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3D ANSYS Quench Simulation of Cosine Theta Nb_3Sn High Field Dipole Magnets

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***Abstract*—To study detailed quench behavior of cosine theta Nb_3Sn high field dipole magnets a three-dimensional simulation program is made using ANSYS finite element analysis program. The simulation program reproduces the detailed end structure, as well as the straight section, based from a CAD file of I-DEAS. It can calculate the thermal and its resulting mechanical stress distribution inside the coil after a quench. Its detailed method is explained. With the present program, quench propagation along the cable length and also azimuthal quench propagation is shown. Animation programs based on this quench program are shown very effective for the detailed quench analysis.**

Index Terms—**3D ANSYS Quench Simulation, Superconducting Magnet, 3D Animation.**

I. Introduction

THE superconducting magnets for next generation hadron colliders will be built with Nb_3Sn instead of NbTi material [1]. We expect the quench characteristics of the long Nb_3Sn superconducting magnets will have much different characteristics as far as its thermal and mechanical characteristics after a quench is concerned [2]. We have been developing quench simulation programs for one-meter long magnets in this line for the high field Nb_3Sn cosine theta model magnets [3, 4]. In this sense we started with a simple scheme by following the quench along the whole length of the cable, taking into account also the lateral heat propagation through the insulation layer [3]. Then we started using the ANSYS program to simulate the quench effect, first in 2 dimensional analysis, and made a simple 3 dimensional analysis by extruding the 2 dimensional cross section [4]. Now we have started to reconstruct the real 3 dimensional analysis, importing the 3 dimensional geometry of the magnet modeled with a CAD program I-DEAS [5]. In this paper, we describe how we import the CAD geometry into ANSYS program, and solve the quench problems related to thermal and resulting mechanical stress. We describe the result of the thermal problem in the coil in this paper, and the thermal stress problems of the whole magnet will be discussed further in the near future. In the near future we will extend this simulation program with stress analysis when we incorporate all elements.

A similar method using ANSYS and Pro Engineer CAD program has been applied to racetrack type Nb3Sn magnets at LBNL [6].

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II. Simulation Theory

A. Simulation Background

This simulation takes a slightly different approach to using ANSYS to simulate a quench [7]. Many quench simulations in ANSYS use an electrical-thermal coupled field approach where the ANSYS solver routine computes all electrical and thermal data needed to simulate the quench. However, this 3D ANSYS Quench Simulation takes a different approach by relying on ANSYS only for thermal simulation, while the electrical portion of the quench is computed using physical equations and the ANSYS scripting language. This method has some advantages over the coupled-field approach, including:

- The simulation can incorporate factors not computed in the ANSYS solver routine, ranging from new output data (like MIITs or energy absorbed by the magnet) to new physical calculations to simulate other aspects of a quench.
- There is less of a chance of a solution failure since the ANSYS solver routine only needs to compute one dimension (temperature).

However, there are some problems associated with this approach when compared to a coupled-field approach. The solver routine in the 3D ANSYS Quench Simulation can only adjust thermal properties during a solution run, such as heat capacitance and thermal conductivity. Any electrical properties or derivatives of electrical properties, such as current or heat generation due to resistance, are adjusted only at the end of every solution run. However, the coupled field approach can adjust both electrical and thermal properties while the solution is running. Therefore, if the same time step is used, this 3D ANSYS Quench Simulation might not be as accurate as the coupled field approach since any changes to the temperature during a solution run will not be reflected in resistance, current, or heat generation until the run is completed. This disparity can be remedied by reducing the time step in the simulation, but at a cost of time and hard disk space.

B. *Algorithm*

The chart in Fig. 1, illustrates how the program executes after creating the model described earlier. All of the boxes surrounded in thick lines indicate ANSYS processing, while thin lines entail processing through the simulation codes.

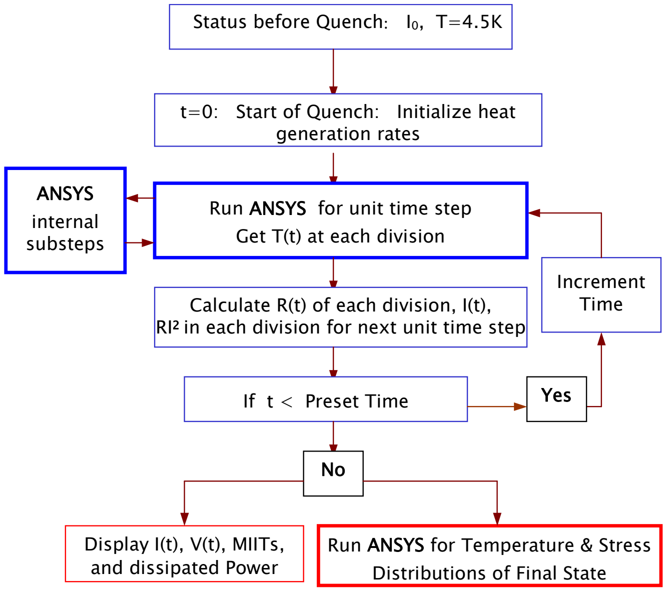

Fig. 1. 3D ANSYS Quench Simulation Process. Only boxes with thick lines use ANSYS processing.

The program begins with basic initializations, such as initializing the current, temperature, and various simulation parameters. Next, it initializes the heat generation rates for all parts of the coil. This step simulates a quench-causing event in the location specified by the parameters, such as a hot spot activation or a slight movement in the cable.

Then the program enters the iterative portion of the simulation. It first uses the ANSYS solution routine to solve for the temperature distribution at the end of one time step. While the evaluation is running, ANSYS will use smaller sub steps during periods of rapid thermal changes to increase the accuracy of the simulation. As mentioned above, these sub steps update the thermal properties of the conductor, such as temperature, thermal conductivity, and heat capacitance, but they do not update the resistance, heat generation, or the current.

After the solution is complete, ANSYS writes the results at the end of the time step to the result file. The script then takes over by retrieving the temperatures and calculating the resistance for each division, finding the new current, and finding and applying the new power output. It also checks to see if the quench protection circuits have detected a quench by seeing if the voltage across the entire magnet has gone over the amount of voltage set with the *detection* parameter. If it has, then it signals the dump resistor and heaters to activate after their delays have passed, specified through the parameters *r_delay* and *heatdelay*. After all this processing is complete, the simulation repeats by restarting the ANSYS solution with newly computed heat generation values. This cycle continues until the program reaches the final iteration specified by the parameter *endingtime*, at which point it is possible to find the temperature distribution, plot current, voltage, or other values as a function of time, or run the stress simulation to get the stress distribution.

The stress simulation is much less complicated. It reads in the temperature values from the last time step recorded in **heatfull3d.rth**, then computes the thermal stresses due to those temperatures. The result file from the temperature solution which contains the desired temperature distribution must be renamed to **heatfull3d.rth** so it can be read in by the stress simulation.

III. Simulation Model

The overall insulation and the naked conductor coil without insulation used in the model are shown in Fig.2. There are three main sections to the model: Lead end section, straight section, non-lead end section.

The lead and non-lead end sections are constructed very similarly using direct volume generation for the conductors, Boolean subtraction for the insulation, map meshing for the conductors, and smartsized free-meshing for the insulation. The straight section is extruded from the non-lead end section, and has a much coarser mesh density to reduce the number of elements. The next sections describe the model origins and construction in more detail.

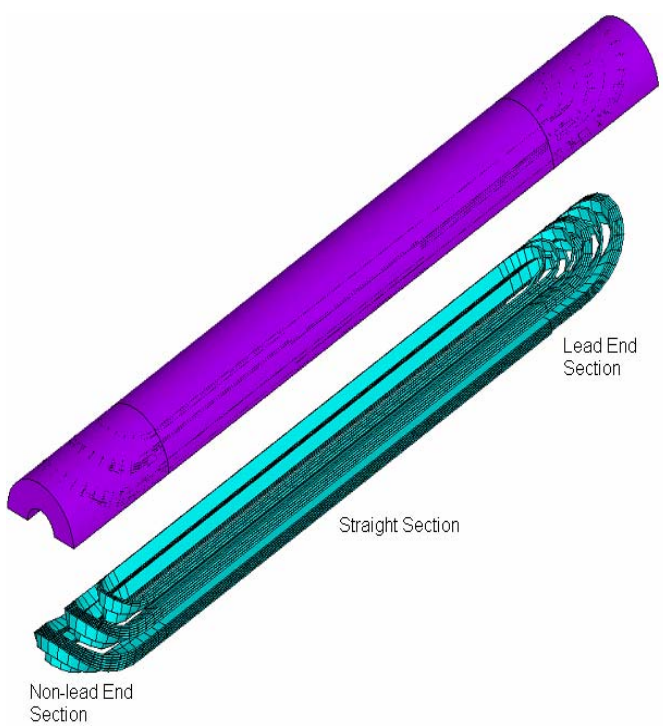

Fig. 2. Picture of the naked conductor cable alone (below) and insulation casing (above), which is applied over the conductor cable.

C. Model origins

The model of the coil came from an assembly drawing of the HFDA-01 magnet that was originally created in I-DEAS [5]. Unfortunately, the size of the cables in the model includes both the conductor and the insulation, but the 3D ANSYS Quench Simulation needs to treat the conductor and insulation separately. Therefore, meshing the model in I-DEAS or directly exporting the model to ANSYS would not work. Instead, an alternate method that relied on keypoints was used to change the model into the form needed for the simulation.

D. Model construction

The model is constructed in nine steps. The first two are saved in **coil.db**:

1. **Import the I-DEAS model into ANSYS through an IGES file.**
2. **Modify the geometry of the IGES model to help construction and meshing.**

The rest of the steps are done by the simulation:

3. **Create keypoints along the corners of the cables in the coil.db model.**
4. **Create the hollow cylinders to be used for the insulation.**
5. **Create the conductors in the end section by modifying the keypoints from step 3.** The insulation width is removed from the keypoints, and new keypoints are created that represent the dimensions of the conductor alone. These new keypoints are then used to create the volumes that represent the conductor, creating the cable as a linked set of hexahedral-shaped volumes.
6. **Extrude the straight conductor sections from the non-lead end of the magnet, and then merge them with the conductors on the lead end of the magnet.**
7. **Subtract the conductors in the magnet ends from the insulation cylinders.** This creates the insulation around the conductors in the end sections of the magnet.
8. **Mesh the coil.** The conductors are all meshed with a swept hexahedral map mesh.
9. **Mesh the insulation.** The non-lead side insulation cylinder is meshed first with a smartsized tetrahedral free mesh. This mesh is then extruded through the straight section of the magnet, creating the insulation in the straight section of the model. Finally, the insulation cylinder in the lead end is meshed with a smartsized tetrahedral free mesh.

At this point, the model is complete and meshed. In total, there are about 250,000 elements and 100,000 nodes using 8-node brick elements.

E. Simplified geometry in model

There are three minor simplified geometries in the present model. The transition between the inner and outer layers is shortened. The leads are shortened. The insulation and spacers in both ends are created from two homogeneous volumes, so the volumes can only be assigned one set of material properties. These simplifications will be improved in the future model.

D. Simulation loads on model

There is one temperature load used for the simulation. A 4.5° K temperature constraint located along the inside of the insulation cylinders is used to simulate the effect of liquid helium in the bore.

There are three symmetry constraints in the stress simulation. One lies along the bottom of the insulation cylinders to simulate the other half coil below the model. The other two lie along the front and back of the insulation cylinders to simulate the pressure from the end plates.

SOLID70 elements are used in the temperature analysis, and SOLID45 elements are used in the stress analysis. For better accuracy, SOLID90 and SOLID95 can be used instead.

E. Divisions in mode

Due to the method used to simulate a quench, the simulation must divide the coil into smaller divisions for data recording and heat generation purposes in the end sections and in the straight section. Each of these divisions has their own values for temperature, resistance, and heat generation, which are updated after each ANSYS solution run.

When some calculations require the length of a division (such as resistance), the length of the division in an end section is defined as the average length of the 4 lines that lie along the length of the conductor. In all cases, the temperature of each division is recorded as the average temperature of all the nodes in that division.

IV. Data Sample

This 3-D quench simulation program was applied to one meter long model magnet. It took 10 days to calculate the thermal distribution from 0 to 100 ms period with a time step of 1 ms.

The data results are shown in Fig. 3, 4 and 5. In this case the quench was started at return end of the innermost turn of

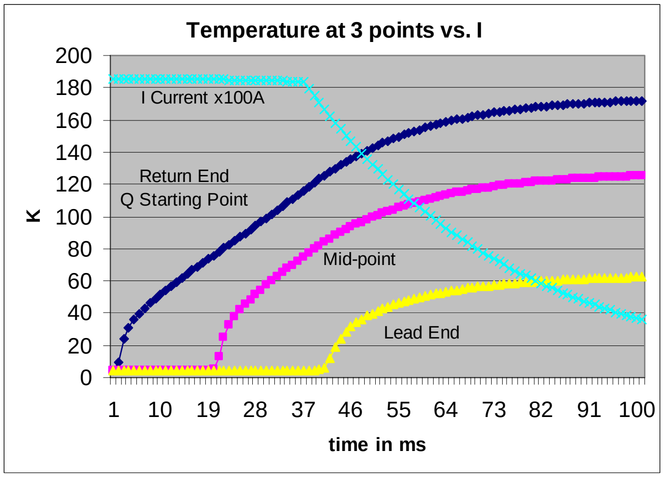

Fig. 3. Temperature distributions at the return end, where the quench is started, at the other lead end, and at the middle point are shown together with the current.

the inner coil with a heat input of 3 mJ. The temperature variations at three points (at the both ends of the inner-most turn and their middle point) are shown in Fig. 3 for the quench starting at time t = 1 and up to 100 ms. From this display we can observe the quench propagation and we can estimate the quench velocity is 17.3 m/sec along the length of the conductor. The magnet current is also shown with 38 ms delayed triggering of a dump resistor.

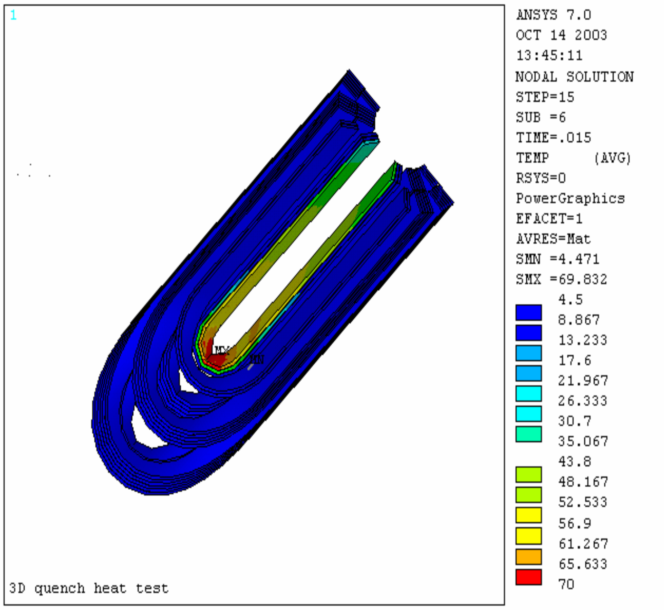

Fig. 4. Temperature distribution in the conductor at t = 15 ms. The quench started at the end of the inner most turn of the inner layer of the coil. At t = 15 ms, its highest temperature is 70 K at the end. The quench has propagated azimuthally, and the next turn is already quenched and it is now at 45 K.

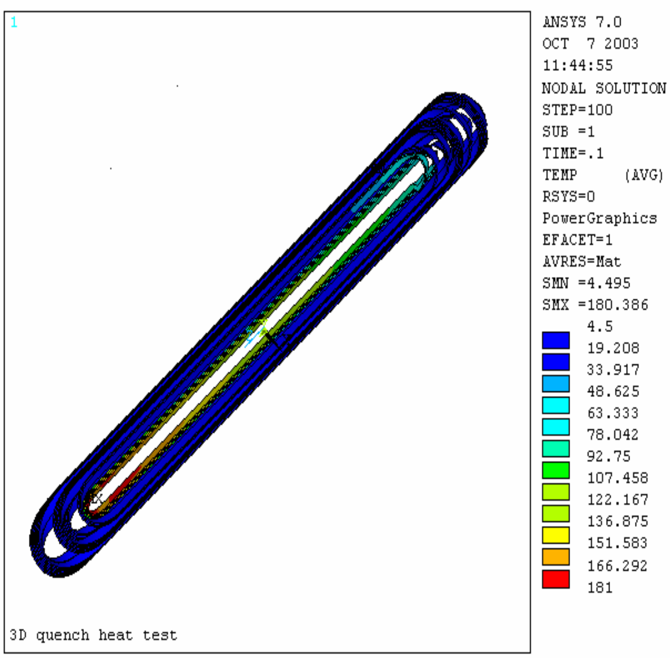

Fig. 5. The temperature distribution at t = 100 ms. The quench started at the return end of the innermost turn of the inner layer (lower left). Its temperature is 181 K. At 100 ms, it is clearly shown that the quench has propagated into the innermost turn of the outer layer at the lead end (upper right).

The temperature variation around the return end, where the quench is started, can be seen vividly with animation. Its data at 15 ms is shown in Fig 4. The temperature of the quench starting point is now at 70 K, and the next turn is at 45 K, clearly indicating the azimuthal quench propagation.

Similarly the quench propagation along the conductor cable can be observed in animation. The temperature variation at 100 ms is shown in Fig. 5 along the length of the coil assembly. At 41ms we can observe the quench is propagating into the other half of the coil, crossing into the other half of the outer layer.

V. Future Improvements

We intend to improve the present model further to include the following capability. Electro-magnetic forces will be incorporated into the stress analysis by adding force components to certain points on the stress model. We will simulate the eddy current and quenchback effect. Separation of the bronze blocks from the insulation material will be incorporated and the stress analysis of the whole magnet geometry will be done. We will also incorporate the detailed structure of the splice region into the model.

VI. Conclusion

We demonstrated a method to import the CAD file successfully into ANSYS and fully do the thermal analysis. We can expand this method with full geometry of the 3 dimensional magnets in the near future. With an animation program we will benefit to investigate the quench mechanism in superconducting magnets in real 3 dimensional ways.

It will be used to compare with the experimental data of short model magnets in near future, and will be used for the prediction of thermal and stress problem with much longer magnets.

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