ELECTROMAGNETIC SIMULATIONS

This software was developed to help students understand the physics of electromagnetic. There are many opportunities for electromagnetic fields plotting, including design of structures for analysis of static electromagnetic fields and waves. The electromagnetic problems were solved using analytical equations and numerical methods (FEM, FDTD) but these methods are transparent to the user. Only the input and the output are visible to the user.

The software components are:

1 - Vector Addition
2 – Contour Lines - Gradient
3 – Electrostatic fields
    Point Charges
    Potential
4 - Electrical Current
5 – Magnetostatic fields
6 – Electromagnetic waves

Many of these components are self explanatory, and for each there is an example that can be run. In some cases the variables of the example can be changed by the user. In these instances, the variables are entered with <space> between them and <Enter> after the variables (for more than one line of values, type <Enter> at the end of each line). A <;> can be used instead of <Enter>.

1 – VECTOR ADDITION

This function is provided to help understand the meaning of vectors, with the possibility of plotting in 2 and 3 dimensions. The system of coordinates is rectangular, with axes denoted as *x, y* and *z*.

A vector is defined by 2 points, in 2D: $P_1(x_1, y_1)$ ---------> $P_2(x_2, y_2)$;
3D: $P_1(x_1, y_1, z_1)$ ------> $P_2(x_2, y_2, z_2)$.

The vector arrow will be directed from P_1 to P_2. The easiest way to enter the vectors' coordinates is to write $x_1\ y_1\ x_2\ y_2$ <Enter> (keyboard) in the field provided for this purpose. The same can be done in 3D but now the sequence is $x_1\ y_1\ z_1\ x_2\ y_2\ z_2$ <enter>.

After entering one or more vectors, one must press ENTER. The vectors will be plotted in blue. Each vector is held in memory; after that one can use ADD to add to the previously entered vectors (new vectors will be plotted in red). The first vector is used as reference, so all subsequent vector will be placed in the correct position with respect to

this first vector. Pressing on the CLEAR field erases de memory. The vector component on the *z* axis in 3D will not have an arrow at its end, but rather a < + >.

The projection of the vectors can be seen selecting the field *Projections*; if it is 2D the projection will be over de axes, if it is 3D, the projection will be over de planes *xy*, *xz*, *yz*. The vector projection will be plotted in cyan.

2 – CONTOUR LINES - GRADIENT

This function is intended to show how scalar functions (in three dimensions) look and how contour lines and gradients relate to the functions. Gradients are indicated as vectors (arrows). There are 4 different examples of functions starting from the simple to the more complex. To run an example the field *Run Example* must be assigned.

Any function can be entered in the field *Function z = f(x,y)*. The correct way to type the function is the same as used in MATLAB©, a dot must be used before the symbols of multiplications, division, and exponential. The values used to calculate *z* (*x* and *y*) are assigned in the field *xy Values* (in the following way: *start value: space increment: end value*. For example: -1:0.1:1, so the values will start with -1 at increments of 0.1 up to 1.) One must pay attention not to allow the space increment to be zero at some point if the function divides by *x* or *y* (division by zero).

3 – ELECTROSTATICS

POINT CHARGES

In this part of the software it is possible to see the interaction between point charges in free space (including forces between them) and near perfect conductors. Positive charges are plotted as red points and negative charges as blue points. The potential and field lines are shown as well. The individual forces between the charges are plotted in red and, the total forces are plotted in black. One can use image theory to see the behavior of the electric field in the presence of perfect conductors.

The following simulations can be carried out:

Free Space

2D

1Q – One point charge, one can change the sign of the charge to see the fields.

2Q – One can enter the value of two point charges (the difference between de charges value is used). You can choose to see the arrows (vectors) in the plot.

NQ – One can enter any number of charges and their respective *xy* coordinates, in the follow order *Q x y* <Enter>. You can choose to see the arrows (vectors) in the plot.

Capacitor – This is not an ideal capacitor, but it is a simulation of a capacitor using point charges over two parallel plates. One can choose the number of charges per plate (indicating charge density), the length of the plates and the distance between them. Positive charges are plotted as +, negative charges as points.

3D – the same, as in 2D.

Image Theory

1Q – one point charge over a perfect ground conductor. One can change de value of the charge and its height, and choose to see the image.

NQ – any number of charges over a perfect ground conductor, with their respective *xy* coordinates, in the follow order *Q x y* <Enter>

Tilted planes – one can choose between different angles of perfect conductors and then entering the position of the charge and the charge value. The *x* and *y* coordinate must be inside of the plane section defined by the conducting planes, otherwise the software will change their value or indicate an error.

Metal Box – this function uses image theory to calculate the electric field produced by a point charge inside a perfectly conducting metal box. One can change the value of the charge, position, length and height of the box. In this simulation only the first 4 image charges and the original charge are used. An exact solution would require an infinite number of image charges. Nevertheless, the result obtained, while approximate, is quite good.

ELECTRIC POTENTIAL

In this section of the software one can see the behavior of electric static fields when electric potential is applied on conducting surfaces and using different types of dielectric materials. The simulation relies on the finite difference method which is explained next. Although a fairly complex method, its application in simple cases is fairly easy and is explained next. The method requires geometrical modeling of the objects and space in which a solution is needed.

FDM

Finite Differential Method is used with square cells, to solve for static electric fields within defined boundaries. The problem discussed here is a metallic box in free space, in which each wall is separated from the others by a very small gap. The potential on each wall can be assigned V_1, V_2, V_3, *and* V_4. The dimension of the cell is defined by *Dxy*. *I* and *J* are the number of cells in *x* and *y* directions respectively. *# of iterat* is the number of iterations used by the FDM algorithm. The algorithm will converge to the answer after a number of iterations (see bibliography).

FEM

Finite Element Method (see bibliography) is used with triangular cells to solve the electrostatic field equations. To simplify the geometric modeling required, the finite elements are restricted to be right angle triangles. One can define the dimension of the

triangle cells by *Dx* and *Dy*. The number of cells in *x* and *y* direction are *I* and *J* respectively. See Fig. 1 for an example (*I* = 4, *J* = 3, *Dx* = 1, *Dy* = 1).

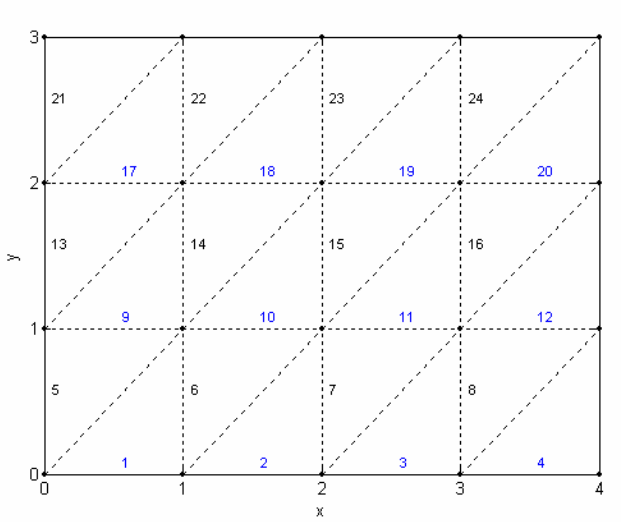

Figure 1. FEM mesh. The numbers inside the mesh are the element numbers (triangles).

To solve the problem it is necessary to assign boundary conditions. These are known potentials over the boundaries.

The ***boundaries*** are assigned in the follow order:

$x_1\ y_1\ x_2\ y_2\ V_b$ <Enter> - two points for one line, if one point is used -> $x_1\ y_1\ x_1\ y_1$

V_b -> potential over the boundary condition [(x_1, y_1)--(x_2, y_2)]. The line can be tilted, but must have the same number of cells in the *x* and *y* direction (projection).

The properties of the dielectric are assigned through ***properties*** are in the follow order:

$x_1\ y_1\ x_2\ y_2\ x_3\ y_3\ x_4\ y_4$ *Per* <Enter>, four points a box, for triangle use $x_4 = x_3$ and $y_4 = y_3$, it MUST always be isosceles (same number of CELLS on x and y direction) with a right angle (e. g. |_) . The points (*x*, *y*) MUST always be numbered in anti-clockwise direction starting from the lowest *x* and lowest *y* values (x_{min}, y_{min}), see Fig. 2.

Per -> relative electric permittivity inside the *xy* area. The permittivities are assigned in descending order (first element to last one). This means that the second line of permittivities will overwrite the first one and so on. Elements not assigned will have *Per* = 1. At least one geometry property must be assigned.

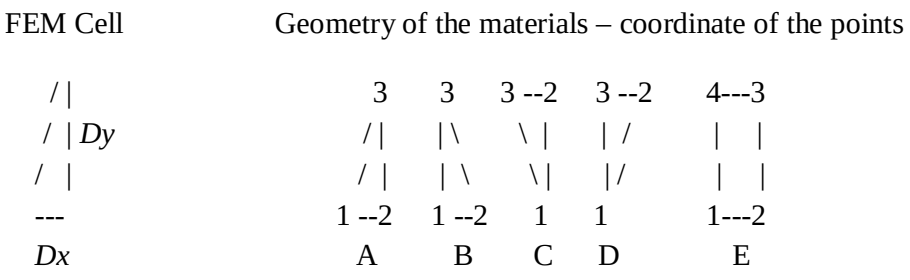

Figure 2. Possible geometries and assignment of properties for the FEM mesh.

Examples considering Fig. 1 and Fig. 2:

Boundaries: 0 0 2 0 V_1 --
1 1 3 3 V_2 /
0 3 3 0 V_3 \

Properties - A : 0 0 0 2 2 2 2 2 Per_A
B: 1 1 3 1 1 3 1 3 Per_B
C: 4 0 4 3 1 3 1 3 Per_C
D: 2 1 4 3 2 3 2 3 Per_D
E: 1 1 3 1 3 2 1 2 Per_E

There are 5 examples that can be run. Of these, 3 examples deal with capacitors in which the permittivities can be changed. Also there are some options for plotting. To run an example the field *Run Example* must be pressed. After run any example the values used will be appear in the properties and boundary conditions fields and can be viewed on the screen. At this point it is still possible to change values in the boundary and properties fields, but in this case the *Run Example* must not be pressed again. The boundaries will be shown in blue and the properties contour in black.

Note: The FEM algorithm is not protected against entering wrong coordinates. One must be sure to enter the correct position of the properties and boundaries according to the mesh. The mesh will change according to the Boundary and Properties values.

4 – ELECTRICAL CURRENT

In this section one can see the magnetic field lines around parallel infinite conductors. In 2D it is also possible see the force between the conductors. The red point indicates a current flowing out of the screen, the blue point indicates a current flowing into the screen. In 3D the field plot is a rough plot of the magnetic field lines. The values of the currents can be changed.

5 – MAGNETOSTATICS

In this section is the Finite Element Method is used in a fashion similar to that used above for the electrical potential. Therefore the mesh and the parameters entered are similar. The material properties and the boundary conditions are entered in the same way as for the electrical potential.

One can use two kinds of FEM calculations for static magnetic fields; one is calculated using scalar potential and the other with vector potential (see bibliography).

One can define the dimension of the triangle cells by *Dx* and *Dy*. The number of cells in the *x* and *y* directions are defined by *I* and *J* respectively.

The *boundaries* are assigned in the following order:

$x_1\ y_1\ x_2\ y_2\ P_b$ <Enter>

P_b -> potential over the boundary condition [(x_1, y_1)--(x_2, y_2)]. For vector potential the boundaries surrounding the mesh have P_b=0.

The *properties* are assigned in the follow order:

$x_1\ y_1\ x_2\ y_2\ x_3\ y_3\ x_4\ y_4\ Mu$ <Enter>

Mu -> relative magnetic permeability inside the *xy* area. The geometry of the material is the same as for static fields. Elements not assigned will have *Mu* = 1.

The *source* is assigned in the following order:

$x_1\ y_1\ x_2\ y_2\ J_s$ <Enter> - the same as for boundaries condition.

J_s -> current density on the point or line [(x_1, y_1)--(x_2, y_2)].

There are 4 examples for vector potential and one for scalar potential that can be run. For these examples a number in the name of the example, e. g. *[2M]* means that 2 material properties can be changed in the permeability field. The order is from top to bottom, that is, from material 1 to material 5. To run an example the field *Run Example* must be pressed. After that the values used will appear In the properties and boundary conditions fields and can be seen on the screen. It is still possible to change values over the boundary and properties fields, but in this case the *Run Example* must not be pressed again.

6 – WAVES

In this section one can see the interaction between electromagnetic waves and matter including potential and current in transmission lines. Electromagnetic propagation in two dimensions is shown. This is calculated using the Finite Difference Time Domain (FDTD) algorithm. Although the FDTD is used, the user has no interaction with the model: the model is internal and any change in parameters are handled by the program as inputs. Thus the details of the FDTD method are not important.

Reflection and Transmission

In this section, the reflection and transmission of a plane wave in different media is explored. The first option, *Metallic Walls*, is an example of a Gaussian pulse hitting metallic walls; the reflection of the electric and magnetic fields can be seen as they occur. The number of iterations can be changed to suit. In the next part, one can see a sinusoidal planar wave (electric field) crossing different types of media. There are 3 possibilities (1, 2 and 3 media); the electric properties of each medium can be assigned at will. *Length [P]* is the length of the medium in periods of excitation. *Time [P]* is the number of excitation periods to simulate. *Freq. [Hz]* is the frequency of the excitation in Hertz. In the plot option one can choose what waves to plot, *transmitted* (red), *reflected* (green) and *total* (blue).

Transmission Lines

Here one can see the electric potential, current, and input impedance on a transmission line, the potential, input impedance and current at the load are also shown. The phase shown for the load current is the angle assuming zero phase angle for potential at the load. The transmitted fields are plotted in red, the reflected fields in green and the total fields in blue.

The parameters are:

V_{source} = potential of the source [Volts];

Z_{source} = impedance of the source, must be $a + bi$, where i means imaginary number;

Z_{line} = impedance of the transmission line;

Attenuat. = attenuation over the line in Nepers/meter [Np/m];

Phase = phase constant [Rad/m];

Length = length of the transmission line in meters;

Z_{load} = impedance of the load;

Freq. = frequency of the source in Hertz;

Time [P] = number of periods of excitation.

It is also possible to calculate the input impedance Z_{in} at any point on the transmission line, where Z_{in} -> *x[m]* means the distance from the source, so at 0 one has the full length of the transmission line. At the full length the Z_{in} is equal Z_{load}. When this function is used a figure is generated showing the input impedance on the line (magnitude and angle).

FDTD – TE mode

In this part one can see the interaction of the electromagnetic waves with matter in two dimensions, with the possibility of changing parameters such as excitation and material properties. To compute the fields the Finite Differential Time Domain method is applied in a square mesh ($D = Dx = Dy$ = 0.0273 m) in which a TE mode (Transverse Electric Mode) $E_x – E_y$ - H_z. See Fig. 3 and bibliography.

Excitation parameters:

Type = Gaussian Pulse (no frequency assigned, fixed shape) or Sinusoidal (frequency $\leq 10^9$ Hz);

Field = E_x and/or E_y, or H_z.

Plot parameters:

Field = modulus (magnitude) of electric field ($|E|$), or E_x, or E_y, or H_z;

# of interat. to plot = this value means the number of iteration for a new plot, so one can see the wave propagating during the simulation time. If this field is left empty, the fields values of the last iteration (mesh parameter) will be plotted.

One can choose to see the contour of the metal and/ or properties on the mesh.

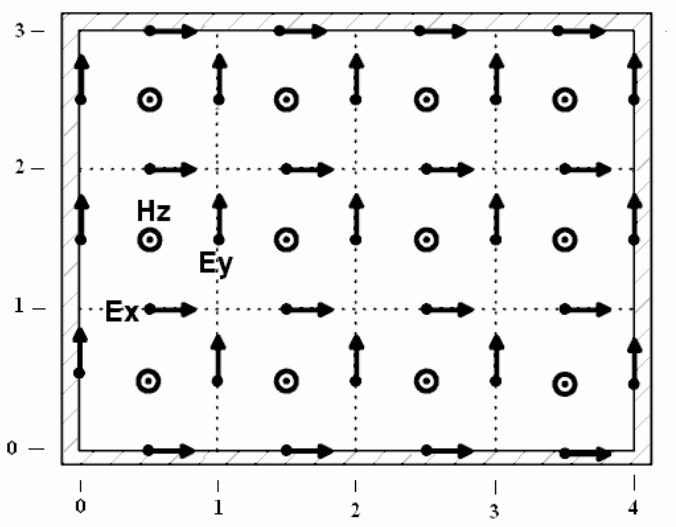

Figure 3. FDTD with square mesh, mode TE. $I = 4$, $J = 3$.

Mesh parameters:

I = number of cells in x direction;
J = number of cells in y direction;
# of iteract. = number of iterations to simulate.

The *excitation* is assigned in the following order:

$x_1\ y_1\ x_2\ y_2$ <Enter>, excitation points over a line defined by 2 points, must be vertical (E_y or H_z) or horizontal (E_x or H_z) ($0 \le x \le I$, $0 \le y \le J$, entire values), example = [0 0 1 0], vector in the first cell. The excitation can also be tilted as the metal boundaries.

The *metal* boundaries are assigned in the following order:

$x_1\ y_1\ x_2\ y_2\ 0$ <Enter> perfect metallic boundary conditions, a line defined by 2 points, can be vertical, horizontal or tilted. If tilted it MUST always have the same number of CELLS in x and y directions)

For a circle:

px py R Qu1 Qu2 <Enter>; *px, py* -> position [x, y] of the circle center;

R -> radius of the circle; number of cells, must be ≥ 3.

Qu1 and *Qu2* (1 = [0º- 90 º], 2 = [90 º -180 º], 3 = [180 º -270 º], 4 = [270 º - 360 º].

If *Qu1* = *Qu2* just one quarter of the circle is assigned. For a complete circle *Qu1* = 1 and *Qu2* = 4; The properties are assigned in anti-clockwise sequence.

If no metallic boundaries are to be used, this field must be left empty.

The *properties* are assigned in the following order:

x_1 y_1 x_2 y_2 x_3 y_3 x_4 y_4 *Per Cond* <Enter>; four points of a box; for triangle use $x_4 = x_3$ and $y_4 = y_3$; it MUST always be isosceles (same number of CELLS in x and y direction) with a right angle (e. g. |_) . The points (x, y) MUST always be entered in anti-clockwise direction starting from the lowest x and x values, (x_{min}, y_{min}); see Fig. 4. At least one property must be assigned.

For a circle:

px py R Qu1 Qu2 0 0 0 Per Cond <Enter>, *px*, *py* -> position [x, y] of the circle center. *R* -> radius of the circle, number of cells, must be ≥ 3.

Qu1 and *Qu2* (1 = [0º- 90 º], 2 = [90 º -180 º], 3 = [180 º -270 º], 4 = [270 º - 360 º].

If *Qu1* = *Qu2* just one quarter of circle is assigned. For a complete circle *Qu1* = 1 and *Qu2* = 4; The properties are assigned in anti-clockwise sequence.

Per -> relative electric permittivity inside the *xy* area. The permittivities are assigned in descending order (first element to last). This means that the second line of permittivities will overwrite the first line and so on. Elements not assigned will have *Per* = 1.

Cond -> electric conductivity in Siemens/meter inside the *xy* area. The condutivities are assigned in descending order (first element to last). Elements not assigned will have *Cond* = 0.

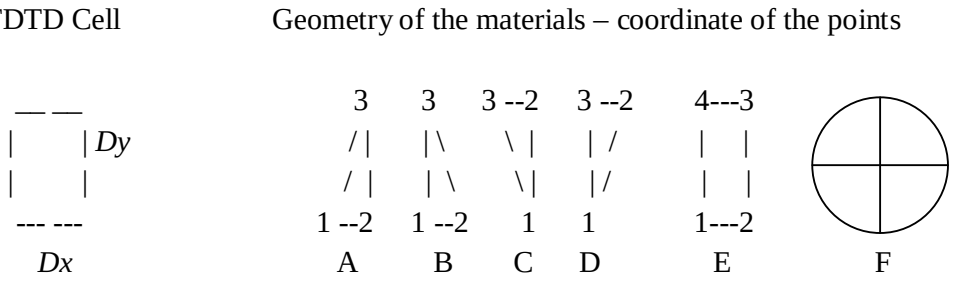

Figure 4. Possible geometries to assign properties into the FDTD mesh.

Examples (see Fig. 3 and Fig. 4):

Excitation:
0 0 2 0 --
0 0 0 3 |
1 1 2 2 /
4 0 1 3 \

Metal:
0 0 3 3 0 /
1 3 4 0 0 \
1 1 4 1 0 --
3 0 3 3 0 |

Properties - A : 0 0 0 2 2 2 2 2 Per_A $Cond_A$
B: 1 1 3 1 1 3 1 3 Per_B $Cond_B$
C: 4 0 4 3 1 3 1 3 Per_C $Cond_C$
D: 2 1 4 3 2 3 2 3 Per_D $Cond_D$
E: 1 1 3 1 3 2 1 2 Per_E $Cond_E$

Considering a mesh with I = 100 and J = 0, for circles (for metal will be the same):

F: 50 50 10 1 4 0 0 0 Per_1 $Cond_1$ - [0 º - 360 º] full circle
30 40 10 1 2 0 0 0 Per_2 $Cond_2$ - [0 º - 180 º]
90 90 20 4 4 0 0 0 Per_3 $Cond_3$ - [270 º - 360 º]

Boundaries surrounding the mesh

Two algorithms can be use, one will use *metallic* boundaries and the other will use absorbing boundary condition (*ABC*) simulation the free space (Perfect Matched layer is used – *PML*, see bibliography).

Examples

Free Space GP - a Gaussian pulse propagates in the free space using PML. E_x E_y and H_z are shown.

3D Cavity – show a Gaussian pulse inside of a metallic cavity (box).

Scattering – shows waves hitting metallic walls and scattering from them.

Diffraction - A planar wave undergoing diffraction at a metallic wall with a gap.

Cylinder – two different materials, one in the shape a circle. Inside it there is a small metal circle.

Many Shapes – many properties and metals with different shapes.

Monopole – a small monopole over a metal ground.

Dipole – a small dipole in free space

Waveguide – a waveguide surrounded by two different media, excited with a planar wave.

In the first 4 examples above the properties cannot be changed. The other examples are self explanatory and their configurations can be changed. To run the examples the *Run Example* must be pressed.

Note: The software does not protect against wrong coordinates, so one must be sure to use the correct coordinates according to the mesh, and inside the calculate domain. Because de cell dimensions are fixed the coordinate values are integer numbers.

Staircase lines will be used when straight lines cannot possible (due to the FDTD mesh).

The plots will be shown after the computation is finished (It takes some time before the plots appear).

When the function PAUSE is used, pressing any key on the keyboard will re-start the plot. Some functions do not stop if PAUSE is pressed just once.

To stop plotting, one must use < Control + c >.

Hint: When the *waves* window is open, do not select *Run Example*, and push the FDTD button (a “ready made” example will be executed).

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