

MAFIA - A Three-Dimensional Electromagnetic CAD System for Magnets, RF Structures, and Transient Wake-Field Calculations

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INTRODUCTION

The acronym MAFIA stands for the solution of Maxwell's equations by the Finite Integration Algorithm, and is the name given to a set of codes intended for use in the computer-aided design of three-dimensional magnets, rf structures, and structures in which wake-field effects are important. Figure 1 shows the interconnection of the various codes in the MAFIA collection. M3 is the mesh generator used by all the MAFIA codes, T3 is the wake-field code, R3 generates the matrix whose eigenvalues and eigenvectors yield the frequencies and electric field components, respectively, of the normal modes of electromagnetic oscillations of an rf structure, E3 is the eigenvalue solver, and P3 is the postprocessor that calculates the quantities of physical interest, such as shunt impedance, quality factor, deflection integrals, etc. The code S3, now being written, will solve electro- and magnetostatic problems.

The collection of programs M3, R3, E3, and P3 are also known as URMEL-3D. The program T3 is described in another paper at this conference and so will not be further described here. We proceed to give a quick description of the FIT method, followed by brief descriptions of the codes M3, R3, E3, and P3. Finally we describe how one can get and use these codes.

THE FIT METHOD

The Finite Integration Technique [1,2] is an algorithm that produces a first-order approximation to Maxwell's equations by replacing the line and surface integrals, appearing in Faraday's law and Ampere's law, by mean field values times path lengths and areas, respectively. Figure 2 shows the basic cell geometry used in this method. Note that the electric field components are not defined at a single point, but at the midpoints of the sides of the rectangular cells. The magnetic field components are defined in the center of the faces of the cells, and taken together form a mesh dual to that defined for the electric field. Only continuous components are involved in the assignment of field values to the mesh, and thus the cells of the mesh may be individually filled with arbitrary permittive and permeable media. Using the FIT method one can write the discrete form of Faraday's law as

$$C \mathbf{D}_e \mathbf{e} = \mathbf{D}_A \mathbf{b},$$

where \mathbf{e} and \mathbf{b} are vectors of length $3N$ where N is the number of nodes of the mesh, C is a $3N$ by $3N$ matrix containing only the values 0, 1, and -1 and which corresponds to taking the curl of a field, \mathbf{D}_e is a $3N$ by $3N$ diagonal matrix containing the lengths of the sides of the mesh cells, and \mathbf{D}_A is a $3N$ by $3N$ diagonal matrix containing the areas of the mesh cell surfaces. Similarly Ampere's law can be written

$$\tilde{C} \mathbf{D}_h \mathbf{h} = \tilde{\mathbf{D}}_A (\mathbf{d} + \mathbf{j}),$$

where the tilde indicates that the matrix corresponds to the dual mesh. When the material distribution is taken into account and a

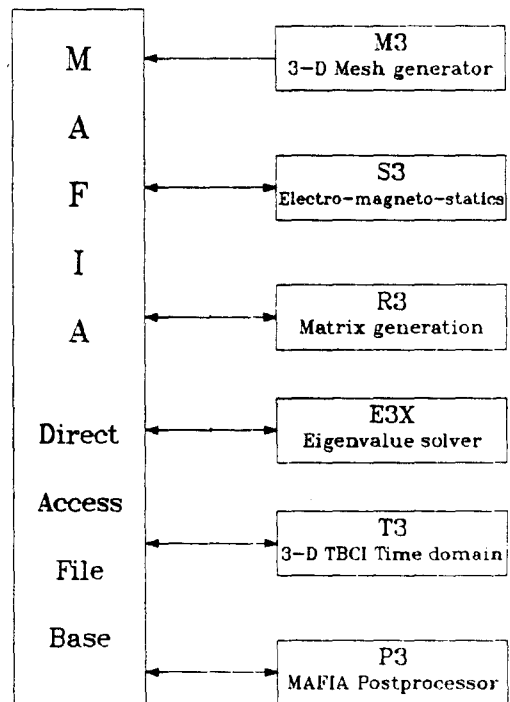


Figure 1: The Mafia System

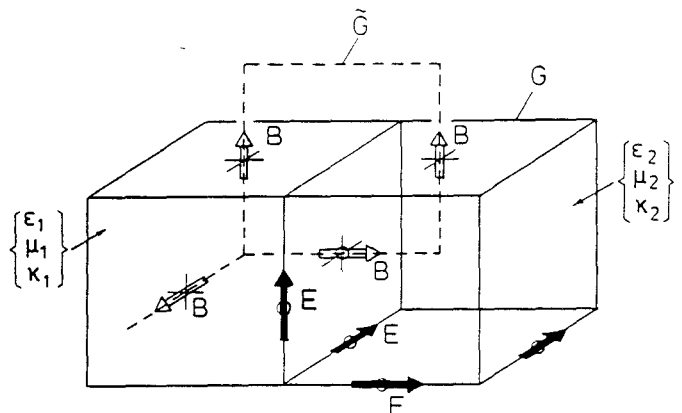


Figure 2: Geometry and allocation of field components used in the FIT method

leapfrog integration technique in the time variable is used, one finds the recursive algorithm for the calculation of time-dependent fields:

$$\begin{aligned} \mathbf{b}^{n+1} &= \mathbf{b}^n - \delta t (\mathbf{D}_A^{-1} \mathbf{C} \mathbf{D}_s) \mathbf{e}^{n+1/2}, \\ \mathbf{e}^{n+3/2} &= \mathbf{e}^{n+1/2} + \delta t (\mathbf{D}_e^{-1} \tilde{\mathbf{D}}_A^{-1} \tilde{\mathbf{C}} \tilde{\mathbf{D}}_s \mathbf{D}_\mu^{-1}) \mathbf{b}^{n+1} - \delta t \mathbf{D}_e^{-1} \mathbf{j}^{n+1}, \end{aligned}$$

where the superscripts refer to the time step ($t_n = n\delta t$), and \mathbf{D}_e and \mathbf{D}_μ are diagonal matrices describing the filling of the mesh with permittive and permeable media. These last two equations are solved by T3; given the initial values of the fields, fields at a subsequent time require only two multiplications of a matrix with a vector, per time step.

If we are interested in free oscillations (i.e. undriven oscillations) of the electromagnetic field, we find that combining Faraday's law and Ampere's law yields a linear eigenvalue problem, in which the eigenvalues are the squares of the angular frequency of oscillation:

$$(\mathbf{D}_e^{-1} \tilde{\mathbf{D}}_A^{-1} \tilde{\mathbf{C}} \tilde{\mathbf{D}}_s \mathbf{D}_\mu^{-1} \mathbf{D}_A^{-1} \mathbf{C} \mathbf{D}_s) \mathbf{e} = \omega^2 \mathbf{e}.$$

For the practical solution of this eigenvalue problem, this equation can be transformed into one in which the matrix is symmetric. The program R3 constructs this symmetric matrix, incorporating material distribution and boundary conditions into the process of construction. A more detailed treatment of the application of this method to problems of electromagnetism may be found in Ref. [3]

M3

The mesh generator for all the MAFIA codes, M3, can be used either interactively or in batch mode. It can produce two- and three-dimensional (perspective) color plots of the mesh, the material distribution(s), and the input geometry. Two- and three-dimensional (plane by plane) printer plots of the material distribution can also be produced. Figure 3 is a three-dimensional mesh plane plot of a typical cavity, produced by M3. A large number (approx. 25) of shapes are predefined for ease of input, and provision is made for repeating a shape any number of times at a fixed interval. The individual cells of the cartesian mesh can be filled by two materials separated by a diagonal plane joining opposite sides of the cell.

As input to the program, the user specifies a number of mesh planes and their spacing. A program option permits the code to insert planes as needed to improve the fit. Filaments can be defined (for magnet coils). An option to produce an output file for use by the three-dimensional magnet code PROF1[5] is available. The code can produce either a sequential output file or a direct access file. The output file contains all the mesh and material distribution data.

R3

This code uses the direct access file and reads the mesh data and material distribution information written by M3. An additional input file provided by the user supplies boundary conditions and information about material properties. That is, the program M3 specifies the distribution of materials 0 through 8, but the specification of the characteristics of the materials is left until it is necessary to have that information to form the system matrix. Aside from material numbers 0,1, and 2 which are defined to be vacuum, perfectly conducting metal, and an infinitely permeable medium, respectively, the user can specify (complex) tensor permittivity and (complex) tensor permeability for materials 3 through 8. The tensors must be diagonal, and the imaginary part is not used at present. The user can also specify metals with differing conductivity, although in setting up the system matrix these are treated as perfectly conducting. The conductivity of various materials is stored on the direct access file and used by the postprocessor program P3 in the calculation of power dissipation, using a perturbation formula.

The system matrix is symmetric, and is written on the direct access file in block form to be read by the eigenvalue solver E3.

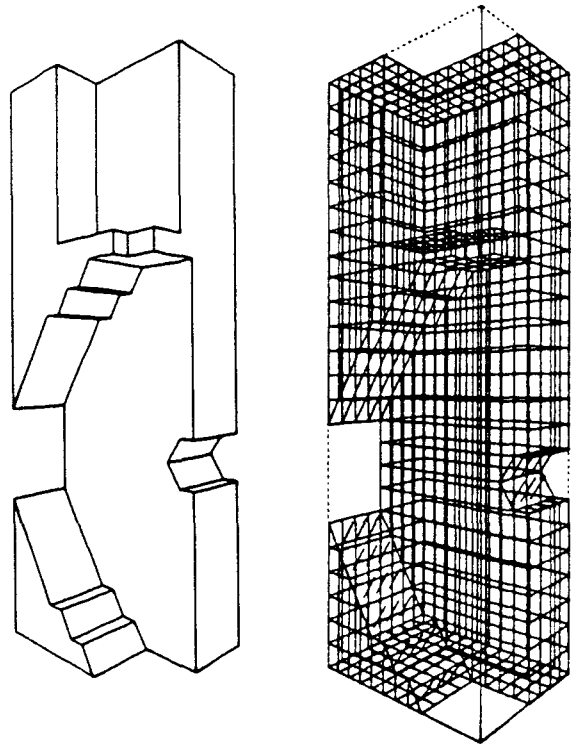


Figure 3: Typical M3 mesh plot

E3

There actually two eigenvalue solvers, currently named E31 and E32. E32 uses a multigrid [4] method and is presently undergoing final testing. E31 uses a semi-analytic procedure [6] and is a modification of an EISPACK[7] routine. The user specifies the number of eigenvalues and eigenvectors to be calculated. Both E31 and E32 then try to solve the problem holding the entire matrix in core, but if this cannot be done, they automatically switch to a block-by-block mode of operation. The solutions are checked to insure that Maxwell's equations are satisfied, and then a user-specified number of eigenvectors is written to the direct access file for further analysis by P3.

P3

The postprocessor P3 is intended for interactive use, although it can be run using a command file to produce either online or offline output. An interactive session can be run mixing terminal commands and command-file commands. A log file of a session can be kept and can then be used as a command file to a subsequent session. The program itself creates arrow plots of the field vectors in any plane, produces isometric plots of functions in any plane, displays graphs of functions along a line, calculates line integrals of the Lorentz force for arbitrary particle speed, calculates quality factors (Q) of the modes, and in general enables the user to determine what he wants about the eigenmodes found by E3. Figure 4 shows a typical arrow plot of the electric and magnetic fields of the TM_{110} mode of a circular pillbox cavity coupled to a waveguide. P3 can also be used to display the electromagnetic fields at any given time produced by T3, and

can view and analyse the magnetic fields produced by the PROFI[5] code. Figure 5 shows a correction dipole for HERA, calculated using PROFI, and Fig. 6 is a P3-generated isoplot of the dipole field versus position in the midplane.

S3

At present we use PROFI to calculate 2D and 3D nonlinear static field problems. We are writing a new static solver named S3 as part of the coherent MAFIA package.

T3

As stated previously, T3 solves the discretized time-dependent Maxwell equations driven by a line current density with a specified spatial and temporal dependence. A further description of T3 and some of its applications is given in an accompanying paper at this conference[8].

AVAILABILITY

The MAFIA codes are written in FORTRAN 77 and currently run on IBM 3081, CRAY, and VAX computers. They are also available to the public in executable form on the magnetic fusion energy (MFE) CRAY-1s, machines C and D. On these machines they are available via a typical file storage read command:

```
filem read .3011 .mafiac xm3
```

for M3, say. Documentation is available with the command

```
filem read .3011 .mafiac doclib
```

For those users who want to use the codes at their own installation, there are three graphics interfaces available: DISSPLA, PLOT 10, and GKS. The distribution center for the codes is DESY, and the codes are available without charge to non-profit organizations. Users are asked not to modify or distribute the codes, and to be friendly and sometimes patient.

References

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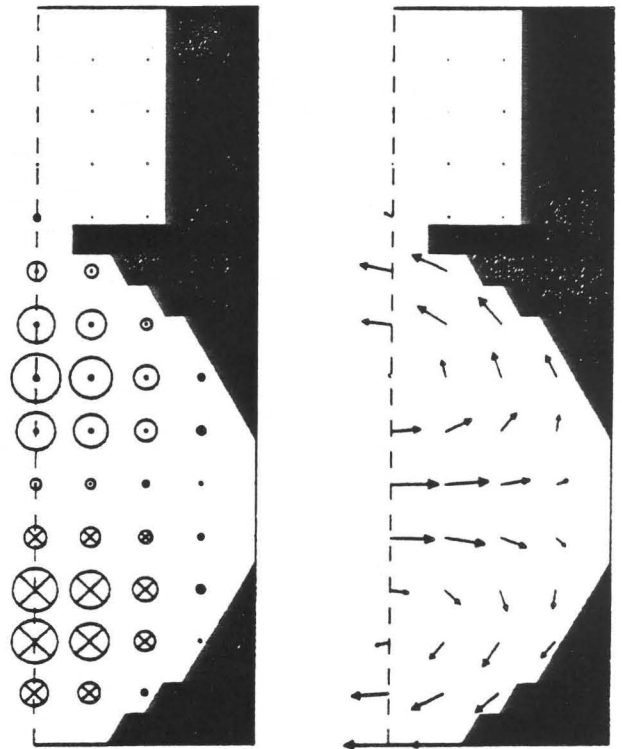


Figure 4: Arrow plots of electric and magnetic fields

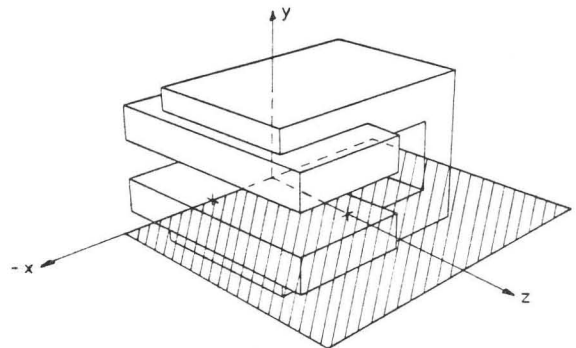


Figure 5: Correction dipole magnet calculated by PROFI

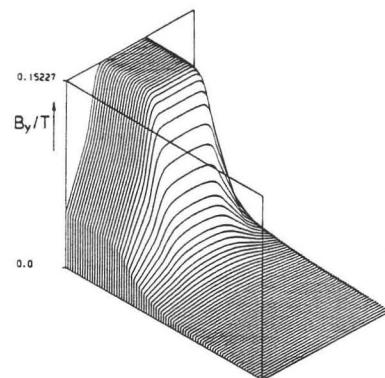


Figure 6: Isoplot of y-component of magnetic field versus position