Seismic Analysis of Magnet Systems in Helical Fusion Reactors Designed With Topology Optimization

Seismic analysis of magnet systems in helical fusion reactors designed with topology optimization

Hitoshi Tamura (田村 仁), Takuya Goto (後藤拓也), Junichi Miyazawa (宮澤順一), Teruya Tanaka (田中照也), and Nagato Yanagi (柳 長門)

***Abstract*— Superconducting magnets in fusion reactors are subjected to a huge electromagnetic force of >100 MN/m. The magnets have to be sustained with a strong-body structure to avoid high stress and deformation. The total weight of the magnet system in the fusion reactor is estimated to be more than 20,000 tons. We applied topology optimization technique to the magnet support structure to reduce the weight of fusion reactors. Compared with the conventional design, we achieved a weight reduction of >25%. Static and seismic analyses were carried out to validate the soundness of the topology-optimized design. Consequently, the stress against the electromagnetic force in the structure was within the permissible range. It was discovered that using seismic isolation structure can adequately prevent the damage to the magnet system even when directly subjected to a massive earthquake.**

***Index Terms*—Fusion magnet, superconducting coil, topology optimization, electromagnetic force, seismic analysis**

I. Introduction

In a magnetic confinement type fusion reactor, superconducting coils are subjected to a huge electromagnetic (EM) force that reaches the order of several tens of MN/m. A strong coil support structure is required to prevent large deformation and stress in the coils during excitation. Extrapolating from previous devices, the total weight of the device should be predictable [1]. Fig. 1 shows the estimation of the cryogenic mass, which is the total weight of the coil and its support, as a function of the stored magnetic energy of coils. The weight of the DEMO class fusion reactor is estimated to be >20,000 tons. The material procurement, processing, assembly, and decommissioning should be performed as efficiently as possible.

Topology optimization is an analytical method to reduce the volume of the structure by removing the part that does not affect the strength. Topology optimization has the potential to generate novel shapes that would not be possible using conventional design schemes [2]. We used topology optimization to improve the overall design of the coil support structure in a helical fusion reactor. Meanwhile, the topology-optimized shape appeared sensitive to unusual loads, such as earthquakes even though it is sound in normal excitation operation. Seismic analysis is also performed using the mode superposition method with references to recent significant earthquakes in Japan.

This work was supported in part by JSPS KAKENHI Grant Number 20H01884, 2021, and by the grant from National Institute for Fusion Science, UFZG-010, 2021.

H. Tamura, T. Goto, J. Miyazawa, T. Tanaka, and N. Yanagi are with the National Institute for Fusion Science, Toki 509-5292, Japan (e-mail: tamura@nifs.ac.jp; goto.takuya@nifs.ac.jp; miyazawa.junichi@nifs.ac.jp; tanaka.teruya@nifs.ac.jp; yanagi@nifs.ac.jp).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier will be inserted here upon acceptance.

II. Topology Optimization

A. Helical Fusion Reactor FFHR-c1

The National Institute for Fusion Science has developed a conceptual design for a helical fusion reactor known as the FFHR [3], [4]. Fig. 2 shows the schematic of the helical fusion reactor FFHR. The helical fusion reactor comprises one pair of helical coils (HCs), one pair of NITA coils, and two sets of vertical field coils (VFCs) [5]-[9]. Among the various design schemes of FFHR, FFHR-c1 generates the highest magnetic field intensity of 7.3 T at the plasma center with a major and a minor radius of the main helical coil of 10.92 m and 2.8 m, respectively. The magnetic energy is stored at the rate of 157 GJ. In the case of FFHR-c1, the operating current of the single superconductor is 90 kA, and the overall magnetomotive force is 46 MA. The coil experiences a maximum magnetic field of 20 T. The total EM force at a given toroidal angle is calculated by integrating a magnetic field across the coil cross-section there

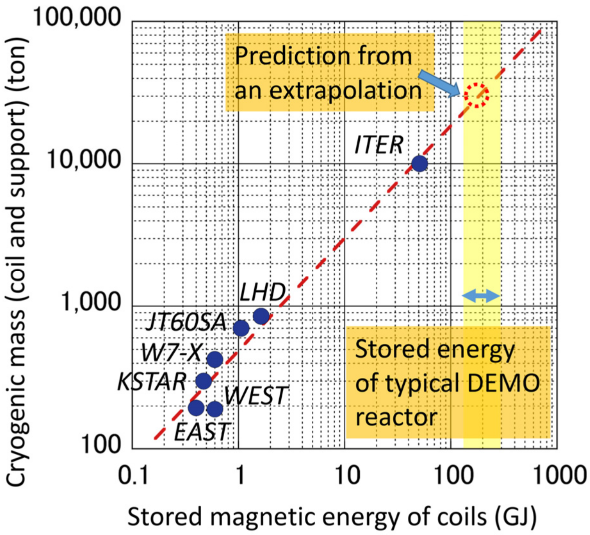

Fig. 1. Cryogenic mass of superconducting magnet system in fusion devices as a function of a stored magnetic energy.

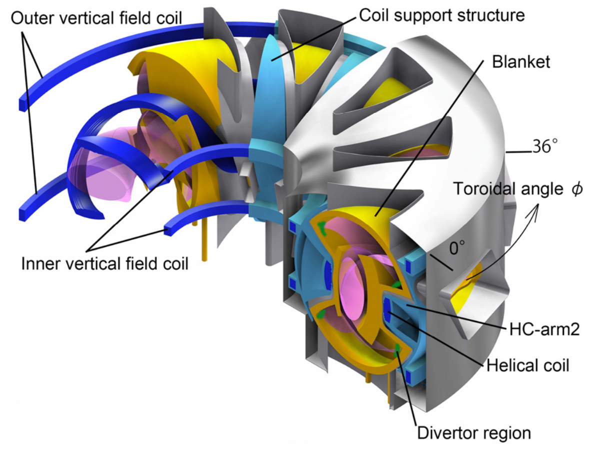

Fig. 2. Schematic of the helical fusion reactor, FFHR.

and multiplying it by the current of the superconductor. The EM force on the HC can be divided into two components in the hoop and overturning directions concerning the coil winding direction. For the VFC, a force in the radial direction indicates the hoop force, while a force in the vertical direction indicates an attractive or a repulsive force. The calculated maximum overall EM force among the coils was the hoop force of 119 MN/m in the HC and 138 MN/m in the inner VFC.

B. Conventional Design

The support structure was assumed to be made of 200-mm-thick ITER grade SS 316LN [10]. The support structure was designed to enclose the entire coil while leaving as much space as possible open for maintenance of the in-vessel components and clearance from the blanket with a vacuum vessel. The design and analysis were repeated until the stresses remained within the allowable limits. Consequently, the maximum von Mises stress of 1 GPa appeared on the outer-port corner as the peak stress. The spatial stress distribution appears to be less than 800 MPa. The soundness of the support structure will be ensured. The maximum deformation is approximately 18 mm, and it appears in the outer-VFC region. The weight of the support structure in the conventional design was about 11,000 tons. The entire support structure weighed 7,800 tons.

C. Optimization Result

Structural modification against the conventional design using topology optimization was applied to the support structure aiming to remove unnecessary regions. A density-based optimization with a compliance minimization method was used. Only the support structure has been optimized [11]. The coil winding and surfaces in contact with the coils were excluded from the optimization goal. The exact force was applied as in the case of conventional design.

Fig. 3 shows the result of the topology optimization. The total weight of the support structure significantly decreased from 7,800 to 4,800 tons. The calculated topology-optimized shape has a complicated fine three-dimensional structure. It is not easy to manufacture such a complicated structure with a large-scale device such as a fusion reactor, and it is not practical in

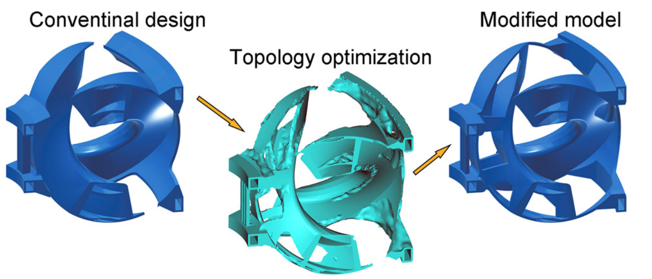

Fig. 3. Volume reduction by the topology optimization and rebuilt model for the soundness verification analysis.

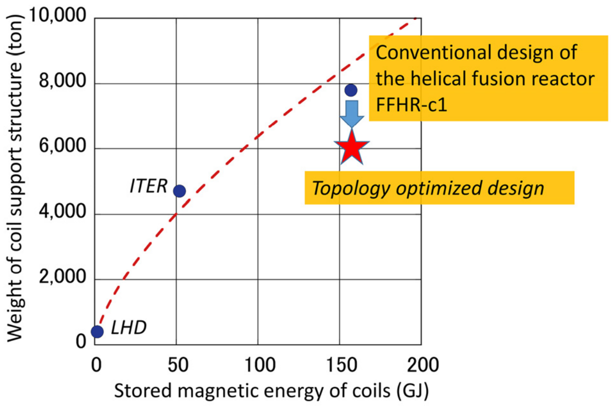

Fig.4. Weight reduction of the support structure using the topology optimization.

terms of expense. Therefore, the model was reconstructed while retaining its basic thickness of 200 mm, as shown in the right drawing in Fig. 3. The modified model was used for verification analysis, which confirmed the structural soundness of the resultant topology-optimized structure. The weight of the verification model is 5,900 tons, which is a 25% reduction from the conventional design. Fig. 4 shows the relationship between the weight and stored magnetic energy of the coil support structures of LHD, ITER, and FFHR-c1. It can be seen that a significant weight reduction has been achieved compared to the conventional design.

The result of the soundness verification is shown in Fig. 5. The maximum stress of 1006 MPa appeared at the corner of the aperture in the conventional design, which was determined to be the peak stress. Meanwhile, in the topology-optimized model, the maximum stress of 857 MPa appeared in the lower region of the HC, and this model lacked peak stress. It was

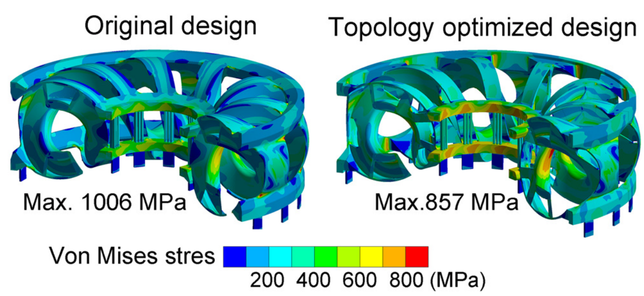

Fig. 5. Stress distribution of the original and topology-optimized coil support structure.

confirmed that the stress of the topology-optimized structure was acceptable for the material. However, the maximum deformation increased approximately from 18 to 21 mm and appeared in the HC and outer-VFC regions.

III. Seismic Analysis

A. Modal Analysis

The topology-optimized shape appears to be susceptible to unusual loads such as earthquakes. Therefore, seismic analysis was performed on the optimized shape. Because the symmetry of the structure cannot be taken into account in seismic analysis, the entire circumferential direction must be modeled. To simplify the full torus model, the coils and support were unitized, and the apparent physical properties were applied in consideration of their volume fractions, density = 7250 kg/m^3, Young's modulus = 166 GPa, and Poisson's ratio = 0.3. The gravity support has a rectangular solid of 1.8-m height, 1.2-m width, and 0.219-m thickness with a density, Young's modulus, and Poisson's ratio of 3000 kg/m^3, 50 GPa, and 0.3, respectively.

First, a modal analysis was performed to confirm the vibration modes of the entire structure. The eigen vibration modes whose eigen frequency is less than 40 Hz were obtained. Table I shows the results of modal analysis. The ratio of effective mass to total mass for each two horizontal directions and the vertical direction are shown along with the vibration frequency of each mode. The x- and y-directions correspond to the toroidal angles ϕ = 0 and 90° in the horizontal direction as shown in Fig. 2, respectively, and the z-direction corresponds to the height direction. Focusing on the horizontal direction, we can see that the first and second eigenmodes having an eigen frequency of 7.6 Hz are dominant. In the vertical direction, the eighth and tenth eigenmodes have considerable influence. Fig. 6 shows a schematic of typical eigen vibration modes. The stiffness of the gravity support has a considerable effect on the eigen vibration. The eigen frequencies of the first to fifth eigenmodes are around 10 Hz, while higher modes are above 20 Hz. The lower eigenmodes were determined by the rigidity of the gravity support, while the higher modes were dependent on the rigidity the coil support structure. Generally, earthquakes tend to resonate in the vibration mode around 10 Hz. Depending on the assumed earthquake waveform, response analysis is considered to be necessary.

TABLE I
Frequency and Effective Mass for Each Eigen Vibration Mode

Mode number	Frequency (Hz)	Ratio of effective mass to total mass		
		x direction	y direction	z direction
1	7.6	0.117	0.865	*
2	7.6	0.865	0.117	*
3	10.7	*	*	*
4	12.9	*	*	*
5	12.9	*	*	*
:	:	*	*	*
8	20.9	*	*	0.631
9	20.9	*	*	0.0626
10	21.0	*	*	0.193
:	:	*	*	*
22	28.2	*	*	0.0211
:	:	*	*	*
32	31.7	*	*	0.0484
:	:	*	*	*
45	37.7	*	*	0.0143
:	:	*	*	*
49:	39.8	*	*	*
Summation		0.996	0.996	0.971

* below 0.005

B. Mode Superposition Method

In practice, the earthquake waveforms must be evaluated at the construction site, but in this study, we conducted vibration analysis based on the waveforms of a massive earthquake that occurred in Japan in recent years. Figs. 7 and 8 show the acceleration response spectrum that is obtained from two typical earthquakes. Seismic analysis by the mode superposition method was performed using the virtual

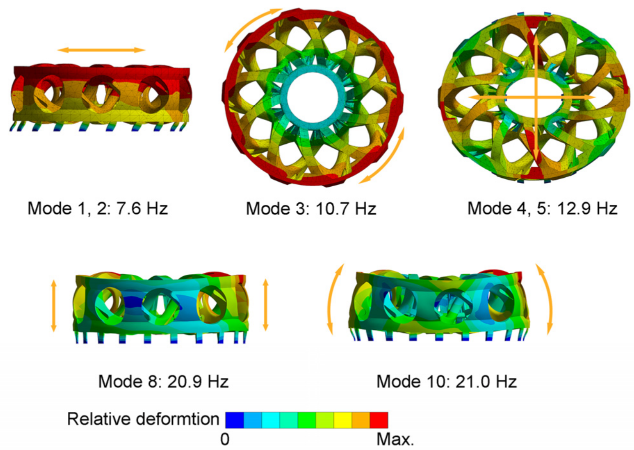

Fig. 6. Typical eigen vibration mode for the magnet system with gravity supports.

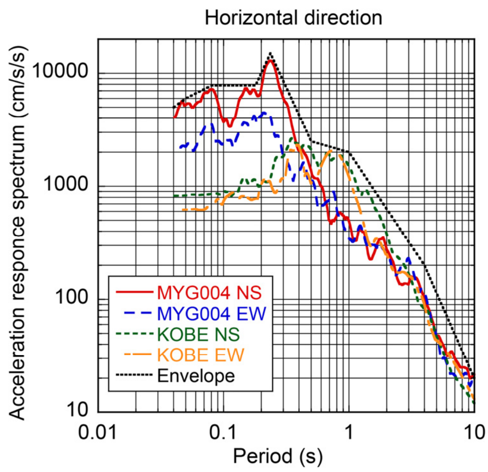

Fig. 7. Acceleration response spectrum calculated from the earthquake wave observed at Tsukidate, Miyagi, Japan in 2011 (MYG004) [12], and Kobe, Japan in 1995 (KOBE) [13]. NS: north-south direction, EW: east-west direction. Envelope: virtual envelope line including whole spectrum.

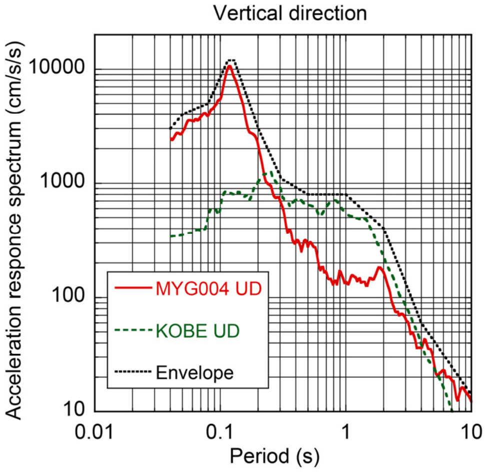

Fig. 8. Acceleration response spectrum calculated from the earthquake wave observed at Tsukidate, Miyagi, Japan in 2011 (MYG004) [12], and Kobe, Japan in 1995 (KOBE) [13]. UD: up and down direction, Envelope: virtual envelope line including whole spectrum.

envelope of acceleration response spectrums shown in Figs. 7 and 8 including all 49 eigen vibration modes obtained from the modal analysis. Consequently, the maximum von Mises stress of 1 GPa appeared at the connection between the support structure and the gravity support, as shown in Fig. 9. Fig. 10 shows stress distribution except for the gravity support legs. The support legs can be damaged, but the magnet system will be unharmed.

IV. Discussion

When acceleration acts directly on the gravity support legs, stress above the allowable level is generated at gravity support. Countermeasures against avalanche damage to the support legs are required to prevent the superconducting magnet itself from being destroyed. In the case of a seismically isolated building, the seismic isolation system absorbs all frequencies except for a period of around 2 s, or 0.5 Hz, so the response acceleration is reduced to about 1/4, and from the calculation results based on this envelope, the stress in the structure is less than 1/200. Even in that case, precautions must be taken to avoid contact with the in-vessel components and piping connected at the seismic isolation boundary.

The deformation at the coil region is greater than that of before topology optimization. The effect on plasma confinement conditions must be validated and compensated. The confined magnetic field can be ensured by making the structure in such a way that the coil shape after excitation becomes the prescribed shape or by including a correction coil.

V. Conclusions

The design modification of the magnet support structure for the helical fusion reactor FFHR-c1 using topology optimization and its soundness evaluation were reported. Consequently, the weight of the magnet system can be reduced by about 25% when compared with the previous design. The soundness of the optimized structure against the EM force was confirmed.

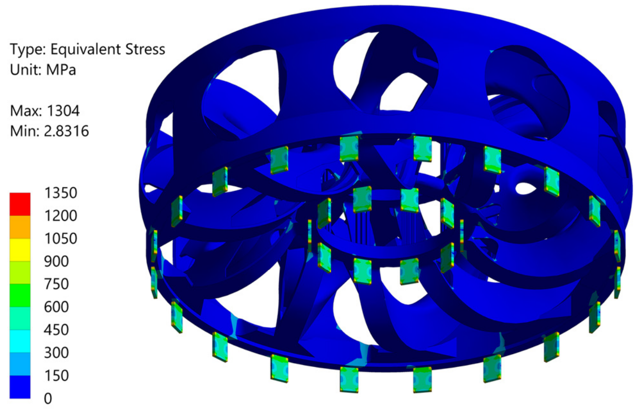

Fig. 9. Result of mode superposition analysis for the magnet system with gravity legs. Envelop in Fig. 7 was applied to the horizontal direction, and one in Fig. 8 to the vertical direction.

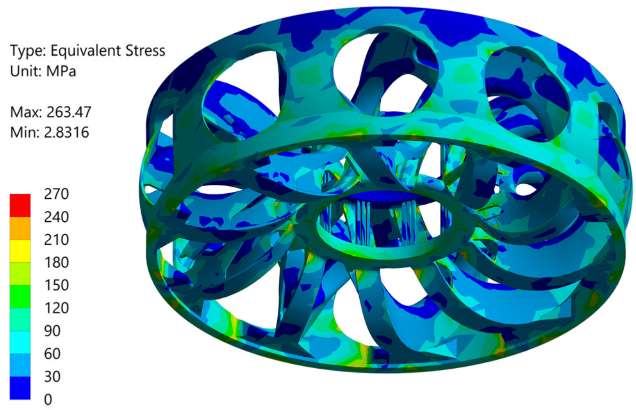

Fig. 10. Stress distribution in the magnet system. The same result as in Fig. 9, only the coil support part is shown.

The mechanical response to an earthquake is determined by the ground and building structures; however, the safety of the magnet system excludes the gravity supports, which can be compensated even in the absence of seismic isolation building.

In the actual construction phase, simulated seismic waves are set based on the ground and building style, and collisions with the in-vessel components and piping connections at the building boundary due to deformation and displacement must be carefully checked.

References

[1] K. Takahata, "Superconducting Coils for Fusion," *J. Plasma Fusion Res.* Ser. vol. 81, no. 4, Arp. 2005, p273-279 (in Japanese).

[2] M.P. Bendsoe and O. Sigmund, Topology Optimization: Theory, Methods and Applications, Berlin: Springer, 2003.

[3] A. Sagara, T. Goto, J. Miyazawa, N. Yanagi, T. Tanaka, H. Tamura, R. Sakamoto, M. Tanaka, K. Tsumori, O. Mitarai, S. Imagawa, T. Muroga, and The FFHR design group, "Design activities on helical DEMO reactor FFHR-d1," *Fusion Eng. Des.*, vol. 87, no. 5/6, 594–602, 2012.

[4] T. Goto, J. Miyazawa, H. Tamura, T. Tanaka, R. Sakamoto, C. Suzuki, R. Seki, S. Satake, M. Nunami, M. Yokoyama, N. Yanagi, A. Sagara, and FFHR Design Group, "Conceptual design of a compact helical fusion reactor FFHR-c1 for the early demonstration of year-long electric power generation," *Nucl. Fusion* vol. 59 076030, 2019.

[5] H. Tamura, N. Yanagi, T. Goto, J. Miyazawa, T. Tanaka, A. Sagara, S. Ito, and H. Hashizume, "Mechanical Design Concept of Superconducting Magnet System for Helical Fusion Reactor," *Fus. Sci. Technol.* 75 384-390, 2019.

[6] H. Tamura, T. Goto, N. Yanagi, J. Miyazawa, T. Tanaka, A. Sagara, S. Ito, and H. Hashizume, "Effect of coil configuration parameters on the mechanical behavior of the superconducting magnet system in the helical fusion reactor FFHR," *Fus. Eng. Des.* vol. 146(A), 586-589, 2019.

[7] N. Yanagi, T. Goto, H. Tamura, J. Miyazawa, and A. Sagara, "NITA Coil — Innovation for Enlarging the Blanket Space in the Helical Fusion Reactor," *Plasma Fus. Res.* vol. 11, 2405034, 2016.

[8] H. Tamura, N. Yanagi, T. Goto, J. Miyazawa, T. Tanaka, A. Sagara, S. Ito, and H. Hashizume, "Design modification of structural components for the helical fusion reactor FFHR-d1 with challenging options," *Fus. Eng. Des.* vol. 124, 605-609, 2017.

[9] H. Tamura, N. Yanagi, K. Takahata, A. Sagara, S. Ito, and H. Hashizume, "Multiscale Stress Analysis and 3D Fitting Structure of Superconducting Coils for the Helical Fusion Reactor," *IEEE Trans. Appl. Supercond.* vol. 26, no.3, Apr. 2016, Art. no. 4202405.

[10] Y. Chida, M. Iguchi, K. Takano, H. Nakajima, K. Oosemochi, K. Niimi, D. Tokai, and R. Gallix, "Validation of welding technology for ITER TF coil structure," *Fusion Eng. Des.*, vol. 86, no. 12, pp. 2900–2903, 2011.

[11] H. Tamura, T. Goto, J. Miyazawa, T. Tanaka, and N. Yanagi, *J. Phys.: Conf. Ser.* 1559, 012108, 2020.

[12] K-NET, National Research Institute for Earth Science and Disaster Resilience, doi:10.17598/NIED.0004, 2019.

[13] Japan Meteorological Agency, https://www.data.jma.go.jp/svd/eqev/data/kyoshin/jishin/hyogo_nanbu/index.html.