NASA/CR-1998-208709

User's Manual for FEMOM3DR

Version 1.0

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Prepared for Langley Research Center
under Cooperative Agreement NCC1-231

September 1998

Available from the following:

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1. INTRODUCTION

FEMOM3DR is a computer code written in FORTRAN 77 to compute electromagnetic(EM) radiation characteristics of antennas on a three dimensional object with complex materials (fig. 1) using combined Finite Element Method (FEM)/Method of Moments (MoM) technique[1]. This code uses the tetrahedral elements, with vector edge basis functions for FEM in the volume of the cavity and the triangular elements with the basis functions similar to that described in [2], for MoM at the outer boundary. By virtue of FEM, this code can handle any arbitrarily shaped three-dimensional bodies filled with inhomogeneous lossy materials. The basic theory implemented in the code is given in Appendix 1.

The User's Manual is written to make the user acquainted with the operation of the code. The user is assumed to be familiar with the FORTRAN 77 language and the operating environment of the computers on which the code is intended to run. The organization of the manual is as follows. Section 1 is the introduction. Section 2 explains the installation requirements. The operation of the code is given in detail in Section 3. Three example runs, the first EM radiation characteristics of an open coaxial line in a 3D PEC body, the second radiation characteristics of an open rectangular waveguide in a 3D PEC body, and the third EM radiation characteristics of an open circular waveguide in a three dimensional cavity are demonstrated in Section 4. Users are encouraged to try these cases to get themselves acquainted with the code.

2. INSTALLATION OF THE CODE

The distribution disk of FEMOM3DR is 3.5" floppy disk formatted for IBM compatible PCs. It contains a file named `femom3dr.tar.gz`. This file has to be transferred to any UNIX machine via `ftp` using binary mode. On the UNIX machine, use the following commands to get all the files.

```
gunzip femom3dr.tar.gz
tar -xvf femom3dr.tar
```

This creates a directory `FEMOM3DR-1.0`, which in turn contains the

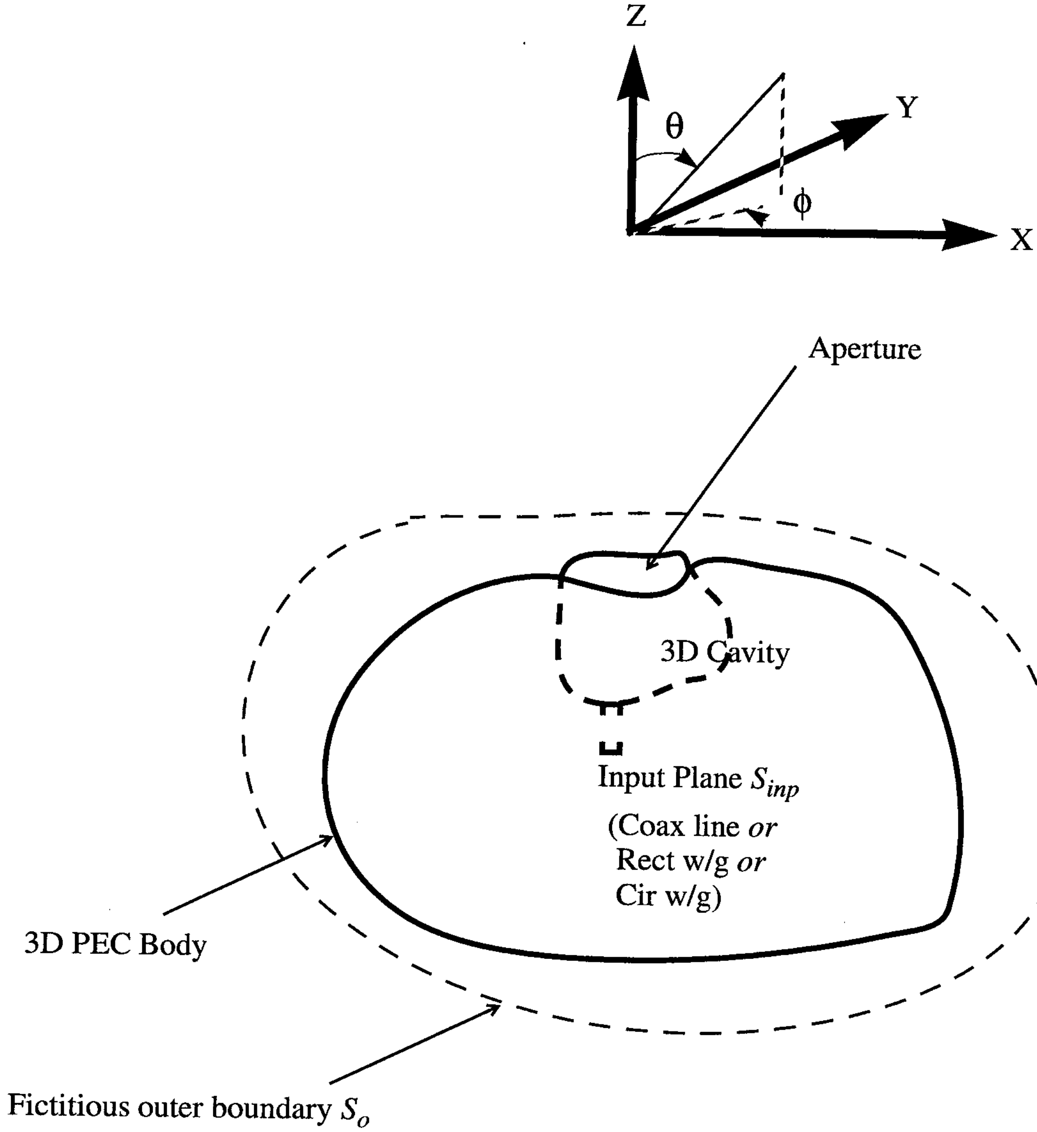


Figure 1 Illustration of cavity-backed radiating aperture in a 3D PEC body. The cavity is fed by a coaxial line or a rectangular waveguide or a circular waveguide at the input plane S_{inp}. The fictitious outer surface S_o is used to terminate the FEM computational domain.

subdirectories, `FEMOM3DR` (source files for the main code), `PRE_FEMOM3DR` (source files for preprocessing code), `Example1`, `Example2` and `Example3` As the code is written in FORTRAN 77, with no particular computer in mind, the source code in these directories should compile on any computer architecture without any problem. The code was successfully complied on a SGI machine, and the compilation can be done by using a `makefile` file for the different machines such as SUN, DEC or CONVEX etc. The complete listing of the directories in the distribution disk is given in Appendix 2.

3. OPERATION OF THE CODE

The computation of EM radiation characteristics from a specific geometry with FEMOM3DR is a multi-stage process as illustrated in figure 2. The geometry of the problem has to be constructed with the help of any commercial Computer Aided Design (CAD) package. In our case, we used COSMOS/M[3] as our geometry modeler and meshing tool. As FEMOM3DR uses edge based basis functions, the nodal information supplied by most of the meshing routines cannot be readily used. Hence, a preprocessor PRE_FEMOM3DR is written to convert the nodal based data into edge based data and then is given as input to FEMOM3DR. For the convenience of the users, who use different CAD/meshing packages other than COSMOS/M, PRE_FEMOM3DR accepts the nodal based data in a generic format also. The procedures involved for using COSMOS/M input data file or generic input data file are explained below.

With the help of COSMOS/M, the geometry is constructed and meshed with tetrahedral elements. The user is assumed to be familiar with COSMOS/M package and its features. Once the mesh is generated, one needs to identify the following to impose proper boundary conditions:

(a) tetrahedral elements with different material parameters[1],

(b) elements on PEC surfaces

(c) elements on the outer boundary

(d) elements on the input plane

1. COSMOS/M has a feature by which it can group tetrahedral elements with different material properties into different groups. For a generic file input, the user has to specify the material property index for each tetrahedral element to indicate its material property group(see Appendix 4).

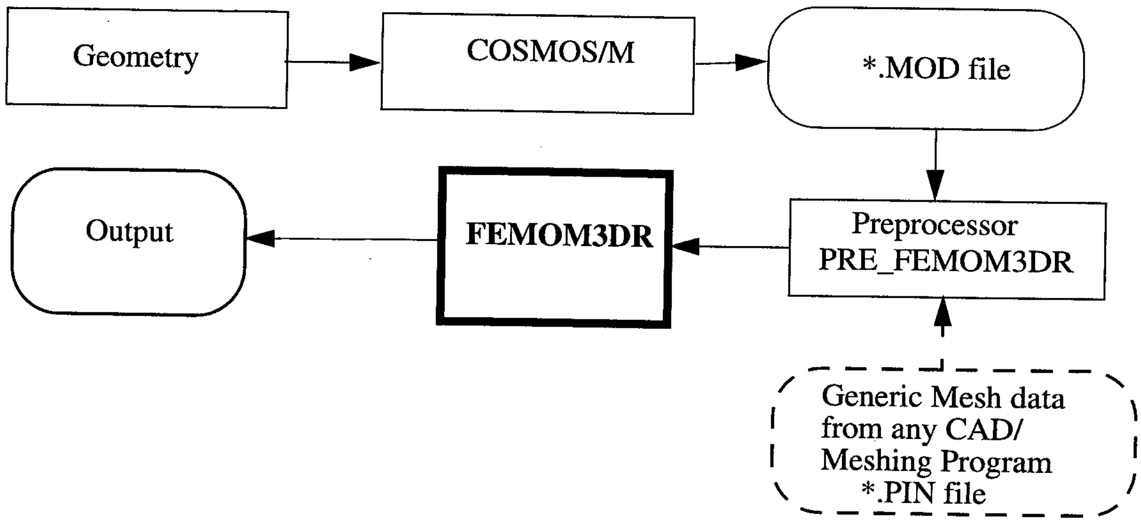


Figure 2 Flow chart showing the various steps involved in using FEMOM3DR

This is done using the available features in COSMOS/M. Sample *.SES files of COSMOS/M which illustrate these features are given in Appendix 3. Finally the *.MOD file is generated with the required mesh information. PRE_FEMOM3DR accepts the *.MOD file as input and generates the required edge based data.

For users, who can do geometry modelling and meshing of the model with any other CAD package, the nodal based information is required to be placed in a file `problem.PIN`, where `problem` is the name of the problem under consideration. The format required for `*.PIN` file is given in Appendix 4. Note that all the dimensions of the geometry are assumed to be in centimeters.

The PRE_FEMOM3DR code gives the following prompts:

```
pre_femom3dr
Give the problem name:
```

The problem name is the user defined name for the particular problem under consideration.

```
COSMOS file (1) or GENERIC (2) file?
```

If you are using *.MOD file from COSMOS/M, give 1 or using the generic input data file explained above, give 2.

PRE_FEMOM3DR generates the following files with required edge based information.

(a) `problem_nodal.DAT` - Node coordinates and the node numbers for each element

(b)`problem_edges.DAT` - Information on edges, such as nodes connecting each edge, etc.

(c) `problem_surfed.DAT` - Information on edges on outer surfaces.

(d) `problem_surfel.DAT` - Information on edges on input surface.

(e) `problem.POUT` - General information on the mesh.

The files (a) to (d) are used as input for FEMOM3DR. Users need not interact or modify the above files.

After PRE_FEMOM3DR is run, all but one input data file required for FEMOM3DR are ready. FEMOM3DR expects to find `problem.MAT` file which contains the material constants information required for the volume elements. The format of the `problem.MAT` is as given below:

N_g,	Maximum number of material groups
ε_{r1}, μ_{r1}	Complex relative permittivity, complex relative permeability respectively
ε_{r2}, μ_{r2}	for material groups 1, 2, 3, ..., N_g
.	
.	
ε_{rN_g}, μ_{rN_g}	

In the PRE_FEMOM3DR, all the terahedral elements are given the material group index. The material parameters given in `problem.MAT` are read into FEMOM3DR and the proper material parameters are assigned to each tetrahedral element according to its material property index. Once the `problem.MAT` is ready, FEMOM3DR code can be run. The FEMOM3DR code gives the following prompts:

```
femom3dr
Give the problem name :
```

This name should be the same as given for PRE_FEMOM3DR

```
Frequency (GHZ) :
```

This is the frequency of operation. If the dimensions of the problem are in wavelengths, frequency should be specified as 30 GHz as FEMOM3DR assumes that all dimensions are in centimeters.

```
Give the type of feed line :
 coax(1), rect wg(2), cir wg(3)
```

This is to specify the type of feed line to be used. User should give 1 if coaxial feed is used, or 2 if rectangular waveguide is used as feed, or 3 if circular waveguide is used as feed. Depending on the feed line to be used, FEMOM3DR gives different prompts to input the feed line parameters.

For coax(1)

```
Coaxial feed line
Give Inner rad, r1(cm), Outer rad, r2(cm):
```

Specify the inner radius and outer radius of the coaxial line.

```
Dielectric const for the coaxial line, er1
```

Specify the dielectric constant used for the coaxial line.

For rect wg(2)

```
Rectangular waveguide feed
Give waveguide dimensions : a(cm), b(cm)
```

Specify the waveguide dimensions, broad wall dimension a(cm), narrow wall dimension b(cm)

For cir wg(3)

```
Circular waveguide feed
Give the radius of circular waveguide aa(cm):
```

Specify the radius of the circular waveguide in cms.

```
For computing radiation pattern, give Theta(degs) -
 start angle, stop angle and increment
```

Specify the start and stop angles of θ in degrees. Radiation patterns will be computed in both $\phi = 0^o$ and $\phi = 90^o$ planes.

FEMOM3DR generates the file *problem*.OUT, which contains information on CPU times for matrix generation, matrix fill, the input characteristics and the radiation pattern data. FEMOM3DR also generates another file *problem*_bicgd.DAT which contains information on convergence history of diagonally preconditioned biconjugate gradient algorithm used to solve the matrix equations.

4. SAMPLE RUNS

Three example runs are illustrated in this section. They are selected to illustrate some of the features of FEMOM3DR.

Example 1 : Radiation from an open coaxial line in a 3D PEC body

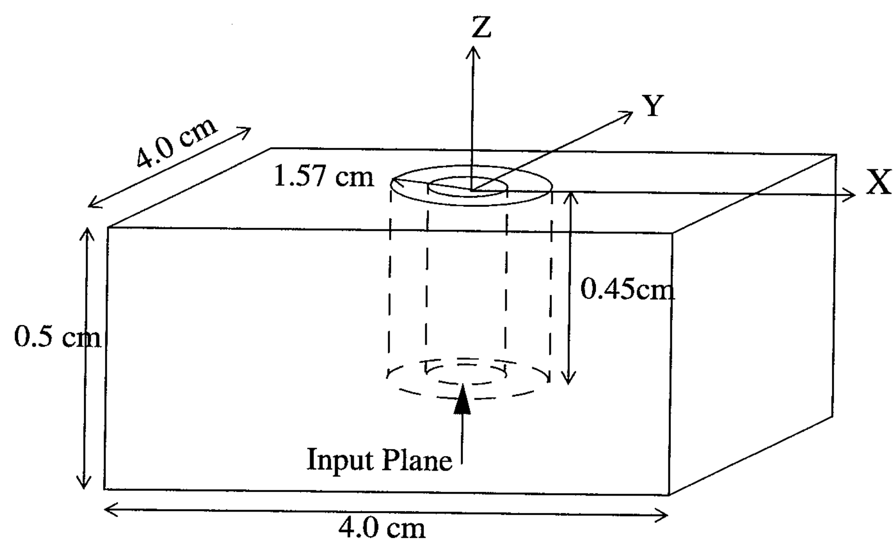


Figure 3 Open coaxial line in a 3D PEC box. The analysis is carrired out at 5.73GHz. Inner radius of the coaxial line is 1.0cm and outer radius is 1.57cm.

An open coaxial line in a 3D PEC box is considered. Assuming the dominant TEM mode propagation in the coaxial line the radiation pattern and input characteristics (z=0 as reference plane) are calculated.

First the PRE_FEMOM3DR

```
cjr@caph:{53} pre_femom3dr
 Give the problem name :
coax
 COSMOS file(1) or GENERIC(2) file ? :
1
  Opening file :coax.MOD

 Read the following data
 Nodes=          403
 Elements=         1201
 Elements on surface 1=           468
 Elements on surface 2=            44
  Max number of material groups=           1

 Forming the edges !!! Be patient !!!

  Order of the FEM matrix- nptrx=        1554

 ***************************************************

 Number of nodes=          403
 Number of elements=         1201
 Number of total edges=         2001
 Number of elements on Surface 1=          468
 Number of elements on Surface 2=           44
 Number of edges on surface 0(pec)=          447
 Number of edges on surface 1=          702
 Number of edges on surface 2=           84
 Max number of material groups=           1

 Order of FEM matrix=         1554
 Order of MoM matrix(electric cuurent)=           702
 Unknown for the magnetic current=          702
 Number of unknowns on Input plane=          48

 Order of Hybrid FEM/MoM matrix=         2256
 ***************************************************
```

The `coax.MAT` file for this problem is given below:

```
1

(1.0,0.0) (1.0,0.0)
```

And then FEMOM3DR :

```
cjr@caph:{55} femom3dr

 Give the problem name :
coax
  Reading the input !!
 Finished reading the data
 Give frequency of operation : GHz
5.73
  Give the type of feed line :
  coax(1), rect wg(2), cir wg(3)
1
  Coaxial feed line
  Give Inner rad, r1(cm), Outer rad, r2(cm):
1.0 1.57
  Dielectric const for the coaxial line, er1
1.0
 For Computing the radiation pattern, give Theta(degs)-
             Give start angle, stop angle and increment
-180 180 10

 **************************************
 *                                    *
 *                                    *
 *        FEMoM3DR(Version 1.0)       *
          Problem : coax
 *         (BiCGDNS Solver)           *
 *                                    *
 *                                    *
 **************************************

RADIATION CHARACTERISTICS OF AN ANTENNA ON
     A 3D BODY USING FEM/MOM HYBRID METHOD

Frequency (GHz)            =   5.730000
Order of the FEM-MoM matrix=        2256
Order of the MoM matrix    =         702

Coax feed is used
with characteristic impedance(ohms)=   27.06454
Radius of inner conductor(cm)=   1.000000
Radius of outer conductor(cm)=   1.570000
Dielectric constant =   1.000000

*------------------------------------*
```

```
 Generating FEM matrix
 Number of non zeros in amat(zmatrices)=        17790
Time to fill FEM matrix(secs)=  0.2383671
 net=          1554
Time to fill zmatrixeh=  5.1747322E-02
 Generating Zmatrices
Entering zmatrixej
Time to fill zmatrixej(secs)=   155.7325
Entering zmatrixem
Time to fill zmatrixem(secs)=   221.0665
Time to fill zmatrices (secs)=   377.7292
Total no of non zeros after adding zmatrices=      900366
 Calling selmts_coax
Entered selmts.f
beta10=    1.200088     r2=    1.570000
 r1=    1.000000     zc=    27.06454

 Out of selmts
 Total nonzeros in amat after smat=       902502
Solving the system of equations Ax=B by BiCGDNS
CONVERGENCE ACHIEVED in         1833 iterations
Residual Norm=  6.8373792E-04
Time to solve by BiCGDNS(secs)=   1133.188

Input parameters for the coaxial feed

Reflection Coefficient S11= (0.2084835,-0.6935343)
Return Loss (db) =    -2.802917
Normalized Input Admittance,Yin/Yo= (0.2449467,0.7144601)
Normalized Input Impedance,Zin/Zo= (0.4293905,-1.252445)

*-------------------------------------*
        RADIATION PATTERN (phi=0 deg plane)

Theta(deg)     10log|Eth|^2     10log|Eph|^2

         -180   -54.19743        -48.60585
         -170   -10.79702        -46.29274
         -160   -5.749784        -45.47018
         -150   -3.863171        -46.03180
         -140   -3.623751        -48.02142
         -130   -4.477120        -51.30671
         -120   -5.877765        -52.62412
         -110   -6.739963        -49.10905
         -100   -5.970154        -45.52240
          -90   -4.136563        -42.71252
```

-80	-2.249640	-40.37156
-70	-0.6981635	-38.32143
-60	0.4049507	-36.53478
-50	0.9726373	-35.07118
-40	0.8663030	-34.02491
-30	-0.1586271	-33.50406
-20	-2.607281	-33.62665
-10	-8.010056	-34.52869
0	-36.21795	-36.36510
10	-7.811026	-39.21128
20	-2.518029	-42.22832
30	-0.1083566	-42.46354
40	0.8974382	-40.67097
50	0.9943753	-39.39063
60	0.4234217	-38.98084
70	-0.6786989	-39.25732
80	-2.226301	-40.00126
90	-4.108023	-41.00850
100	-5.937835	-42.10268
110	-6.708505	-43.18414
120	-5.847709	-44.28653
130	-4.445064	-45.59224
140	-3.588042	-47.41969
150	-3.822448	-50.17274
160	-5.698858	-53.34728
170	-10.70996	-52.22258
180	-54.19810	-48.60595

RADIATION PATTERN (phi=90 deg plane)

Theta(deg)	10log|Eth|^2	10log|Eph|^2
-180	-48.60547	-54.19707
-170	-10.82473	-48.70198
-160	-5.750631	-46.34335
-150	-3.852743	-46.03323
-140	-3.605450	-47.45369
-130	-4.451667	-49.95887
-120	-5.845438	-50.09461
-110	-6.704795	-46.91512
-100	-5.939765	-43.87301
-90	-4.112114	-41.47113
-80	-2.229023	-39.44118

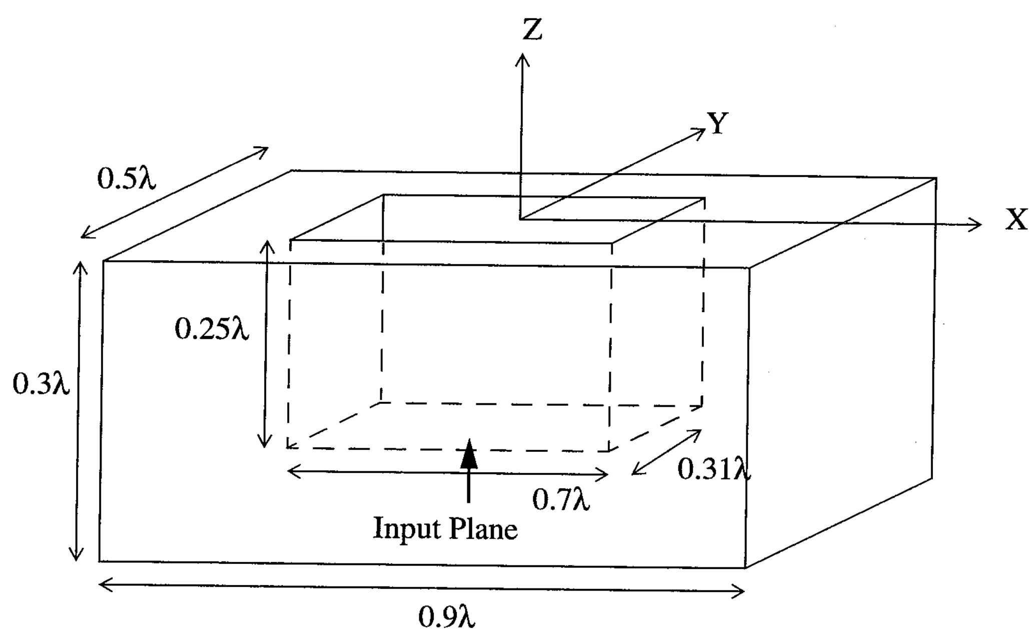
```
   -70 -0.6802469        -37.61844
   -60  0.4204952        -35.99508
   -50  0.9857212        -34.65906
   -40  0.8764857        -33.73360
   -30 -0.1524250        -33.34271
   -20  -2.608197        -33.59753
   -10  -8.031898        -34.57314
     0  -36.36512        -36.21797
    10  -7.751746        -38.06224
    20  -2.476610        -39.02908
    30 -7.2064906E-02    -38.79224
    40  0.9319770        -38.36481
    50   1.028536        -38.43649
    60  0.4578517        -39.14530
    70 -0.6437781        -40.43156
    80  -2.191107        -42.17726
    90  -4.073897        -44.22516
   100  -5.909275        -46.39298
   110  -6.691441        -48.57036
   120  -5.837529        -50.81551
   130  -4.433287        -53.07823
   140  -3.571158        -54.74577
   150  -3.798558        -56.00808
   160  -5.664153        -59.84210
   170  -10.64892        -69.49425
   180  -48.60628        -54.19751

*--------------------------------------*

****************************************
```

The complete session of this run on a SGI machine along with all the files is kept in the directory `./FEMOM3DR-1.0/Example1`.

Example 2 : Radiation from an open rectangular waveguide in a 3D PEC body



OUTER BOUNDARY FOR FEM-MoM : 1.0λX0.6λX0.5λ

Figure 4 Open Rectangular waveguide in a 3D PEC box

An open rectangular waveguide in a 3D PEC box is considered. Assuming the dominant TE_{10} mode propagation in the waveguide the radiation pattern and input characteristics (z=0 as reference plane) are calculated.

First the PRE_FEMOM3DR

```
cjr@caph:{11} pre_femom3dr
 Give the problem name :
rwg
 COSMOS file(1) or GENERIC(2) file ? :
1
  Opening file :rwg.MOD

 Read the following data
 Nodes=          565
```

```
  Elements=          1743
  Elements on surface 1=          560
  Elements on surface 2=           56
   Max number of material groups=          1

  Forming the edges !!! Be patient !!!

   Order of the FEM matrix- nptrx=        2159

  ***************************************************

  Number of nodes=          565
  Number of elements=          1743
  Number of total edges=          2836
  Number of elements on Surface 1=          560
  Number of elements on Surface 2=           56
  Number of edges on surface 0(pec)=          677
  Number of edges on surface 1=          840
  Number of edges on surface 2=           95
  Max number of material groups=          1

  Order of FEM matrix=          2159
  Order of MoM matrix(electric cuurent)=          840
  Unknown for the magnetic current=          840
  Number of unknowns on Input plane=           73

  Order of Hybrid FEM/MoM matrix=          2999
  ***************************************************
cjr@caph:{12}
```

The `rwg.MAT` file for this problem is given below:

```
1

(1.0,0.0) (1.0,0.0)
```

And then FEMOM3DR :

```
cjr@caph:{18} femom3dr
 Give the problem name :
rwg
  Reading the input !!
 Finished reading the data
 Give frequency of operation : GHz
30.0
  Give the type of feed line :
```

```
  coax(1), rect wg(2), cir wg(3)
2
  Rectangular waveguide feed
 Give waveguide dimensions : a(cm), b(cm)
0.7 0.31
 For Computing the radiation pattern, give Theta(degs)-
            Give start angle, stop angle and increment
-180 180 10

 ***************************************
 *                                     *
 *                                     *
 *         FEMoM3DR(Version 1.0)       *
           Problem : rwg
 *          (BiCGDNS Solver)           *
 *                                     *
 *                                     *
 ***************************************

 RADIATION CHARACTERISTICS OF AN ANTENNA ON
      A 3D BODY USING FEM/MOM HYBRID METHOD

 Frequency (GHz)              =   30.00000
 Order of the FEM-MoM matrix=         2999
 Order of the MoM matrix      =        840

 Rect w/g feed is used
 a(cm)=  0.7000000     b(cm)=  0.3100000


 *--------------------------------------*
  Generating FEM matrix
  Number of non zeros in amat(zmatrices)=        25494
 Time to fill FEM matrix(secs)=  0.3556371
  net=         2159
 Time to fill zmatrixeh(secs)=  6.2365055E-02
  Generating Zmatrices
 Entering zmatrixej
 Time to fill zmatrixej(secs)=   219.9152
 Entering zmatrixem
 Time to fill zmatrixem(secs)=   316.8897
 Time to fill zmatrices (secs)=   537.7435
 Total no of non zeros after adding zmatrices=     1393424
  calling selmts_rwg
 Entered selmts.f
  Total nonzeros in amat after smat=      1398430
```

```
Solving the system of equations Ax=B by BiCGDNS
CONVERGENCE ACHIEVED in          1172 iterations
Residual Norm=  8.4834168E-04
Time to solve by BiCGDNS=   1134.912

Input parameters for the Rect W/G feed

Reflection Coefficient S11= (-9.9301338E-05,-0.2776211)
Return Loss (db) =   -11.13095
Normalized Input Admittance,Yin/Yo= (0.8570415,0.5156051)
Normalized Input Impedance,Zin/Zo= (0.8567256,-0.5154150)

*-------------------------------------*
       RADIATION PATTERN (phi=0 deg plane)
```

Theta(deg)	10log|Eth|^2	10log|Eph|^2
-180	-61.92020	-15.32931
-170	-61.31005	-15.91580
-160	-63.44328	-17.62041
-150	-68.74234	-20.02731
-140	-70.03734	-21.95038
-130	-66.70441	-22.52033
-120	-66.59460	-22.63553
-110	-69.86186	-22.92205
-100	-80.20856	-22.88857
-90	-75.01617	-21.71360
-80	-66.67963	-19.52076
-70	-61.93605	-17.02657
-60	-58.61893	-14.62941
-50	-56.34359	-12.44571
-40	-54.92506	-10.51392
-30	-54.19392	-8.882670
-20	-54.09115	-7.628004
-10	-54.73644	-6.834783
0	-56.31515	-6.567938
10	-58.89853	-6.851701
20	-62.37308	-7.662488
30	-66.48820	-8.935760
40	-68.71347	-10.58671
50	-65.26954	-12.53923
60	-61.62342	-14.74527
70	-59.33685	-17.16811
80	-58.21431	-19.69254
90	-58.07228	-21.91248
100	-58.69095	-23.08877

110	-59.40402	-23.10446
120	-59.10530	-22.81736
130	-58.09814	-22.72412
140	-57.81826	-22.14926
150	-59.14966	-20.15278
160	-62.25060	-17.67859
170	-63.91365	-15.93773
180	-61.92001	-15.32932

RADIATION PATTERN (phi=90 deg plane)

Theta(deg)	10log|Eth|^2	10log|Eph|^2
-180	-15.32931	-61.92018
-170	-16.02150	-65.08558
-160	-18.24953	-70.05646
-150	-22.28396	-66.70027
-140	-23.93000	-61.27969
-130	-19.31891	-58.02380
-120	-15.70994	-56.15014
-110	-13.44800	-55.23307
-100	-12.02561	-55.06901
-90	-11.12439	-55.57724
-80	-10.53237	-56.79272
-70	-10.08482	-58.91708
-60	-9.642760	-62.51046
-50	-9.107477	-69.14857
-40	-8.457344	-70.94614
-30	-7.761731	-63.66030
-20	-7.142992	-59.79226
-10	-6.719075	-57.57387
0	-6.567938	-56.31525
10	-6.716807	-55.73727
20	-7.140977	-55.68583
30	-7.764509	-56.01447
40	-8.469784	-56.53829
50	-9.131585	-57.07994
60	-9.675299	-57.59613
70	-10.11881	-58.23421
80	-10.56100	-59.23457
90	-11.14358	-60.82451
100	-12.03413	-63.11628
110	-13.44629	-65.54780
120	-15.69828	-65.80795

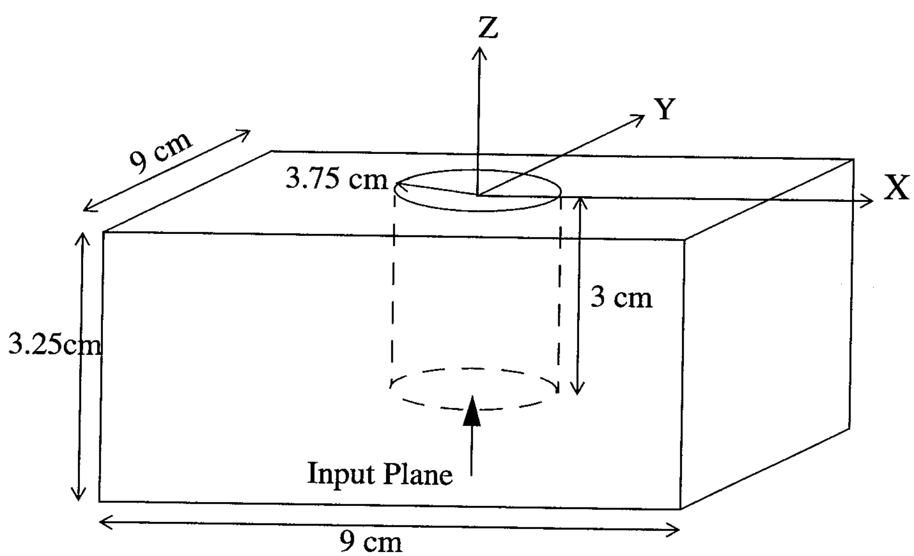
```
130   -19.29325         -63.71844
140   -23.87317         -61.69011
150   -22.24701         -60.44720
160   -18.23417         -60.01572
170   -16.01494         -60.42999
180   -15.32931         -61.92015

*-------------------------------------*

*************************************
```

The complete session of this run on a SGI machine along with all the files is kept in the directory `./FEMOM3DR-1.0/Example2.`

Example 3: Radiation from an open circular waveguide in a 3D PEC box



OUTER BOUNDARY FOR FEM-MoM : 10cmX10cmX4cm

Figure 5 An open circular waveguide in a 3D PEC box

An open circular waveguide in a 3D PEC box is considered. Assuming the dominant TE_{11} mode propagation in the waveguide the radiation pattern and input characteristics (z=0 as reference plane) are calculated at 2.8GHz.

First the PRE_FEMOM3DR

```
cjr@caph:{60} pre_femom3dr
 Give the problem name :
cwg
 COSMOS file(1) or GENERIC(2) file ? :
1
  Opening file :cwg.MOD

 Read the following data
 Nodes=         601
 Elements=        1915
 Elements on surface 1=        564
 Elements on surface 2=         64
  Max number of material groups=          1

 Forming the edges !!! Be patient !!!

  Order of the FEM matrix- nptrx=        2332

 ***************************************************

 Number of nodes=          601
 Number of elements=         1915
 Number of total edges=         3071
 Number of elements on Surface 1=          564
 Number of elements on Surface 2=           64
 Number of edges on surface 0(pec)=          739
 Number of edges on surface 1=          846
 Number of edges on surface 2=          106
 Max number of material groups=            1

 Order of FEM matrix=          2332
 Order of MoM matrix(electric cuurent)=          846
 Unknown for the magnetic current=          846
 Number of unknowns on Input plane=           86

 Order of Hybrid FEM/MoM matrix=          3178
 ***************************************************
```

The `cwg.MAT` file for this problem is given below:

```
1

(1.0,0.0) (1.0,0.0)
```

```
cjr@caph:{65} femom3dr
 Give the problem name :
cwg
  Reading the input !!
 Finished reading the data
 Give frequency of operation : GHz
2.8
  Give the type of feed line :
  coax(1), rect wg(2), cir wg(3)
3
  Circular waveguide feed
 Give the radius of circular waveguide aa(cm):
3.75
 For Computing the radiation pattern, give Theta(degs)-
             Give start angle, stop angle and increment
-180 180 10

 ***************************************
 *                                     *
 *                                     *
 *       FEMoM3DR(Version 1.0)         *
         Problem : cwg
 *        (BiCGDNS Solver)             *
 *                                     *
 *                                     *
 ***************************************

 RADIATION CHARACTERISTICS OF AN ANTENNA ON
      A 3D BODY USING FEM/MOM HYBRID METHOD

 Frequency (GHz)            =   2.800000
 Order of the FEM-MoM matrix=       3178
 Order of the MoM matrix    =        846

 Circular w/g feed is used
 Radius of the w/g(cm)=   3.750000


*-------------------------------------*
 Generating FEM matrix
 Number of non zeros in amat(zmatrices)=        27988
Time to fill FEM matrix(secs)=  0.3919129
 net=         2332
Time to fill zmatrixeh=  6.6025734E-02
 Generating Zmatrices
Entering zmatrixej
```

```
CONVERGENCE ACHIEVED in          2245 iterations
Residual Norm=  8.8973634E-04
Time to solve by BiCGDNS(secs)=   2174.860

Input parameters for the cir waveguide feed

Reflection Coefficient S11= (-0.1300059,3.4798384E-02)
Return Loss (db)  =    -17.42023
Normalized Input Admittance,Yin/Yo= (1.295194,-9.1804117E-02)
Normalized Input Impedance,Zin/Zo= (0.7682255,5.4452278E-02)

*-------------------------------------*
        RADIATION PATTERN (phi=0 deg plane)

Theta(deg)     10log|Eth|^2     10log|Eph|^2

        -180  -22.75692        -63.35085
        -170  -24.54149        -60.63559
        -160  -30.61100        -59.22809
        -150  -27.98133        -58.73494
        -140  -21.97158        -58.88988
        -130  -19.15922        -59.52450
        -120  -17.95044        -60.42453
        -110  -17.54107        -61.02032
        -100  -17.34824        -60.33348
         -90  -16.88481        -58.21341
         -80  -15.86516        -55.56404
         -70  -14.29549        -53.00042
         -60  -12.37232        -50.69931
         -50  -10.33036        -48.69147
         -40  -8.376839        -46.99461
         -30  -6.681361        -45.64932
         -20  -5.375779        -44.71483
         -10  -4.553909        -44.25065
           0  -4.271783        -44.29565
          10  -4.548341        -44.85369
          20  -5.365640        -45.88722
          30  -6.668044        -47.32177
          40  -8.360756        -49.06322
          50  -10.30902        -51.02592
          60  -12.33875        -53.16288
          70  -14.23919        -55.49183
          80  -15.77886        -58.11651
          90  -16.77509        -61.16561
         100  -17.23692        -64.18618
         110  -17.45133        -64.79224
```

120	-17.89702	-62.96498
130	-19.15180	-61.55912
140	-22.02265	-61.53593
150	-28.06933	-63.19190
160	-30.24335	-66.42630
170	-24.41655	-67.00469
180	-22.75692	-63.35098

RADIATION PATTERN (phi=90 deg plane)

Theta(deg)	10log|Eth|^2	10log|Eph|^2
-180	-63.35092	-22.75693
-170	-61.79300	-23.50035
-160	-62.38220	-25.78485
-150	-65.55884	-29.34372
-140	-64.24979	-32.63723
-130	-58.26767	-33.54564
-120	-54.45654	-31.86797
-110	-52.24393	-27.87085
-100	-51.02455	-23.65279
-90	-50.39310	-20.07571
-80	-50.00290	-17.06390
-70	-49.51344	-14.43425
-60	-48.66899	-12.06949
-50	-47.46519	-9.930590
-40	-46.14532	-8.040731
-30	-45.00156	-6.461413
-20	-44.24279	-5.266761
-10	-43.98824	-4.522365
0	-44.29570	-4.271783
10	-45.18002	-4.530254
20	-46.61389	-5.283057
30	-48.51177	-6.487364
40	-50.69865	-8.078716
50	-52.88061	-9.984387
60	-54.68048	-12.14472
70	-55.80803	-14.53915
80	-56.25292	-17.21146
90	-56.26787	-20.28884
100	-56.18223	-23.97681
110	-56.26547	-28.39919
120	-56.69032	-32.71435

```
130   -57.53803        -34.63153
140   -58.86083        -33.68311
150   -60.81037        -29.88833
160   -63.46891        -26.00092
170   -65.06511        -23.57710
180   -63.35083        -22.75694

*-----------------------------------*

************************************
```

The complete session of this run on a SGI machine along with all the files is kept in the directory `./FEMOM3DR-1.0/Example3`.

5. CONCLUDING REMARKS

The usage of FEMOM3DR code is demonstrated so that the user can get acquainted with the details of using the code with minimum possible effort. As no software can be bug free, FEMOM3DR is expected to have hidden bugs which can only be detected by the repeated use of the code for a variety of geometries. Any comments or bug reports should be sent to the author. As the reported bugs are fixed and more features added to the code, future versions will be released. Information on future versions of the code can be obtained from

Electromagnetics Research Branch (MS 490)
Flight Electronics and Technology Division
NASA-Langley Research Center
HAMPTON VA 23681

ACKNOWLEDGEMENTS

The author would like to thank Mr. Fred B. Beck and Dr. C.R. Cockrell of NASA Langley Research Center for the useful discussions and constant support during the development of this code.

Appendix 1

Theory for FEMOM3DR

This appendix is intended to give a brief description of the theory behind the code. The geometry of the structure to be analyzed is shown in figure 1. S_o represents the area of the fictitious outer boundary to be used for terminating the FEM computational domain and S_{inp} represents the area of the input plane. The electric field inside the compuational domain satisfies the vector wave equation[4]

$$\nabla\times\left(\frac{1}{\mu_r}\nabla\times\mathbf{E}\right)-k_o^2\varepsilon_r\mathbf{E} = 0 \qquad (1)$$

where ε_r and μ_r are the relative permittivity and relative permeability of the medium. The time dependency of $\exp(j\omega t)$ is assumed through out this report. To facilitate the suitable solution of the partial differential equation in (1) via FEM, multiply equation (1) with a vector testing function $\mathbf{T}$ and integrate over the volume of the computational domain. By applying suitable vector identities, equation(1) can be written in its weak form as,

$$\iiint_V \frac{1}{\mu_r}(\nabla\times\mathbf{T})\bullet\left(\frac{1}{\mu_r}\nabla\times\mathbf{E}\right)dv-k_o^2\varepsilon_r\iiint_V\mathbf{T}\bullet\mathbf{E}dv = \iiint_V\nabla\bullet\left(\mathbf{T}\times\frac{1}{\mu_r}\nabla\times\mathbf{E}\right)dv \qquad (2)$$

Applying the divergence theorem to the right hand side of equation(2), the volume integral is written as sum of the surface integral over the surface S_o terminating the FEM computational domain and the surface integral over S_{inp} at the input plane.

$$\iiint_V \frac{1}{\mu_r}(\nabla\times\mathbf{T})\bullet(\nabla\times\mathbf{E})dv-k_o^2\varepsilon_r\iiint_V\mathbf{T}\bullet\mathbf{E}dv = -\iint_{S_o}\mathbf{T}\bullet\left(\hat{n}_o\times\frac{1}{\mu_r}\nabla\times\mathbf{E}\right)ds$$

$$-\iint_{S_{inp}}\mathbf{T}\bullet\left(\hat{n}_i\times\frac{1}{\mu_r}\nabla\times\mathbf{E}\right)ds \qquad (3)$$

where $\hat{n}_o$ is the unit outward normal to the surface S_o and $\hat{n}_i$ is the unit outward normal to the surface S_{inp}.

To discretize the above volume and surface integrals, the FEM computational domain is subdivided into small volume tetrahedral elements. The electric field is expressed in terms of vector edge basis functions[2] which enforce the divergenceless condition of the electric field implicitly

$$\mathbf{E} = \sum_{i=1}^{6} e_i \mathbf{W}_i \tag{4}$$

where e_i's are the unknown coefficients associated with each edge of the tetrahedral element and $\mathbf{W}_i$'s are the basis functions and are given in detail in [5]. The testing function $\mathbf{T}$ is taken to be the same set of basis functions as given in equation (4), i.e.,

$$\mathbf{T} = \mathbf{W}_j \qquad j=1,2,3,4,5,6 \tag{5}$$

The discretization of the FEM computational volume automatically results in discretization of surfaces S_o and S_{inp} in triangular elements. The evaluation of the surface integral over the outer boundary is carried out either by using Method of Moments(MoM) and the evaluation of the surface integral over the input plane is carried out using mode matching method.

Evaluation of surface integral over S_o - MoM formulation:

At the fictitious outer boundary the electric field is subjected to the condition that the fields are continuous across the boundary, i.e.,

$$\mathbf{E}\big|_{at\ S_o^+} = \mathbf{E}\big|_{at\ S_o^-} \tag{6}$$

where S_o^+ denotes the outer side of S_o and S_o^- denotes the inner side of S_o. The electric field $\mathbf{E}\big|_{at\ S_o^-}$ is the field quantity being evaluated in the computational volume through FEM. The electric field ouside S_o is evaluated explicitly using the following equation[4, eq.3-83]:

$$\mathbf{E}\big|_{at\ S_o^+} = -\nabla\times\mathbf{F} - j\omega\mu_o\mathbf{A} + \frac{1}{j\omega\mu_o}\nabla\nabla\bullet\mathbf{A} \tag{7}$$

where

and

$$\mathbf{A} = \text{Magnetic Vector Potential} = \frac{1}{4\pi}\iint_{S_o}\frac{\mathbf{J}\exp(-jk_o|\mathbf{r}-\mathbf{r}_o|)}{|\mathbf{r}-\mathbf{r}_o|}ds \tag{8}$$

$$\mathbf{F} = \text{Electric Vector Potential} = \frac{1}{4\pi}\iint_{S_o} \frac{\mathbf{M}\exp(-jk_o|\mathbf{r}-\mathbf{r}_o|)}{|\mathbf{r}-\mathbf{r}_o|} ds \tag{9}$$

$\mathbf{J}$ and $\mathbf{M}$ are assumed to be equivalent electric and magnetic currents respectively at the outer surface S_o. The equivalent currents radiating in free space are used in the equation (7) to compute the electric field outside V (figure 6).

Substituting equation (7) into equation (6) and multiplying by a testing function $\hat{n}_o \times \mathbf{T}$ on both sides and integrate over the surface S_o, results in:

$$\iint_{S_o} (\hat{n}_o \times \mathbf{T}) \bullet \mathbf{E} ds = -\iint_{S_o} (\hat{n}_o \times \mathbf{T}) \bullet (\nabla\times\mathbf{F}) ds - j\omega\mu_o \iint_{S_o} (\hat{n}_o \times \mathbf{T}) \bullet \mathbf{A} ds$$
$$+ \frac{1}{j\omega\varepsilon_o} \iint_{S_o} (\hat{n}_o \times \mathbf{T}) \bullet (\nabla\nabla \bullet \mathbf{A}) ds \tag{10}$$

After some mathematical manipulations [6, pp.42], [7, pp.135], and substituting equations (8) and (9) in the above equation, it can be rewritten as:

$$\frac{1}{2}\iint_{S_o} (\hat{n}_o \times \mathbf{T}) \bullet \mathbf{E} ds + \frac{1}{4\pi}\iint_{S_o} (\hat{n}_o \times \mathbf{T}) \bullet \left(\iint\!\!\!\!\!\!-\!\!\!-_{S_o} \mathbf{M} \times \nabla' G ds' \right) ds$$
$$+ \frac{j\omega\mu_o}{4\pi} \iint_{S_o} (\hat{n}_o \times \mathbf{T}) \bullet \left(\iint_{S_o} \mathbf{J} G ds' \right) ds$$
$$+ \frac{1}{j\omega\varepsilon_o(4\pi)} \left(\iint_{S_o} \{\nabla \bullet (\hat{n}_o \times \mathbf{T})\} \left\{ \iint_{S_o} (\nabla \bullet \mathbf{J}) G ds' \right\} ds \right) = 0 \tag{11}$$

where $\iint\!\!\!\!\!\!-\!\!\!-$ indicates that the singular point has been removed and

$$G = \frac{\exp(-jk_o|\mathbf{r}-\mathbf{r}_o|)}{|\mathbf{r}-\mathbf{r}_o|} \tag{12}$$

Equation (11) is written in a matrix form by choosing the proper basis functions for $\mathbf{M}$ and $\mathbf{J}$ and accordingly using the testing function $\hat{n}_o \times \mathbf{T}$. Within each surface triangle, the surface currents can be expressed as

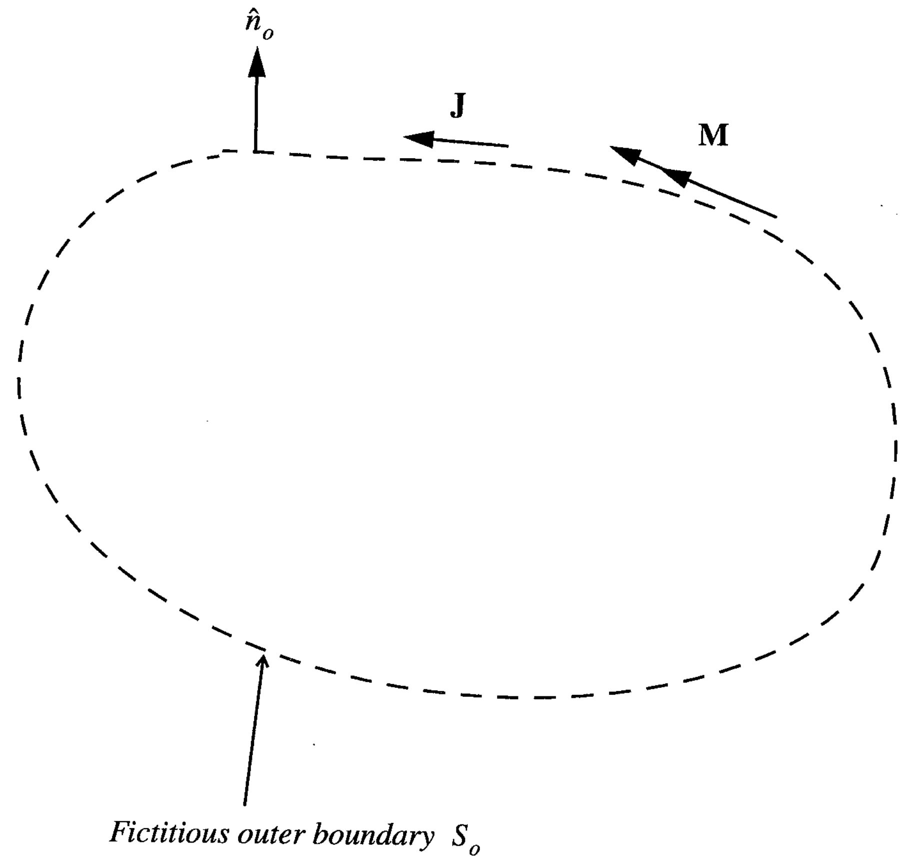


Figure 6 Equivalent current representation of the outer surface S_o

$$\mathbf{M} = \mathbf{E} \times \hat{n}_o = -\sum_{i=1}^{3} e_i(\hat{n}_o \times \mathbf{W}_i) \tag{13}$$

$$\mathbf{J} = \sum_{i=1}^{3} I_i(\hat{n}_o \times \mathbf{W}_i) \tag{14}$$

and the testing function as

$$\hat{n}_o \times \mathbf{T} = \hat{n}_o \times \mathbf{W}_j \qquad\qquad j=1,2,3 \tag{15}$$

In equation (13), e_i represents the same unknown coefficient as in equation (4) and in equation(14) I_i represents the unknown coefficient for the surface electric current densisty. In equations (13) and (14), it is interesting to note that, the vector edge basis functions $\mathbf{W}_i$, which are initially used for electric field are used to represent the surface current densities in the form of $\hat{n}_o \times \mathbf{W}_i$. The expansion functions $\mathbf{W}_i$ are used to build tangential continuity into the field representation. In contrast, the cross product of $\hat{n}_o$ with these functions results in another set of basis functions which guarantee normal continuity with zero curl and nonzero divergence and hence are ideally suited for representing surface current densities[2]. During the current investigation, it has been observed that the roof top basis functions for triangular patches used by Rao[6] and the basis functions used here proved to be numerically identical to each other confirming the above point of view.

Equations (13-14) are substituted in equation (11) and integrated over all the triangular patch elements on surface S_o to obtain the following matrix equation:

$$\left[M_1\right]\{e\} + \left[M_2\right]\{I\} = \{0\} \tag{16}$$

where

$$\left[M_1\right] = \frac{1}{2}\iint_{S_o} (\hat{n}_o \times \mathbf{T}) \bullet \mathbf{E} ds + \frac{1}{4\pi}\iint_{S_o} (\hat{n}_o \times \mathbf{T}) \bullet \left(-\!\!\!\!\!\!\iint_{S_o} \mathbf{M} \times \nabla' G ds'\right) ds \tag{17}$$

$$\left[M_2\right] = \frac{j\omega\mu_o}{4\pi}\iint_{S_o} (\hat{n}_o \times \mathbf{T}) \bullet \left(\iint_{S_o} \mathbf{J} G ds'\right) ds$$

$$+ \frac{1}{j\omega\varepsilon_o(4\pi)}\iint_{S_o} \{\nabla\bullet(\hat{n}_o \times \mathbf{T})\}\left\{\iint_{S_o} (\nabla\bullet\mathbf{J}) G ds'\right\} ds \tag{18}$$

and $\{0\}$ is the null vector. The singularities in evaluating the integrals in equation (18) are handled analytically by using the closed form expressions given in [8].

Using Maxwell's equation $\nabla\times\mathbf{E} = -j\omega\mu_o\mu_r\mathbf{H}$, the surface integral on the right hand side of the equation (3) can be written as

$$-\iint_{S_o}\mathbf{T}\bullet\left(\hat{n}_o\times\frac{1}{\mu_r}\nabla\times\mathbf{E}\right)ds-\iint_{S_{inp}}\mathbf{T}\bullet\left(\hat{n}_i\times\frac{1}{\mu_r}\nabla\times\mathbf{E}\right)ds = \iint_{S_o}\mathbf{T}\bullet(\hat{n}_o\times\mathbf{H})ds$$
$$+\iint_{S_{inp}}\mathbf{T}\bullet(\hat{n}_i\times\mathbf{H}_{inp})ds \qquad (19)$$

where $\mathbf{H}_{inp}$ is the magnetic field over the input plane obtained from matching the modal expansion of waveguide fields with the unknowns fields at the input plane[9]. By equivalence principle, it can be noted that $\mathbf{J} = \hat{n}_o\times\mathbf{H}$ on the surface S_o. Substituting this into equation (19), equation (3) can be rewritten as:

$$\iiint_V\frac{1}{\mu_r}(\nabla\times\mathbf{T})\bullet(\nabla\times\mathbf{E})dv-k_o^2\varepsilon_r\iiint_V\mathbf{T}\bullet\mathbf{E}dv = \iint_{S_o}\mathbf{T}\bullet\mathbf{J}ds+\iint_{S_{inp}}\mathbf{T}\bullet(\hat{n}_i\times\mathbf{H}_{inp})ds \qquad (20)$$

Substituting equations (4), (5) and $\mathbf{H}_{inp}$ in the above equation and integrating over all the tetrahedral elements to evaluate the volume integrals on the left hand side and integrating over all the surface triangular elements to evaluate the surface integrals on the right hand side, it can be written in a matrix form as

$$[F_1]\{e\}+[F_2]\{I\} = \{b_1\} \qquad (21)$$

where $[F_1]$ includes the volume integration and the surface integration over the input place due to mode matching,

$$[F_2] = \iint_{S_o}\mathbf{T}\bullet\mathbf{J}ds \qquad (22)$$

and $\{b_1\}$ is the excitation vector due to the dominant mode incident in the waveguide. The evaluation of the volume integrals over a tetrahedral element is given in detail in [5].

Equations (21) and (16) are combined to form a system matrix equation:

$$\begin{bmatrix}F_1 & F_2\\ M_1 & M_2\end{bmatrix}\begin{bmatrix}e\\ I\end{bmatrix} = \begin{bmatrix}0\\ b_1\end{bmatrix} \qquad (23)$$

In the above system matrix F_1 and F_2 are sparse matrices and M_1 and M_2 are dense matrices and also the total matrix is complex and non-symmetric in nature. This matrix equation is solved using a diagonally preconditioned biconjugate gradient algorithm, where it is necessary to store only the non zero entries of the matrix.

The solution of equation (23), enables the computation of the electric field in the computational volume and the equivalent magentic and electric current densities on the surface terminating the computational domain. Using the equivalent electric and magnetic current densities on the surface terminating the computational domain, the radiated electric far field is computed as [4]

$$\mathbf{E}_{frad}(\mathbf{r})\big|_{r \to \infty} = -jk_o\eta_o\frac{\exp(-jk_o r)}{4\pi r}\iint(\hat{\theta}\hat{\theta} + \hat{\phi}\hat{\phi})$$

$$\bullet\, \mathbf{J}(x', y')\exp(jk_o\sin(\theta(x'\cos\phi + 'y\sin\phi) + z'\cos\theta))dx'dy'$$

$$+ jk_o\frac{\exp(-jk_o r)}{4\pi r}\iint(-\hat{\theta}\hat{\phi} + \hat{\phi}\hat{\theta})$$

$$\bullet\, \mathbf{M}(x', y')\exp(jk_o\sin(\theta(x'\cos\phi + 'y\sin\phi) + z'\cos\theta))dx'dy' \qquad (24)$$

where (r, θ, ϕ) are the spherical coordinates of the observation point. The solution of equation (23) will also enables the calculation of electric field at the input plane, which can be used to calculte the reflection coefficient Γ at the input plane [9]. The input admittance is then calculated as

$$Y_{in} = \frac{(1-\Gamma)}{(1+\Gamma)}Y_o \qquad (25)$$

where Y_o is the characteristic admittance of the feed transmission line.

Appendix 2

Listing of the Distribution Disk

```
/FEMOM3DR-1.0

total 10
drwxr-xr-x   2 cjr         1024 Jul  2 09:47 Example1/
drwxr-xr-x   2 cjr          512 Jul  2 09:48 Example2/
drwxr-xr-x   2 cjr         1024 Jul  2 09:49 Example3/
drwxr-xr-x   2 cjr         2048 Jul  2 09:50 FEMOM3DR/
drwxr-xr-x   2 cjr          512 Jul  2 09:51 PRE_FEMOM3DR/

/FEMOM3DR-1.0/PRE_FEMOM3DR

total 63
-rw-r--r--   1 cjr          202 Jul  2 09:52 README
-rw-r--r--   1 cjr         6741 Oct 31  1997 cosmos2fem.f
-rw-r--r--   1 cjr         5295 Oct 31  1997 edge.f
-rw-r--r--   1 cjr          307 Oct 31  1997 makefile
-rw-r--r--   1 cjr         1076 Oct 31  1997 meshin.f
-rw-r--r--   1 cjr         1723 Oct 31  1997 param0
-rw-r--r--   1 cjr         1289 Oct 31  1997 pmax.f
-rw-r--r--   1 cjr         9090 May 20 14:02 pre_femom3dr.f
-rw-r--r--   1 cjr         3854 Oct 31  1997 surfel.f

/FEMOM3DR-1.0/FEMOM3DR

total 380
-rw-r--r--   1 cjr          472 Jul  2 09:51 README
-rw-r--r--   1 cjr         4825 Oct 30  1997 analy.f
-rw-r--r--   1 cjr         4195 Oct 30  1997 basis.f
-rw-r--r--   1 cjr          885 Oct 30  1997 bessj.f
-rw-r--r--   1 cjr          984 Oct 30  1997 bessj0.f
-rw-r--r--   1 cjr         1010 Oct 30  1997 bessj1.f
-rw-r--r--   1 cjr         3921 Jun 11 09:40 bicgdns.f
-rw-r--r--   1 cjr         2027 Oct 30  1997 elembd.f
-rw-r--r--   1 cjr         4090 May 14 16:03 elmatr.f
-rw-r--r--   1 cjr        21317 Jul  1 10:14 femom3dr.f
-rw-r--r--   1 cjr         1887 Oct 30  1997 fourier_rwg.f
-rw-r--r--   1 cjr         2640 Oct 30  1997 fourierxy.f
-rw-r--r--   1 cjr          658 Jun  5 14:37 makefile
-rw-r--r--   1 cjr         4405 Jul  1 09:59 param
```

```
-rw-r--r--    1 cjr          882 Oct 30  1997 pleq.f
-rw-r--r--    1 cjr         4933 Oct 30  1997 quadpts.f
-rw-r--r--    1 cjr         3102 May 20 14:07 radpattn.f
-rw-r--r--    1 cjr         2983 Jun  2 09:55 scatter_coax.f
-rw-r--r--    1 cjr         4240 May 27 16:29 scatter_cwg.f
-rw-r--r--    1 cjr         4384 Jul  1 10:32 scatter_rwg.f
-rw-r--r--    1 cjr          307 Oct 30  1997 second.f
-rw-r--r--    1 cjr         4338 Jun 15 09:45 selmts_coax.f
-rw-r--r--    1 cjr         5312 Oct 30  1997 selmts_cwg.f
-rw-r--r--    1 cjr         9097 Oct 30  1997 selmts_rwg.f
-rw-r--r--    1 cjr         2219 Oct 30  1997 triang1_rwg.f
-rw-r--r--    1 cjr         2682 Oct 30  1997 triang_coax.f
-rw-r--r--    1 cjr         2611 Oct 30  1997 triang_cwg.f
-rw-r--r--    1 cjr          819 Oct 30  1997 triang_rwg.f
-rw-r--r--    1 cjr         1438 Oct 30  1997 triangeh.f
-rw-r--r--    1 cjr         2905 Oct 30  1997 triangej.f
-rw-r--r--    1 cjr         3089 Oct 30  1997 triangej0.f
-rw-r--r--    1 cjr         2449 Oct 30  1997 triangej01.f
-rw-r--r--    1 cjr         3105 Oct 30  1997 triangem.f
-rw-r--r--    1 cjr         1693 Oct 30  1997 triangem0.f
-rw-r--r--    1 cjr         1238 May  8 10:08 unorm.f
-rw-r--r--    1 cjr          469 Oct 30  1997 vcross.f
-rw-r--r--    1 cjr          382 Oct 30  1997 vdot.f
-rw-r--r--    1 cjr         5148 May 19 08:37 zmatrixeh.f
-rw-r--r--    1 cjr         9146 Jul  1 10:12 zmatrixej.f
-rw-r--r--    1 cjr         7738 Jul  1 10:12 zmatrixem.f
```

```
/FEMOM3DR-1.0/Example1

total 1684
-rw-r--r--    1 cjr           22 Jun  2 08:55 coax.MAT
-rw-r--r--    1 cjr        75111 Jun 11 09:31 coax.MOD
-rw-r--r--    1 cjr         5050 Jul  1 13:47 coax.OUT
-rw-r--r--    1 cjr       133383 Jul  1 13:15 coax.PIN
-rw-r--r--    1 cjr          751 Jul  1 13:15 coax.POUT
-rw-r--r--    1 cjr         1113 Jun 11 09:30 coax.SES
-rw-r--r--    1 cjr           80 Jul  1 13:47 coax_bicgd.DAT
-rw-r--r--    1 cjr       317686 Jul  1 13:15 coax_edges.DAT
-rw-r--r--    1 cjr        93462 Jul  1 13:15 coax_nodal.DAT
-rw-r--r--    1 cjr       220044 Jul  1 13:15 coax_surfed.DAT
-rw-r--r--    1 cjr        12126 Jul  1 13:15 coax_surfel.DAT
-rw-r--r--    1 cjr           37 Jun 15 09:46 input
```

```
/FEMOM3DR-1.0/Example2

total 2302
-rw-r--r--    1 cjr          32 May 21 09:42 input
-rw-r--r--    1 cjr          22 May 12 15:24 rwg.MAT
-rw-r--r--    1 cjr      106939 May 12 15:23 rwg.MOD
-rw-r--r--    1 cjr        4895 Jul  1 10:30 rwg.OUT
-rw-r--r--    1 cjr      187701 Jul  1 09:50 rwg.PIN
-rw-r--r--    1 cjr         751 Jul  1 09:50 rwg.POUT
-rw-r--r--    1 cjr          80 Jul  1 10:30 rwg_bicgd.DAT
-rw-r--r--    1 cjr      460142 Jul  1 09:50 rwg_edges.DAT
-rw-r--r--    1 cjr      134680 Jul  1 09:50 rwg_nodal.DAT
-rw-r--r--    1 cjr      263284 Jul  1 09:50 rwg_surfed.DAT
-rw-r--r--    1 cjr       16644 Jul  1 09:50 rwg_surfel.DAT

/FEMOM3DR-1.0/Example3

total 2475
-rw-r--r--    1 cjr          22 May 21 09:15 cwg.MAT
-rw-r--r--    1 cjr      115058 May 27 14:46 cwg.MOD
-rw-r--r--    1 cjr        4934 Jul  1 14:50 cwg.OUT
-rw-r--r--    1 cjr      202757 Jul  1 14:01 cwg.PIN
-rw-r--r--    1 cjr         751 Jul  1 14:01 cwg.POUT
-rw-rw----    1 cjr        1611 May 27 14:45 cwg.SES
-rw-r--r--    1 cjr          80 Jul  1 14:50 cwg_bicgd.DAT
-rw-r--r--    1 cjr      506778 Jul  1 14:01 cwg_edges.DAT
-rw-r--r--    1 cjr      147036 Jul  1 14:01 cwg_nodal.DAT
-rw-r--r--    1 cjr      265164 Jul  1 14:01 cwg_surfed.DAT
-rw-r--r--    1 cjr       19282 Jul  1 14:01 cwg_surfel.DAT
-rw-r--r--    1 cjr          32 May 27 15:37 input
```

Appendix 3

Sample *.SES files of COSMOS/M

The geometry modeling and meshing can be accomplished by using COSMOS/M. A variety of commands are available to define geometries. The constructed geometry is meshed and the mesh data can be written to a file with the `Modinput` command. Dielectric materials are identified by using material property command before meshing the corresponding part of the dielectric material. These are used as indices to tetrahedral elements, which will correspond to an entry in the *problem*.MAT file. Specification of the surfaces which are perfectly conducting, surfaces forming the radiating aperture and the input plane is accomplished by enforcing pressure boundary conditions on respective surfaces. Before the pressure condition is specified, a load condition has to be defined to indicate what type of surface is being specified. Load conditions of 1, 2, and 3 corresponds to perfectly conducting surface, surface at the fictitious outer boundary and surface at the input plane respectively.

The *.SES files for the sample runs presented in section 4 are given below.

Example 1:

```
C*
C*   COSMOS/M        Geostar V1.75
C*          Problem     :     /usr0/cjr/COSMOS/3d/FEMOM3DR/coax/coax
Date :
C*
PLANE Z 0 1
VIEW 0 0 1 0
PT 1 0 0 0
PT 2 1 0 0
SCALE 0
CRPCIRCLE 1 1 2 1 360 4
SCALE 0
PT 6 1.57 0 0
SCALE 0
CRPCIRCLE 5 1 6 1.57 360 4
SCALE 0
CT 1 0 0.5 1 1 0
CT 2 0 0.5 1 5 0
RG 1 2 2 1 0
```

```
PT 10 -2 -2 0
SCALE 0
PT 11 2 -2 0
PT 12 2 2 0
SCALE 0
PT 13 -2 2 0
CRLINE 9 10 11
CRLINE 10 11 12
CRLINE 11 12 13
CRLINE 12 13 10
CT 3 0 0.5 1 9 0
RG 2 1 1 0
RG 3 2 3 2 0
SFEXTR 9 12 1 Z -0.5
VIEW 1 1 1 0
CT 4 0 0.5 4 13 16 18 20 0
RG 4 1 4 0
SF4CORD 5 -2.25 -2.25 0.25 2.25 -2.25 0.25 2.25 2.25 0.25 -2.25
2.25 0&
.25
SFGEN 1 5 5 1 0 0 0 -1.0
SFEXTR 21 24 1 Z -1.0
SCALE 0
CLS 1
CLS 1
SELINP SF 1 4 1 1
SELINP RG 1 4 1 1
PH 1 SF 1 0.5 0.0001 1
INITSEL,SF,1,1
INITSEL,RG,1,1
SELINP SF 5 12 1 1
PH 2 SF 5 0.5 0.0001 1
PART 1 1 2 2
INITSEL,SF,1,1
MA_PART 1 1 1 0 0 4
NMERGE 1 403 1 0.0001 0 0 0
NCOMPRESS 1 403
CLS 1
CLS 1
ACTSET LC 1
PSF 1 1 4 1 1 1 4
PRG 2 1 2 1 1 4
PRG 3 1 4 1 1 4
CLS 1
ACTSET LC 2
PSF 5 2 10 1 2 2 4
```

```
CLS 1
ACTSET LC 3
PRG 1 3 1 1 3 4
```

Example 2:

```
C*
C*  COSMOS/M      Geostar V1.75
C*  Problem : /usr0/cjr/COSMOS/3d/FEMOM3DR/rwg              Date :
7
C*
C* FILE rwg.in 1 1 1 1
SF4CORD 1 -0.35 -0.155 0 0.35 -0.155 0 0.35 0.155 0 -0.35 0.155
0
SCALE 0
SFEXTR 1 4 1 Z -0.25
SCALE 0
CLS 1
SF4CR 6 5 12 8 11 0
PH 1 SF 1 0.1 0.001 1
PT 9 -0.45 -0.25 0
PT 10 0.45 -0.25 0
PT 11 0.45 0.25 0
PT 12 -0.45 0.25 0
SCALE 0
CRLINE 13 9 10
CRLINE 14 10 11
CRLINE 15 11 12
CRLINE 16 12 9
CT 1 0 0.1 4 1 2 3 4 0
CT 2 0 0.1 4 13 14 15 16 0
RG 1 2 2 1 0
SFEXTR 13 16 1 Z -0.3
CLS 1
SF4CR 11 17 20 22 24 0
SF4CORD 12 -0.5 -0.3 0.1 0.5 -0.3 0.1 0.5 0.3 0.1 -0.5 0.3 0.1
SCALE 0
SFEXTR 25 28 1 Z -0.5
CLS 1
SF4CR 17 29 36 32 35 0
CLS 1
PHPLOT 1 1 1
SELINP SF 1 1 1 1
SELINP SF 7 11 1 1
SELINP RG 1 1 1 1
CLS 1
```

```
PH 2 SF 7 0.1 0.001 1
CLS 1
UNSELINP SF 1 1 1 1
UNSELINP SF 7 11 1 1
UNSELINP RG 1 1 1 1
SELINP SF 12 17 1 1
PH 3 SF 12 0.1 0.001 1
PART 1 1 1
PART 2 2 3
CLS 1
PARTPLOT 2 2 1
PARTPLOT 1 2 1
MPROP 1 PERMIT 1
MA_PART 1 1 1 0 0 4
MA_PART 2 2 1 0 0 4
NMERGE 1 605 1 0.0001 0 0 0
NCOMPRESS 1 605
CLS 1
INITSEL,SF,1,1
INITSEL,RG,1,1
CLS 1
ACTSET LC 1
PSF 2 1 5 1 1 1 4
PSF 7 1 11 1 1 1 4
PRG 1 1 1 1 1 4
ACTSET LC 2
PSF 12 2 17 1 2 2 4
ACTSET LC 3
PSF 6 3 6 1 3 3 4
```

Example 3:

```
C*
C*  COSMOS/M        Geostar V1.75
C*  Problem : cwg            Date :  5-27-98  Time : 15: 3:49
C*
C* FILE cwg.in 1 1 1 1
PLANE Z 0 1
VIEW 0 0 1 0
PT 1 0 0 0
PT 2 3.75 0 0
CRPCIRCLE 1 1 2 3.75 360 4
SCALE 0
CT 1 0 1.2 1 1 0
RG 1 1 1 0
PT 6 -4.5 -4.5 0
PT 7 4.5 -4.5 0
```

```
PT 8 4.5 4.5 0
PT 9 -4.5 4.5 0
SCALE 0
CRLINE 5 6 7
CRLINE 6 7 8
CRLINE 7 8 9
CRLINE 8 9 6
CT 2 0 1.2 1 5 0
RG 2 2 2 1 0
SFEXTR 1 4 1 Z -3.0
VIEW 1 1 1 0
RGGEN 1 1 1 1 0 0 0 -3.0
PT 14 -4.5 -4.5 -3.25
PT 15 4.5 -4.5 -3.25
PT 16 4.5 4.5 -3.25
PT 17 -4.5 4.5 -3.25
CLS 1
CLS 1
SCALE 0
SCALE 0
CRLINE 17 14 15
CRLINE 18 15 16
CRLINE 19 16 17
CRLINE 20 17 14
CT 4 0 1.2 1 20 0
RG 4 1 4 0
SFEXTR 5 8 1 Z -3.25
CLS 1
SELINP SF 1 4 1 1
SELINP RG 1 1 1 1
SELINP RG 3 3 1 1
CLS 1
PH 1 SF 1 1.2 0.0001 1
PART 1 1 1
INITSEL SF 1 1
INITSEL RG 1 1
PT 18 -5 -5 0.5
PT 19 5 -5 0.5
SCALE 0
PT 20 5 5 0.5
PT 21 -5 5 0.5
CRLINE 25 18 19
CRLINE 26 19 20
CRLINE 27 20 21
CRLINE 28 21 18
CT 5 0 1.2 1 28 0
```

```
RG 5 1 5 0
RGGEN 1 5 5 1 0 0 0 -4.0
SFEXTR 25 28 1 Z -4.0
CLS 1
SELINP SF 5 12 1 1
CLS 1
SELINP RG 1 2 1 1
SELINP RG 4 6 1 1
CLS 1
PH 2 RG 1 1.2 0.0001 1
PH 3 RG 5 1.2 0.0001 1
PART 2 2 3
CLS 1
INITSEL SF 1 1
INITSEL RG 1 1
PARTPLOT 1 2 1
CLS 1
PARTPLOT 1 1 1
MA_PART 1 1 1 0 0 4
CLS 1
PARTPLOT 2 2 1
MA_PART 2 2 1 0 0 4
PARTPLOT 1 2 1
NMERGE 1 644 1 0.0001 0 0 0
NCOMPRESS 1 644
ACTSET LC 1
PSF 1 1 8 1 1 1 4
PRG 2 1 2 1 1 4
PRG 4 1 4 1 1 4
ACTSET LC 2
PRG 5 2 6 1 2 4
PSF 9 2 12 1 2 2 4
ACTSET LC 3
PRG 3 3 3 1 3 4
```

Appendix 4

Generic Input file format for PRE_FEMOM3DR

The following is the format of the generic input file (`problem.PIN`) to be supplied to PRE_FEMOM3DR with required nodal data.

N_n N_e N_p N_{a1} N_{a2} N_g	• N_n: Number of nodes • N_e : Number of trahedral elements • N_p : Number of triangular elemets on PEC surfaces • N_{a1} : Number of triangular elements on surface at the outer boundary • N_{a2} : Number of triangular elements on surface at the input plane • N_g : Maximum number of material groups
x_1, y_1, z_1 x_2, y_2, z_2 . . . . . $x_{N_p}, y_{N_p}, z_{N_p}$	Coordinates of the nodes 1,2,3...,N_n
$n_{11}, n_{21}, n_{31}, n_{41}, mg(1)$ $n_{12}, n_{22}, n_{32}, n_{42}, mg(2)$ $n_{1N_e}, n_{2N_e}, n_{3N_e}, n_{4N_e}, mg(N_e)$	Node numbers connecting each tetrahedral element 1, 2, 3, ...,N_e, and material group index number for each element

N_{e1} , n_{11}, n_{21}, n_{31} N_{e2} , n_{12}, n_{22}, n_{32} . . . $N_{eN_p}, n_{1N_p}, n_{2N_p}, n_{3N_p}$	Global number of the terahedral element with a triangular face on PEC surface $(N_{e1}, N_{e2}, ..., N_{eN_p})$ and three nodes connecting the triangular element
N_{e1}, n_{11}, n_{21}, n_{31} N_{e2}, n_{12}, n_{22}, n_{32} . . . . $N_{eN_{a1}}, n_{1N_{a1}}, n_{2N_{a1}}, n_{3N_{a1}}$	Global number of the terahedral element with a triangular face on the outer boudary surface $(N_{e1}, N_{e2}, ..., N_{eN_{a1}})$ and three nodes connecting the triangular element
N_{e1} , n_{11}, n_{21}, n_{31} N_{e2}, n_{12}, n_{22}, n_{32} . . . . . $N_{eN_{a2}}, n_{1N_{a2}}, n_{2N_{a2}}, n_{3N_{a2}}$	Global number of the terahedral element with a triangular face on input plane surface $(N_{e1}, N_{e2}, ..., N_{eN_{a2}})$ and three nodes connecting the triangular element

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 07704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1998

3. REPORT TYPE AND DATES COVERED
Contractor Report

4. TITLE AND SUBTITLE
User's Manual for FEMOM3DR
Version 1.0

5. FUNDING NUMBERS
NCC1-231

522-11-41-02

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Hampton University
Hampton, Virginia 23668

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
NASA Langley Research Center
Hampton, VA 23681-2199

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/CR-1998-208709

11. SUPPLEMENTARY NOTES
Langley Technical Monitor: Fred B. Beck

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category ~~04~~ 32 Distribution: Nonstandard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

FEMoM3DR is a computer code written in FORTRAN 77 to compute radiation characteristics of antennas on 3D body using combined Finite Element Method (FEM)/Method of Moments (MoM) technique. The code is written to handle different feeding structures like coaxial line, rectangular waveguide, and circular waveguide. This code uses the tetrahedral elements, with vector edge basis functions for FEM and triangular elements with roof-top basis functions for MoM. By virtue of FEM, this code can handle any arbitrary shaped three dimensional bodies with inhomogeneous lossy materials; and due to MoM the computational domain can be terminated in any arbitrary shape. The User's Manual is written to make the user acquainted with the operation of the code. The user is assumed to be familiar with the FORTRAN 77 language and the operating environment of the computers on which the code is intended to run.

14. SUBJECT TERMS
FEM, MoM, Hybrid Method, Cavity-Backed Aperture Antennas, Input Admittance, Radiation pattern

15. NUMBER OF PAGES
48

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102