Computer Simulation Scores a Boundary

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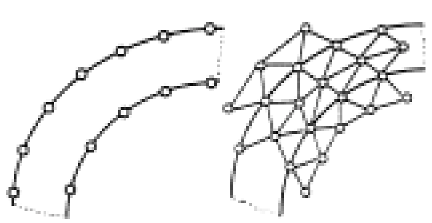
The boundary element method (BEM) is a valuable technique in the electromagnetic field modelling carried out by many pulsed power engineers during the design phase of their work. Pulsed power is an expensive technology and a tool which can help predict device performance can be a great cost and time saver. BEM has found wide application in pulsed power design from the modelling of components (insulators, bushings, electrodes, laser heads) to complete systems (transmission lines, transformers, capacitor banks, Marx generators). Sandia National Labs, British Aerospace and the University of Strathclyde, amongst others, all use it in various electromagnetic research programmes.

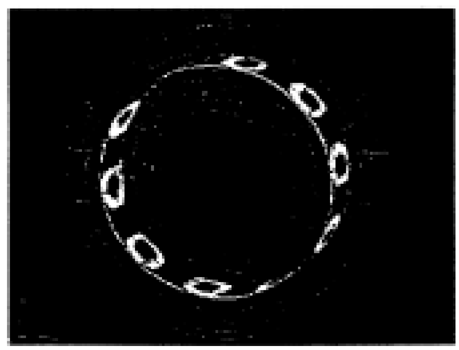


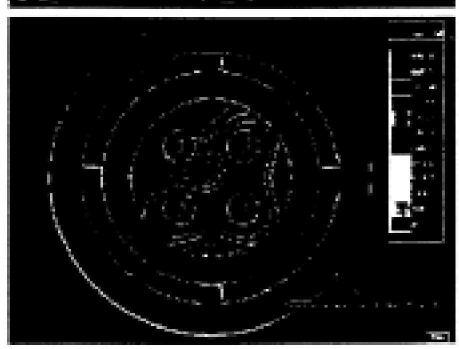
The boundary element method (BEM) is shown on the left, with its rival the finite element method (FEM).

BEM is a numerical technique which describes electromagnetic phenomena by Maxwell's equations in integral form. Enforcing the boundary conditions along material interfaces allows one to obtain a set of boundary integral equations with the unknowns as the equivalent sources or field variables along the interface. One may then separate the boundaries into boundary elements, represent the unknowns on elements, and obtain a system of linear equations. All field variables at any point in space may be obtained by performing integrations associated with the equivalent sources or fields on the boundaries.

The finite element method (FEM) is the obvious alternative to BEM. It is a numerical technique for solving Maxwell's equations in differential form. For a given design, FEM requires the entire design, including the surrounding region, to be modelled with finite elements. A system of linear equations is generated to calculate the potential (scalar or vector) at the nodes of each element.

The basic difference between these two techniques is the fact that BEM only solves the unknowns on the boundaries, whereas FEM solves for the whole space. FEM must use a 3D finite element mesh in the whole space, but BEM uses only 2D elements on the surfaces which are the material interfaces. Users can set up a problem quickly and easily and since only elements on interfaces are involved in the solution procedure, problem modifications are also easy. For example, in motor design optimisation, solutions are required for different rotor positions. Using BEM software, only one boundary element distribution is necessary to solve all the rotor positions, and no element reassignments are required. With FEM software, finite elements in the whole space must be re-generated for every new rotor position.





A three dimensional clutch magnetic field contour ring lines (right top) and a two dimensional cable system electric field contour (bottom right), both simulated by Integrated Engineering Software's 2D/RS BEM-based package.

BEM allows all field variables at any point in space to be obtained accurately. Also, the results are more precise because the integration operation is smoother, making BEM inherently more accurate than FEM's differential operation. By using these physical variables, global quantities such as force, torque, stored energy, inductance and capacitance, amongst others, can be accurately obtained with some simple techniques.

Calculating external fields

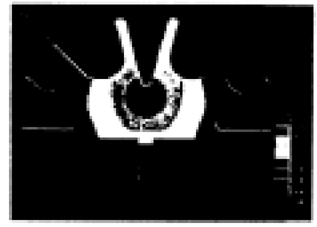
The analysis of unbounded structures (for instance, electromagnetic fields exterior to a strip-line or capacitor bank) can be solved by BEM without additional effort because the exterior field is calculated in the same way as the interior field. The field at any point in space can be calculated (even at infinity). Therefore, for any closed or open boundary problem, you need only to deal with real geometry boundaries. Since most electromagnetic field problems are associated with open boundary structures, BEM naturally becomes the best method for general field problems.

Calculating the field distributions with FEM is faster than with BEM. The reason is that FEM calculates the field value using differential operations on the potential variables, while BEM has to perform an integration along the boundaries. However, since the differentiation introduces discontinuities, it is difficult for FEM to obtain accurate field quantities by using simple direct differentiation. With BEM, all field quantities are derived by integration which is inherently stable. Although BEM takes longer to calculate the fields, it gives more accurate results.

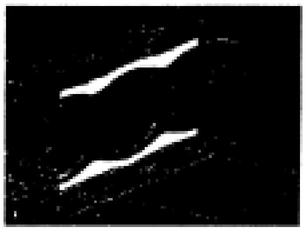
From Green's theorem, one can show that if (and only if) the solution satisfies the boundary conditions on all the boundaries, the result at any point in the solution space obtained from the variables on the boundaries is correct. Therefore, after solving a problem with certain element distribution, users can perform an error analysis by checking the boundary conditions along the boundaries. One can improve the solution by simply adding more elements on the boundary where a large error has been found. This is based on the fact that the largest errors occur on the boundary, and that for the fields on a region, the largest contributors are the elements close to the region.

Without delving into a detailed discussion of Maxwell's equations, non-linearity for magnetostatics may be explained as follows:

Basic field theory provides that any magnetised



The boundary element method can also be used to calculate heat transfer from high power loads.



A cathode ray tube modelled in three dimensions with the boundary element method.

body, such as magnets and iron, will produce a magnetic field which can be exactly modelled by a set of equivalent surface and volume currents on and within the structure. This is true whether the materials are linear or non-linear. In cases where it is assumed that the materials are linear, it can easily be shown that the equivalent volume current will be zero and that only the equivalent surface current will be present.

Using BEM for non-linear problems

For linear problems, it is precisely these equivalent surface currents which are calculated in BEM. A matrix of linear equations is generated from the boundary elements. The matrix is solved to determine the equivalent approximation to the surface currents. Any field parameter can then be found via straightforward integration.

For non-linear problems, BEM is still applicable with a little modification. The method must be expanded to deal with the equivalent volume currents. The field produced by the volume currents is small compared to that of the surface currents, and for many practical problems it can simply be neglected. However, if volume currents are significant, the regions changing rapidly from an unsaturated to a saturated state need to be separated. There are three approaches to determining the volume currents:

- Generating subareas and subvolumes and finding equivalent volume currents by an iterative scheme. These are put in the right hand side of the system of equations, rather than in the system matrix.
- Other methods that deal with non-linear problems using integral equations require that the volume unknowns appear in the system matrix. This results in a volume rather than boundary integral formulation. These usually result in significantly larger matrices and longer solution times.
- Multiple layers of boundary elements to account for non-linearities have also been developed.

Within the last few years, significant hurdles have been overcome in the writing of BEM software. While the actual programming remains difficult, the resulting BEM software packages have become usable tools. Problems previously believed to be insurmountable, such as non-linear calculations, are now easily solved.

For further information on the Boundary Element Method contact Andrew McPhee on +44 1803 200655.