Rigidity evaluation of a superconducting helical coil for an LHD-type fusion magnet

H Tamura, S Imagawa, K Takahata, T Mito and A Sagara
National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

E-mail: tamura@nifs.ac.jp

Abstract. The large helical device (LHD) type fusion power reactor has many advantages in operations such as steady state and no active plasma current. The magnet system of the LHD-type fusion device consists of superconducting helical coils and superconducting poloidal coils. Since the helical coil is a complicated three-dimensional structure, designs of the coil and the supporting structure have to be performed carefully. Clarifying the mechanical behavior during coil excitation is very important for a design of the coil system. The mechanical behavior for components in the helical coil can be estimated using a simplified two dimensional axisymmetric model which has a mean radius of curvature of the actual helical coil. To evaluate the accuracy of this simplified model, stress distribution was calculated with three-dimensional finite element model and the result was compared with that of the simplified model. The stress distribution of a candidate design of LHD-type helical reactor was estimated by using the simplified model and the result showed that the stress/strain level were within the reasonable range for composed materials.

1. Introduction

The components of a magnetic confinement fusion reactor work under a huge electromagnetic force. Since the electromagnetic force is induced by the interaction between the magnetic field and the electric current, each type of the fusion reactor such as helical/stellarator and Tokamak, has its own characteristic of electromagnetic force distribution. Clarifying the mechanical behavior considering geometry of coils and the electromagnetic force is very important for a design of the magnet system, and both an overall deformation and a stress at every single component have to be taken into account.

Experimental results with the large helical device (LHD) have shown that a LHD-type fusion power reactor has many advantages, a steady-state operation, no need for active plasma current, constant current coil excitation, for example [1]. Aiming for a demonstration device of a fusion power reactor, the LHD-type force free helical reactor (FFHR) is being studied at the National Institute for Fusion Science with universities [2]. Figure 1 shows the conceptual draw of the FFHR. Several design parameters considered thus far, the magnetic energy for a 2 GW fusion power design was estimated to be 120 GJ with the coil current of 43.3 MA. The superconducting magnet system in the FFHR consists of one pair of helical and two pairs of poloidal coils. The current flow of a single superconductor and the maximum magnetic field on coil could be 100 kA and 13 T, respectively. Although the helical coil has a complicated three-dimensional structure and it is difficult to describe the mechanical behavior of the coil, it is important to estimate the mechanical behavior and rigidity in order to optimize the coil design and integrity assessment of the materials. In this paper, the mechanical behaviour of the helical coil in the FFHR is analyzed using a three-dimensional (3-D) finite element model and a simplified
two-dimensional (2-D) axisymmetric model. The 2-D axisymmetric model is useful because it is easier to modify the model according to the geometrical and conditional changes than the 3-D modelling. The accuracy of the result by the 2-D axisymmetric model is confirmed by comparing with that by the 3-D model. The rigidity evaluation using the 2-D axisymmetric model for the helical coil with aluminum alloy jacketed Nb3Sn, which is indirectly cooled, is introduced at last.

2. Geometry of helical coil

The locus of the current center of the helical coil is defined by the torus coordinate shown in figure 2 as

$$\theta = \frac{m}{l} \phi + \alpha' \sin\left(\frac{m}{l} \phi\right)$$

where $\theta$, $\phi$, $l$, $m$, $\alpha'$ and $R_c$ are the poloidal angle, toroidal angle, polo number, pitch parameter and major radius to the torus center, respectively. Let the coordinate axes $hx$ and $hy$ be chosen such that they are in the cross sectional plane of the helical coil and coincide their direction to coil height and width as shown in figure 3. The $hz$ axis is perpendicular to the coil cross section and is consistent with the winding direction of the coil. Since the helical coil has a cyclic symmetry of $m/l$, the first $2\pi(m/l)$ should be considered. Here we set the parameter $l = 2$, $m = 10$, $\alpha' = 0.1$ and $R_c = 14.0$ m according to the design of FFHR2m1 [3]. The minor radius to the coil center is 3.22 m. In this case, it has the cyclic symmetry of 5, and the section of 72 degree should be taken into account.

The curvature at the center of the helical coil at each location is calculated from (1). The radius of curvature changes through the toroidal angle. Figure 4 shows the radius of curvature in the case of FFHR2m1. In this case, the radius of curvature varies from 5.25 m to 6.0 m.
3. **Analytic model**

Boundary conditions applied to the 3-D model were as follows:

\[
\begin{align*}
  u_{hz} \big|_{\phi=0} &= u_{hz} \big|_{\phi=\pi/5} \\
  u_{hp} \big|_{\phi=0} &= u_{hp} \big|_{\phi=\pi/5} \\
  u_{hz} &= 0
\end{align*}
\]  
(2)

The first and the second conditions represent the cyclic boundary at the edge. The third condition in (2) represents the assumption that the helical coil is supported by a torus shaped structure, which restricts an out-plane deformation of the cross section perpendicular to the winding direction of the coil. The width and the height of the coil cross section were set as 1.8 m and 0.9 m, respectively. This geometry was also adopted in the 2-D axisymmetric model. The 3-D model was made of solid finite elements with 8 nodes. The electromagnetic force subjected to each element was separately calculated precisely and was applied on one surface of the element as a pressure load. The electromagnetic force can be divided into the hoop force and the overturning force. Both components were taken into account in the 3-D analysis. Figure 5 shows the hoop force distribution applied on the finite element model. Figure 6 shows the overturning one.

A circular coil that has a mean radius of curvature similar to that of an actual helical coil is considered to be able to estimate the mechanical behaviour of the helical coil. Here we make a simplified model according to this theory using a 2-D axisymmetric solid element. The radius of the 2-D axisymmetric model was set as 5.5 mm from the calculation of the mean radius of curvature of the coil.

![Figure 4](image1.png)

**Figure 4.** The radius of curvature of the helical coil along the toroidal angle in case of FFHR2m1.

![Figure 5](image2.png)

**Figure 5.** The hoop force distribution applied on the model.

![Figure 6](image3.png)

**Figure 6.** The overturning force applied on the model.
actual helical coil as shown in figure 4. Since the electromagnetic force intensity was different in every cross-section, the electromagnetic force along the circumference had to be transformed to the uniform distribution through the circumference. Thus the electromagnetic force distribution was averaged through one cyclic region. The result was bilaterally symmetrical about the $hy$ direction. Figure 7 shows the axisymmetric model with applied electromagnetic force distribution. ANSYS version 11.0 was used for calculation.

4. Result

The coil was assumed that it consisted of one isotropic material that had Young’s modulus of 150 GPa with Poisson’s ratio of 0.3. Figure 8 and 9 show the results of calculation by the 3-D model with the hoop stress loading and the overturning force loading with respect to the amount of deformation. The maximum amount of deformation was approximately 12.4 mm at the inner torus equatorial region for the hoop force loading, while it appeared at the outer equatorial region for the overturning force. The hoop force was more effective for deformation than that of the overturning force. Figure 10 and 11 show the von Mises stress distribution for each loading case. Similar to the deformations’, the maximum value appeared at the inner torus equatorial region for the case of hoop force loading and at the outer torus region for the case of the overturning force. The maximum von Mises stress for the hoop force case was three times as much as that of the overturning force one. As the result, it is believed that the deformation, stress and strain against the hoop force should be considered at first priority for an evaluation of the helical coil.

To see the distribution in the cross section at the inner torus equator, half of the model was revealed as shown in figure 12. This figure shows the same result for the amount of deformation against the hoop force loading as shown in figure 8. Figure 13 shows the result of calculation using 2-D
axisymmetric model. The distribution in the 2-D axisymmetric model was similar to that of the inner torus region in the 3-D calculation except the maximum value was approximately 25% higher than that of 2-D model. This tendency also appeared in the stress distribution as shown in figure 14 and 15. These figures show the hoop stress distribution calculated by each analytical method. In this case, the maximum stress value in the 3-D model was 20% much higher.

Figure 10. The von Mises stress distribution in 3-D model by the hoop force loading.

Figure 11. The von Mises stress distribution in 3-D model by the overturning force loading.

Figure 12. The amount of deformation in 3-D model by the hoop force loading (half below).

Figure 13. The amount of deformation in 2-D axisymmetric model by the hoop force loading.

Figure 14. The hoop stress distribution in 3-D model by the hoop force loading.

Figure 15. The hoop force distribution in 2-D model axisymmetric by the hoop force loading.
5. Discussion

The stress and displacement level in 2-D model that applied mean electromagnetic force distribution was slightly lower than that of the calculation result in 3-D model. If the total electromagnetic force in a cross-section of the coil coincides with peak value in the actual electromagnetic force, the results of 3-D and 2-D model will be closed. In fact, the difference between the maximum hoop force and the average through the circumference was approximately 24%, which was very close proportion concerning with the differences between the calculation results of them.

Although the hoop force was more effective than the overturning force, an effect of the overturning force should be known. The axisymmetric model usually does not consider a load which changes adjacent to the circumferential direction. However, if the deformation or the force is expressed using a sinusoidal function (i.e. using Fourier transform), it is possible to calculate stress and displacement using the same 2-D axisymmetric model.

The boundary condition expressed in (2) can be applied when the helical coils are surrounded by a support which is rigid enough for the coil winding direction (i.e. thick torus). Further research on a relationship between supporting method of the helical coil and the boundary condition for the equivalent analytic model will determine precise mechanical behavior.

6. Application to the coil design

An aluminum-alloy-jacketed Nb₃Sn superconductor and indirect cooling using cooling panels within the coil was proposed as a candidate magnet system for the LHD-type reactor [4]. Indirect cooling is an alternative approach to the force-flow with a cable-in-conduit conductor. Authors have developed an aluminium-jacketed Nb₃Sn superconductor for use in the indirectly cooled superconducting helical coil. In the study of the indirect-cooled superconductor, stress /strain level was estimated by using the axisymmetric model proposed in this paper [5]. Here we introduce the modelling and the analytic result for a conceptual design of the indirect-cooled helical coil.

As shown in Figure 16, the structure has a rectangular cross-section of 1.8 m in width and 0.9 m in height. There are 432 superconductors made of Nb₃Sn with an aluminum-alloy jacket. The major and minor radii of the helical coil are 14 m and 3.22 m, respectively. The mean radius of curvature was set 5.5 m. The superconductor has a 50 mm square shape and a 32 mm square Nb₃Sn superconducting region. The superconductor includes an 18-mm-thick aluminum alloy and 1-mm-thick insulation. The cooling panels are placed at every two or four turns of the winding.

The insulator was assumed to be made of alumina ceramics with resin. A stainless steel coil case with a thickness of 300 mm at the top and 150 mm at both sides of the coil section was also considered.

![Figure 16. The cross sectional view of the analytic model for a conceptual design of an indirect-cooled superconducting helical coil.](image)
in the analytic model. An averaged electromagnetic force along the circumference was applied at every single superconductor position. Furthermore, a constant value was added to the averaged force so that the total hoop force in the cross-section was equal to the maximum overall hoop force.

As the result, the superconductor was estimated to be subjected to a transverse compression of approximately 100 MPa. The maximum hoop stress of 336 MPa appeared in the cooling panel. The maximum strain by the hoop force was 0.173%, which is reasonable level for Nb₃Sn superconductor. The stress and strain values in the coil were sufficiently low compared with the allowable level for each component material.

7. Conclusions
The mechanical behavior of the helical coil in the LHD-type fusion reactor was investigated using the 3-D and 2-D axisymmetric finite element model. Results are followings:

The hoop force was more effective than the overturning force for the generation of stress and strain in the coil cross section.

2-D axisymmetric model which has the mean radius of curvature can estimate a mechanical behavior of a helical coil with a condition that the electromagnetic force has to be defined considering the peak value.

Using the 2-D axisymmetric method, mechanical behavior of an indirect-cooled type superconducting helical coil was evaluated. It was confirmed that all stress and strain levels for each component were within the permissible values.

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References
[1] Motojima O, et al. 2006 Fusion Eng. Des. 81 2277
[2] Sagara A, et al. 2006 Fusion Eng. Des. 81 2703
[3] Imagawa S, Takahata K, Tamura H, Yanagi N, Mito T, Obana T and Sagara A 2009 Nucl. Fusion 49 075017
[4] Takahata K, Mito T, Tamura H, Imagawa S and Sagara A 2007 Fusion Eng. Des. 82 1487
[5] Tamura H, et al. “Conceptual Design and Development of an Indirect-cooled Superconducting Helical Coil in FFHR” Plasma and Fusion Research to be published