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CALCULATION OF EDDY CURRENTS IN THE CTH VACUUM VESSEL AND COIL FRAME

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Knowledge of eddy currents in the vacuum vessel walls and nearby conducting support structures can significantly contribute to the accuracy of Magnetohydrodynamics (MHD) equilibrium reconstruction in toroidal plasmas. Moreover, the magnetic fields produced by the eddy currents could generate error fields that may give rise to islands at rational surfaces or cause field lines to become chaotic. In the Compact Toroidal Hybrid (CTH) device (R0 = 0.75 m, a = 0.29 m, B ≤ 0.7 T), the primary driver of the eddy currents during the plasma discharge is the changing flux of the ohmic heating transformer. Electromagnetic simulations are used to calculate eddy current paths and profile in the vacuum vessel and in the coil frame pieces with known time dependent currents in the ohmic heating coils. MAXWELL and SPARK codes were used for the Electromagnetic modeling and simulation. MAXWELL code was used for detailed 3D finite-element analysis of the eddy currents in the structures. SPARK code was used to calculate the eddy currents in the structures as modeled with shell/surface elements, with each element representing a current loop. In both cases current filaments representing the eddy currents were prepared for input into VMEC code for MHD equilibrium reconstruction of the plasma discharge.

I. INTRODUCTION

The Compact Toroidal Hybrid (CTH) device at Auburn University, shown in Figure 1, has a major radius of 0.75 m, minor radius (at vacuum vessel) of 0.29 m and toroidal magnetic field of 0.7 T. CTH is a five field-period device. The Helical Field coil (HF, red in Figure 1) is wound in a trough formed by the Helical Coil Frame (HCF, green). The vacuum vessel (grey) is encased inside of the HCF and the vacuum vessel ports protrude through openings in the HCF. A set of Vertical Field Coils (brown and red) allow for radial positioning of the vacuum field equilibrium. The Toroidal Field Coils (TF, yellow) act to produce an auxiliary toroidal field to either raise or lower the vacuum rotational transform.

The Helical Coil Frame is composed of 10 identical pieces. Each piece (shown in Figure 4) is cast with A356 aluminum alloy. The 10 pieces are electrically isolated from one another, the vacuum vessel and all magnet coils. They are assembled in a five field-period stellarator symmetric fashion shown in Figure 2.

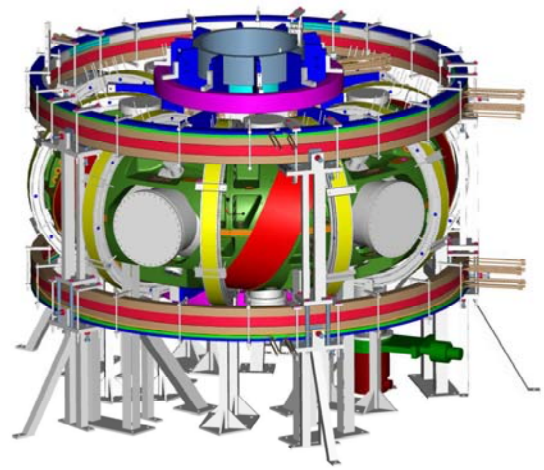

Figure 1: CTH experiment showing the helical coil frame (green), helical coil (red), and toroidal field coils (yellow) surrounding the vacuum vessel (grey).

The vacuum vessel is toroidally continuous and is made of Inconel® 625. In each field period the vacuum vessel has an upper vertical port, a lower vertical port, a horizontal port, and two angled ports that protrude through the helical coil frame (Figure 2).

The Ohmic heating coils (OH, shown in brown in Figure 2) are three sets of coils in series, OH1 (44 turns), OH2 (12 turns) and OH3 (1 turn), each composed of two individual upper and lower coils.

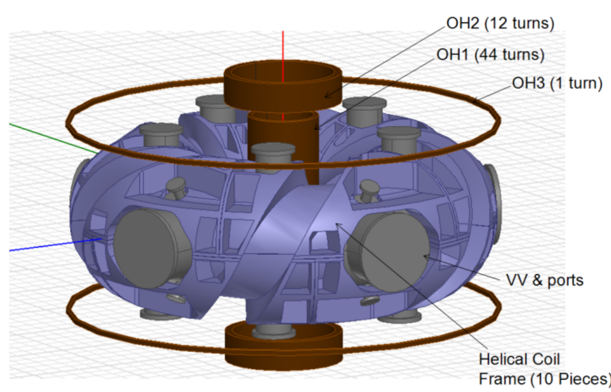

Figure 2: CTH coil frame, vacuum vessel and OH coils

Operation of ohmic heating (OH) coils causes eddy currents to flow in the vacuum vessel and the helical coil frame pieces. These eddy currents can significantly affect the accuracy of free-boundary magnetohydrodynamic (MHD) equilibrium reconstruction which is performed by VMEC[1] for CTH. This paper describes how time-dependent modeling of eddy currents in the aluminum frame piece and in the vacuum vessel, resulting from a specified current waveform in the OH coil set was carried out. The intent of the calculation is to provide a multi-filament model of the eddy currents that can be imported into VMEC.

In section II of this paper we give details of the OH coils' currents that drive the eddy currents in the vacuum vessel and helical coil frame pieces. Section III describes the 3D modeling and transient simulation of the eddy currents using MAXWELL[2] finite element code and conversion of the current density results to current filaments using the JFIL code. Section IV is a description of the eddy current 2.5D modeling using the SPARK[3] code and presentation of the results in the form of closed current filament loops. Conclusions and suggestions for future work are outlined in section V.

II. OH Current

Total of 6 OH coils (OH1, OH2 & OH3 upper and lower) are connected in series and driven by a pulse of current shown in Figure 3. The flux change of the OH coils is the primary driver of the eddy currents in the vacuum vessel and coil frame. The time period of interest is the period of rapid rise of current, from approximately 1.62 s to 1.65 s, from 0 to approximately 14 kA. A current waveform mimicking this current rise was used to drive the OH coils in both MAXWELL and SPARK simulation models.

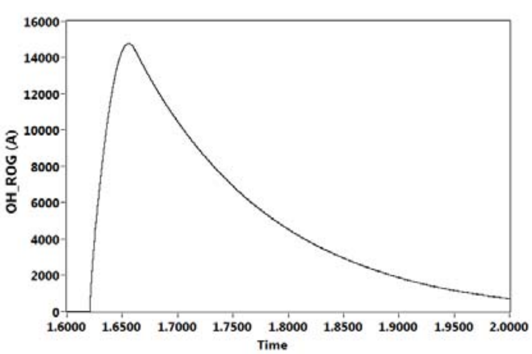

Figure 3: OH coil set drive current waveform

III. 3D FINITE ELEMENT ANALYSIS

MAXWELL 3D, a commercial EM finite element code, was used to model and simulate the transient eddy currents in the CTH helical field coil and vacuum vessel during the OH pulse shown in Figure 3. The entire model consisting of the 10 pieces of the helical coil frame and the whole vacuum vessel were modeled and meshed. No cyclic symmetry was used to reduce model and mesh size since. This is ecause MAXWELL can only use symmetry planes that lie entirely in one poloidal plane, and the present geometry does not lend itself to that symmetry without slicing the individual coil frame pieces. The coil frame pieces were modeled with very thin air gaps between them to ensure they are modeled as being insulated from each other.

MAXWELL uses tetrahedral elements to mesh the 3D volume. The finite element mesh for one of the coil pieces is shown in Figure 4. MAXWELL calculates eddy currents at each node of the mesh (and at mid-side nodes of each tetrahedral element). Eddy current density results for t=0.025 s (approximately ¾ way up the OH current ramp) for the toroidally continuous vacuum vessel are plotted in Figure 5. As expected the current density vectors are toroidal in direction and higher on the inboard region which is closer to the OH and smaller in major radius. The eddy current density results in the coil frame pieces are more interesting. They are shown in Figure 6. Here we see circulating current patterns the most prominent of which we see in the middle curved portion of the coil frame piece.

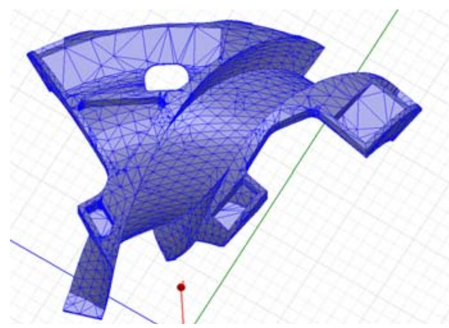

Figure 4: MAXWELL finite element mesh in a helical coil frame piece

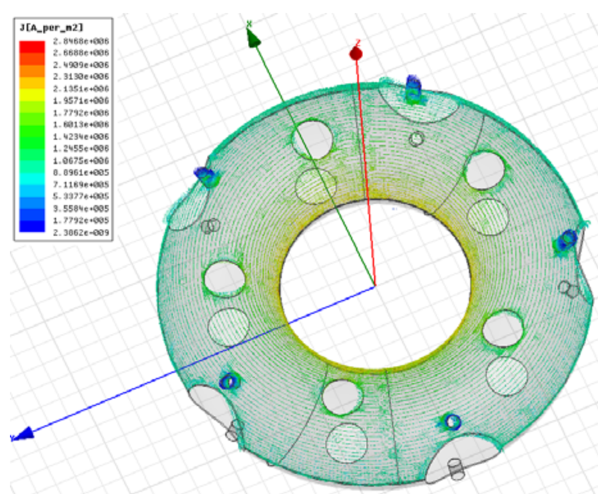

Figure 5: Eddy current densities in the CTH vacuum vessel

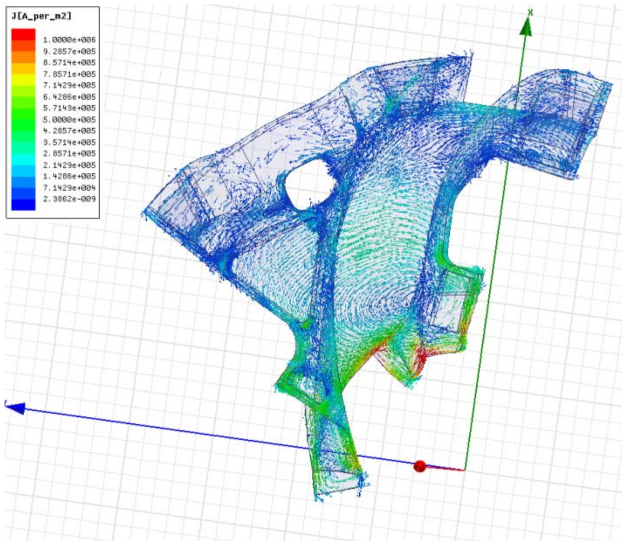

Figure 6: MAXWELL eddy current densities in a coil frame

The JFIL code was used to convert the current density results into equivalent current filaments (sticks) in space each with a start and an end point and magnitude. These current filaments, each representing the current in a mesh element can be directly used in VMEC. The time varying current in the filaments can also be used to calculate current induction in the magnetic diagnostic coils. JFIL results are shown graphically in Figure 7 for the eddy currents in a helical coil frame.

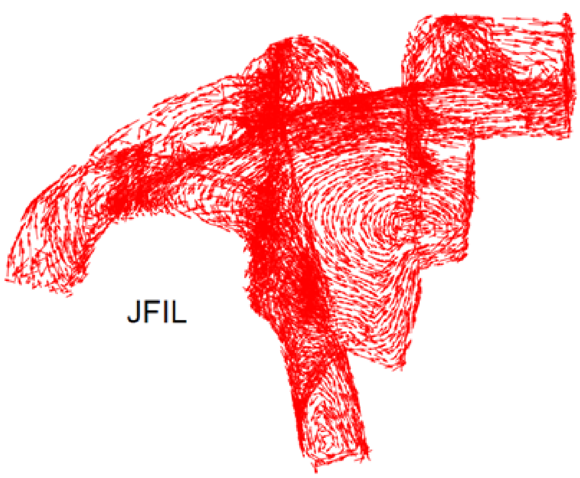

Figure 7: Current filament representation of eddy currents in a coil frame piece

IV. ANALYSIS USING SPARK

SPARK code[3], developed at PPPL, is a 2.5D code designed to calculate eddy currents on conducting surfaces where current flow is assumed to be zero in the direction normal to the surface. Surfaces can be modeled with triangular or quadrilateral elements.

It is simple to model the vacuum vessel with a surface where the current flow is assumed zero in the direction normal to current flow. This is because the vacuum vessel has more or less uniform thickness and the induced potential is toroidal in direction. However, for the coil frame piece which is 3D in nature, the choice of representative surfaces is more difficult. Guided in part by the MAXWELL results, we extracted connected surfaces from the coil frame piece solid model using ANSYS Workbench[4] code which would represent the eddy current conducting volume. The model is shown in Figure 8 in a 1/5 cyclic symmetric section of the device including the vacuum vessel and helical coil frame. The figure also shows the mesh consisting of mostly quadrilateral elements and some triangular elements. Each element consists of a closed loop (coil) made up of its 4 or 3 sides.

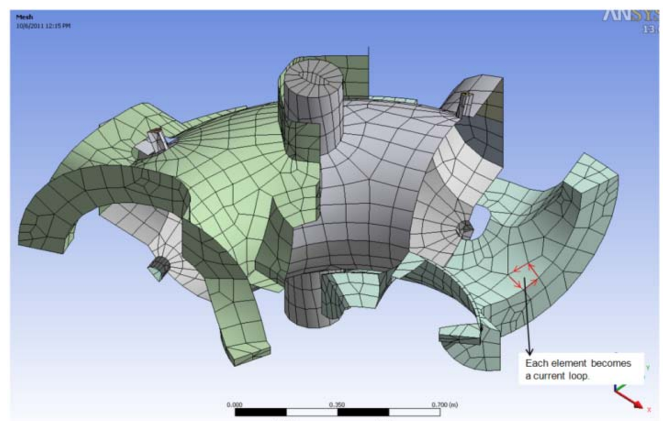

Figure 8: 1/5 cyclic symmetry model of the CTH for SPARK

SPARK was used to calculate the eddy currents induced by the OH flux change on the mesh. The resulting eddy currents at t=0.025 s are shown in Figure 9. The eddy currents on the vacuum vessel are in the toroidal direction as expected and also seen in MAXWELL results. The circulating currents in the coil frame piece shown in Figure 10 also match the pattern seen in the MAXWEL eddy current results of Figure 6.

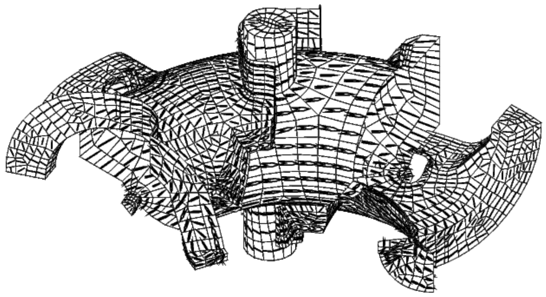

Figure 9: Eddy current vectors calculated using SPARK

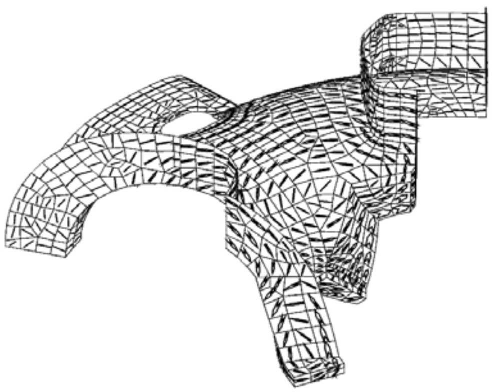

Figure 10: Eddy current vectors in a coil frame piece calculated using SPARK

SPARK calculates eddy currents by solving for current circulating in each mesh element. It does this by differentiating with respect to time the OH flux linking the surface of each element. It can therefore represent the eddy current results as loops of current for each individual mesh element made up of 4 or 3 current filaments making the sides of the (quadrilateral or triangular) elements. This could be directly used by VMEC.

V. CONCLUSIONS AND FUTURE WORK

Two separate methods were demonstrated to calculate eddy currents resulting from the OH flux change in the CTH vacuum vessel and conducting structures. Results of the two methods were shown to be similar. The tools developed to present eddy currents in a format usable in the VMEC MHD reconstruction code were discussed. These methods could in principle be used to calculate eddy currents in conducting structures of any plasma device (i.e. stellarators or tokamaks) and provide output in the format usable by MHD equilibrium codes to account for the effects of these currents on the plasma MHD equilibrium and/or magnetic field diagnostics.

Specific to the CTH device, future plans include integration of the eddy current results obtained in this work in the CTH MHD equilibrium reconstruction. Furthermore, using these methods, one can predict where to make insulating cuts or other modifications in the coil frame for maximum effectiveness in reducing the eddy currents or disrupting their patterns while still maintaining structural integrity.

ACKNOWLEDGMENTS

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