

ACCURATELY DETERMINING THE PARAMETERS OF A MAGNET COIL BY 3D CAD DESIGN

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Abstract

Traditionally, the average turn length and number of turns of a conventional magnet coil is roughly estimated during the magnet physical design. Based on these estimates, the resistance, water flow and overall dimensions of the coil are calculated. But for a complex coil shape, it is very difficult to determine how many turns a coil will have and, more importantly, specifically how it will be wound. In many cases, an engineer will use a scale model to do a winding trial, but the coil parameters, such as the conductor length and overall coil dimensions, still cannot be precisely determined. 3D CAD modeling was used for the design of the Advanced Light Source (ALS) combined function sextupole magnet coils [1]. The winding procedures for 11 types of coils were all determined by the models. The resistances and water flow requirements of those coils were calculated from the 3D models, and those parameters were used as criteria for production quality control thereafter. This paper will introduce some basic modeling techniques that are useful for 3D CAD modeling of magnet coils. The coil data comparison between 3D model and true built coils will be introduced as well.

BASIC APPROCHES

The sextupole coil of G type combined function magnet (GCFS) is the most complicated coil among 11 types [2]. This paper will use it as an example to introduce the 3D CAD modelling approach. Fig. 1 is a 3D model of the GCFS coil that was created with Solid Edge, and it has 5 layers (inside to outside). The circles in each layer differ from 21 to 2 circles (up-and-down), and those layers and circles make 51 turns total (1turn=360°) of the coil.



Figure 1: 3D model of GCFS coil.

In brief, the model is created by a cross section of GCFS coil conductor sweeping along the coil winding path selected from the “solids” tool menu of “Solid Edge”. To create a correct and continuous path is a key factor. There are five basic approaches to follow:

1. First of all, create a winding mold that has the exact dimensions of the one that will be used for true coil winding and then, copy it as a “construction body” into the “part” file where the coil will be created (refer to Fig. 2).

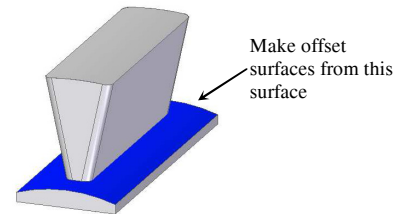


Figure 2: 3D model of coil winding mold.

2. Create circle paths in 1st layer by offsetting dark color surface of winding mold in Fig. 2 (refer to Fig. 3).

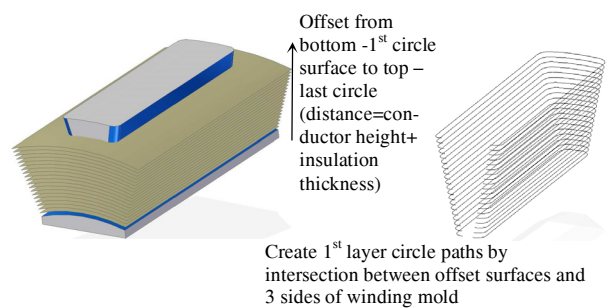


Figure 3: Create 1st layer circle paths.

3. Create next layer circle paths by offsetting sides of winding mold (refer to Fig. 4).

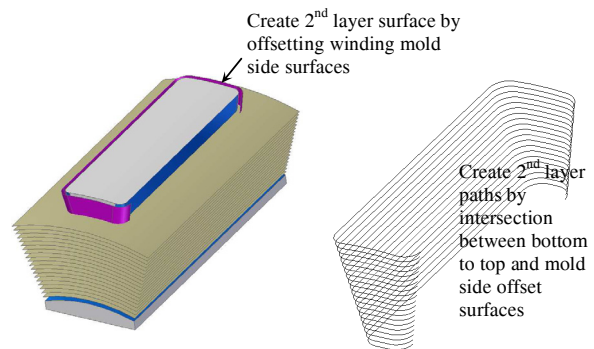


Figure 4: Create next layer circle paths.

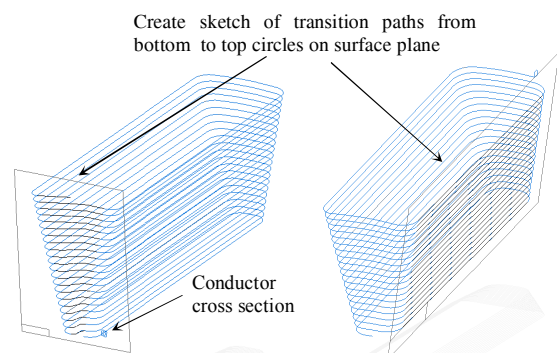


Figure 5: Create transition paths from bottom to top.

4. Create transition paths from lower circle to upper circle (refer to Fig. 5). In the first layer, lower to upper circle transitions happen at the front end of the winding mold; in the 2nd layer, the transitions occur at the right side of the winding mold. These transition paths are not intersection lines between surfaces; they are sketches being drawn on planes. The front end plane can be created parallel to the base reference XZ plane and coincident with the end surface of the winding mold; the side plane can be created to be coincident with the winding mold side surface.

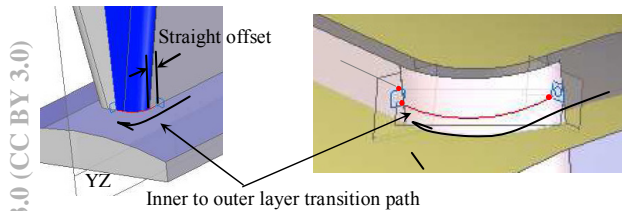


Figure 6: Create transition path from inner to outer.

5. Apart from the up-and-down circle transition, there is also inner to outer layer transition. This type of transition is rather complicated. There are two kinds of layer to layer transitions. The left figure in Fig. 6 shows inner layer changes to outer layer from straight side to curved end; the right figure in Fig. 6 shows inner layer not only changing from curved end to outer layer but also transforming to lower circle at the same time. To do the transition shown in the left figure, first of all, split the end surface of the mold into two sections by base reference YZ plane, then intersect right section of mold end surface (dark blue) with bottom surface to obtain the transition path (red line). Note: the radius of this transition is the same as the inner layer's, but it extends backward with a straight line to a distance equaling to layer-to-layer offset. For the transition in the right figure, create a plane by picking up the end point of the inner curve, the end point of the straight line within the same layer, the end point of the lower circle straight line in outer layer and then draw an arc on this plane that is tangential both with end curve and lower circle straight line in the next layer (red line).

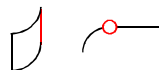


Figure 7: Two type path symbols.

So far, we have two types of paths: one is created by intersection, one is created by sketch. To be able to use these paths as one sweeping path, we have to connect two types of paths into one by using the "Derived" tool under the "Surfacing" – "Curve" menu. In Fig. 7, left symbol presents the "intersection" path and right symbol presents the "sketch". Select all paths in one type and check out, and then select all paths in another type and check out, click "Finish" button afterwards.

CREATE 3D COIL

Now, we are ready to create a 3D model of the coil by sweeping the conductor cross section along the path that

has been created. Note: the 3D model file of this 5 layers, multiple circles in each layer, 51 total turns coil will be very big; sweeping the conductor cross section along the entire path will take a long time for the computer. Any small modification of the model may cause the computer to crash, not mention that the inner layer change to outer layer path that has been created in left side figure of Fig. 6 will not be able to connect to the 1st layer path directly. The best way to finish the model is to separate the coil into a few parts; maybe one part includes one layer only, and circle to circle and layer to layer transition segments are individual parts as well. After all those parts are created, open an "Assembly" file and assemble them into one coil (refer to Fig. 8). Note: there is sketch of the conductor cross section shown in Fig. 5 and 6 at the end(s) of the path. It is a good idea to make each part by sweeping the front cross section to the end cross section along the path; doing this, the connection between two parts in the "assembly" file will have no gap or seam and will make a perfect, seamless coil. In other words, each layer or transition part is created by a single path between two cross sections – one at the beginning and one at the end. Either the cross section at the beginning or at end, or both is(are) created on an angled plane. The angled plane will follow the pitch of the winding mold.

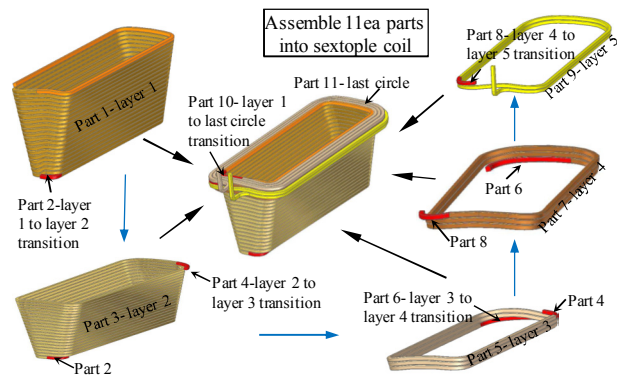


Figure 8: Assemble 11 parts into one coil.

CALCULATION OF COIL PROPERTIES

Conductor Length

In the coil "assembly" file, right click part 1 in the path finder, select "Edit" under "Application button" of this part, and select "Material table" in "Properties". In the "Material table" dialog, select any type of material for this calculation. As long as the material for all parts is identical, it will be correct. Click "Apply to model" and then, "Close and Return" button on the top of the tool bar – return to assembly file. Repeat the same steps for parts 2 to 11. After all parts are assigned to the same material, open "Properties" of "assembly" file that is inside the "Physical Properties" tool bar, click "Update" button, and the volume of assembly-coil will be calculated. Take the value (mm³) shown in the "Volume" divided by the cross section area of the conductor (mm²) (Fig. 9) and conductor length of the coil will be obtained. Ignore the hole, since the water channel was not created during the

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sweeping to reduce the size of file An extra length for two coil leads that is equal to true coil leads shall be added to this calculated length.

Coil Water Flow Quantity

The water hole dimension of the GCFS coil conductor is $\Phi 2.5\text{mm}$ and, now that the conductor length is known, the water flow for the coil can be calculated.

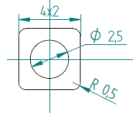


Figure 9: Cross section of GCFS coil conductor.

COMPARISON BETWEEN CALCULATED AND MEASURED COIL VALUES

Conductor Length

The SINAP (Shanghai Institute of Applied Physics) workshop was awarded the ALS sextupole magnet contract. 162 GCFS coils were built. Comparing with the calculated conductor length - 30.32m, the true conductor usage for each coil ranged between -180mm to +160mm as compared to calculated value. The discrepancy of the calculated length and true values is very small – less than 0.6% (refer to Fig. 10).

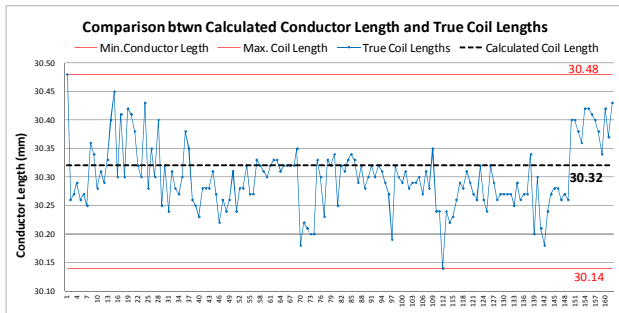


Figure 10: Conductor length comparison.

Coil Water Flow Quantity

The calculated water flow quantity of the GCFS coil is 0.45l/min.; the true coil water flow quantity varies from 0.40l/min. to 0.415l/min. (89% to 92% of calculated value). Considering the coil has been bent more than 200 times at corners during the winding and the water channel was deformed at those curves, we can say that the true water flow quantities of coils agreed with the calculated value very well (refer to Fig. 11).

Coil Resistance

The calculated resistance at 40°C of the GCFS coil is 49.12 $\mu\Omega$. The minimum measured coil resistance after subtracting the bridge resistance is 49.61 $\mu\Omega$ (101% of calculated value), and maximum value is 51.87 $\mu\Omega$ (105.6% of calculated value). Taking into account the dimensional variance of the conductor, and the resistivity varying among different conductor reels, the variation range among all coils' resistances and their difference from the calculated value is reasonably small (Fig. 12).

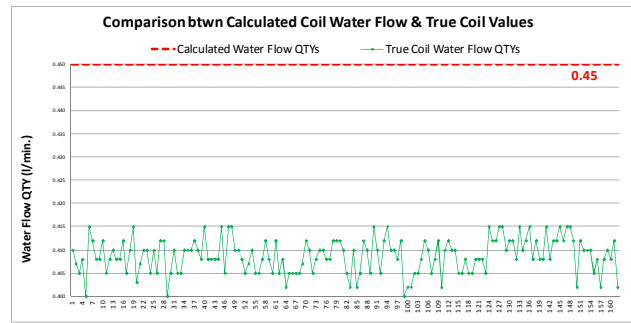


Figure 11: Coil water flow comparison.

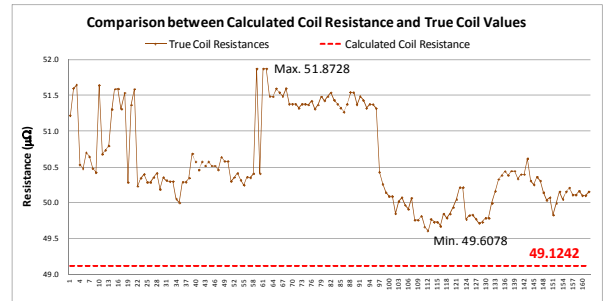


Figure 12: Coil resistance comparison.

DERIVE TO WINDING PROCEDURE

Because of the complicated configuration of the GCFS coil, it is very difficult to explain to technicians how to wind it with specified turns and shape. As a matter of fact, in the very beginning of the fabrication, the GCFS coils were wound different from each other, which resulted unqualified magnetic field after installing 6 coils in a magnet.

This led to the 3D model of the coil being created. The winding sequence and method from layer to layer and at each transition section became visual. Furthermore, the vacant areas at those transitions were located and G10 strips were inserted during the winding. Therefore, a large volume of pure epoxy is avoided during coil potting, which ensures improved quality of coil insulation.

CONCLUSION

A 3D model of a coil is easily created using Solid Edge. The model not only allows the conductor usage of the coil to be calculated precisely, but also, the water flow and resistance of the coil can be calculated with reasonable accuracy, which can be used as criteria to estimate if the coil is wound correctly during production; i.e. no damage at corners and the number of turns is correct. The derived step-by-step winding procedure from the 3D model guarantees the consistency of the coil winding. The 3D model is a key factor of the success of GCFS coil fabrication.

REFERENCES

- [1] A. Madur and N. Li, "Combined Function Magnet Specifications", (2010).
- [2] LBNL Drawing 26H500.