Magneto-Mechanical Coupling Analysis of A Hybrid Superconducting Solenoid

Using FEM with Different Approaches

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Background

The high-field superconducting magnet carrying with high current density are commonly exposed to large Lorentz forces leading to the unavoidable deformation in superconducting coils. The deformation will further disturb the magnetic field quality and the operating safety and stability of the magnet. An accurate estimation of the magneto-mechanical behaviors of superconducting coils during excitation is a crucial point.

Objectives

A coupled magneto-mechanical modeling for an hybrid superconducting solenoid was developed, to give a more accurate predictions on the composite structure, the finite element (FE) model utilized an orthotropic homogenized model to connect the micro-scale of the superconducting filaments to the macro-scale of the superconducting coil with RVE method, and a detailed hierarchical model consists of multilevel structures like superconducting wire, wire insulation and filling material were suggested, and compared with the predictions by an isotropic homogenized model and the experiment measurements.

Method

A hybrid superconducting solenoid with maximum central magnetic field up to 10 T, consisting of a central Nb3Sn/Cu main solenoid coil, Nb3Sn/Cu solenoid and two Nb3Sn/Cu shield coils.

In our study, the central Nb3Sn solenoid would be main considered, because it sustains high field and the Nb3Sn filaments are strain sensitive and brittleness.

Coupled FE modeling

Maxwell electromagnetic theory

\[ \mathbf{V} = \mathbf{V}^0 - \mathbf{J} \times \mathbf{B} 

The FEM formulas for magneto-mechanical coupling analysis was implemented based on the following governing equations and constitutes

\[ \mathbf{V} = \mathbf{v} + \mathbf{u} + \mathbf{w} 

When the coils deform caused by the Lorentz force, the current in the cogs and the magnetic field will accordingly alter, which further change the force distribution. Such a coupled problem arises from the electromagnetic force and structural deformation.

Isotropic Homogenized Model (IHM)

The isotropic material properties of the superconducting coil was obtained by the rule of mixture

\[ E = \sum E_i \frac{v_i}{\sum v_i} 

The Point 1 and Point 2 are the locations of the strain measurement.

Results

The numerical predictions show an almost linear relation between the magnetic field and radius locations at the symmetry plane of the Nb3Sn coil package.

The simulation results are almost consistent, and agree with the experimental value at the central position of the solenoid.

The prediction results of IHM and DHM are almost at the same, and match well with the experimental results at both locations.

The results of the IHM have some differences between the predictions and measurements under the higher fields at the both locations.

The prediction of IHM show the best agreement with the experimental results, the results of the DHM is second, while the worst at the point 2 location.

The experimental results at the top right corner of this figure, we can see that the maximum stresses are all occur within superconducting wire, the region of superconducting wire and wire insulation are both under tensile stress.

Fig.3. Hoop strains versus the carrying current of the Nb3Sn coil package at point 14 and 24

Detailed Hierarchical Model (DHM)

The detailed hierarchical model, the Nb3Sn coil package is taken as a composite one, which consists of superconducting wire, wire insulation and copper. The superconducting wires were homogenized according to the micro-structure of the composite wire. The exciting currents just only are evenly loaded on superconducting wire.

Fig.4. Axial strains versus the carrying current of the Nb3Sn coil package at point 14

Conclusions

For the magneto-mechanical behavior predictions, the prediction results of detailed hierarchical model shows the best agreement with the experimental results, the results of orthotropic homogenized model is second, isotropic homogenized model is the worst, especially under the high fields.

We also found that the maximum stresses all occur within the superconducting wire by means of the detailed hierarchical model, and the simulation results of the detailed hierarchical model could show more details on the stress state of superconducting wire, wire insulation and filling material, one that the isotropic/orthotropic homogenized FE model could never achieve.

These results would help the high field superconducting magnet designers to numerically predict the magneto-mechanical behaviors of the superconducting solenoid.

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