User Defined Elements in ANSYS for 2D Multiphysics Modeling of Bi2212 Magnets

Lucas Brouwer
Lawrence Berkeley National Laboratory

June 27th, 2018

6th International Workshop on Numerical Modeling of HTS
Overview

**Development:** user defined elements in ANSYS keep all meshing, solving, and post-processing capabilities, while adding
1. interfilament coupling current losses
2. quench behavior
3. internal material property fits (T, B, quench state)

**Validation:** comparison to existing COMSOL and LEDET codes (CERN)

**First Application to HTS magnets:**
1. Bi2212 racetrack coils to be tested at LBNL
2. Bi2212 solenoid tested with background field at FSU/MAGLAB
User Defined Elements can Extend the Capability of ANSYS to Include Superconducting Specific Behavior

Keep all features of standard ANSYS…

- modeler, mesher, post-processor
- transient electromagnetic and thermal solvers
- eddy currents in structure
- external circuit coupling
- yoke saturation

... and add what is missing with user elements

- eddy currents in conductor (IFCC, +)
- current sharing + quench propagation
- coupling to thermal model with full (T,B) mat. prop.
User Elements are Implemented by Replacing the Code Which Generates the Finite Element Matrices

Geometry Generation
Meshing
Boundary conditions
Loads

Solution

Post processing
Load transfer between models

Replace code which builds element matrices and compile custom ANSYS.exe

From Default ANSYS
node location
loads
node temp.
material prop.
ANSYS functions

User Programmed Matrix Generation Adds Features
- Equiv. magnetization for IFCC
- Mat. property fits (T, B, Jc, etc.)
- Current sharing + quench

Back to Default ANSYS
matrices: stiffness, damping, load, etc.
Material Property Fits are Internally Programmed for Simulations with NbTi, Nb$_3$Sn, and Bi2212

User chooses materials and fits using element key options and real const.

Example format: NIST rhocu(T, RRR, B)*

Heat capacity, resistivity, thermal conductivity, critical current, etc.
Coupled EM, Circuit, and Thermal Simulations can be Performed using the Multi-Field Solver

Electromagnetic Regions

- FEM
  - default (ex. PLANE53)
    - iron, air, structure areas
    - eddy currents in structure
    - mat. prop. (temp)
  - user defined (USER102)
    - conductor areas
    - conductor loss (IFCC)
    - quench, current sharing loss
    - mat. prop. (B, temp)
- Circuit
  - default (CIRCU124)
    - QPS: dump resistor, CLIQ, etc.

Thermal Regions

- FEM
  - default (ex. PLANE77)
    - iron, structure areas
    - mat. prop. (temp)
  - user defined (USER101)
    - conductor areas
    - quench propagation
    - mat. prop. (B, temp, quench state)

Coupled with stranded formulation

multi-field solver
ANSYS user elements have been verified by CERN/STEAM using IFCC induced quench back simulations for a Nb$_3$Sn dipole.

Crosscheck of the ANSYS-COMSOL 2D FEM implementations for magnetothermal transients in accelerator magnets.

At 5.0 ms dump resistor is put in series: dB/dt -> IFCC -> heats coil to quench.

IFCC + coil resistance growth drives current down faster (quench back).

Agreement requires accuracy across EM, circuit, and thermal coupling.
HTS Subscale Magnet Program at LBNL Motives Study of the Quench Behavior of Bi2212 Racetrack Coils

Upcoming test of two racetracks in a common coil configuration (~5 T dipole)

RC series wound at LBNL and OP reacted at MAGLAB have demonstrated a dramatic increase in Jc for single coils

Test bed for quench behavior studies (Dan Davis – FSU PhD Thesis)

Tengming Shen (LBNL)
ANSYS Predicts Current, Resistance, and Temperature Rise for Bi2212 Racetrack Coils During Extraction

At 5.0 ms a 20 mOhm dump resistor is placed in series with the magnet (extraction at 90% of SS)

**LEDET is a lumped element code from Emmanuele Ravaioli. (CERN), simulations by D. Davis (FSU)**

Two very different codes (ANSYS-FE, LEDET-Lumped Elem.) predict similar behavior
ANSYS is also being used to prepare for upcoming testing of the RC coils with a CLIQ unit.

Capacitor bank (CLIQ) is discharged across coils to induce field oscillation (increases IFCC losses)

with no losses

A Simple Current Sharing Model Dramatically Changes the CLIQ Results for the Common Coil with Losses Included

CLIQ -> dB/dt -> IFCC heating -> quench

Linear current sharing

Fully quenched immediately at Tcs

Upcoming tests at LBNL will probe CLIQ induced quench behavior

\[ 1 - \frac{T_{CB} - T}{T_{CB} - T_{cs}} \]
Test of “PUP4” Bi2212 Solenoid in Background Field at MAGLAB Allows for First Comparison of Modeling with CLIQ Data

ANSYS model with insert, outsert, and their equivalent circuits

**NbTi Outset (7.8 T)**

**Bi Insert (2.2 T)**

Experiment led by Dan Davis (FSU/MAGLAB)

10.0 T Bore

Capacitor bank (CLIQ) is discharged across two sections of the solenoid to induce current oscillation (increases IFCC losses)

This work is funded by the Department of Energy (HEP Award No. 227011-520-032288), the National Institute of Health (Award No. R21GM111302), the National Science Foundation (Award No. DMR-1157490), and by the State of Florida. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists, Office of Science Graduate Student Research (SCGSR) program. The SCGSR program is administered by the Oak Ridge Institute for Science and Education (ORISE) for the DOE. ORISE is managed by ORAU under contract number DE-SC0014664.
Comparison of ANSYS to Data From the PUP4 Tests at 4.5 K

CLIQ at 4.5 K with 7.8 T background field: $C = 4.75$, $V = 100$ V

ANSYS/LEDET show agreement, match to data is promising

Experimental data from D. Davis (FSU)
First Comparisons of ANSYS to 77 K Tests Show Loss Case Better Representing Data

CLIQ at 77 K with no background field: \( C=4.75 \text{ mF}, \, V=50\text{V} \)

ANSYS/LEDET show agreement, loss case better matches data
- there is still much to understand and more data coming from the racetrack tests

Experimental data from D. Davis (FSU)
User Elements in ANSYS can

• simulate IFCC and quench
• include NbTi, Nb$_3$Sn, and Bi2212 in the same simulation
• include full material property fits (T, B, quench state, etc.)

Initial validation studies comparing to existing COMSOL and LEDET codes are complete (with CERN)

First studies are being performed to support Bi2212 and Hybrid tests within the US-Magnet Development Program

• modeling predictions guide upcoming Bi2212 racetrack tests (LBNL)
• comparisons to first Bi2212 CLIQ test data is promising (FSU)
Thanks To

Paul Scherrer Institute
• Bernhard Auchmann, Jiani Gao

Cern
• Edvard Stubberud, Lorenzo Bortot, Bernhard Auchmann

LBNL
• Diego Arbelaez, Daniel Davis (also FSU-Maglab), Emmanuele Ravaioli (also CERN), Tengming Shen, and others

Our goal is develop a tool for the broader community. If you are interested in helping or using the elements please let us know. lnbrouwer@lbl.gov
Extra Slides
Equiv. Magnetization Term is Included in the FEM Formulation to Include IFCC Losses in ANSYS

Equivalent Magnetization for Inter-filament Coupling Current Losses has already been successfully implemented in many codes (ROXIE, LEDET, COMSOL, etc.)

\[ \mu_0 \mu_r \vec{M}_{eddy} = \tau_{eq} \frac{\partial \vec{B}}{\partial t} \]

\[ \nabla \times \left( \mu_0^{-1} \mu_r^{-1} \nabla \times \vec{A} \right) = \vec{J}_{ext} + \nabla \times \vec{M}_{eddy} \]

Tau is dependent on conductor properties: twist pitch, rho_eff(T,B,RRR)
 Implementation is User Friendly

ANSYS scripted input

```
*-------------------EM Elements-------------------*
  et,1,plcon53     l2d EM: Az
  keyopt,1,1,0
  let,2,user102    l2d EM: Az,cur,emf (stranded circ)
  !-------------------EM Elements-------------------*

  et,2,user102
  keyopt,2,1,0     ! AZ
  keyopt,2,2,0     ! no field transfer to therm
  keyopt,2,3,1     ! DEML AS fit
  keyopt,2,5,0     ! table/fixed for lsyx
  keyopt,2,7,0     ! allow c.s. + quench
  keyopt,2,8,0     ! yes IFCC

  fac=1
  facd=1
  RRR=200
  Lp = 1.0
  feff = 1.0

  R,2,0,0,cond,feff,0, ! set real constants
  Rmore,0,RRR,Lp,feff

  cmass,5,cond1
  cmass,a,cond2
```

These lines are the only deviation from a default ANSYS simulation using plane53
- choose USER102 for conductor
- set keyopts (IFCC_flag, mat. prop fit. Etc)
- set real constants (RRR, Lp, ect.)

No modification to re-run existing models, very little new knowledge required beyond default ANSYS