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

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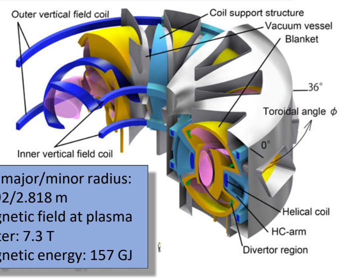
Introduction

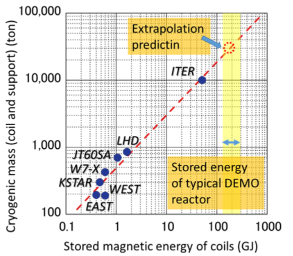
- In a magnetic confinement type fusion DEMO reactor, electromagnetic (EM) force reaches **over 100 MN/m**. To support the huge EM force, a strong coil support structure is required.
- In recent years, the **topology optimization** method contributes novel designs that overturn conventional designs.
- On the other hand, the topology-optimized shape seemed sensitive to unusual loads, such earthquakes even if it is sound in normal excitation operation.
- In this study, the topology optimization is applied to design of the coil support structure in the helical fusion reactor **FFHR-c1,** which is being designed as the LHD-type DEMO, to reduce the total weight of the magnet system. A **seismic analysis** is also performed using the mode superposition method referencing recent **significant earthquakes**.

Helical Fusion Reactor FFHR-c1

T. Goto, et al., Nucl. Fus. 59 (2019).
H. Tamura, et al., Fus. Sci. Tech. 75 (2019)

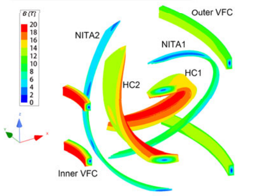


Coil major/minor radius: 10.92/2.818 m
Magnetic field at plasma center: 7.3 T
Magnetic energy: 157 GJ

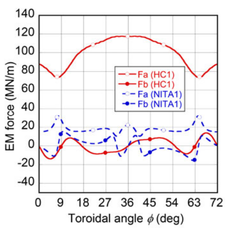


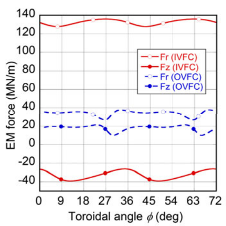
Total weight of magnet system in fusion devices.

EM force on coil



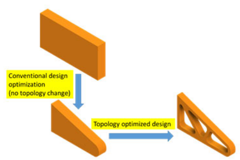
Magnetic field distribution on coils.



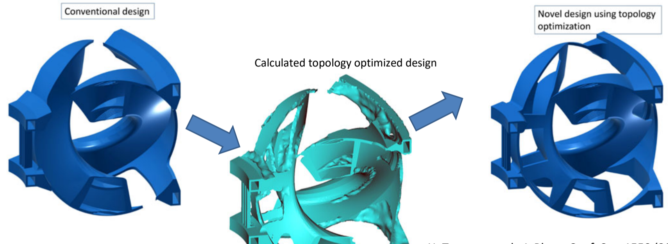


- 3D magnetic field and EM force distribution induced by the coils were calculated with ANSYS. The EM force on the HC and NITA coil could be divided into two components in the hoop and overturning directions, F_a and F_b.
- For the inner/outer vertical field coil (IVFC/ OVFC), the force in the radial direction indicates the hoop force, F_r, and in the vertical direction indicates an attractive or repulsive force, F_z.
- The maximum EM force reaches over 120 MN/m. Thick (200 mm) and heavy (8000 tons) support structure was needed by a conventional design method.

Topology optimization



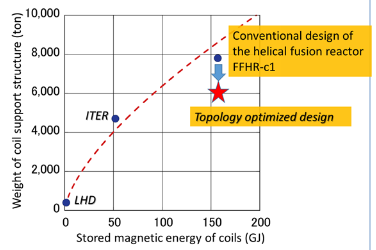
- Structural modification using topology optimization was applied to the coil support structure aiming to remove unnecessary region.
- Density based topology optimization with compliance minimization method was adopted.
- Accurate EM force was applied and the area in contact with the coils were excluded from the optimization target.



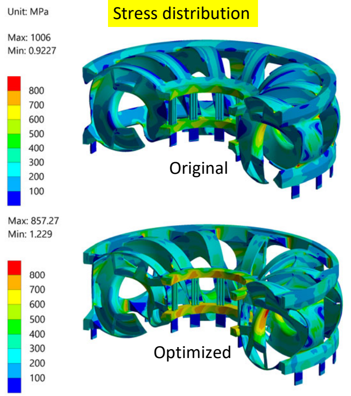
H. Tamura, et al., J. Phys.: Conf. Ser. 1559 (2020).

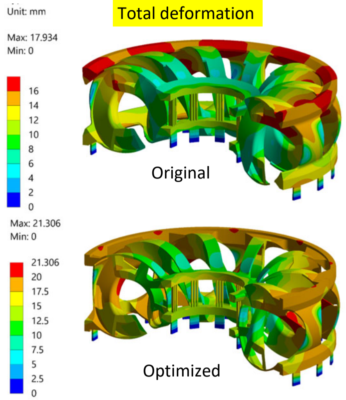
Result of the topology optimization

The calculated topology optimized shape has complicate 3D shape. It is not practical to use the shape directly considering a productivity.
The model was rebuilt keeping its basic thickness. As the result;
- ✓The total weight of the support structure decreased from 7,800 to 5,900 ton (-25%).
- ✓The maximum stress is 860 MPa at the HC bottom region.
- ✓Maximum deformation is 21 mm at the HC and OVFC region.



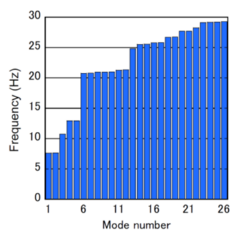
Weight reduction of the support structure using topology optimization.



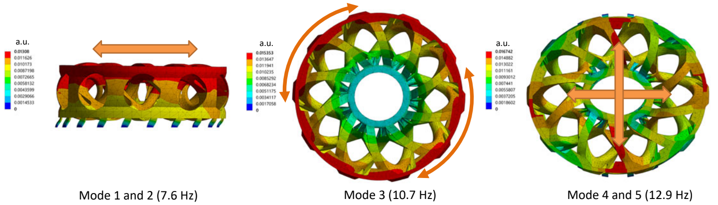


Seismic analysis

- The topology optimized shape looks sensitive to unusual loads such as earthquakes. Therefore, seismic analysis was performed on the optimized shape.
- To simplify the full torus model, the coils and support were united, and the apparent physical properties were applied in consideration of their volume fractions. Density = 7250 kg/m³, Young's modulus = 166 GPa, Poisson's ratio=0.3.
- The gravity support is a rectangular of 1.8H X 1.2W X 0.219t with density, Young's module, and Poisson' ratio of 3000 kg/m³, 50 GPa, and 0.3, respectively.
- Modal analysis and response spectrum with a mode-superposition method were conducted.



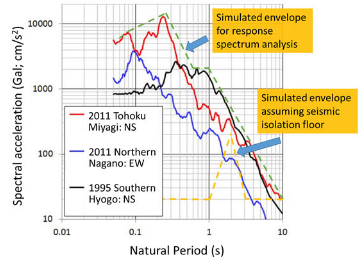
Result of the modal analysis for the topology optimized coil support structure.



Eigen vibration mode from the first to under 20 Hz for the coil support structure in FFHR-c1.

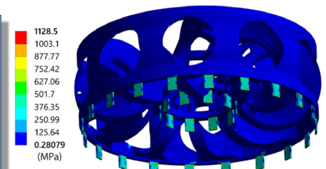
Result of the modal analysis

The first to sixth eigenmodes are below 20hz, and they are thought to have the potential to resonate with earthquakes.
The lower eigen modes were dependent on the rigidity of the gravity support while the higher modes were dependent on that of the support with coils.
Seismic analysis by the mode superposition method was performed using the virtual envelope of acceleration spectrums for recent giant earthquakes.



Wave data from 22nd Gifu Symposium, Japan, held by Gifu Univ. (2011).

- Maximum von Mises stress of 1 GPa appeared at the connection between the support structure and the gravity support. The support legs can be damaged, but the magnet system will be safe.
- Seismic isolated building can be prepared for a fusion facility. In that case, the stress and displacement could be low enough (approximately 1/200).



Result of mode-superposition analysis; von Mises stress distribution

In the case of yet another helical reactor

- Generally, EM force and stress intensity yield the following scaling law:
  EM force F [N/m] $\propto B \times I \propto R \times B^2$.
  Stress σ [N/m²] $\propto F \times R / R^2 \propto B^2$.
  R; device size,
  B; magnetic field intensity.
- Eigen frequency depends on the design of the gravity support.

Example

Using the result for the FFHR-c1, in the case of device having similar shape and following specification;
major radius 7.8 m, and magnetic field 6.6 T,
- ✓Maximum EM force can be 70 MN/m
- ✓Maximum stress can be 700 MPa with basic thickness of 142 mm.
- ✓Eigen mode: 10.7 Hz (1st), 18.1(5th), and 29.1 (6th).

Summary

- The design of the magnet support structure for the helical fusion reactor FFHR-c1 using topology optimization was reported. Consequently, it is possible that the weight of the structure can be reduced by about 25% compared with conventional design.
- Soundness of the optimized structure against the EM force was confirmed.
- Soundness against an earthquake depends on the structure of the ground and buildings, however, safety of the magnet system can be compensated even without seismic isolation building.