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The Axial Displacement and Its' Effects on the Mechanical Behavior of Pulsed High-field Magnets

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I. Introduction

- The service lives of magnets operated over 90 Tesla in practice are significantly shorter than those predicted theoretically, while the designed stress safety margin is adequate. Some high-field failure experiments showed that there are some serious ***scorch marks*** occurred at the end of magnets. The axial displacement is the most suspect and it might also be the reason for the short service lives.
- Traditional 1-D pulsed magnet design software are effective and quick but can ***only calculated the stress on the mid-plane***. In the former 2-D models, the treatment of axial mechanical behavior are rough. Only few contact pairs are set and ***the ideal adhesion*** is used due to the difficulties on the convergence.

Considering these, a precise 2-D finite element model of pulsed magnets is firstly built. The contact pairs are set on all the interfaces between different materials. Using this model, the axial displacement and its' effects on the mechanical behavior of magnets are discussed in detail. The influencing factors are also discussed

II. Simulation Technology

A semi-axisymmetric model is established in ANSYS 19.0. The wires are surrounded by the insulation and each layer of the conductors are reinforced by one fiber reinforced plastic (FRP) layer.

- *The load transfer method* is used to deal with the multi-physics coupling problem.
- *Perfect magnetic and thermal contacts* are used to deal with the discontinuous boundary.
- Use *the augmented Lagrangian algorithm* and utilize *the integral Gaussian point* as the contact detective point to guarantee the convergence of the contact problem.
- Adjust *the contact stiffness* and *time step* in each load step to prevent the sudden change of the contact status.
- *The Coulomb friction model* is used and the coefficient of friction μ is set as 0.2.

III. The Axial Displacement of Magnets and Its' Effects

A. The displacement at the end

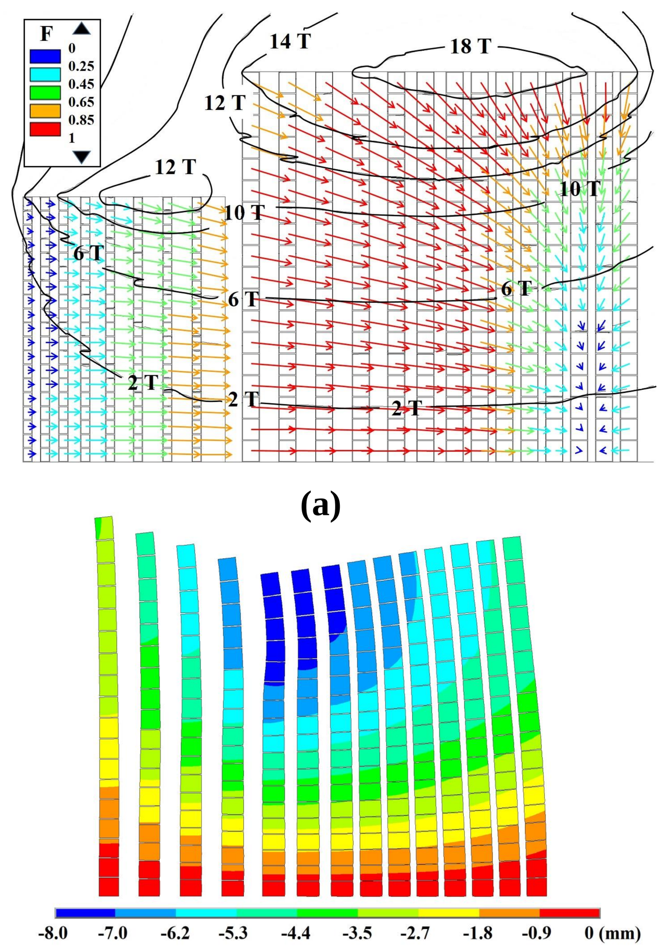

Fig. 1

The outer coil of a 95 T dual-coil prototype is taken as an example. The prototype is originally designed by self-developed 1-D software PMDS. Main attributes of the outer coil are listed below:

- Number of conductor layers: 14
- Number of conductors per layer: 36
- Height: 263 mm
- Bore diameter: 160 mm
- Peak field: 45 T
- Conductor dimension: 5.5 mm × 6.9 mm
- Insulation thickness: 0.2 mm
- FRP thickness: #1-14: 6.5, 6.5, 6.5, 6, 4, 4, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 20 mm

- The contour of radial magnetic flux density and the normalized magnetic forces are showed in *Fig. 1 a)*. The outer coil suffers more axial forces than inner coil since the radial magnetic field is larger in there and the outer coil is longer.
- The axial displacement of the conductors of outer coil at peak field is plotted in *Fig. 1 b)*. Most axial forces aren't sustained by the conductors themselves but transferred to the underlying conductors. This can be explained from the axial mechanical equilibrium equation: $\partial\sigma_z/\partial z+(\partial\tau_{rz}/\partial r+\tau_{rz}/r)=jB_r$. The shear stress is less than 40 MPa and the second term could be ignored.

B. The effects on the mechanical behavior

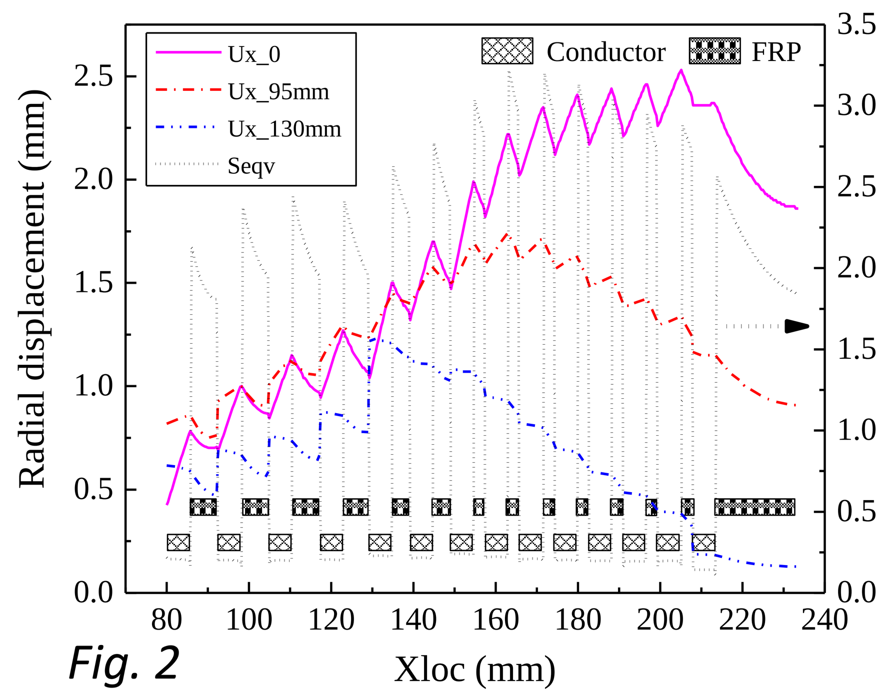

Fig. 2

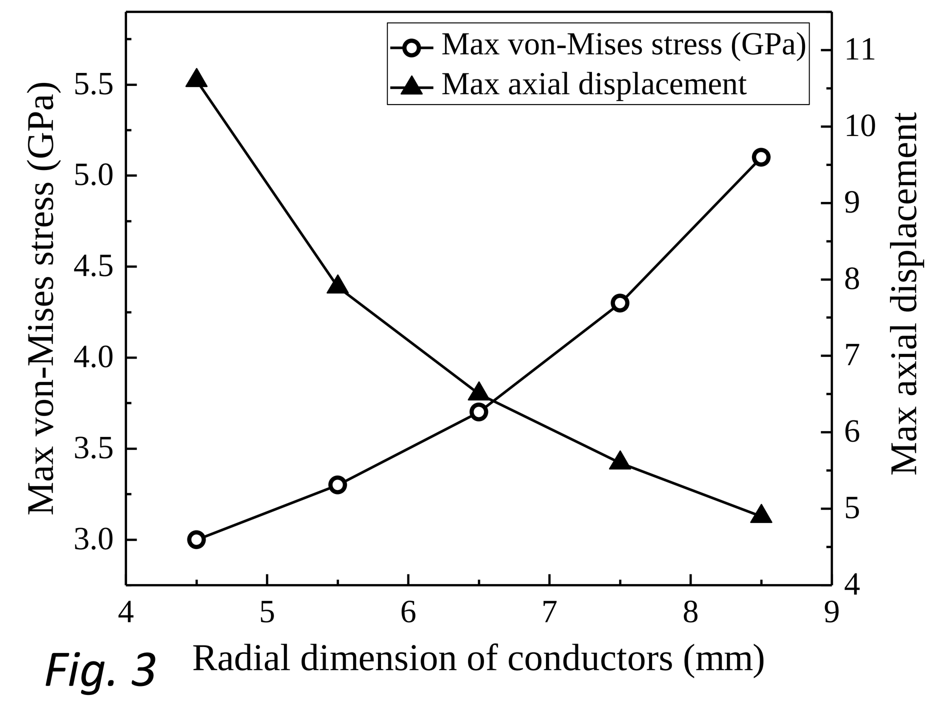

Fig. 3

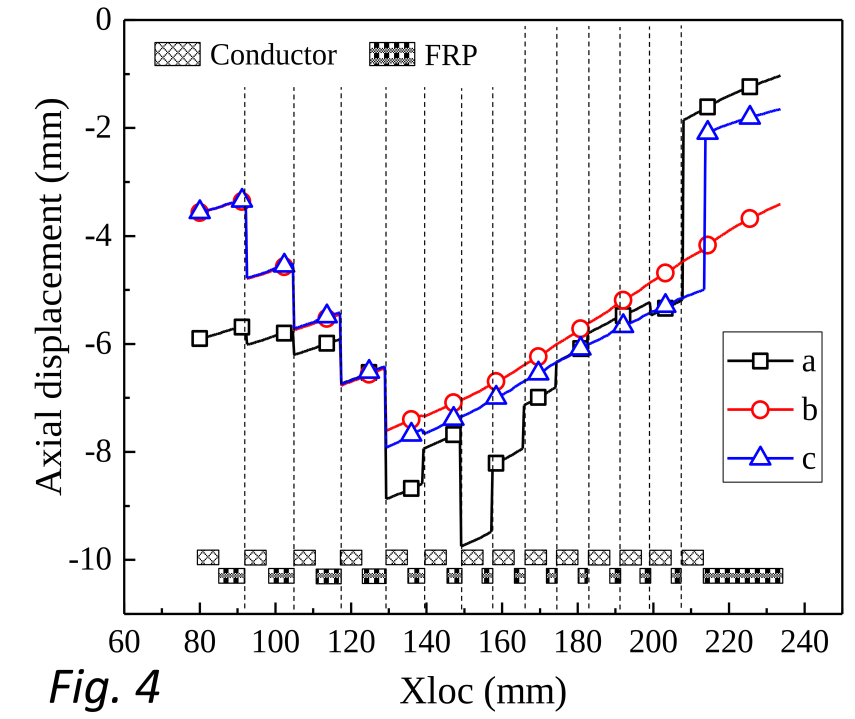

Fig. 4

The von-Mises stress on the mid-plane and the radial displacement on different planes are plotted in *Fig. 2*. The first four layers are free-standing in the original 1-D design. This happens at the end of magnet in 2-D analyses ***but all of them gradually disappear*** as the accumulation of axial compression. The stress distribution is then ***totally changed***. The stresses are transferred to the outer layers and the inner FRP seems some overused.

The reason of the difference is ***the constant axial strain hypothesis*** in 1-D calculations. 2-D simulations show that the max axial strain on the mid-plane is up to 1.3 ‰ while the minimum is only 0.8 ‰.

C. Influencing factors of the axial displacement

- *The geometry of magnets.* Less height means less axial magnetic forces and accumulations but more energies will be required. The cross-section of conductors is another concern. The magnet with different cross-section of the conductors are compared, as shown in *Fig.3*. The area of the cross-section is fixed as 38 mm^2.
- *The axial stiffness of the materials.* For conductors, Cu-Al_2O_3, Cu-Ag or Cu-SS might be a good decision. For FRP, the transverse elastic module is set as 3 GPa, 30 GPa and 60 GPa. The corresponding max axial displacement is 8 mm, 3 mm and 1.9 mm, respectively. Hence, the FRP with high axial stiffness is required.
- *The interface characteristics.* The axial displacements with different μ and the ideal adhesion are shown in *Fig. 4*. a) ideal adhesion, b) μ =0.2, c) μ=0.8. The axial displacements in b) and c) are smaller than a). It is because that a considerable interfacial friction is induced by compressive radial stresses in the interfaces between the conductor layers and the FRP layers ahead them. The difference is significant in the last layer since the radial compressive forces are tiny there and the interface characteristics becomes sensitive.

IV. Conclusion

The axial displacement and its' effects were discussed in detail. A precise 2-D finite element model was built. Simulations showed that the axial compression leaded a significant axial displacement. All the free-standing parts, which were originally calculated from 1-D code, disappeared. Since then, further 2-D optimizations are necessary after 1-D fast designs and the influencing factors of the axial displacement should be account.

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