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Effective Young's Modulus of Spiral Accumulating Core Used for Permanent Magnet Motor

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Abstract. Recently, permanent magnet motors are widely used in wide industrial fields because they are suitable for compact mechanical system. The motor core is usually manufactured from magnetic steel sheet with press machine. However, usually most parts of the plate are scalped, and only small percent of the sheet is used for the core. The spiral accumulating core system is suitable for manufacturing the core more ecologically because in this system more than 50% of the magnet steel sheet can be used. In this study, therefore, the effective Young's modulus of the spiral accumulating core is considered in order to find out a good method to fix the core. In this analysis, effective Young's modulus of spiral accumulating core used for permanent magnet motor is considered by the application of the finite element method to 3D models, whose layers and slits are periodically arranged. Then, effects of slits, layers and embossing interlockings on effective Young's modulus are analyzed. Finally, a convenient method of calculation based on rule of mixture is newly proposed for estimating the effective Young's modulus of the real spiral accumulating core.

Introduction

The PM synchronous motor is a rotating electric machine where the stator is a classic three phase stator like that of an induction motor and the rotor has surface-mounted permanent magnets. Recently, permanent magnet motors are widely used in wide industrial fields because they are suitable for compact mechanical system. The motor core is usually manufactured from magnetic steel sheet [1] with press machine. However, usually most parts of the plate are scalped, and only small percent of the sheet is used for the core. The spiral accumulating core system [2]-[6] is suitable for manufacturing the core more ecologically because in this system more than 50% of the magnet steel sheet can be used (see Fig.1).

In this analysis, effective Young's modulus of spiral accumulating core used for permanent magnet motor is considered by the application of the finite element method to 3D models, whose layers and slits are periodically arranged. Then, effects of slits, layers and embossing interlockings on effective Young's modulus are analyzed. Finally, a convenient method of calculation based on rule of mixture is newly proposed for estimating the effective Young's modulus of the real spiral accumulating core.

Method of analysis

Figure 2 shows (a) Axis and Rotor and (b) Housing and stator after shrink fitting. The compressive stress always acts in the direction of the circumference when the stator is fixed on the outside housing. Since the slit sustains the compressive stress, there is little effect on the Young's modulus. However, when the rotor is fixed on the axis, the tensile stress appears in the circumference direction. Therefore it is necessary to analyze the effective Young's modulus for rotor in order to fix it properly. Figure 3 shows three types of layers. Assume three layers are in the range of $\theta = 36^\circ - 90^\circ$ (see Fig.3). For example, each layer of core shape in the range of $90^\circ - 144^\circ$ coincide with that in the range of 36°-90°. The fourth layer is the same as the first layer. In this study, the effective Young's modulus of the spiral accumulating core is evaluated by applying the finite element method to this model.

Figure 4 shows the example of FEM mesh for 3D model. In this study, the linear hexahedron element is used. The total number of elements is 60450, and total number of nodes is 77868. Figure 5 shows the boundary condition of the model. As shown in Fig.5, the displacement in the θ direction at $\theta = 36^{\circ}$ is fixed, and displacement in the θ direction at $\theta = 90^{\circ}$ is fixed, that is, u_{θ}=0 at θ=36, 90°. The displacement in the z direction is fixed at the top and bottom surface of the 1st layer and of the 3rd layer, that is u_z=0 at the top and bottom surfaces. Then the constant displacement in the r-direction

Fig.1 Automatic spiral accumulating

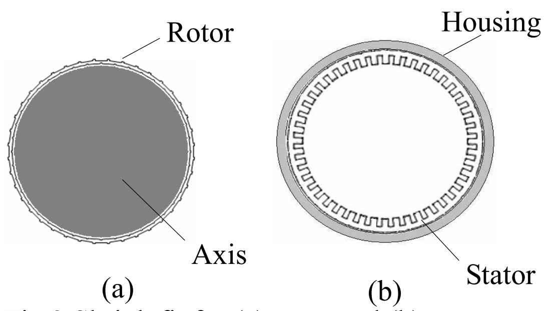

Fig.2 Shrink fit for (a) rotor and (b) stator

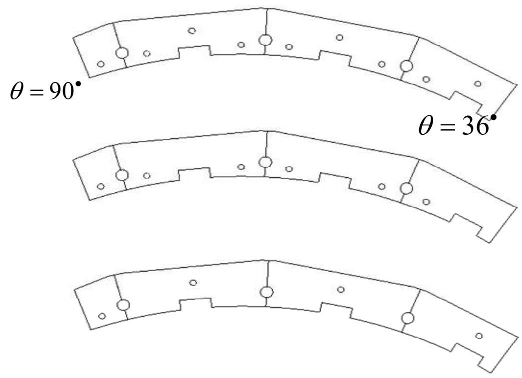

Fig.3 Three types of layers

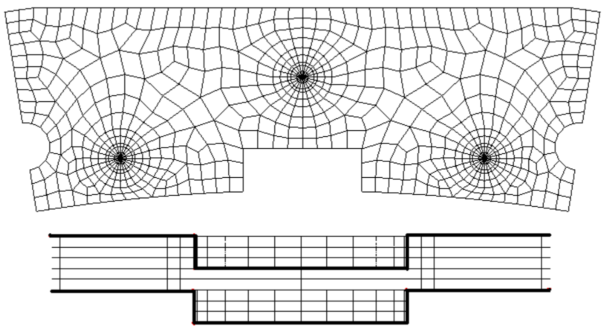

Fig.4 Example of FEM mesh for 3D model

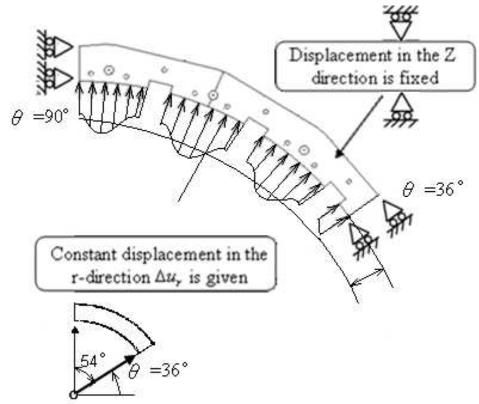

Fig.5 Boundary conditions of the model

$$E^* = \frac{\sigma_{\theta av}}{\varepsilon_\theta} = \frac{\sigma_{\theta 1}+\sigma_{\theta 2}+\sigma_{\theta 3}}{3(\Delta R/R)} \quad \ldots(1)$$

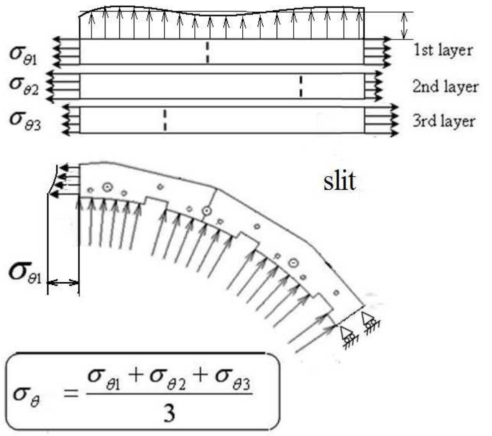

Fig.6 Method of analysis

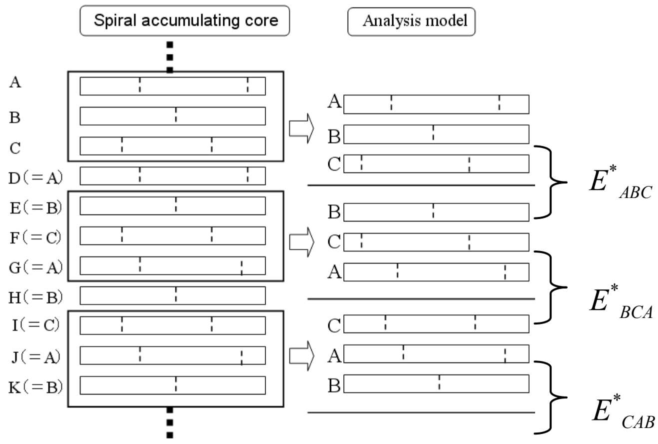

Fig.7 Three kinds of models analyzed for 54° Model in Fig.5.

$u_r=\Delta R$ is given at $r = R$.

The effective Young's modulus of the 3D dimensions model is given by Eqs. (1). In Fig.6, $\sigma_{\theta 1}, \sigma_{\theta 2}, \sigma_{\theta 3}$ are the average stress of first layer, second layer and third layer of the model respectively, the stress $\sigma_{\theta av}$ is the average stress of three layer accumulating model, and ε_θ is a strain of the direction of θ, and the value is equal to the strain value of the direction of R. Moreover, R is a radius in the core, and ΔR is constant displacement in the radial direction.

Results and discussion

First of all, three kinds of models are analyzed as shown in Fig.7. The effective Young's modulus of three kinds of models are $E^*_{ABC}=118$ GPa, $E^*_{BCA}=121$ GPa, $E^*_{CAB}=122$GPa. The average effective Young's modulus is $E^*_{av}=120$ GPa. Since periodic conditions at the top and bottom surfaces can not be applied, the results are slightly different.

Figure 8 shows the example of simple model for two layer's model. The second layer has phase difference of two embossing interlockings from the first layer. Here, 60° model as shown in Fig.8 is used to approximate 54° spiral model because spiral core is not suitable for examing the effect of slits and dimensions. Figure 9(a) shows detail view of Fig.8 from the z-direction. Figure 9(b) shows the detail view of Fig.8 from the r-direction. Since the gray region (block2) has almost no stress due to the slits, block2 can be regarde as a single layer as shown in Fig.9(c) ($E_2=E_o/2$). Equation (2) shows the rule of mixture for series model. Here, the values E_0 =206GPa and E_2 =103GPa[$E_2= E_0/2$] are Young's modulus for block1 and block2, respectively.

$$E^* = \frac{E_2 E_o}{E_o V_2 + (1-V_2)E_2} \qquad (2)$$

E^*: Effective Young's modulus, E_o: block1's Young's modulus, E_2 : block2's Young's modulus, V_2 : block2's volume fraction

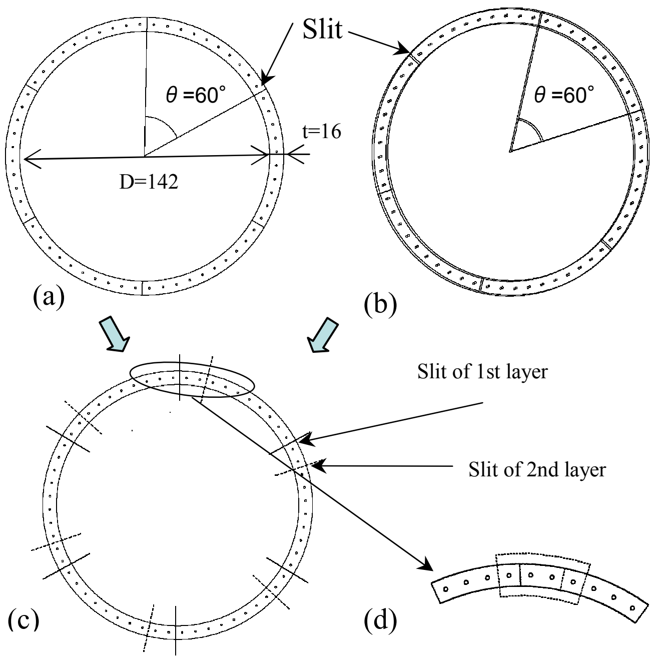

Fig.8 Two layer's model to approximate the spiral core
(a)First layer with slits at $\frac{n\pi}{3}$ (n=0, 1, 2, 3, 4, 5)
(b)・Second layer with slits at $\frac{(5n+1)\pi}{15}$ (n=0, 1, 2, 3, 4, 5)
(c)Two layers are fixed at embossing interlockings
(d)Unit cell

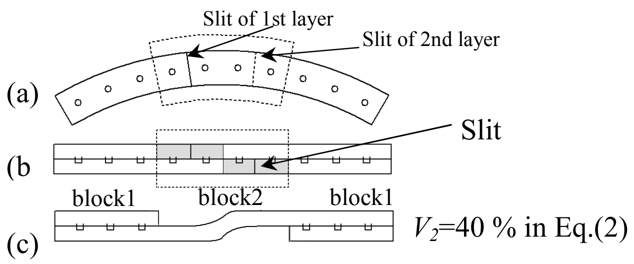

Fig.9 Unit cell of two layer's model
(a) Two layers model (b) Positions of silts
(c) Approximation method

Table1 Effect of number of slit N_S on E^*
(N_S :Effect of number of slit of one layer)

N_S	Effective Young's modulus E^* [GPa]					
	D=142[mm],t=16[mm]		D=142[mm],t=32[mm]		D=284[mm],t=16[mm]	
	FEM	ROM	FEM	ROM	FEM	ROM
12	106	113	85.6	90.4	115	128
6	138	146	120	126	148	158
3	163	171	149	157	172	179
2	176	181	163	170	182	187
1	187	193	178	186	192	196

As shown in Table 1, the effective Young's modulus of the simple core are analyzed by applying the finite element method to 3D model. And, Table 1 shows the values of the rule of mixture in Eq.(2). Estimating the effective Young's modulus can be given by using rule of mixture in Eq. (2) with less than 10% accuracy.

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