§7. Rigidity Evaluation Method of LHD-type Superconducting Helical Coil

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The helical in the LHD-type fusion reactor 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 to optimize the coil design and integrity assessment of the materials. The mechanical behaviour of the helical coil was 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.

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. The *hz* axis is perpendicular to the coil cross section and is consistent with the winding direction of the coil. Boundary conditions applied to the 3-D model in case the coil has the cyclic symmetry of 5were follows

$$u_{hx}\Big|_{\phi=0} = u_{hx}\Big|_{\phi=\pi/5}, u_{hy}\Big|_{\phi=0} = u_{hy}\Big|_{\phi=\pi/5}, u_{hz} = 0 \quad (1)$$

where ϕ is the toroidal angle. 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 torus shaped structure, which restricts an out-plane deformation of the cross section perpendicular to the winding direction of the coil. The 3-D model was made of solid finite elements with 8 nodes. The electromagnetic force subjected to each element was separately calculated precisely according to the design of FFHR2m1[1)] and was applied on one surface of the element as a pressure load.

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. Since the electromagnetic force intensity in the actual coil 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. The coil was assumed that it consisted of one isotropic material in order to compare the stress distribution simply. As the result, displacement and stress / strain distribution for each analytic model were obtained. Fig. 1 and 2 show the hoop stress distribution by the hoop force loading for 3-D and 2-D model, respectively. The direction of “hoop” coincides to *hy* axis in this case. 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 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 (e.g. using Fourier transform), it is possible to calculate stress and displacement using the same 2-D axisymmetric model. The boundary condition expressed in (1) 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. Using this rigidity evaluation method, mechanical behavior of an indirect-cooled type superconducting helical coil, which is a candidate magnet system for the LHD-type fusion reactor FFHR, was evaluated and it was confirmed that all stress and strain levels for each component were within the permissible values.[2)]

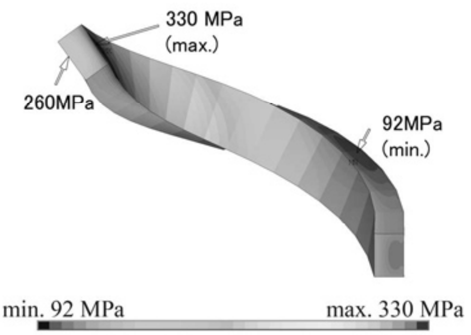

Fig. 1. The hoop stress distribution in 3-D model by the hoop force loading.

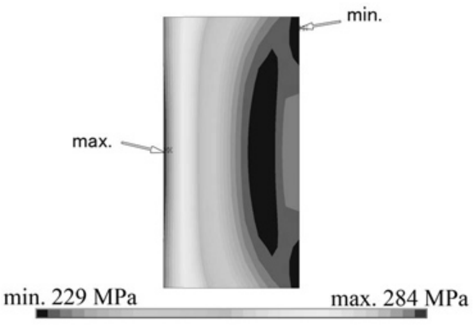

Fig. 2. The hoop force distribution in 2-D axisymmetric model by the hoop force loading.

1) Imagawa, S. et al.: Nuclear Fusion **49** (2009) 075017.
2) Tamura, H. et al.: Plasma and Fusion Research **5** (2010) S1035.