Using CAE to Design Magnetic Shielding Solutions

INTRODUCTION

Electromagnetic designs are found in a wide variety of industrial and R&D applications: cables, magnetic shielding, transmission lines, high voltage systems, and other EM systems. Engineers need to understand the electromagnetic behaviors (e.g. fields, forces, eddy currents, etc.) of these designs so that costs and performance can be effectively managed. In the past, engineers were limited to costly prototyping or restrictive analytic models. Today, engineers use electromagnetic computer-aided engineering (EM-CAE) software tools that provide cost effective design solutions.

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CAE - BOUNDARY ELEMENT TECHNOLOGY

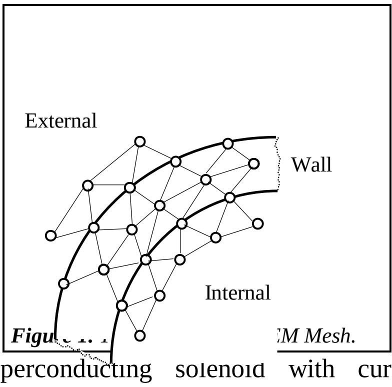
Two distinct numerical approaches exist for EM-CAE software tools: the finite element method (FEM) and the boundary element method (BEM). While the FEM approach, based on a differential formulation, is more familiar to engineers, the BEM approach offers some unique advantages. BEM is based on solving Maxwell's equation in the integral form. The BEM approach requires only the design's surface to be modeled with boundary elements in contrast to the FEM approach which requires the design's entire domain, including free space, to be modeled with a finite element mesh. This means the BEM model is an order of magnitude less complex then the FEM model[1]. BEM allows for easy visualization of the element distribution, especially for three-dimensional designs where FEM meshes are all but impossible to represent and comprehend.

> *BEM can provide designers with an alternative numerical approach to magnetic shield design.*

To even model the behavior of an two-dimensional electromagnetic design, FEM techniques require meshing of the design's structural walls, and the design's internal and external regions (Figure 1). Also, a FEM mesh must be created inside the design's structural walls. For BEM, the boundary elements are distributed only on the design's walls (Figure 2). BEM solutions are easier to use and consume smaller amounts of computer storage and analysis time than FEM solutions.

MAGNETIC SHIELDING BACKGROUND

One suitable application for the BEM approach is magnetic shielding in nuclear magnetic resonance (NMR) systems. NMR imaging is a vital part of the radiologist's suite of imaging techniques and it requires a very homogeneous magnetic field. Traditionally, a large superconducting solenoid with current density in its coils on the order of 15,000 to 20,000 A/cm^2 is used to create the magnetic field. Given a current density J on three defined coil pairs in space, the radial and axial extent of the 5-gauss (G) line can be determined via analytical or numerical means.



Figu *EM Mesh.*

Design issues arise because the 5-G line's spatial extent from a 1-m warm bore superconducting magnet affects other critical hospital space. Magnetic shielding is used to reduce the fringe field of a 15,000-G magnet to that of a 3,000-G magnet, thus making adjoining hospital rooms more useful for other radiological procedures. Three design parameters must be considered when designing the shielding:

- 5-G radial and axial extent
- magnet's homogeneity
- shield's size and weight

The shielding's interior size is fixed by the magnet's outer vacuum vessel and by the need to center the magnet coils inside the shielding. Coil centering is required to avoid differential forces between the coils and the shield's interior, which can easily destroy a $400,000 magnet. The ability to simulate the different coil positions within the ferromagnetic structure and calculate the forces is therefore important.

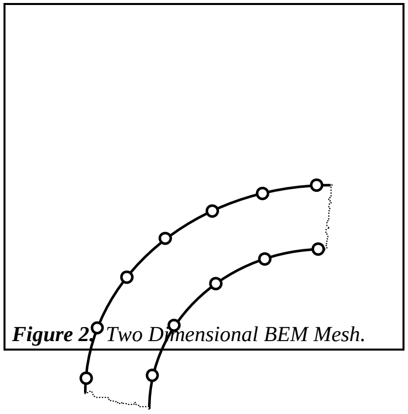
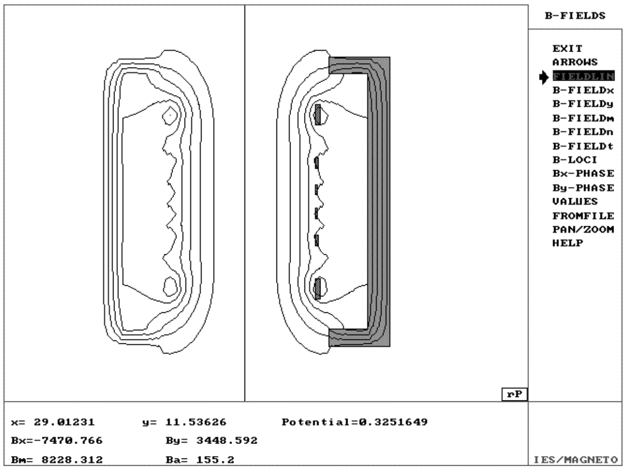


Figure 2. *Two Dimensional BEM Mesh.*



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x= 29.01231      y= 11.53626      Potential=0.3251649
Bx=-7470.766        By= 3448.592
Bm= 8228.312        Ba= 155.2
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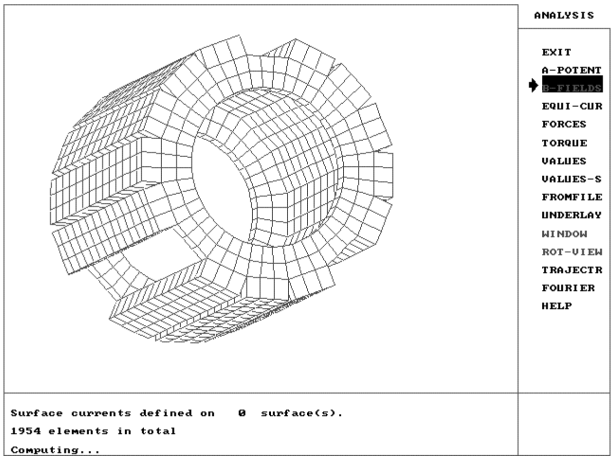
Figure 3. Magnetic shielding: Magnetic fields from 2D axisymmetric model.



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Surface currents defined on   0  surface(s).
1954 elements in total
Computing...
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Figure 4. Magnetic shielding: 3D model with boundary elements.

	15,000 G No Shield	15,000 G With Shield	2,500 G No Shield
5-G Axial	1205 cm	696 cm	670 cm
5-G Radial	947 cm	471 cm	515 cm

Table 1. *Final Cylindrical Configuration.*

With FEM analysis the task is extremely difficult because of remeshing required during iterative modeling of the system's complex three-dimensional, asymmetric structure. In BEM no remeshing is required as only the interfaces between permeable materials are meshed. The objects in BEM analysis are easily modified in an arbitrary magnetic field. This simplifies simulating the relationship between the sources (coils, permanent magnets, earth's magnetic field, etc.) and the permeable materials such as non-linear iron.

MAGNETIC SHIELDING SIMULATION

Starting with a known magnet coil arrangement, the coils and the outside of the magnet were modeled to determine the 5-G line's radial and axial extent and the base magnet homogeneity. At this stage, a simplified perfect cylinder two-dimensional axisymmetric model was used[2] (Figure 3). The shielding ratios were estimated by comparing the simulated results to the design requirements. Magnetic shielding shunts the field between the magnet's poles. It does not shield, in the conventional sense, as lead does with ionizing radiation via an absorption mechanism. Generally, NMR systems require a magnet to be homogeneous to within +/- 5 ppm over a 50-cm. diameter spherical volume.

The strength limits of the shim set used to adjust the magnet were determined and used as the acceptance criteria of the analysis. Five parameters were changed during simulation:

- shell wall thickness
- inside diameter of the shell
- length of the shell
- end cap wall thickness
- inside diameter of the end cap

The spherical and tesseral harmonics of the shield were calculated analytically from simulated data for the various sizes and compared to the shimming strength of the magnet shim set (active and passive), while still satisfying the 5-G line design requirements. As a result, the second and fourth order harmonics were the dominant ones of the shield, with the second being the most variable. It was strongly controlled by the interior diameter of the end cap, which also controlled the axial extent of the 5-G line. A shield size was selected and at this point the simplified perfect cylinder two-dimensional axisymmetric model of the shield was converted to the complete non-perfect cylinder three-dimensional model [3] (Figure 4).

Holes for the magnet legs, cryogen fill ports, quench burst port, and supports were placed in the three dimensional model, and analysis run in both a centered and non-centered coil conditions. The results were acceptable and a prototype was constructed. The magnet came up to field, shimmed, and met specification on the first try. Simulated results matched design requirements, and the design was released to production. The shield's final cylindrical configuration is given in Table 1.

Similar techniques have been used to design close fitting shields for 12T and 14T (120,000-G and 140,000-G) ion cyclotron magnets.

If the magnetic shielding had been designed using FEM, each iteration would have require tedious FEM remeshing because of test changes to shield components. BEM-based electromagnetic software tools offer engineers a proven and effective method for reducing design costs and optimizing designs of magnetic shielding systems because no remeshing is required when adjusting shield components.

SUMMARY

The introduction of new technology like the boundary element method (BEM) is meant to simplify and enhance engineering work environments. The magnetic shielding application confirms that the BEM approach can provide designers with an alternative numerical approach to magnetic shield designing. Such CAE tools enhance engineering productivity and increase competitive advantages.

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CONTRIBUTORS

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