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Effect of electromagnetic force on a quad-pancake coil wound with a Nb$_3$Sn CIC conductor

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Abstract. In the performance verification tests of the JT-60SA central solenoid model coil, the hydraulic characteristics of the model coil improved during the coil energization. As a cause of this phenomenon, it was suggested that a new cooling channel is made by the cable deformation due to the electro-magnetic (EM) force. To investigate the new cooling channel, the EM structural coupling analysis was conducted. The analytical results indicated that new cooling channels in the coil winding occur, and the cooling channels become larger as the position of the cable moves away from the center of the coil winding.

1. Introduction

Performance verification tests of the JT-60SA central solenoid (CS) model coil were conducted to verify the coil manufacturing process and fabrication jigs [1]. The test results indicated that the model coil met the design requirements, and the hydraulic characteristics of the model coil improved during coil energization. The occurrence of a new cooling channel in the coil winding is considered as a cause of the improvement. To investigate the new cooling channel, electromagnetic (EM) structural coupling analysis for the model coil was carried out. In this paper, the coupling analysis and the compressive tests for the analysis are described.

2. Model coil

A model coil is wound with a Nb$_3$Sn cable-in-conduit (CIC) conductor. As shown in Figure 1, the configuration of the model coil is a quad-pancake [1]. The inner and outer diameters are 1.3 m and 2 m, respectively. The number of turns is 40. Regarding the CIC conductor, the specifications of the conductor are as follows: the number of Nb$_3$Sn strands is 216, the number of Cu wires is 108, void fraction is 34 %, jacket size is 27.9 mm×27.9 mm, and cabling diameter is 21 mm [2].

3. Compressive tests of a Nb$_3$Sn cable

For the structural analysis of the model coil, overall elastic modulus [3] of a Nb$_3$Sn cable was measured. The measurement was conducted using the universal testing machine (AG-10kNX plus) under room temperature. Figure 2 shows the schematic view of the experimental apparatus. A Nb$_3$Sn cable removed from the CIC conductor was set on the U-shaped jig made from SUS316L. Then, the cable was covered with the cap which is made of a part of the conduit removed from the CIC conductor. Finally, the T-

shaped jig made from SUS316L was set on the cap. In the measurement, the cable deformation was measured in the vertical direction while compacting the cable by the universal testing machine.

Figure 3 shows the relation between the compressive force per unit length and the displacement of the cable. The cable is composed of many voids, so that the displacement changes with very little compressive force. In the displacement over 1.2 mm, however, the compressive force increases drastically with the increase of the displacement. This phenomenon will occur because the voids in the cable decrease with the compressive force, and the stiffness of the cable increases.
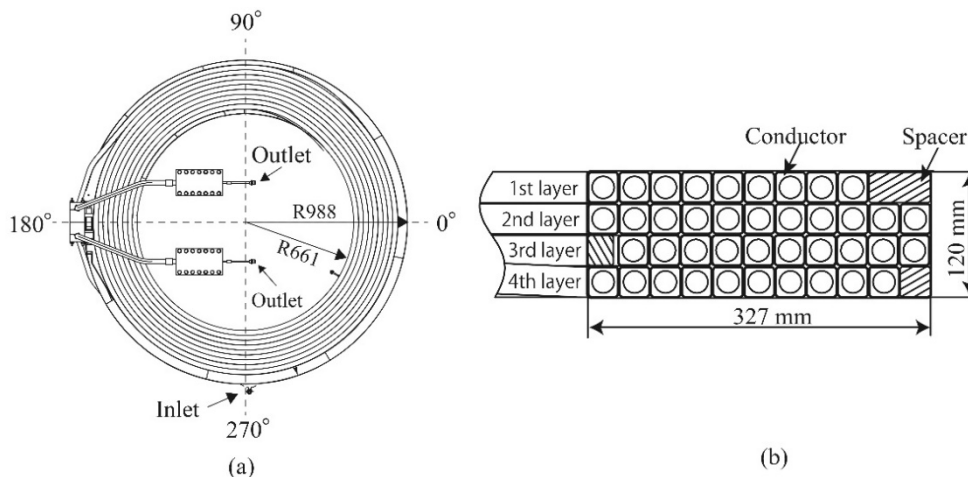

Figure 1. Configuration of the CS model coil. (a) Top view (b) Cross-sectional view of the coil at 0°.
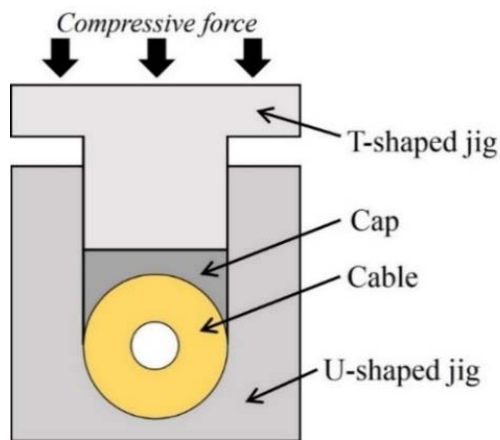

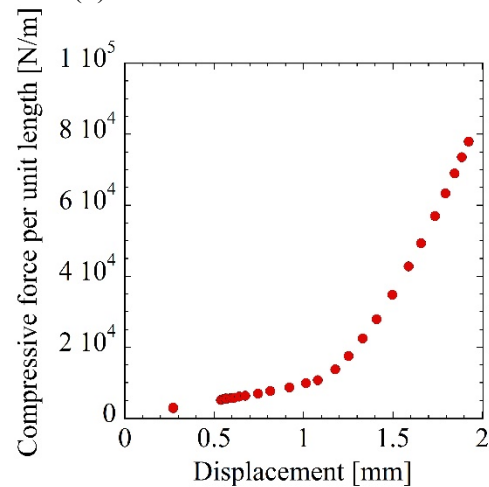**Figure 2.** Schematic view of the apparatus for the compressive test.

Figure 3. Result of the compressive test.

4. EM structural coupling analysis of the coil

To understand the deformation of the coil configuration, the EM structural coupling analysis was conducted using ANSYS, which is a commercial software product.

4.1. Model and boundary condition

Based on the configuration of the coil winding, the models for the coupling analysis were developed. Figure 4 shows the model for EM analysis of the coil. The model is a two-dimensional model, the configuration of which is an axial and vertical symmetry. The components of the model are as follows: cable, structural material, vacuum area, and infinite boundary area. The cable was assumed to be a conductor, the cross-section of which is a circle without a central cooling channel and twisted strands. The structural material was treated as an integrated conduit of the CIC conductor in the coil winding.

The permeability of each component was assumed to be the permeability in vacuum. In terms of the boundary conditions for the EM analysis, the natural condition was used in r-axis, the fixed boundary condition was used in z-axis, and an infinite boundary condition was used in other boundaries as illustrated in Figure 4 (a).

Figure 4 (b) shows the model consisting of the cable and structural material for the structural analysis. The model is the same as the EM analysis model removing the vacuum and infinite boundary area as illustrated in Figure 4 (a). In the structural analysis, a contact element was used between the cable and the structural material to simulate precisely the cable deformation due to the EM force. Regarding material property, the Young's modulus of 200 GPa and the Poisson's ratio of 0.3 are used in the structural material. Additionally, in the cable used in the model, the Poisson's ratio was 0.3 and the Young's modulus was 0.4 GPa which was the overall elastic modulus derived from the compressive test results of a twisted cable removing a conduit from the CIC conductor. In terms of the boundary conditions, the bottom surface of the material structure was fixed vertically.
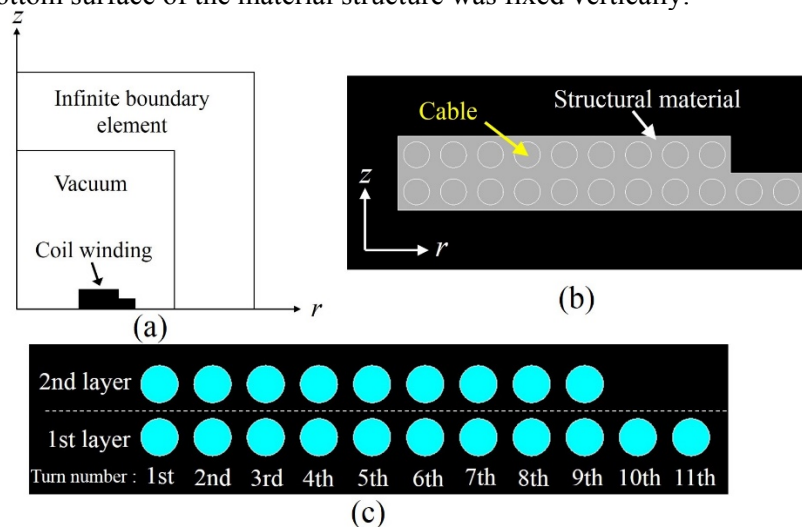

Figure 4. (a) Schematic view of the EM analysis model. The coil winding is composed of cables and structural material. (b) Coil winding in the EM analysis model. (c) Position of the cable in the coil winding.
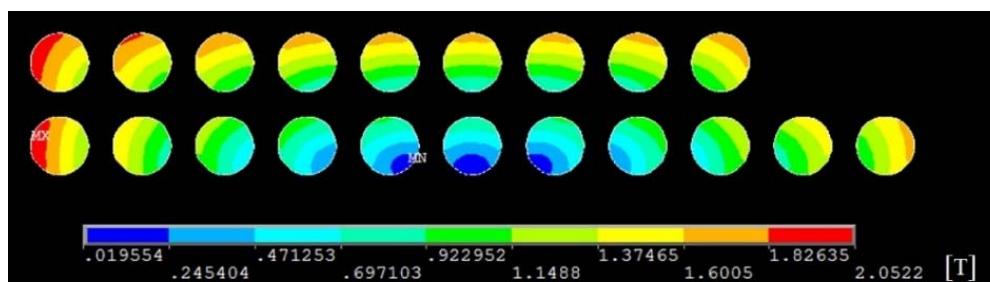

Figure 5. The distribution of the magnetic flux density at the cable of the coil winding.
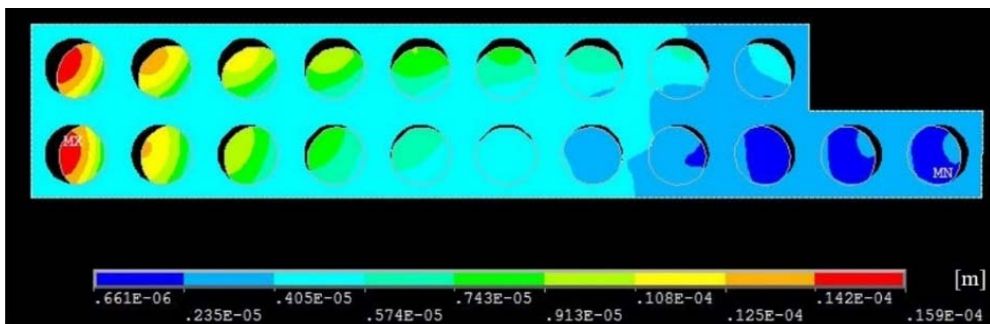

Figure 6. Deformation in the coil winding due to the EM force. The displacement at ×500 magnification is shown.

4.2. Results

The magnetic field analysis of the model coil was conducted where the coil current was 25 kA. The magnetic flux density in the cable is shown in Figure 5. The magnetic flux density increases as the position moves away from the middle of the coil winding. At the coil inner side, the magnetic flux density becomes maximum.

After the magnetic field analysis, the structural analysis was conducted with the data of the EM force derived from the magnetic field analysis described above. Figure 6 shows the result of the structural analysis when the coil current is 25 kA. The cable deformation, which means an occurrence of a new cooling channel, becomes larger as the position of the cable moves away from the center of the coil winding. At the coil inner side, the cable deformation is maximized.

To evaluate the cable deformation at each cable position, the cable deformation was calculated, assuming that there is no deformation in the structural material. Figures 4 (c) and 7 show the position of the cable in the coil winding and normalized space caused by the cable deformation at each cable position, respectively. The space in the second layer is larger than that in the first layer, and the space in the middle turn number tends to be small. The result indicates that the EM force creates non-uniform space distribution in the coil winding.
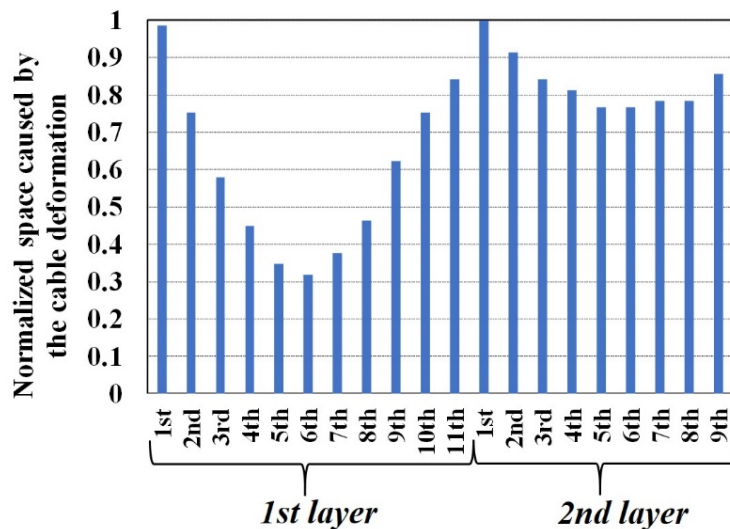

Figure 7. Normalized space caused by the deformation at each cable position. The space at each cable position is normalized by the space at the first turn in the second layer, which is the largest space.

5. Conclusion

To understand the deformation of the JT-60SA CS model coil during the coil energization, the EM structural coupling analysis for the model coil was conducted. The results of the analysis indicated that new cooling channels occur by the deformation of the cable in the coil winding, and the cable deformation becomes larger as the position of the cable moves away from the center of the coil winding.

References

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