SIMULATION AND OPTIMIZATION USING *em*, HP HFSS AND MAXWELL EMINENCE

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Abstract   In this report, a microstrip line is simulated using Sonnet, Maxwell Eminence and HP HFSS, respectively. Comparative results are presented. Several issues which are critical to accuracy, resource consumption and the validity of comparison are discussed. Two optimizations are carried out through Empipe and Empip3D with a microstrip line. The difficulty encountered in the comparison of optimization results is discussed and overcome by adding the ZPRI[1] command into the original include file created by Empipe3D.

I.   INTRODUCTION

Sonnet's em, Ansoft's Maxwell Eminence and HP HFSS are electromagnetic simulators using different numerical techniques. The moment method is employed by em. Both Maxwell Eminence and HP HFSS use the finite element method. Given a problem solved by any one of them, it is interesting and useful to validate the result using the other two simulators. The essential difference between the two techniques makes it totally different how to set up a simulation problem properly and get accurate results. In Sonnet, accuracy largely depends on grid size while in the finite element simulators, adaptive analysis is critically important. When running frequency sweep in Maxwell Eminence and HP HFSS, the location of adaptive frequency also affects accuracy. Port reference impedance on which the definitions of generalized and normalized S parameters are based is discussed. In order to make meaningful comparison, the difference of port reference impedance between em and the finite element simulators should be eliminated. It is achieved by renormalizing generalized S parameters.

Using OSA90/hope[1], a microstrip line is optimized through Empipe and Empipe3D which drive em and Maxwell Eminence, respectively.   The comparative results are based on 50 ohm port reference impedance.

II.   SIMULATION COMPARISON

Before we show the comparative results, it is necessary to illustrate the adaptive solution process carried out in Maxwell Eminence and HP HFSS. The flow chart is shown in Appendix I.

At the beginning, a coarse mesh is generated and a field solution is calculated based on the mesh. Then the mesh is refined in the areas of highest error. The error is determined by substituting the field solution computed for each element back into the equation being solved. The further away an element's field solution is from satisfying the equation, the higher its error. Second field solution is generated based on the refined mesh. The error is calculated again and the mesh is refined again. This is so called adaptive iterations(passes). A criteria is defined by the user to stop the adaptive process. Generally, allowable delta S and number of adaptive passes[3][4] are used as stopping criteria for the adaptive process. In Maxwell Eminence and HP HFSS, a structure can also be simulated from scratch without adaptive analysis. But the results are not expected to be accurate.

Comparison 1

First we simulate a lossless microstrip line with the three simulators at a single frequency point, 10 GHz. The substrate specification, the whole structure and the size of the airbox in which the line is enclosed is given in Fig.1. In the finite element simulators, we use delta S equal to 0.001 as the stop criteria which is strict enough. The system will continue to refine the mesh until the change of both real and imaginary part of every element in S matrix between the latest two consecutive passes is less than 0.001. The results from *em*, Maxwell Eminence and HP HFSS are given in Table I. Note that the generalized S parameters from Maxwell Eminence and HP HFSS without renormalization are obviously different from the S parameters given by *em*. The difference of port reference impedance accounts for the difference between the two kinds of S parameters.

In Sonnet, the port reference impedance is defined by default as 50 ohm which means the S parameters obtained are normalized to 50 ohm. In the finite element simulators, it is assumed that each port is connected to a semi-infinitely long waveguide that has the same cross section as the port, which means the S parameters calculated before renormalization are generalized S parameters.

In order to make meaningful comparison, generalized S parameters are renormalized to 50 ohm in the finite element simulators. First the system calculates a unique impedance matrix associated with the structure. This unique impedance matrix, Z is defined as follows:

$$Z = \sqrt{Z_0}\,(I + S)(I - S)^{-1}\sqrt{Z_0}$$

where S is the generalized S-matrix, I is an identity matrix and Z_0 is a diagonal matrix having the characteristic impedance of each port as a diagonal value. The renormalized S-matrix is then calculated from the unique impedance matrix using this relationship:

$$S_\Omega = \sqrt{Y_\Omega}\,(Z - Z_\Omega)(Z + Z_\Omega)^{-1}\sqrt{Z_\Omega}$$

where Z is the structure's unique impedance matrix, Z_Ω and Y_Ω are diagonal matrices with 50 and 1/50 as diagonal values.

The characteristic impedance of each port is needed in renormalization. The approximate value can be calculated in three ways[3][4] and the values are not expected to be the same. Using Z_{pi} [3][4], we get the renormalized S parameters from Maxwell Eminence and HP HFSS which are shown in Table I together with the results from *em* for comparison. Consistency is found in the simulation results from the three simulators.

It is also noted that the simulation using Maxwell Eminence is much more time and memory consuming than using *em* on the same machine with the same problem. While the simulation using *em* can finish in less than one minute, the simulation using Maxwell Eminence takes more than one hour of CPU time.

Comparison 2

Here we discuss the effect of the location of adaptive frequency on the accuracy of S parameters when frequency sweep is used in the finite element simulators. The reason for the discussion lies in the fact that when you run frequency sweep, the finite element simulators refine the mesh only at one predefined frequency point and apply this refined mesh to the all frequency points in the frequency range of the sweep. It is shown that inaccurate results may be produced if the frequency range is Inaccurate results may be produced if the frequency range is too large or the adaptive frequency is too large or the adaptive frequency is improperly located.

Here, only a simple comparison is presented to illustrate the effect. Using the same example in *Comparison 1*, the structure is simulated at 10 GHz with the mesh refined at 5 GHz, 10GHz and 15 GHz respectively. The results are shown in Table II. We find obvious change in S parameters when we change the adaptive frequency. Since we are simulating a ideal transmission structure, the result corresponding to the highest adaptive frequency (15GHz) is the most accurate.

III. OPTIMIZATION COMPARISON

Two optimizations are applied to a lossless microstrip line at one frequency point, 10 GHz. One uses Empipe3D which drives Maxwell Eminence. The other uses Empipe which drives *em*. The width of the microstrip line, *W* is chosen as the optimization variable. The nominal structure of the line, the substrate specification and the size of the airbox being used are show in Fig.1.

In the optimization comparison, couple of things are taken into consideration. First, a sound physical explanation should be available for the problem so that we get confidence about what the correct results should be. This can be thought of as an ultimate validation of our results.

It is shown in Table I that for the same structure, Maxwell Eminence provides the generalized S parameters which are not expected to be consistent with the S parameters normalized to 50 ohm provided by *em*. In order to obtain meaningful comparative results, we have to make the S parameters of every simulation in the optimization carried out through Maxwell Eminence renormalized to the port reference impedance of 50 ohm. It can be achieved by adding ZPRI command into the include file created by

Empipe3D. The include file created by Empipe3D establishes a connection between OSA90 and Maxwell Eminence through a COMD Datapipe[1] block. The file is shown in Appendix II. The output array, DATA[N_FREQ,N_OUT] has the following format:

$$
\begin{bmatrix}
f_1\ MS11\ PS11 \cdots MS1n\ PS1n \cdots MSn1\ PSn1 \cdots MSnn\ PSnn\ RZ_{pv1}\ IZ_{pv1}\ RZ_{pi1}\ IZ_{pi1}\ RZ_{vi1}\ IZ_{vi1}\ Rb_1\ Ib_1 \\
\quad \cdots RZ_{pvn}\ IZ_{pvn}\ RZ_{pin}\ IZ_{pin}\ RZ_{vin}\ IZ_{vin}\ Rb_n\ Ib_n \\
f_2 \qquad \cdots \\
.\qquad\quad \cdots \\
.\qquad\quad \cdots \\
.\qquad\quad \cdots \\
f_n \qquad \cdots
\end{bmatrix}
$$

where f_i is the ith frequency point in the frequency range defined.

$MSij$, $PSij$ are the magnitude and phase of S_{ij} (Generalized), respectively.

RZ_{pvi}, IZ_{pvi} are the real and imaginary part of the PV characteristic impedance[3] of port i,

respectively. The same notation is also applied to PI and VI[3] characteristic impedance.

Rb_i, Ib_i are the real and imaginary part of the propagation constant at port i, respectively.

In our problem, optimization is applied at only one frequency point, 10 GHz. And the microstrip line is a two port structure. It is shown in Appendix II that the information in the output array is reorganized into several arrays each of which contains a specific part of the Datapipe output array.

The include file shown in Appendix II which we used in the optimization is different from the original include file created automatically by Empipe3D which doesn't have the bold part. In the original include file, "SPORT 1 2 0 FMP=SMP;"[1] imports S parameters into OSA90 system but doesn't provide the information about port reference impedance.

Notice that the default value of port reference impedance in OSA90 is 50 ohm. Using the original include file, when we use the following command in the OSA90 input file:

<div align="center">PORT 1 0 R=50;   PORT 2 0 R=50;</div>

it doesn't change the generalized S parameters transferred from Maxwell Eminence. It means that

OSA90 treats the generalized S parameters imported through the original include file (Appendix II except for the bold part) as S parameters normalized to 50 ohm, which is not the truth.

Thus the bold part is added to the original include file. Array C contains the information of port reference impedance of the micrstrip line. "ZPRI=C" tells OSA90 that the S parameters imported are with respect to the reference impedance defined in array C. Consequently OSA90 will automatically renormalize the S parameters to 50 ohm by default when they are imported. In the include file shown in Appendix II, PI impedance[3] is used.

Two optimizations are carried out through Empipe and Empipe3D, respectively. The optimization specification is MS11=0, at 10 GHz. The results are shown in Table III.

Since our port reference impedance is 50 ohm, we are actually designing a 50 ohm microstrip line, which means that the solution should be unique. Thus in the optimizations, only one starting point is used.

The characteristic impedance, Z_0 of the optimized structures is calculated using a empirical formula. It is noted that the two optimal solutions are very similar but not exactly the same point as what we expected. The nature of the problem excludes the possibility of multiple optimal solutions. It is also shown that MS11 of the optimal structure from Empipe3D and Maxwell Eminence is ironically closer to the ideal result, 0 while Z_0 of the optimal structure given by Empipe and *em* is closer to 50 ohm, given that the empirical formula being used is quite accurate at 10 GHz.

Looking back to the essential difference between the finite element simulators and *em*, we get an idea about the reason for the inconsistency. The accuracy of Maxwell Eminence is largely dependent on the number of adaptive iterations used in simulations[3]. The generalized S parameters corresponding to different number of passes are given in Table IV which illustrates how much difference a strict stop criteria can make. It is shown that S parameters change constantly with the number of adaptive iterations increasing.

In our example, because of the limitation in computer resources, we only use 8 passes. The eighth pass need about 30-40 MB of memory and the next pass will need more. After eight passes, the simulation finishes no matter whether or not the delta S has already been small enough. With this stop criteria, the generalized S parameters may be inaccurate.   More passes and more strict stop criteria are desired if the computer resource permits.

CONCLUSIONS

With simple examples, the simulation results given by the three simulators have been compared. Consistency is found. It is also shown that the location of adaptive frequency affects the accuracy of frequency sweep in the finite element simulators.

In optimization comparison based on 50 ohm port reference impedance, it is necessary to renormalize the generalized S parameters from Maxwell Eminence. This is achieved by adding ZPRI command into the include file created by Empipe3D. The limited inconsistency of comparative results has been investigated. It has been demonstrated that the number of adaptive passes is critically important to the accuracy of the finite element simulators.

It has also been found that for microstrip circuits, the finite element simulators are much more time and computer resource consuming. Sonnet is more efficient in analyzing microstrip circuit.

REFERENCES

[1] $OSA90/hope^{TM}$, $Empipe^{TM}$ and $Empipe3D^{TM}$, Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1994

[2] em^{TM} and $xgeom^{TM}$, Sonnet Software, Inc., 135 Old Cove Road, Suite 203, Liverpool, NY, 13090-3774, USA

[3] $Maxwell\ Eminence^{TM}$, Ansoft Corporation, Four Station Square, Suite 660, Pittsburgh, PA, 15219, USA

[4] $HP\ HFSS^{TM}$, Hewlett-Packard Company, USA

TABLE I.   SIMULATION RESULTS OF A MICROSTRIP LINE AT 10 GHZ USING THE FINITE

ELEMENT SIMULATORS (ADAPTIVE FREQUENCY IS 10 GHZ) AND *em*

	MS11	MS21
HP HFSS (Generalized S)	0.0085	1
HP HFSS (Renormalized to 50ohm)	0.1090	0.994
Maxwell Eminence (Generalized S)	0.0079	1
Maxwell Eminence (Renormalized to 50ohm)	0.0898	0.9960
Em (Normalized to 50ohm)	0.0876	0.9962

TABLE II.   SIMULATION RESULTS OF A MICROSTRIP LINE AT 10 GHZ USING

DIFFERENT ADAPTIVE FREQUENCY

GENERALIZED S PARAMETERS COMPARISON

	MS11	MS21
Adaptive Freq. =10 GHz	0.0079	1
Adaptive Freq. =5 GHz	0.0089	1
Adaptive Freq. =15 GHz	0.0034	1

TABLE III.   COMPARISON OF OPTIMIZATION RESULTS

Optimization specification: at 10 GHz, MS11=0

Optimization variable: W, width of the microstrip line

Optimizer: minimax

(a)   Using PV impedance[3] as port reference impedance

	Starting point (mils)	MS11 before optimization	Optimal structure (mils)	MS11 after optimization	Z_0 (Ω)
Optimization Using Empipe and *em*	20	0.08760	15.9978	0.01331	50.0588
Optimization using Empipe3D and Maxwell Eminence	20	0.06769	16.2411	0.00126	49.6987

(b)   Using PI impedance[3] as port reference impedance

	Starting point (mils)	MS11 before optimization	Optimal Structure (mils)	MS11 after optimization	Z_0 (Ω)
Optimization Using Empipe and *em*	20	0.08760	15.9978	0.01331	50.0588
Optimization using Empipe3D and Maxwell Eminence	20	0.08761	15.4106	0.00059	50.9513

(c) Using VI impedance as port reference impedance

	Starting point (mils)	MS11 before optimization	Optimal structure (mils)	MS11 after optimization	Z_0 (Ω)
Optimization Using Empipe and *em*	20	0.08760	15.9978	0.01331	50.0588
Optimization using Empipe3D and Maxwell Eminence	20	0.07765	15.8006	0.00124	50.3548

TABLE IV.   COMPARISON OF S PARAMETERS CORRESPONDING TO DIFFERENT

NUMBER OF PASSES

Width of the microstrip line=20 mils, Frequency=15GHz

	MS11	MS21
10 passes	0.0065	1
9 passes	0.0067	1
8 passes	0.0052	1
6 passes	0.0127	0.9999

180 mils

220 mils

20 mils

substrate specification:
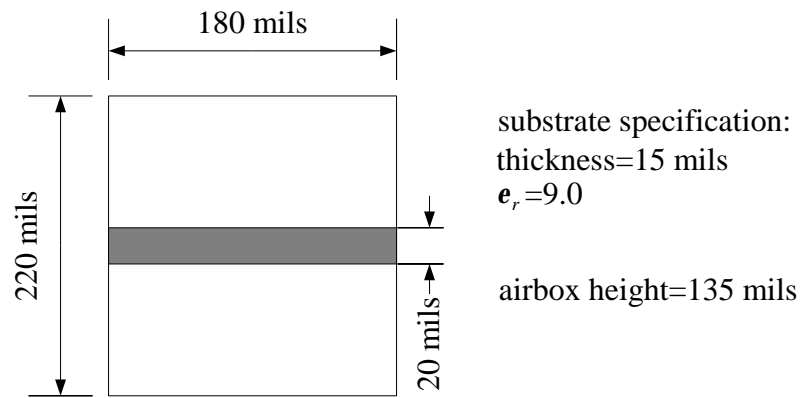thickness=15 mils
e_r=9.0

airbox height=135 mils

Fig. 1.   Dimension of the microstrip line.

Appendix I

Modified Include File Used in the Optimization through Empipe3D and Maxwell Eminence

! User-Parameterized Structure: TESTLINE

```
ELEMENT TESTLINE 1 2 0
INDEX=1 MODEL=1 REPORT=1
W=20MIL {
N_Pars = 1;
Pars[1] = [(w/1mil) ];
Grids[1] = [2];
Delta[1] = [0];
Char DBS[]= "testline";

#define SETUP_INFORMATION_TESTLINE {
 NOMINAL PROJECT line3d0
```

Parameter Name	Project Name	Nominal Value	Perturbed Value	# of Divs	Unit Name
W	line3d1	20	24	2	mil

```
@VARS 1 3
  1 0 0 0 20 0 20

SPECS 2 1
  1 0 2 10 10 1 0 1

MODEL 7
}

  char gen_file[] = "
@GEM PARAMETERS: 1 2
@GEM NOMINAL: 20
@GEM COE:
 2.540000000010160e-04   1.270000000005081e-05
 2.540000000010160e-04   1.270000000005081e-05
";

N_FREQ=1;
N_PORTS=2;
N_SP=2*N_PORTS*N_PORTS+1;
N_IMP=8*N_PORTS;
N_OUT=N_SP+N_IMP;
Char Simulator[] = "emeic";
Datapipe: COMD FILE="empipe3c" PRO=849 N_INPUT=(7+3*N_Pars)
     INPUT=(INDEX, MODEL, REPORT, DBS, Pars, GEM_file,
         Grids, Delta, Simulator, N_PORTS)
     N_OUTPUT=(N_FREQ*N_OUT) OUTPUT=(DATA[N_FREQ,N_OUT]);
SMP[N_FREQ,N_SP]=SUBSET(DATA,1,1);
CIMP[N_FREQ,N_IMP]=SUBSET(DATA,1,(N_SP+1));
PIMP[N_IMP]=ROW(CIMP,1);
```

```
QIMP[(4*N_PORTS),2]=[PIMP];
Zpv[N_PORTS,2]=SUBSET(QIMP,1,1);
Zpi[N_PORTS,2]=SUBSET(QIMP,(N_PORTS+1),1);
Zvi[[N_PORTS,2]=SUBSET(QIMP,(2*N_PORTS+1),1);
Gamma[N_PORTS,2]=SUBSET(QIMP,(3*N_PORTS+1),1);
RZpv_testline[N_PORTS]=COL(Zpv,1);
IZpv_testline[N_PORTS]=COL(Zpv,2);
RZpi_testline[N_PORTS]=COL(Zpi,1);
IZpi_testline[N_PORTS]=COL(Zpi,2);
RZvi_testline[N_PORTS]=COL(Zvi,1);
IZvi_testline[N_PORTS]=COL(Zvi,2);
RGamma_testline[N_PORTS]=COL(Gamma,1);
IGamma_testline[N_PORTS]=COL(Gamma,2);
A[1,2]=ROW(Zpi,1);
B[1,2]=ROW(Zpi,2);
C[1,4]=[A B];
SPORT 1 2 0 FMP=SMP ZPRI=C;
};
```

APPENDIX II

Flow Chart of Adaptive Analysis Process In The finite element Simulators[3]

(w_{test} refers to the adaptive frequency)

Create initial finite element mesh.

Compute excitation wave pattern for each port at $w = w_{test}$

Refine the mesh at the ports

No

Test excitation signal at each port by comparing $\nabla \times H$ to E and $\nabla \times E$ to H

Acceptable ?

Yes

Compute field solution inside structure due to excitation at ports for $w = w_{test}$

Refine the mesh inside the structure.

No

Compute S-matrix for $w = w_{test}$

Delta S Acceptable ?

Yes

Perform frequency sweep if requested

Make S-matrix available for viewing, renormalizing and de-embedding. Allow user to analyze desired dominant or higher-order mode solution at a particular port associated with the last frequency for which a solution was generated.