ROXIE - A COMPUTER CODE FOR THE INTEGRATED DESIGN OF ACCELERATOR MAGNETS

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Abstract

The paper describes the ROXIE software program package which has been developed for the design of the superconducting magnets for the LHC at CERN. The software is used as an approach towards the integrated design of superconducting magnets including feature-based coil geometry creation, conceptual design using genetic algorithms, optimization of the coil and iron cross-sections using a reduced vector-potential formulation, 3-D coil end geometry and field optimization using deterministic vector-optimization techniques, tolerance analysis, production of drawings by means of a DXF interface, end-spacer design with interfaces to CAD-CAM for the CNC machining of these pieces, and the tracing of manufacturing errors using field quality measurements.

1   INTRODUCTION

The LHC magnet system consists of 1232 superconducting dipoles and 386 main quadrupoles together with about 20 different types of magnets for insertions and correction. The design and optimization of these magnets is dominated by the requirement of a extremely uniform field which is mainly defined by the layout of the superconducting coils. Even very small geometrical effects such as the insufficient keystoning of the cable (cable inner and outer diameter not following curvatures of circles), the insulation, grading of the current density in the cable due to different cable compaction and coil deformations due to collaring, cool down and electromagnet forces have to be considered for the field calculation. In particular for the 3-D case, commercial software has proved to be hardly appropriate for this task. Therefore the ROXIE (**R**outine for the **O**ptimization of magnet **X**-sections, **I**nverse field calculation and coil **E**nd design) program package was developed at CERN for the design and optimization of the LHC superconducting magnets. It is now also more and more applied in institutes outside CERN. The development of the program was driven by three main objectives:

• To write an easy-to-use program for the design of superconducting coils in two and three dimensions considering field quality, quench margin and persistent current multipoles.

• To include the program into a mathematical optimization environment for field optimization and inverse problem solving.

• To include appropriate methods for the calculation of the iron magnetization without meshing of the coil and

• to develop an integrated design tool with sophisticated graphic routines and interfaces to CAD-CAM systems for the making of drawings and manufacture of coil end-spacers.

2   COIL MODELLER

As will be explained below, the use of a reduced vector potential formulation in FEM does not require the meshing of the coil for the numerical field calculation of iron saturation effects. Therefore the coil modelling and yoke modelling parts are completely separated.

Coil cross sections and ends of accelerator magnets made of Rutherford type superconducting cables are generated from only a few meaningful engineering data such as the number of conductors per block, conductor type, radius of the winding mandrel and the positioning and inclination angles of the blocks. Two assumptions for the coil block positions can be made:

• Alignment of the conductors on the inner diameter, i.e., the shape of the coil being determined by the winding mandrel and the curing mold.

• Alignment on the outer diameter, i.e., the shape is determined by the coil outer resp. the collar inner diameter.

An objective for the coil design is thus to minimize the effect of this alignment uncertainty by finding a design with sufficiently radially placed conductors. The input parameters for the coil-end modelling are the z position of the first conductor of each coil block, its inclination angle in the yz plane, the straight section and the size of inter turn wedges between the conductors. Four options are available:

• Constant perimeter coil-ends with inter turn wedges and conductors placed on the winding mandrel.

• Grouped conductors aligned at the outer radius, featuring endspacers with shelfs.

• Coil-ends for magnets with rectangular cross sections.

• Racetrack coil ends with or without additional straight section suited for the modelling of solenoids, wigglers and torus magnets. The geometric positions of conductors can be printed in different formats suitable for other numerical field calculation packages such as ANSYS and POISSON and in a DXF format. The form of the end spacers can then be generated automatically and the polygons describing the surfaces can be transferred into CAD-CAM systems for the machining of these pieces using 5 axis milling machines.

All the input data necessary for the coil modelling can be defined as design variables and are automatically updated

during the optimization process.

3 YOKE MODELLER

The yoke modeller allows the definition of symbols which can then be used for the definition of key-points in the finite-element domain. Yoke modeller, mesh generator and the finite element software is coupled through file transfer to keep the size of the executable within 250 MB. If optimization algorithms are used, a transfer file contains the updated values of key-point data. As the finite element package requires the meshing of the yoke with higher order quadrilateral elements, the yoke has to be subdivided into quadrilateral facets. These facets can contain holes, slots, or keys which are predefined using the macro language m4.

4 NUMERICAL FIELD CALCULATION

Most commercial 2d field computation software applies a total $\vec{A}$-formulation, where the current density $\vec{J}$ appears on the right hand side of the differential equation. The consequence of this is that using the finite element method for the solution of this problem the relatively complicated shape of the coils has to be modelled in the FE-mesh. Therefore a method is applied, which has been implemented in a collaboration with the University of Graz, Austria [4]. The the vector potential $\vec{A}$ is split into two parts $\vec{A} = \vec{A}_s + \vec{A}_r$ where $\vec{A}_r$ is the reduced vector potential due to the magnetisation and $\vec{A}_s$ is the impressed vector potential due to the source currents in free space, then the relationship between the impressed vector potential $\vec{A}_s$ and the field vector $\vec{H}_s$ respectively the current density $\vec{J}_s$ is given by

$$\bigtriangledown \times \vec{A}_s = \mu_0 \vec{H}_s = \frac{\mu_0}{4\pi} \int_\Omega \vec{J}_s \times \bigtriangledown(\frac{1}{R}) \, d\Omega \qquad (1)$$

where $R = \mid r_q - r_a \mid$ is the distance from the source point r_q to the field point r_a. The field equations in terms of a reduced vector potential $\vec{A}_r$ then differ for the iron region Ω_i and the air region Ω_a where the sources (coils) are located. The $\vec{A}_r$-formulation reads:

$$\bigtriangledown \times \nu \bigtriangledown \times \vec{A}_{r_i} - \bigtriangledown \nu \bigtriangledown \cdot \vec{A}_{r_i} = - \bigtriangledown \times \nu \bigtriangledown \times \vec{A}_s \quad \Omega_i (2)$$
$$\bigtriangledown \times \nu_0 \bigtriangledown \times \vec{A}_{r_a} - \bigtriangledown \nu_0 \bigtriangledown \cdot \vec{A}_{r_a} = 0 \quad \Omega_a (3)$$

together with additional continuity conditions between iron and air which are described in detail in [4]. Applying Ritz's procedure results in a volume integral in the iron region Ω_i and a surface integral on the boundary between iron and air. There the curl of $\vec{A}_s$ does not need to be computed as $\vec{H}_s$ is given by Biot-Savart's law and can be included directly in the right hand side.

The source field is calculated by approximating the conductors by line currents carrying the same current located at the strand position inside the conductor. The grading of the current due to keystoning of the cable is therefore considered. For the peak field calculation the influence of the self field of each strand is neglected. As the critical current density has been measured for a strand without compensation for the self field the correct load line characteristic curves are obtained when the self field is neglected in the calculations. The self inductance of the coil is investigated by calculating the vector-potential in the coil and the flux linkage is then evaluated by means of Stokes theorem. During ramp of the superconducting LHC magnets, so called persistent currents are induced in the filaments. The influence of these currents on the field quality can be evaluated.

For the 3-D field calculation each conductor is sliced up into "bricks" containing line currents the same way as in the 2 dimensional case. The field is calculated in the local coordinate system of each brick thus allowing to calculate forces acting parallel or perpendicular to the broad face of the conductor.

5 MATHEMATICAL OPTIMIZATION

From the beginning, the program has been structured to allow for the application of mathematical optimization techniques. For nonlinear optimization problem there does not exist a single universal method such as the simplex method is used for solving linear problems. Therefore, numerous methods are available for decision making and treatment of nonlinear constraints. These can be combined with optimization algorithms where both search routines (not using the derivative of the objective function) and higher order methods are available. All the evaluated field quantities can be addressed as objectives for the optimization. Decision making methods include objective weighting, distance function, constraint formulation and automatic set-up of payoff tables. Nonlinear constraints can be treated either by a feasible domain method, the penalty transformation or the Augmented-Lagrangian function. The following optimization algorithms are available:

• EXTREM (search routine, suited for most of the problems including objective weighting functions and penalty functions.

• Levenberg-Marquard (first order method, specially suited for inverse field computations i.e. the minimization of a least squares objective function) [3]

• Davidon-Fletcher-Powell (Quasi-Newton method specially suited for Lagrange-Multiplier estimation)The sensitivity analysis with Lagrange multiplier estimation allows to find the hidden resources of a particular design, as the Lagrange multipliers are a measure for the price which has to be paid when a particular objective is to be improved.

• Genetic algorithms which are applied for the conceptual design of magnets [5].

6 INTEGRATED DESIGN

The modelling capabilities of the program together with its interfaces to CAD and CAM and the mathematical optimization routines have inversed the classical design process where numerical field calculation is performed for only a limited number of numerical models (more or less) resem-

bling the engineering design. ROXIE is now more and more used as an approach towards an integrated design of superconducting magnets [2] starting as early as the conceptual phase using genetic algorithms [5]. The interfaces then allow the making of drawings according to the computer models in considerable less time than before. The steps of the integrated design process are as follows.

• Feature-based geometry modelling of the coil and yoke, both in two and three dimensions using only a number of meaningful input data to be supplied by the design engineer.

• Conceptual design using genetic algorithms [5] which allow the treatment of combined discrete and continuous problems (i.e. the change of the number of conductors per block) and the solving of material distribution problems. The applied niching method supplies the designer with a number of local optima which can then be studied in detail.

• Calculation of field errors caused by persistent currents.

• Optimization of the coil cross-section with part compensation of the persistent currents. At this stage the deterministic search algorithms [3] are used.

• Minimization of iron-induced multipoles using a Finite-Element method with a reduced vector-potential ansatz [4].

• 3-D coil end geometry and field optimization including the construction and optimization of the asymmetric connection side [8].

• Tolerance analysis calculating Jacobian-Matrixes and estimation of the standard deviation of the multipole field errors.

• Production of drawings by means of a DXF interface both for the cross-sections and the 3-D end regions.

• End-spacer design and manufacture using interfaces to CAD-CAM and 5 axis milling machines [9].

• Tracing of manufacturing errors from measured field imperfections, i.e. the minimization of a least squares error function using Levenberg-Marquard algorithm [7].

7 REFERENCES

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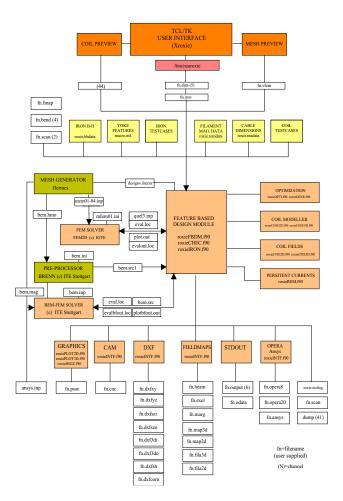
Figure 1: Structure of the ROXIE program featuring a TCL/TK user interface (top), and various interfaces to CAD-CAM (bottom). The interfacing to the finite-element packages is done by means of file transfer.

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