PC-Based BEM Software

ABSTRACT

The analysis of electric and magnetic field distributions is imperative for efficient design of increasingly complex electromagnetic devices. In the past, finite difference and finite elements were used for electromagnetic simulation on mainframe and mini computers. The introduction of the boundary element method (BEM) in an easy-to-use field analysis package circumvents the drawbacks of older methods and enables engineers to accurately analyze fields on microcomputers. This paper presents an overview of BEM and its implementation on the PC. The efficacy of BEM is discussed and a design example is presented.

"Page Down" or use scroll bars to read the article

Presented at the 19th Annual Symposium
on Incremental Motion Systems and Devices,
June 12-15, 1990, San Jose, California

PC-BASED BEM SOFTWARE

Y. Bulent Yildir

Integrated Engineering Software Inc.
347-435 Ellice Avenue, Winnipeg, Manitoba, Canada R3B 1Y6

The analysis of electric and magnetic field distributions is imperative for efficient design of increasingly complex electromagnetic devices. In the past, finite difference and finite elements were used for electromagnetic simulation on mainframe and mini computers. The introduction of the boundary element method (BEM) in an easy-to-use field analysis package circumvents the drawbacks of older methods and enables engineers to accurately analyze fields on microcomputers. This paper presents an overview of BEM and its implementation on the PC. The efficacy of BEM is discussed and a design example is presented.

INTRODUCTION

Today, the design and analysis of electromagnetic equipment is aided by a vast and powerful array of tools. Accuracy in the calculation of field distributions and device parameters remains the foremost consideration in the choice of the appropriate tools, followed by speed of solution and cost.

The three major methods of solution can be categorized as analytical, experimental and numerical. The intent of this paper is to focus on BEM, a numerical method.

The use of analytical methods in complex geometries requires iterative approximations, which leads to highly suspect results. Due to the daily more complex geometries requiring solution, these tools are no longer sufficient to produce full and accurate results. Analytical methods, including the method of images, power series expansions and conformal mapping are most useful in testing numerical methods.

The experimental approach has the clear disadvantage of being costly in most situations. As well, the preparation and testing of a series of models consumes precious time. It is not unknown to discover that the satisfactory results of the miniature model cannot be replicated in the full-size version. The main value of this approach in modern applications is as a test for results obtained either analytically or numerically.

Over the last few decades, numerical methods have gained in accuracy and applicability, thus providing an alternative of choice to the above two methods. The growing power of the microcomputer has put the final touch on the appeal of the numerical approach. Methods that only a few years ago required access to a main frame or minicomputer can now be applied without any loss of precision or speed in the microcomputer environment. Gains in accuracy, cost-effectiveness and speed have marked the emergence of numerical solutions. The most commonly used numerical methods are finite differences, finite elements and boundary elements.

Users of the finite difference method must first describe a grid in every region to be evaluated [1]. The number of unknowns produced is unwieldy and device boundaries are often inaccurately modeled.

In the finite element method, regions are divided into a mesh [2]. The time and effort required of the user might be acceptable were it not for the large numbers of unknowns that are generated. Numerical differentiation of potential is used to calculate fields, leading to inaccurate results.

These disadvantages may explain why field simulation could only be done on large mainframe computers by finite element experts.

BOUNDARY ELEMENT METHOD

In the boundary element method, a variation of Moment Methods [9], the integral equation formulation of the field is solved using unknowns only on boundaries. Accuracy is not sacrificed for critical savings in time and user effort. On the contrary, the accuracy obtained is superior to that of the finite element method. [3],[6].

In comparison to the finite difference and finite element methods, the boundary element method produces reliable results while requiring less data. Open region problems can be solved without resorting to artificial divisions. Complex geometries are as easily and accurately modelled as simpler ones. [5],[6].

An equivalent source which would sustain the field is found by forcing it to satisfy prescribed conditions under a free space Green's function which relates the location and effect of the source to any point on the boundary.

The use of Green's function effectively eliminates the need for a finite element mesh or a finite difference grid.

Once the source is determined, potential and field are computed by integrating the source without interpolation. This provides inherent stability.

The boundary element method provides very accurate results as all parameters are calculated by integrating the equivalent source. In finite elements, fields are calculated by numerically differentiating potential which may give rise to erroneous results.

The boundary element method calculates both the near and far fields at one time with the same accuracy. One can zoom into any area and obtain accurate results. In the FEM, if one were to zoom into a single element, one would only obtain interpolations from the nodal values of that element.

With BEM, the problem is not solved twice in order to calculate forces. Global and local forces are calculated simply by integrating the cross product of the current density with the magnetic induction. Torque calculations are performed with the same ease and accuracy.

MAGNETIC FIELD EQUATIONS

Electromagnetic field is described by Maxwell's equations. Depending on the materials, boundary conditions and sources, the field can be shown to be governed by one or more partial differential equations. The geometry of the problem usually determines if a two- or three-dimensional analysis will be suitable.

In this paper, we will restrict our attention to two-dimensional stationary or slowly varying magnetic fields.

From Maxwell's equations we have,

$$\nabla \cdot \underline{B} = 0 \tag{1}$$

and

$$\nabla \times \underline{H} = \underline{J} \tag{2}$$

(1) permits us to define a magnetic vector potential $\underline{A}$ as,

$$\underline{B} = \nabla \times \underline{A} \tag{3}$$

The constitutive relation in an isotropic material is

$$\underline{B} = \mu(B)\underline{H} \tag{4}$$

Taking the curl of (4) and expanding the right hand side utilizing a well-known vector identity results in,

$$\nabla \times \underline{B} = \nabla \mu(B) \times \underline{H} + \mu(B) \nabla \times \underline{H} \tag{5}$$

substituting (3) and (2) into (5) yields,

$$\nabla \times \nabla \times \underline{A} = \nabla \mu(B) \times \underline{H} + \mu(B) \underline{J} \tag{6}$$

If f is independent of B, we have

$$\nabla \times \nabla \times \underline{A} = \mu \underline{J} \tag{7}$$

For a z-directed current density, in two-dimensions, (7) reduces to

$$\nabla^2 A_z = \mu J_z \tag{8}$$

which is Poisson's equation.

For problems which contain linear materials only, (8) is the governing field equation. In problems which include non-linear materials, (6) has to be solved iteratively [8].

Boundary element method entails the conversion of the partial differential equation into an integral equation, as outlined in [3]. The integrand contains the equivalent source and the free space Green's function or its normal derivative depending on the boundary condition. Along interfaces the discontinuity in the tangential component of magnetization is utilized to arrive at the integral equation. Impressed fields and contributions from permanent magnets form part of the forcing function.

The integral equation is discretized along boundaries and interfaces using the Galerkin method. Galerkin method is one of the projection methods which are also called method of weighted residuals or moment methods [5],[7],[9].

Boundaries and interfaces are divided into small sections which are referred to as boundary elements. This discretization results in a set of linear simultaneous equations for the unknown equivalent current density coefficients. The solution of this system of equations, assuming the matrix is not singular, yields the equivalent current density distribution.

The accuracy of the approximation will obviously depend upon the choice of the expansion and testing functions, and the number of them used. These coordinate functions must be linearly independent as linear dependence will result in a singular S matrix.

The above stated boundary element method is implemented in a magnetostatic field analysis program MAGNETO.

SOLUTION ACCURACY

Needless to say, the value of a method is determined by its accuracy. The boundary element method has very powerful options to test the accuracy of results and to ameliorate them.

For electrostatic problems, in order to verify the accuracy of results, after the solution is obtained the program can be asked to calculate values on the boundaries These values, compared to assigned values represent the greatest error in the solution. Given that the solutions of Laplace's equation are harmonic functions and that such functions have their maximum on the boundary, the error which is the difference between the actual and the calculated solution, is greatest on the boundary.

Finite element and finite difference methods produce results which are interpolated from nodal values. For this reason the verification possible with the boundary element is not accessible with these methods. In fact, such an approach would lead to the assigned value, producing no useful information.

The calculated and actual field discontinuities can be checked along interfaces. The ratio of normal components of the field on either side is inversely proportional to the ratio of respective permeabilities.

In magnetics problems, Ampere's circuital law can be used to verify the accuracy of results.

Unsatisfactory results can be improved with an increase in the number of boundary elements on the surfaces, subareas in regions and re-solving the problem.

MICROCOMPUTER IMPLEMENTATION

Modern microcomputers are rendered daily more powerful; computations that were once possible only on mainframes and mini-computers can now be handled with ease at a workstation equipped with a personal computer. The new micros offer high speed, accuracy and highly interactive graphics capabilities. The sophistication of the results provided is limited only by the scope of the software used.

An electromagnetic field problem is described by defining the geometry, material properties and boundary conditions. It is the geometry of the problem which usually determines if a two- or three-dimensional analysis is most appropriate.

The simulation of fields on the microcomputer requires the input of the above, the numerical solution of the field equation and output of desired parameters. The process is repeated until optimum values for the design parameters are obtained. The efficiency of the procedure is measured by the amount of time required to complete the design.

The factors that affect the efficiency are the ease of use, the accuracy of results, the capabilities and speed of the program.

Industrial users agree that perhaps the most significant issue is the time required to define the problem. In a boundary element package, the user does not mesh every region. This is by far the biggest time saver.

Ease of use is not a concept totally isolated from the numerical technique used. There are a number of important factors which are brought about by the solution technique used in the package which contribute to the ease of use.

The user interface in MAGNETO was designed to require minimal keyboard entry and hand motion. Menus are structured to follow the natural pattern of defining and solving a problem and to incorporate the same sets of commands that operate on different objects. On-line help is provided in every menu.

The geometry, material properties, and other information can be entered with the help of a mouse and immediately displayed. This approach minimizes human error and the time required to enter or modify a particular problem.

The special features of the microcomputer environment (e.g. fast color graphics, color printer, mouse or keyboard entry, math co-processor, hard disk, RAM disk) are fully utilized to integrate problem definition, analysis, data storage, drafting and presentation capabilities.

A SAMPLE ANALYSIS

This sample analysis furnishes a presentation of modeling, solving, and displaying results for one problem. All calculations were done and all illustrations were generated using MAGNETO on an IBM PC-type microcomputer.

The example is a twenty-four slot permanent magnet motor. The problem geometry is shown in Fig. 1. The outer diameter of the stator is 4.0 inches and the outer diameter of the permanent magnets is 1.9 inches.

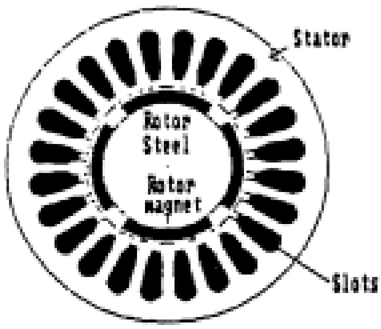

Fig. 1: A twenty-four slot permanent magnet motor.

The problem is modeled by entering the geometry, non-linear B-H curves for the steel and permanent magnets, permanent magnet directions, and volume currents. Boundary elements are then discretely placed on segments where they are required and subareas are generated in regions containing volume currents.

By assigning an appropriate boundary condition, only half of the problem needs to be modeled. This not only reduces set-up time, but the solution time as well.

The motor geometry is given in inches. This can be chosen to be the system of units for data entry and result output. The program permits selection of various systems of units including the user's own.

After the selection of the proper unit system and the real number range in cartesian or polar coordinates, the geometry of the problem is entered. This is done through the geometric modeler which is an integral part of the program. Either the keyboard or the mouse or a digitizer can be used for this purpose.

The geometric modeler provides commands for creating, modifying and inquiring about the geometry. These commands are very similar to those found in a drafting package. First one slot is modeled, as in Fig. 2. This is best achieved in a small window.

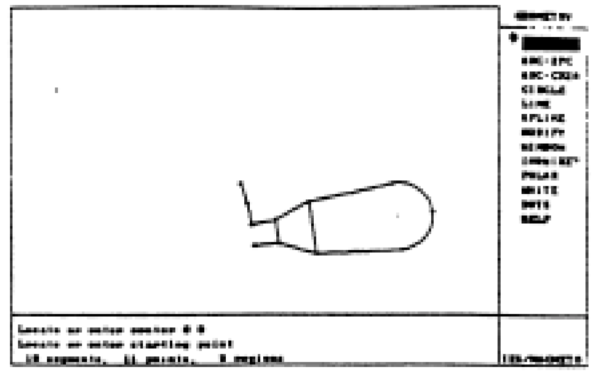

Fig. 2: One slot of the geometric model.

The remaining slots and teeth are generated by rotating and duplicating the first slot. The rest of the geometry is entered with the same ease.

Regions that contain current must be divided into smaller areas for accurate integration of sources. These small subareas can only be generated in four-sided regions. Therefore, cuts are introduced in slots where the windings are located. These cuts are shown in blue. The rotor geometry is entered next using 8 arcs and 7 line segments. The final model is shown in Fig. 3.

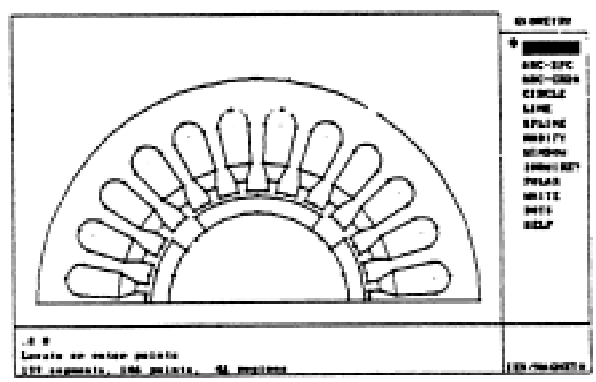

Fig. 3: Geometric model of the motor.

This is all the user has to do for entering the geometry. One can always use the on-line help to obtain explanation on commands. A help screen is shown in Fig. 4.

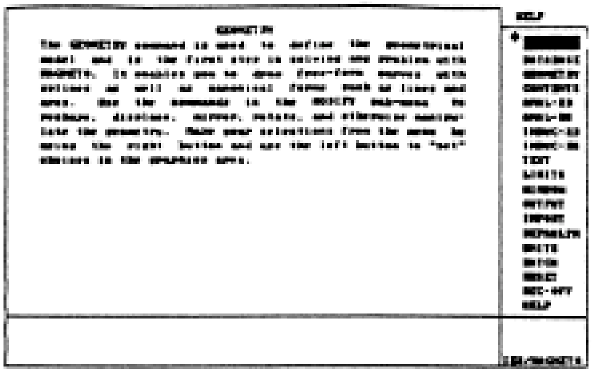

Fig. 4: On-line help screen.

After the completion of the geometric model it is saved in the database. Next step is the definition of the materials, currents and permanent magnets. These properties are entered through an attribute handler which forms the second important module of the program.

The first step is to assign materials to appropriate regions of the geometry. The motor being modeled contains three materials -copper, carbon steel, and magnets.

MAGNETO is supplied with a default table of 15 materials, as shown in Fig. 5.

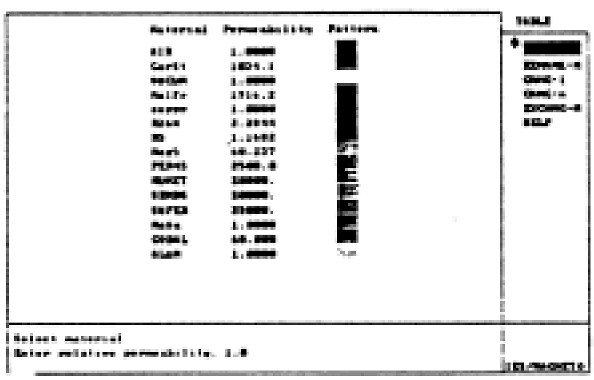

Fig. 5: A default material table.

Since the materials used in the motor problem are not among those listed in the table, they are added to the table using the appropriate menu commands.

The copper in the motor is a linear material. The permeability of a linear material is independent or can be assumed independent of the magnetic induction. Conductors such as copper, silver, and gold have permeabilities almost equal to free space and are practically independent of the field.

In MAGNETO, two to twenty points define the normalized B-H curve. To generate the normalized B-H curve for the carbon steel, twelve points were extracted from the curve provided by the manufacturer. The points in the form (H,B) are as follows: (0,0), (2,3000), (4,8500), (8,12500), (10,13500), (20,15000), (40,16500), (80,17600), (200,18900), (400,20200), (1500,21900), (5000,25800). The curve then appears as in Fig. 6.

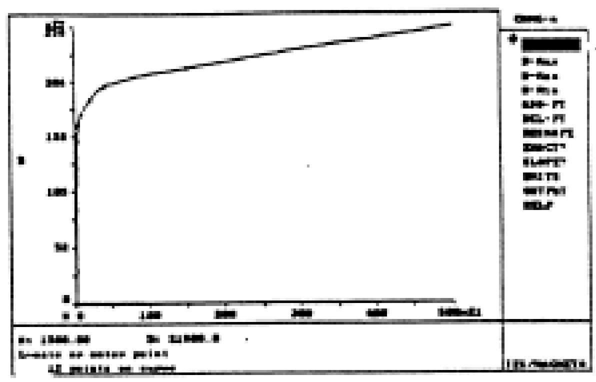

Fig. 6: The non-linear B-H curve for carbon steel.

Magnets are defined by entering their second quadrant - or demagnetization -curves.

After the materials for the problem have been defined, they are placed in the appropriate regions by selecting them from the menu and locating the cursor in the desired region. The closed regions are determined by the program automatically from the topology. The final step in defining a magnet is to specify its direction of magnetization. The motor appears as in Fig. 7.

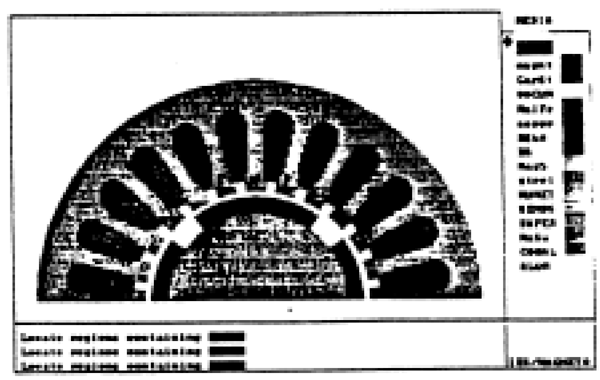

Fig. 7: The motor model with the materials assigned.

After the currents in the windings and symmetry conditions are assigned, the boundary elements and subareas are generated. Subareas are needed (for accurate integration of sources) wherever volume currents exist. In this problem, volume currents have been assigned to the four upper slots and the two slots on the left and right. Each slot has two regions. Subareas are required, therefore, in a total of sixteen regions.

The most crucial part to solving the problem accurately is the generation of boundary elements. Boundary elements are generated only on segments between dissimilar media or with boundary conditions or with surface currents. For this problem 224 boundary elements are used as shown in Fig. 8.

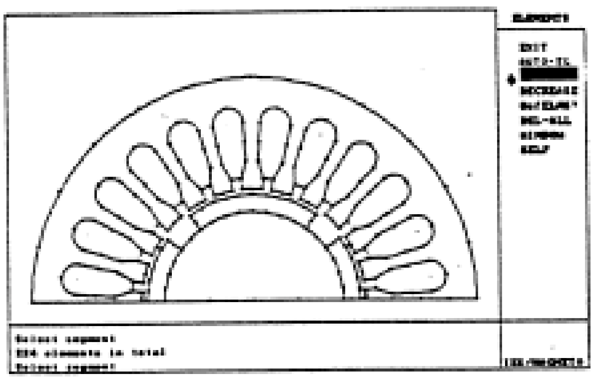

Fig. 8: The boundary element distribution.

The problem is now completely defined. Depending on the type of computer used, the analysis may take from 15 to 150 minutes.

After the calculations are completed various parameters can be obtained. The torque has been calculated to be 898 lb x in/m and the measured torque was 866 lb x in/m. The difference which is less than 4% may be attributed to the end effects.

Arrow plots of the magnetic field can be calculated in any window. Graphs of field values can be obtained along any arbitrary line or curved segment. Fig. 9 shows a graph of the normal component of the B-field along the top of the center magnet.

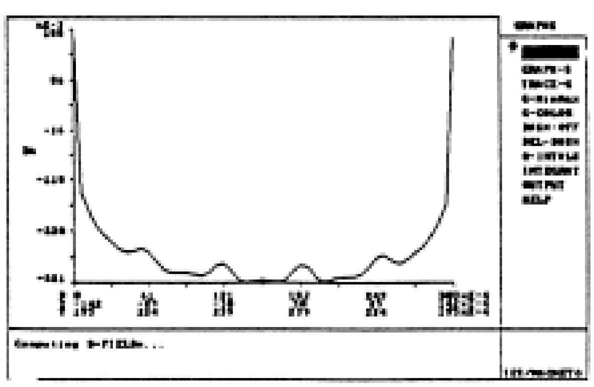

Fig. 9: Normal component of B-field.

Graph utilities provide various options for integration and annotation. For example, integration of the graph in Fig. 9 yields the flux crossing the surface of the magnet. Fig. 10 shows the flux distribution throughout the crossection of the motor.

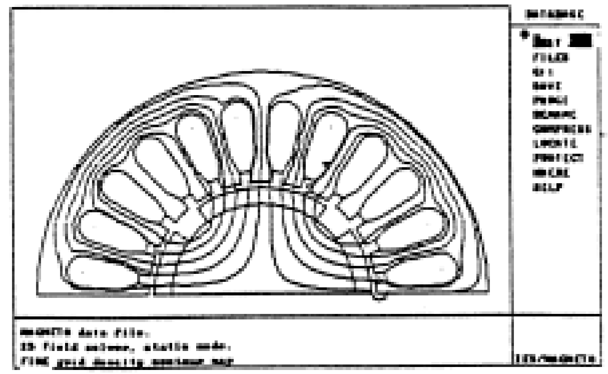

Fig. 10: Flux distribution in the motor.

It would be interesting to see the effect of changing the current from 20 ampere-turns to 40 and 60 ampere-turns. This can be done quite efficiently using the batch option. Many what-if cases can be analyzed unattended.

CONCLUSIONS

The boundary element method has been shown to be an efficient technique for the simulation of electromagnetic design problems on a personal computer.

The main advantages of this method are the reduction of one in problem dimensionality, accurate modeling of geometry, elimination of differentiation and interpolation to calculate potential or its derivatives, precise results due to the smoothness of the integral operator [4] and sound means for checking the accuracy of the solution.

Inductances are calculated from the energy definition. Other parameters are calculated by integrating the equivalent current.

The boundary element method, combined with a highly interactive user interface on a personal computer, automates the analysis of electromagnetic field distributions and provides accuracy, speed and ease of use.

Problem geometries, materials and boundary conditions can be conveniently described from the conceptual stage and analyzed to obtain the optimum design.

ACKNOWLEDGEMENTS

I acknowledge the invaluable contributions of my colleagues at Integrated Engineering Software Inc. K.M. Prasad, David Tong and Bruce Klimpke. They are part of the team that developed MAGNETO.

REFERENCES

[1] G.E. Forsythe and W.R. Wasow, Finite-Difference Methods for Partial Differential Equations. New York: John Wiley & Sons, 1960.

[2] O.C. Zienkiewicz, The Finite Element Method in Engineering Science. New York: McGraw-Hill, 1971.

[3] Y.B. Yildir, "Computer-Aided Field Analysis of High Voltage Apparatus Using the Boundary Element Method", Proc. International Coil Winding Conference, Rosemont, Illinois, Oct. 5-8, 1987.

[4] S.G. Mikhlin, Integral Equations. New York: Pergamon Press, 1964.

[5] Y.B. Yildir, A Boundary Element Method for the Solution of Laplace's Equation in Three-Dimensional Space. Ph.D. Dissertation, University of Manitoba, 1985.

[6] Y.B. Yildir, "Computer-Aided Magnetic Field Analysis Using the Boundary Element Method", Proc. International Coil Winding Conference, Cincinnati, Ohio, Oct. 5-8, 1988.

[7] B.W. Klimpke, A Two-dimensional Multi-media Boundary Element Method. M.Sc. Dissertation, University of Manitoba, Winnipeg, Man., Canada R3T2N2, 1983.

[8] M.H. Lean and D.S. Bloomberg, "Nonlinear Boundary Element Method for Two-dimensional Magnetostatics", J. Appl. Phys., Vol. 55, No.6, 1984.

[9] R.F. Harrington, Field Computation by Moment Methods. Reprinted by R.F. Harrington, R.D.2, West Lake Road, Cazenovia, N.Y., 1968.