided into triangular elements. The strain/displacement and stress/strain relationship can be written as

$$\{\varepsilon\} = [B]\{d\} \tag{7}$$

$$\{\sigma\} = [D]\{\varepsilon\} \tag{8}$$

where $\{\varepsilon\}$ is strain, $\{\sigma\}$ and $\{d\}$ are stress and displacement, respectively.

Using equation (7) in equation (8), the in-plain stress in terms of the unknown nodal degrees of freedom is as follows:

$$\{\sigma\} = [D][B]\{d\} \tag{9}$$

The global structure stiffness matrix and equation are derived by the principle of minimum potential energy [6].

$$\{F\} = [K]\{d\} \tag{10}$$

where $\{F\}$ is the nodal load due to electromagnetic force at the node and $[K]$ is the global structure stiffness matrix.

The stress is calculated by solving the system of algebraic equation given by equation (10) under the boundary condition.

4. Analysis results and discussion

A. Investigation on the effect of link thickness

Fig. 5 shows the electromagnetic exciting force acting on the surface of the link according to the variance of the slot width, when the slot pitch is constant. The forces are calculated by EMC. The sinusoidal magnetic forces are due to the alternation of teeth and slot. As the amplitude of the magnetic force increase with increasing slot width, to reduce stress caused by magnetic force, the slot width should be designed smaller than teeth width if possible.

Fig. 6 shows the variation of reluctance and magnetic torque according to the link thickness. The increase of the link thickness causes the decrease of the magnetic torque about 2.5(N m) because of the decrease of the leakage flux driven by permanent magnet passing through the link. Whereas the change of the link thickness does not have influence on the reluctance torque that is almost constant. Since the link acts as the magnetic path of the flux of permanent magnet, the increase of the link increases the leakage flux through it and decreases air-gap flux density.

Fig. 7 shows the equipotential distribution for the prototype model with 1(mm) link thickness when excited at current angle 90(deg.) and 0(deg.), respectively. The leakage flux passing through the link is shown in each Figure.

Fig. 8 shows bending stress distribution due to the load of the electromagnetic force described in Fig. 5, which is calculated by the exact solution of the beam fixed at both ends. The dimension of the link thickness is from 0.5 to 1.5(mm). From the results, the bending stress in both ends marks higher than any other places.

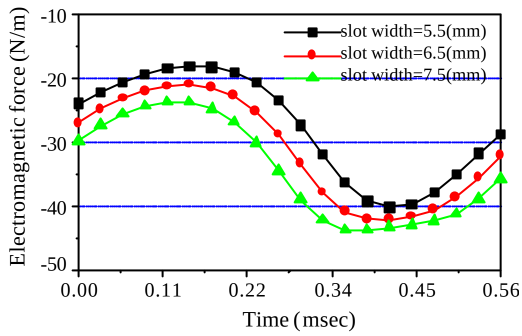


Fig. 5. Electromagnetic force distribution in link surface

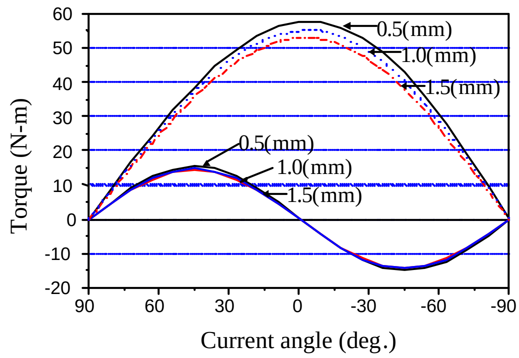
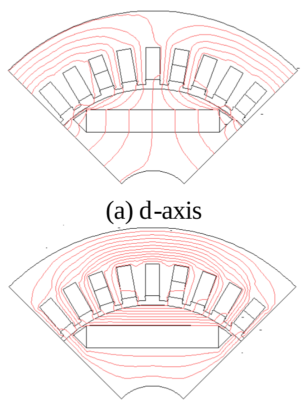


Fig. 6. Reluctance and magnetic torque vs. current angle



(a) d-axis

(b) q-axis

Fig. 7. Equipotential distribution at current angel 90 (deg.) and 0 (deg.)

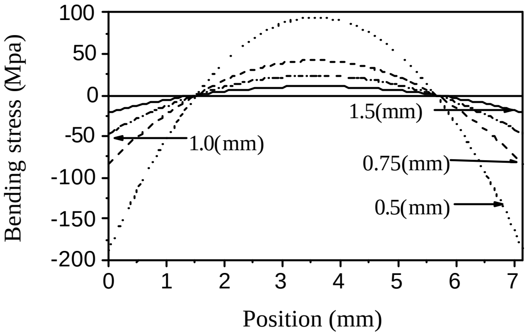


Fig. 8. The distribution of bending stress in the link

Table 2

Results of the stress analysis for the link thickness

Link thickness (mm)	Maximum stress (Mpa)	Total stress (Mpa)	Safety factor
0.50	187.97	303.22	1.20
0.75	83.54	198.79	1.83
1.00	46.99	162.24	2.24
1.50	20.89	127.00	2.67

So the link structure at both ends becomes weaker than the center. As the link thickness is decreased, the stress tends to be increased conspicuously. Accordingly, the decrease of the link thickness allows the torque to increase but the quality of the mechanical strength becomes deterioration.

Table 2 shows the detailed results of the stress analysis with the link thickness. The internal temperature of motor is 75°C in consideration of the change in temperature. When the total stress for the link thickness 1(mm) is compared with a sheet of core tensile strength value of 363 (Mpa), the safety factor becomes only 2.24. To satisfy the stable mechanical construction, the safety factor should be at least 2. Hence, the link thickness of IPM must be designed over 1.0(mm).

B. Improvement of torque and strength

The IPM with the link thickness 0.5(mm) is superior in magnetic torque to any other size, but the mechanical strength is of inferior quality. Hence, the link with fillet radius in the corner is selected to reinforce the strength in this size and the appropriate fillet radius is determined by structural FEM.

Fig. 9 shows the triangular mesh generation of the analysis model of 0.5 (mm) link thickness with fillet 1.2 (mm). Fig. 10 shows the deformation of link due to electromagnetic force load. Table 3 presents the stress analysis results according to several fillet radiuses. It notes that the safety factor is greater than 2 when the fillet radius is 12 (mm).

If the link thickness 0.5 (mm) with fillet radius 1.2(mm) is designed, it is possible to increase the magnetic torque about 2.5(N.m) better than the prototype motor.

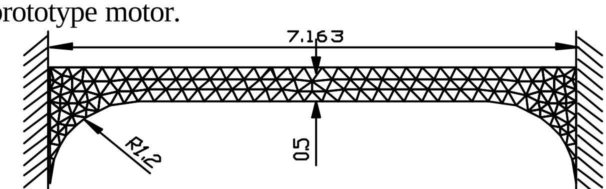


Fig. 9. Mesh generation and dimension of link with fillet

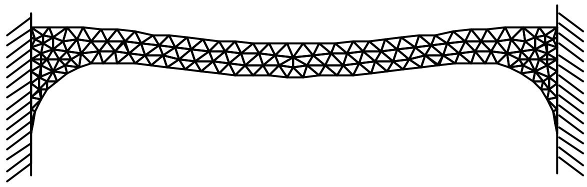


Fig. 10. Deformation of link due to electromagnetic force

Table 3

Stress and safety factor in case of link with fillet radius

Fillet radius (mm)	Total maximum stress (Mpa)	Safety Factor
6	210.24	1.72
8	200.34	1.81
10	189.74	1.91
12	179.84	2.01
13	170.94	2.12

5. Conclusion

The effects of the link thickness on the mechanical stress caused by electromagnetic force and the magnetic torque are investigated to reduce the stress and obtain the high torque. The increase of the link thickness reinforces the mechanical strength, while the magnetic torque is inclined to decrease. To obtain the high magnetic torque and stable mechanical strength in the given prototype motor, the appropriate link thickness with fillet radius is designed by using structural FEM.

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