

AN ASSESSMENT OF VARIOUS MAGNETIC SIMULATION TOOLS

INTRODUCTION

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Introduction

Not numbered among our objectives is any plan to make dogmatic prescriptions for successful computer modeling. What we seek to achieve in this short paper is the sharing of our modeling experience in a development laboratory whose principal mission is design and manufacture of magnetic devices. But the setting in which magnetic design and development is done varies widely. Such variation must be accounted for when assessing computer modeling tool. Moreover, human factors enter each situation and sometimes control whether modeling can be truly effective. Some engineers entertain unrealistic expectations from simulation; others believe only in measurements. The authors choose not to address this imponderable human equation except to plead the case for proper balance between calculation and validation, between simulation and experiment. Also, choice of computing equipment may well be beyond the modeler's control. If only personal computers are available, then choice of developed or purchased simulation software is accordingly limited. The authors have enjoyed the power of a workstation, which includes considerable stand-alone computing power, high resolution graphics and high speed connection to a large mainframe. Cost considerations permitting, a computer workstation is highly recommended for magnetic calculations.

In our view, the best of situations is when each development engineer personally uses modeling tools on computer systems available in his working environment. But it can be argued that (1) not every competent designer is comfortable interacting with computer terminals, and (2) not every modeling program is all that friendly to use, even by an experienced simulation expert. Hence, a sound balance between do-it-yourself modeling and collaboration with simulation experts

seems most likely to enhance computer magnetic modeling for product development.

Over time we have grown a magnetic modeling "center of competence." Under its umbrella are maintained an ensemble of simulation programs for use throughout the development laboratory. They range in complexity from simple "early tools" running mainly on PC's to full three dimensional finite element codes that often require a large host machine. Some are "home grown" and distributed internally; others are purchased commercial packages. The expectation is that each engineer will do as much of his own computer modeling as possible. Simulation experts remain available to consult and (when appropriate) to collaborate on a large simulation projects. In this setting, then, we describe computer simulation methods (programs) that we routinely employ for magnetic device modeling.

The Problem to Solve

We restrict our discussion to calculation of static fields and forces. Clearly time varying phenomena are crucial to device modeling and must, in a general sense, be properly addressed. In simplest terms, we seek approximate solutions for the following subset of the celebrated equations of James Clerk Maxwell:

$$\nabla \times \hat{H} = \hat{J} \quad (1a)$$

$$\nabla \cdot \hat{B} = 0 \quad (1b)$$

$$\hat{B} = \mu(H)\hat{H} \quad (2)$$

where \hat{H} is magnetizing field vector, \hat{J} a current density vector and \hat{B} a flux density vector. μ is permeability of the medium in which field values are to be calculated. H is the magnitude of \hat{H} .

Flux Circuit Models

Equation 1 a may be integrated over some properly smooth open surface S :

$$\int_S \nabla \times \hat{H} \cdot d\hat{S} = \int_S \hat{J} \cdot d\hat{S} \quad (3)$$

Note that the right hand integral of current density over S results in a total current I enclosed by a boundary curve Γ of S . Stokes' theorem can transform the left hand integral of 3, provided that \hat{H} has continuous first derivatives and Γ enjoys a smoothly turning tangent:

$$\int_S \nabla \times \hat{H} \cdot d\hat{S} = \int_{\Gamma} \hat{H} \cdot d\hat{\Gamma} \quad (4)$$

$$\int_{\Gamma} \hat{H} \cdot d\hat{\Gamma} = I \quad (5)$$

Equation 5 is simply Ampere's Law asserting that a line integral H-field around any closed contour equals the current enclosed. If a given magnetic situation confines most of its magnetic flux to highly permeable material and specified air gaps, then 5 provides a sound basis for estimating magnetic parameters. Pursuant to that, consider rewriting 5 in terms \hat{B} instead of \hat{H} , using 2:

$$\int_{\Gamma} \frac{\hat{B} \cdot d\hat{\Gamma}}{\mu\mu_0} = I$$

in which μ is taken to mean relative permeability and μ_0 is the permeability of free space. Dividing a configuration iron and air into pieces, each with prescribed length and cross sectional area, provides a basis for representing the integral above as an approximating sum. Such a sum is,

$$\sum_{i=1}^n \frac{\Phi_i L_i}{\mu\mu_0 A_i} = I \quad (6)$$

In which Φ_i is magnetic flux (product of B and area), L_i is length and A_i is cross sectional area of the i th piece. For n pieces, an analyst must prescribe n independent loops in order to imply n linearly independent equations which may be solved for the Φ . Observe that, if 2 applies as written, the equations are non-linear; matrix coefficients (the branch reluctances) will depend on B-H properties of material composing the branches. Right hand sides will be applied mmf (eg. In amperes), either from current in windings or from magnets in the loops. Magnets, of course, may introduce additional non-linearity into the situation.

It has long been practice to obtain estimates for magnetics problems by using a "lumped parameter" approach as described above. Working by hand an analyst views the topology of his magnetic circuit and "writes down" branch equations from loops he traces out by eye. In so doing, he can see how many unknowns are required, namely, as many unknowns as there are independent loops. Often, by visual inspection, problems may be greatly simplified and the number of unknowns and equations reduced (sometimes dramatically) by recognizing particular features of the given situation.

We chose to implement this flux-circuit model as general purpose computer programs. It is difficult to match the ability of a human being to recognize independent loops in a circuit. Hence, instead of solving branch equations it proves convenient to solve nodal equations. Viewed in terms of its nodes, any magnetic circuit provides just one equation and one unknown for each node. For every node except one, such an equation (for the j th node) is of the form,

$$\sum_{i=1}^k P_{ij} (u_j - u_i) = \Phi_{aj} \quad (7)$$

in which P_{ij} is permeance of that branch joining i th and j th nodes, and u represents node potential

(mmf). ϕ_{aj} represents prescribed flux from branches with windings or magnet branches connected to node j. Equation 7, which denotes k branches connected to node j, is purely formal and does not reflect a finished situation in which all nodes and branches have been properly numbered and corresponding coefficient matrix defined.

We have described the flux circuit model in some detail because we find it to be a powerful tool when available as easy-to-use computer programs. Flux circuit modelling by a skilled designer can be astoundingly effective (Ref. 7) Magnetic simulation software based on the flux circuit model embodies concepts familiar to magnetics designers, is cost effective to prepare and apply and well serves as convenient checkpoints for results from other more complex modelling techniques.

We developed three flux circuit programs, namely Maxboe, Maxnet and Maxslv. Maxboe is a full screen interactive magnetics formula evaluator and units tracker. Maxnet provides a full screen interactive vehicle for defining flux circuit models and Maxslv calculates linear/nonlinear solutions of generated networks. Personal computer solution times for flux circuit networks rarely exceed a few seconds to several minutes. It becomes possible, therefore, to try many configurations and materials for early design steps or make quick independent checks of data from other solution methods.

Finite element Models

To fulfill objectives of this paper we sketch just one possible derivation of a finite element method as applied to magnetostatic simulation. Under assumption that sources of \hat{H} are localized (eg. In current carrying conductors) a total \hat{H} can be expressed as the sum of that due to sources and that due to stray field from magnetized material:

$$\hat{H} = \hat{H}_a + \hat{H}_m$$

The \hat{H}_m field has zero divergence and curl, that is,

$$\nabla \cdot \hat{H}_m = 0$$

$$\nabla \times \hat{H}_m = 0$$

Which implies existence of a magnetic scalar potential function U satisfying,

$$-\nabla \cdot (\mu \nabla U) + \nabla \cdot (\mu \hat{H}_a) = 0 \quad (8)$$

from which \hat{H}_m may be calculated as a gradient:

$$\hat{H}_m = -\nabla U$$

Solving equation 8 by a finite element method requires subdividing (meshing) a prescribed "solution space" into contiguous subregions over each of which the unknown potential function may be adequately represented by simple algebraic functions, say polynomials of degree one or two. Not only that, but other sometimes tedious and vexing details must be attended to, such as prescribing proper conditions on boundaries of the solution space. Two dimensional meshing may at least be semi-automatic. Three dimensional meshing is harder. All these matters of data preparation are done in preprocessing step, like preparing the flux circuit network noted above. After an associated FEM solver has calculated potential values (U) at the meshed nodes, a postprocessing step is typically employed to calculate field or other parameters of interest to the modeller. On balance, it should be plainly stated that in spite of substantial progress toward making FEM magnetic modelling software easier to use, such programs still require a fair amount of understanding, patience and skill to employ. Even such things as whether nonlinear iterations are converging, whether Newton steps or simple update iterations are going to work best in a given situation become a concern of the FEM user. That is the bad news. The good news is that (where appropriate) full nonlinear three dimensional FEM analyses can provide excellent estimates of gap flux, B-H situation in iron parts, operating points of magnets, and the like. In contradiction to the flux circuit model, FEM can also provide good estimates

of stray fields in air surrounding magnetic material, which may be crucial in compact design situations.

Boundary Element Models

The general magnetostatic problem may also be formulated as a Fredholm integral equation of the second kind:

$$(\mu + 1)U(s) = \frac{(\mu - 1)}{\pi} \int_S K(s,t)U(t)dt + 2U_a(s) \quad (9)$$

where $U(s)$ is a magnetic scalar potential, S is a boundary of magnetic material whose relative permeability is μ and $K(s,t)$ is a prescribed function whose form depends on details of formulation and on whether there are two or three space dimensions. U_a is an applied potential from currents in conductors or from permanent magnets in the neighborhood of magnetic material. Solving equation 9 gives distribution of potential on material surface. Companion formulas define the potential everywhere else, so that distribution of field may be calculated.

Typically, using BEM software is easier than FEM software. First, the dimension of the original problem is reduced by one. This means that for a magnetostatic situation in two dimensions, the modeller must only “mesh” simple closed curve bounding regions of iron. In three dimensions only two dimensional surfaces of material must be meshed. Recall that in FEM meshing all of solution space is required. For BEM only iron surfaces need to be meshed. One price of this simplification is that permeability of the iron remains constant in the interior. Some BEM implementations provide optional interior meshing to permit estimating volume divergence of field. Second, general boundary conditions for solution space need not be prescribed as these are accounted for in the solution formulation. In all, problem preparation, such as meshing and other attendant details, are not as demanding for BEM as for FEM magnetic software.

Making Sure Answers are Right

In the world of American jurisprudence an accused is innocent until proven guilty; in magnetic

simulation an answer is wrong until proven correct. In our experience all effort expended to establish correctness is well spent indeed. We see three ways to establish correctness, namely (1) compare with measurement, (2) calculate results in more than one way and (3) assure that answers are self-consistent. Experience keeps a dear school: we have learned not to believe automatically that measurements are correct. Rather, we try to balance measurement and calculation in an even-handed manner.

By way of illustration we include Figure 1. It shows comparisons of calculation and measurement for a simple current energized iron yoke with narrow air gap.¹ Gap field was calculated by flux circuit, BEM and FEM models and compared with measurement. Since flux is confined to iron and narrow gap, the flux circuit model provides a salutary result. But the other models can also show how field varies in gap and iron and provide estimates of stray field in the neighborhood of the device. For the particular case reported in the table, we must ponder, however briefly, why the flux circuit estimate is actually closer to measurement than either of the others.

Flux Circuit	2D BEM	3D FEM	Measured Value
.495 T	.486 T	.465 T	.510 T

Figure 1. Gap Field Comparisons in Test Yoke

Purchasing Simulation Software

During the past decade or so the number of commercially available magnetic simulation software products has increased dramatically. It is impossible to decide from an advertising brochure whether a particular offering can do the work the modeller intends for it.

Here are some practical considerations for making a selection:

1. All magnetic simulation software is not created equal. Beyond the broad distinctions in formulation sketched above there are further differences in capabilities, graphics,

documentation, support and cost. Even methods of charging for use and copy-protecting the software can range from easy to accept to one onerously inconvenient. These often vexing matters of detail should be well in hand before making a decision to buy.

2. By all means, arrange for more than a simple demonstration. Money spent for a one to three month trial lease is well spent. Of particular importance, especially for three dimensional modelling, are pre-processing (data preparation) and post processing (results presentation) facilities. Only by running case after carefully selected case can the prospective buyer tell whether software designers realistically perceived how happily a human being would fare while using their creation.
3. Assure that the vendor will provide accessible, friendly and competent consultation service with the product.

Epilogue

Finally, we include the following table of magnetic simulation software we currently employ. For the future we anticipate additional entries in such a table to meet the ever growing and changing simulation requirements of our laboratory.

<i>Program</i>	<i>Description and Status</i>
Flux	Solver Flux circuit solver as described above. Distributed for personal use on PC's around the development laboratory.
2D-BEM (1)	Two dimensional boundary element magnetic solver. Heavily used over several years through terminals attached to large host machines.
2D-BEM (2)	Two dimensional linear/nonlinear magnetic solver for PC.
3D-FEM	Full nonlinear three dimensional magnetic/electrostatic solver with high

resolution pre- and post-processing graphics.

3D-BEM	Three dimensional (linear) boundary element program for use on workstation/host with companion pre- and post-processor.
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