Topology optimization for superconducting magnet system in helical fusion reactor

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Abstract. In magnetic-confinement-type fusion reactors, the strong electromagnetic force generated by the superconducting coil is of the order of several tens of MN/m. To support this huge force, a strong and heavy coil support structure is required. The total weight of each magnet designed for conventional fusion reactors or experimental devices is several times greater than the ideal value. In recent years, structural optimization has advanced, owing to improvements in computer-aided design and finite-element analysis. For instance, the topology optimization method contributes novel designs that overturn common sense. In the present study, topology optimization is applied to the design of the magnet system used in a helical fusion reactor to reduce the weight of the magnet while maintaining the mechanical soundness of the component. A weight reduction of more than 25% from the conventional design could be achieved.

1. Introduction
The National Institute for Fusion Science is developing a conceptual design for a Large Helical Device (LHD)-type helical fusion reactor, called the FFHR [1, 2]. The helical fusion reactor has several attractive features, such as steady-state operation and a built-in helical diverter, which may be favorable in a practical fusion power plant. There are several FFHR design schemes. For example, FFHR-d1 has been established as a self-ignition commercial reactor considering sufficient blanket space and radial build between the plasma and the helical coil. FFHR-d1 has a major radius of 15.6 m and generates a magnetic field intensity of 4.7 T at the magnetic center. FFHR-c1 is a compact sub-ignition reactor that aims to realize steady electrical self-sufficiency, which has a magnetic field intensity of 7.3 T; its scale is 0.7 times that of FFHR-d1. Figure 1 shows schematics and specifications of LHD, FFHR-d1, and FFHR-c1.

Since FFHR is a magnetic-confinement fusion reactor, a superconducting coil generates a powerful electromagnetic force (EM) that reaches the order of several tens of MN/m. In the case of FFHR-c1, the maximum EM force applied to the coil exceeds 140 MN/m due to the high magnetic field specification. To support this huge force, a strong coil support structure is required. The total weight of the magnet system (coil and support structure) is estimated to be approximately 11,000 tons in recent designs [3].

In recent years, structural optimization has been promoted through improvements in computer-aided design (CAD) and the finite-element method (FEM). For example, topology optimization techniques enable innovative designs that overturn design common sense [4]. In this paper, topology optimization is applied to the design of the FFHR-c1 magnet system to reduce the magnet’s weight while maintaining the mechanical health of the components.
2. EM force on coils
The fundamental layout of the coils and the support structure for FFHR-c1 was modeled as shown in figure 2 [5]. FFHR-c1 consists of one pair of helical coils (HCs), one pair of NITA coils [6, 7], and two sets of vertical field coils (VFCs). The superconductor used in the HC has a square shape, with each side measuring 43.3 mm. The operating current of the single superconductor is 90 kA, the overall magneto-motive force is 46 MA, and the current density is 47.7 A/mm². All material was assumed to be non-magnetic. The magnetic field distribution was calculated with the FEM software ANSYS Maxwell. Since the FFHR-c1 has a cyclic symmetry of 10, only $\frac{2\pi}{5} = 72^\circ$ need to be taken into account. Figure 3 shows the results of the magnetic field calculation. The maximum magnetic field intensity of 20 T appeared in the HC and inner VFC.

![Figure 2. Geometrical configuration of the coil and support structure.](image)

The overall EM force at a certain toroidal angle is calculated by integrating a magnetic field across the coil cross section there and multiplying it by the current of the superconductor. The EM force on the HC and NITA coil could be divided into two components in the hoop and overturning directions with respect to the coil-winding direction. Let the coordinate axes, $h_x$ and $h_y$, be chosen such that they are in the cross-sectional plane of the HC and let their directions coincide with the coil height and width, as shown in

![Figure 1. Schematics and specifications of LHD, FFHR-d1, and FFHR-c1.](image)
figure 4. The \( h_z \) axis is perpendicular to the coil’s cross section and is consistent with the winding direction of the coil, i.e., the current-flow direction. The hoop force, \( F_h \), and the overturning force, \( F_b \), can be defined as the force components in the \( h_x \) and \( h_y \) directions, respectively. For the VFC, a force in the radial direction indicates the hoop force, \( F_r \), and in the vertical direction indicates an attractive or repulsive force, \( F_z \). The calculated maximum overall EM force densities among the coils were the hoop force of 119 MN/m in the HC and of 138 MN/m in the inner VFC, as shown in figure 5 [5].

![Figure 3. Magnetic field distribution on the coils.](image1)

![Figure 4. Definition of the pseudo toroidal coordinate system and direction of coils cross-sectional plane \( h_x-h_y \), and winding direction \( h_z \).](image2)

![Figure 5. Overall EM force on HC, NITA coil.](image3)

![Figure 6. Overall EM force on VFC.](image4)

3. Stress and deformation in the original design of FFHR-c1
In the structural analysis of FFHR-c1, a gas-cooled HTS with a REBCO coated-superconductor was adopted, since the maximum magnetic field on the coil was estimated to reach 20 T. The physical properties of the superconductors used in structural analysis were obtained by performing multi-scale homogenization analysis [5, 8]. The support structure was assumed to be made of SS 316LN (Young’s modulus: 208 GPa and Poisson’s ratio: 0.33) with a basic thickness of 200 mm. The EM force was applied as a surface-load density on each coil. Figure 6 shows the structural-analysis results using the original conventional support structure design. The FEM mesh is slightly different from that calculated in [5]. The maximum von Mises stress of 1 GPa appears on the outer-port corner as the peak stress. The spatial stress distribution seems not to exceed 800 MPa. The soundness of the support structure will be guaranteed if a high-strength material such as that specified for ITER [9] is used. The maximum deformation is approximately 18 mm, and it appears in the outer-VFC region.
4. Topology optimization analysis

The weight of the support structure in the original design of FFHR-c1 was about 11,000 tons. The total weight of a magnet system in a fusion reactor or experimental device has been shown to be proportional to the stored magnetic energy [10]. The total weight of FFHR-c1, with a stored magnetic energy of 160 GJ, is estimated to be in a range between 5,000 (theoretical value assuming an infinite solenoidal coil) and 12,000 tons (extrapolation of existing devices). Weight reduction can be achieved by optimizing the design of the support structure. Topology optimization can be employed to solve this issue. Structural analysis using topology optimization was applied to the magnet support structure of FFHR-c1. In the optimization analysis, a density-based optimization with minimization of the compliance method was adopted. The target weight reduction was set to 50%. Optimization was applied only to the coil support structure and the surfaces in contact with the coils were excluded from the optimization target.

The result of the topology optimization is shown in figure 7. The total weight of the coil support structure (360° excluding coils and legs) decreased from 7,800 to 4,800 tons (-41%).

**Figure 7.** Von Mises stress distribution of the coil support structure of FFHR-c1 original design.

**Figure 8.** Total amount of deformation distribution of the coil support structure of FFHR-c1 original design.

**Figure 9.** Topology density distribution for the coil support structure of FFHR-c1.
5. Verification analysis
Verification analysis is needed to confirm the soundness of the resultant topology optimized structure. The optimized shape can be obtained in an STL format (a CAD file format using triangle facet data) composed of more than 180,000 of facets in this case (original FEM element number is 425,000). It is not practical to use the STL directly as an analytical model, so a modified model was prepared. In the rebuilt model for verification analysis:
- The HC-arm inboard of the torus was cut out significantly.
- The upper and lower edges of the outer opening were extended to the outer-VFC region and made the shape circular.
- The column width was reduced between the inner VFCs.
- The thickness of HC lid was reduced, etc.

The rebuilt design is shown in figure 8. The total weight of the support structure in the verification model is 5,900 tons (25% reduction from the conventional design).

The same EM force and boundary conditions used in the original FEM analysis were applied to the verification model. The result of the calculation is shown in figure 9. The maximum stress decreased from 1 GPa to 860 MPa, since the corner region at which the peak stress had appeared was removed. The stress at the HC-bottom region was around 800 MPa, which is severe but acceptable for the material. A maximum deformation of approximately 21 mm appeared in the HC and outer-VFC regions.

6. Discussions
Topology optimization can be used for any original shape. For instance, assume that the block covers the entire coil but excludes the space occupied by in-vessel components such as the plasma vacuum vessel and shielding blanket. The shape obtained by topology optimization is close to the assumed...
toroidal shape and is sufficiently lightened, as shown in figure 10. By preparing an arbitrary block with the necessary access ports open, it becomes possible to conduct design almost automatically.

The accuracy of the coil-winding section is one of the most important issues for a magnet-confinement-type fusion reactor. By contrast, if weight reduction is given priority, deformation will inevitably increase. The deformation effect on plasma confinement must be confirmed and adjusted simultaneously. The accuracy of the magnetic field can be compensated by structural design (e.g., using a pre-deformed shape) or additional correction coils.

Figure 13. An example of a design method using topology optimization.

7. Conclusion
The results an attempt to design the magnet support structure of the helical fusion reactor FFHR-c1 using topology optimization were reported. It is possible that the weight of the structure can be reduced by about 40% compared with conventional designs. Although the coil displacement increases, it can be overcome by designing with deformation in advance. A novel design method using topology optimization has been proposed and could reduce the design effort.

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