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by

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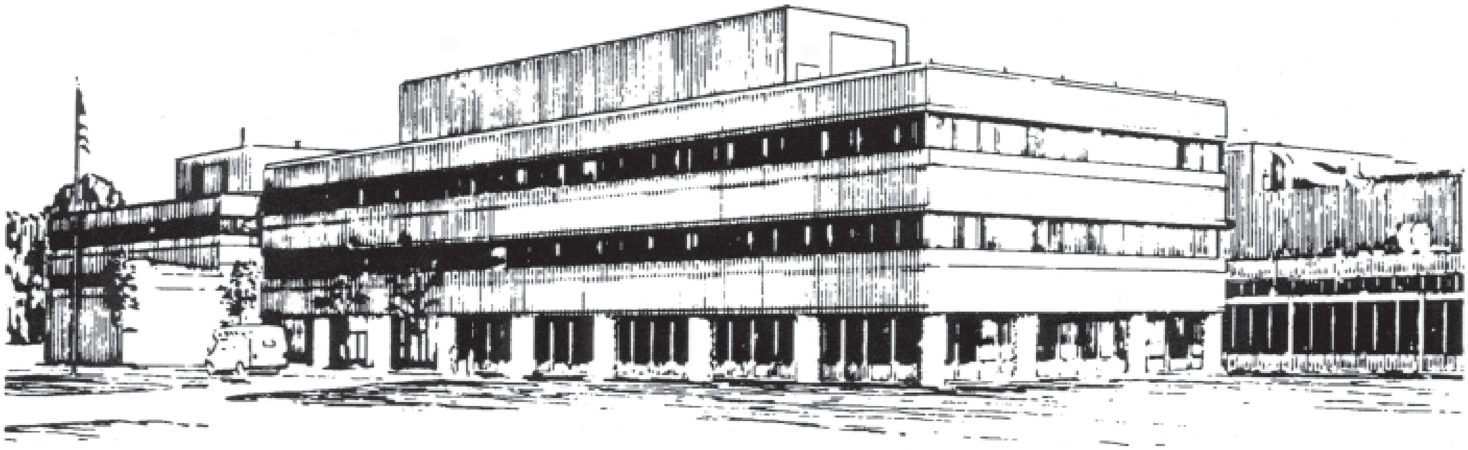

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Engineering Analyses of NCSX Modular Coil and Its Supporting Structure for EM Loads

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***Abstract*. . NCSX modular coil is a major parts of the NCSX coil systems that surround the highly shaped plasma and vacuum vessel. The flexible copper cable conductors are used to form modular coil on both sides of the 'tee' beam, which is cast inside the supporting shell structure. The Engineering analyses comprise sequentially coupled-field analyses that include an electromagnetic analysis to calculate the magnetic fields and EM forces, and a structural analysis to evaluate the structural responses. In the sequential EM-structural analysis, nodal forces obtained from the EM analysis were applied as "nodal force" loads in the subsequent stress analysis using the identical nodal points and elements. The shell model was imported directly from Pro/ENGINEER files in order to obtain an accurate structural representation. The Boolean operations provided by the ANSYS preprocessor were then applied to subdivide the solid model for more desirable finite element meshing. Material properties of the modular coil were based on test results. Analyses using the ANSYS program to evaluate structural responses of the complicated modular coil systems provided a clear understanding of the structural behaviors and the directions for improving the structural design.**

I. INTRODUCTION

The modular coil windings are one of four magnet systems with the primary function of providing the basic quasi-axisymmetric magnetic configuration for the NCSX device. The windings can produce alternate magnetic configurations by varying the current for each coil type independently. The complexity of the coil shapes induce magnetic forces that are different comparing with the conventional PF and TF coils. The requirements of accurate positioning of coil winding and assembly together with the coil support structures that interface with the internal and external components of the stellarator core systems make the modular coil design very challenging.

The coil winding form cast into a structural shell constructs the coil support structure. The main performance requirement for the winding forms is to support the coil electromagnetic loads with a minimum of deflection. The purposes of the paper are to sequentially perform engineering analyses that include 1) an electromagnetic (EM) analysis to calculate the magnetic forces in the modular coils, and 2) a structural analysis to evaluate the displacements and stresses of the modular coils and the coil support systems.

II. MODULAR COILS

The modular coil consists of three field periods with 6 coils per period, for a total of 18 coils. Figure 1 shows the top view of modular coil configuration. Due to symmetry, only three different coil shapes (see A, B, and C in Fig. 1) are needed to make up the complete coil set.

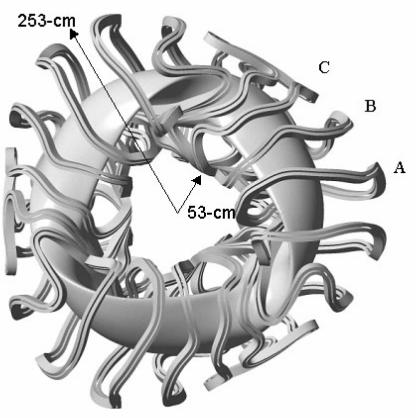

Fig. 1. Modular coil configuration

The design concept uses flexible, copper cable conductor that has been compacted into a rectangular cross-section and wrapped with Kapton and glass tape insulation. The conductor is wound on each side of the structural web, the winding form called 'tee' structure. After winding is complete, the assembly is vacuum pressure impregnated with epoxy to complete the insulation system. The epoxy fills the voids within the cable conductor so the winding pack becomes a monolithic copper-glass-epoxy composite. Auxiliary clamping brackets are then installed to hold the coils in position. The winding form is cast in the structural shell.

III. ELECTROMAGNETIC ANALYSIS

The first part of engineering analyses involves an EM analysis to calculate the magnetic fields and EM forces in the modular coils. The coil currents, interacting with the magnetic fields that are produced by the magnet systems as well as the plasma current, induce the EM forces. To obtain correct magnetic fields in the system, the TF and PF coil currents and the plasma currents shall be incorporated in the EM analysis. The current waveforms have defined several reference operating scenarios from which the worst case of coil currents can be found at their maximum positive or negative value occurred at a time step.

A. Finite element Mode for EM Analysis

The analysis of the EM model consists of finite elements for modular coils, PF coils, TF coils, and plasma current representing by current source elements. By taken the advantage of three field symmetry, the analytic model contains only the coils within a 120-degree region as shown in

Fig. 2. Looking from the center of machine, the three coils on the right-hand side (M1R, M2R, and M3R) are the 180-degree rotational reflection about the x-axis of the three-coil set on the left-hand side (M1L, M2L, and M3L). To calculate the governing loads on the modular coils the maximum currents in the modular coils were selected. From the current waveforms, the maximum modular currents occurred at 0.094 seconds for the 1.9T High Beta Scenario. The coil currents for all coils at the time step are:

M1	777,276 A	PF4	26,400 A
M2	789,660 A	PF5	31,008 A
M3	694,224 A	PF6	88,984 A
PF1	629,640 A	TF	-14,832 A
PF2	629,640 A	Plasma	–134,176 A
PF3	650,008 A		

The positive toroidal current (plasma or PF coil) is defined in the counter-clockwise direction viewed from above while the positive poloidal current (TF or modular coil) flows in the vertical direction in the inner leg.

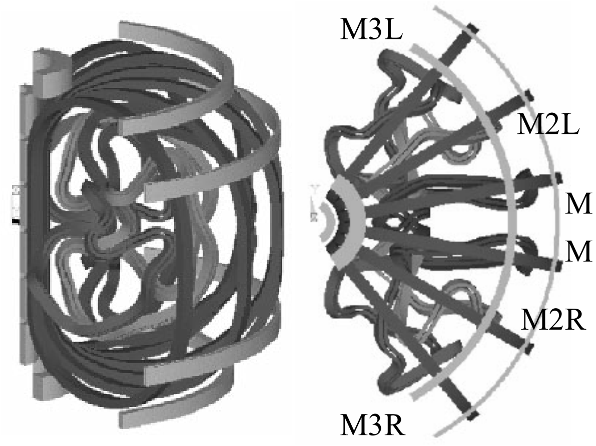

Fig. 2. FEA model for EM analysis

B. Results of EM Analysis

Higher magnetic flux densities were found in modular coils when there were small bend radiuses of curvatures at winding pack. The maximum flux density in the modular coil is 4.736 T in M2. The net forces for the six coils were illustrated in Table I. In the table, the M2 coil generated maximum radial, toroidal, and vertical forces. For left and right coil sets, the net radial forces were always equal in magnitude and acting in the same direction. For the net vertical and toroidal forces, the left and right coil sets have the same magnitude but acting in the opposite directions.

As the coils are wound in the winding form and held by clamps at interval, the magnetic forces along the coil axis are important for the design of clamps. To better understand the force distribution on the modular coil, they were resolved into local coordinate systems in the radial and lateral direction relatively to the winding form structure. The lateral forces are in the direction normal to the surface of supporting web and the radial forces are in the direction toward the shell structure.

TABLE I
NET EM FORCES FOR MODULAR COILS

	Fr	Fθ	Fz
	Pa	Pa	Pa
M1R	-576,474	73,819	23,439
M1L	-576,474	-73,819	-23,439
M2R	-895,472	84,005	417,849
M2L	-895,472	-84,005	-417,849
M3R	243,526	-26,209	415,623
M3L	243,526	26,209	-415,623

Figure 3 plots the element force vectors for the M2L coil. The net radial forces on the coil are outward against the shell structure except at position C where a very small negative force exists.

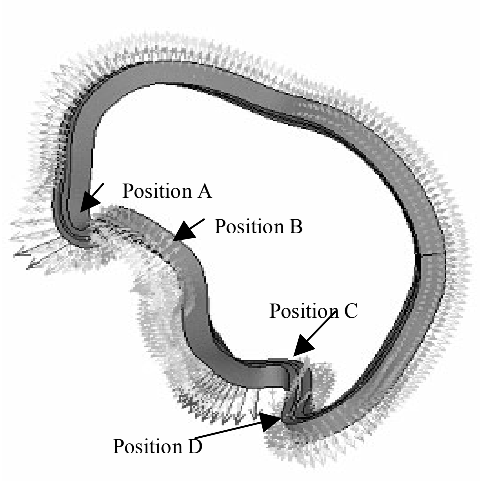

Fig. 3. Plot of Element force vectors for M2L

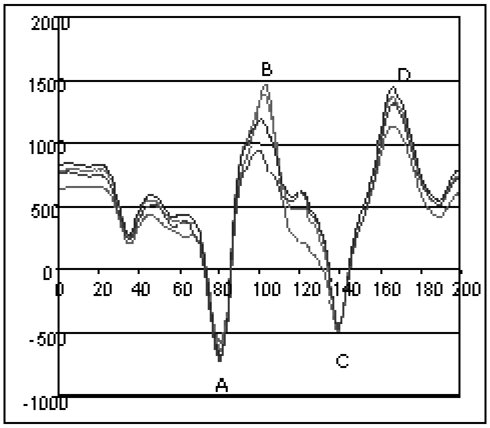

Fig. 4. Force plot of the right winding pack of M2L. Peak forces are found at regions where winding pack contains small bending curvatures.

A more detailed lateral force plot of the right winding pack of M2L coil is shown in Fig.4. In general, the lateral forces are in the direction toward to surface of the supporting web because two winding packs are running parallel in the same direction. However, in the regions of small bending curvature, such as positions A and C in the Fig. 3, the winding pack forces are away from the web structure primarily due to the local peak fields. The forces will be reacted by clamps and by the winding pack acting as a curve beam in the local region.

IV. STRUCTURAL ANALYSIS

The modular coils are supported by the integral winding form and shell structure that interface with the machine base support structure. There are 18 shell segments bolted together to make a continuous shell structure. Each shell contains a winding pack, a winding form, and a poloidal break as a result of the eddy current requirement.

The structural analysis was utilized to evaluate the structural responses that include displacements and stresses of the modular coil and the supporting shell structure. Coupled-field analyses were exercised such that the nodal forces obtained from the EM analysis were applied as nodal loads on the subsequent stress analysis using the identical nodal points and elements. This approach provides accuracy of transferring the loading from one model to the other model. Linear elastic method was used for the analysis that assumes the winding packs were not separating from or sliding with the winding forms.

A. Finite element Mode for Structural Analysis

The shell models were imported from Pro/ENGINEER generated files to provide an accurate shape representation. The Boolean operations in the ANSYS preprocessor were then applied to subdivide the solid model for more desirable finite element meshing. More than 97 % of elements were made by hexahedral elements. Because of threefold cyclic symmetry presented for both the structural configuration and loading, the model can be effectively made by containing only 120 degrees of the structural systems. Boundary conditions were applied at –60-degree and 60-degree sections by coupling nodal degrees of freedom to secure the continuation of shell deformation. The finite element model consists of the winding packs, winding forms, and shell structure as shown in Fig. 5. The model was constrained at the toroidal stiffeners on the bottom side of the shell to simulate the constraints from the machine support structure.

Winding packs are continuously supported by shell structure within each shell segment before the shell assembly as shown in Fig. 6. Wing structures extending from the edges of shell were designed to act as cantilever plates for supporting protruding portions of the modular coils. Analysis of local model revealed that large displacements and stresses were produced by the cantilever behavior. The design was updated to provide an additional support at the adjacent shells for each cantilever tip.

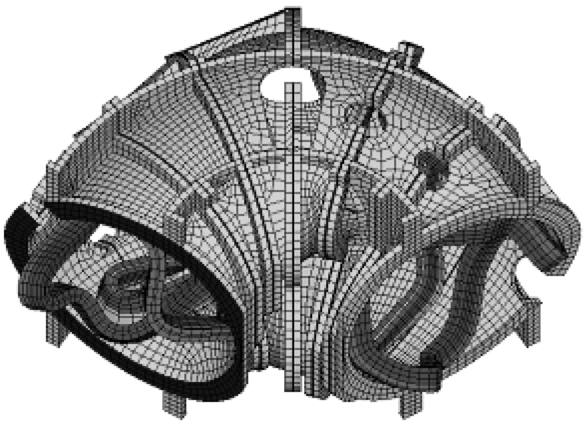

Fig. 5. Finite element model of the modular coil structure consists of winding packs, winding forms, and shell structure spanning in 120 degrees

Due to the difficulty of accurately calculating the composite material properties of the modular coils, test programs were carried out to investigate material properties from 76 K to the room temperature. Test results indicated a compressive modulus of elasticity of 5300 ksi and a tensile modulus of elasticity of 14400 ksi at the temperature of 76K [1]. For conservative reason, the compressive modulus was employed in this analysis. The operation temperature was defined at 80 K. The modulus of elasticity of modular coil, shell and winding form, and equivalent property of combining insulation and bolt connection at toroidal and poloidal breaks are set at 38.3 GPa (5560 ksi), 207.0 GPa (30030 ksi) and 50.0 GPa (7250 ksi), respectively.

Fig. 6. For each shell segment, the modular coil protrudes outside of the shell edges.

B. Results of Structural Analysis

Results indicate the maximum displacement of 0.97 mm (0.038 in) at the outboard side of the shell structure. Peak Von

Mises stress of 181 MPa (26.2 ksi) was found at the edge of shell opening (see Fig. 7) where the podoidal flange stiffeners at both sides of shell edges were removed by openings. Peak stress in winding pack is 67.8 MPa (9.8 ksi) based on the smear property of the composite material. The maximum stress in the winding form is 167 MPa (24.2 ksi) occurred locally at locations where the winding forms encounter the shell edges. Spreading the reactions into wider areas, such as using the wing structure concept, can eliminate these local higher stress regions. The peak stress in the shell can be minimized by thicken the shell thickness or adding stiffener locally.

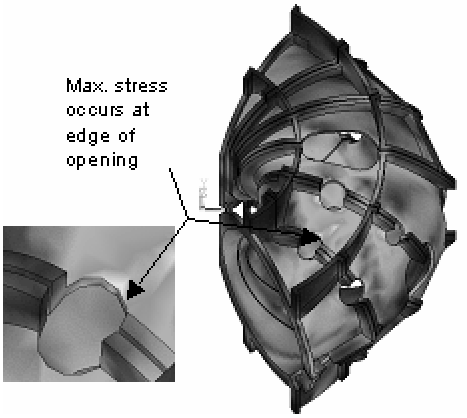

Fig. 7. Peak stress location on shell structure

V. SUMMARY

A model acurately built for the modular coil and its supporting sturcture was made to investigate the structural behaviors due to electromagnetic load induced by the currents in the coils. The finite element model was converted from the Pro/ENGINEER files and coupled-field analyses were performed to compute first the EM forces in the coils and then the displacements and stresses in the structural components. Analyses used ANSYS code demonstrated the design to be adequate. It provided useful information for improving the dedign of modular coil system in the final design stage.

ACKNOWLEDGMENT

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[1] I. Zatz, “Interim Modular Coil Material Properties”, PPPL memo. August 2003.

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