

HFSS OVERVIEW

User perspective on computational electromagnetics

Motivation | The basic problem | Demos

11/28/2018

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Who Am I?

- School at The Ohio State University
 - BS Physics, BS ECE, MS ECE
 - Currently UCSB Physics PhD student
- Engr. at Lake Shore Cryotronics
 - Microwave EM/satellite hardware
 - Terahertz physics/metamaterials
 - Numerical micromagnetics
 - Analog design
 - GaN semiconductor devices





WHY STUDY CEM?

- Impact scale
 - Estimated ~\$5e9 industry value
 - HFSS R18.1 cost companies ~70e3/seat



- RCS simulations of a real M1 Abrams can take a month on a supercomputer
- Learn now!
 - Involved math/physics are deep & profound
 - Leverage lots of hours of research to help your project

*<u>Global Simulation & Analysis Software Market</u>, By Product Type (Finite Element Analysis, Computational Fluid Dynamics, etc.), By End Use Industry (Automotive, Aerospace & Defense, etc.), By Region Competition Forecast and Opportunities, 2012 – 2022; Apr. 2017

PHYSICS THE WORLD GETS CHANGED HERE.

COMPUTATIONAL ELECTROMAGNETICS



Complex-valued, spatially-varying tensors Uniqueness of Maxwell's equations in non-lossy regions?

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SAMPLE PROBLEMS

- Antenna design
- Radar cross sections
- Realistic transmission line impedances
- Balun and adapter design
- Metamaterials and periodic systems
- Scattering & electrically rough interfaces
- Optics and optical fibers
- Electromagnetic interference/compatibility
- ... and many more!

JF Lee, Class Notes for ECE 5510, The Ohio State University, Dept. of Electrical and Computer Engineering, AU2017





THREE WAYS TO DO CEM

Finite Difference Time Domain

- "So easy that even a physicist can do it"
- Low accuracy, especially with multiple length scales
- $\sigma(\omega_{max}^6 L^5)$

Finite Element

- Complex, somewhat difficult to understand
- High accuracy
- Computationally expensive

Method of Moments [MoM]

- Very difficult to understand
- High accuracy
- Computationally easier than FEM in some cases

JF Lee, Class Notes for ECE 5510, The Ohio State University, Dept. of Electrical and Computer Engineering, AU2017





SOLUTION PHILOSOPHY

"You should *always* know the answer to problem before you solve it"

-Ben Munk

- The brother of the venerable JF Lee speaks of students/engineers who just plug their problem in and blindly believe the answer!
- You still have to know the basic programming, engineering, physics and the math to get any meaning behind your results
- Bottom line: don't believe HFSS just because it runs on a computer!



TOY FEM EXAMPLE [1]

• Poisson's eqn: Sturm-Liouville operator in 1D subject to some BCs

$$\mathcal{L}(\Phi) \doteq -\partial_{x}\epsilon_{r}\partial_{x}\Phi = \frac{\rho}{\epsilon_{0}} = 1 \text{ with } \epsilon_{r} = \begin{cases} \epsilon_{1} & 0 < x < \frac{1}{2} \\ \epsilon_{2} & \frac{1}{2} \le x < 1 \end{cases}$$

- Physical meaning: static dielectric interface between ϵ_1 and ϵ_2
- How can we solve this?

$$\begin{array}{c} \mathbf{0} = \\ \mathbf{0} = \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{array}$$



BEN MUNK APPROACH TO THE TOY MODEL

• Integrate twice and apply boundary conditions

$$\Phi(x) = \begin{cases} -\frac{x^2}{2} + x & 0 \le x < \frac{1}{2} \\ -\frac{x^2}{8} + \frac{x}{4} + \frac{9}{32} & \frac{1}{2} \le x < 1 \end{cases}$$

- Physical meaning: static dielectric interface between ϵ_1 and ϵ_2
- BCs: should go to zero at x = 0 and gradient should vanish at x = 1 [OK]



TOY FEM EXAMPLE [2]

• Expand in trial basis functions

$$\Phi(x) \approx \sum_{m=1}^{M} a_m \psi_m(x)$$



• Taking only two terms: one per region with a different dielectric $\Phi(x) \approx \psi_1(x)a_1 + \psi_2(x)a_2 = \begin{bmatrix} \psi_1(x) & \psi_2(x) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$



TOY FEM EXAMPLE [3]

- Use **Galerkin's method** to solve for the expansion coefficients that variationally minimize the residue
- Collapse the operator equation/BCs into a matrix problem

$$a_{1} \int_{0}^{1} \epsilon_{r} (\partial_{x} \phi_{1})^{2} dx + a_{2} \int_{0}^{1} \epsilon_{r} (\partial_{x} \phi_{2})^{2} dx = \int_{0}^{1} \psi_{1} dx$$
$$a_{1} \int_{0}^{1} \epsilon_{r} (\partial_{x} \phi_{1})^{2} dx + a_{2} \int_{0}^{1} \epsilon_{r} (\partial_{x} \phi_{2})^{2} dx = \int_{0}^{1} \psi_{1} dx$$

• For us:

$$\begin{bmatrix} 10 & -8 \\ -8 & 8 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 1/2 \\ 1/4 \end{bmatrix} = \widehat{M} | a \rangle = | b \rangle \implies a_1 = \frac{3}{8} | a_2 = \frac{13}{32}$$



TAKEAWAYS

- Guaranteed to have **minimum residue** under Galerkin weighting
- Based on selection of basis (trial) functions **meshing**
- More meshing, more accurate, more computationally expensive
- Depends on matrix math vulnerable to **condition number**



$$\begin{bmatrix} 10 & -8 \\ -8 & 8 \end{bmatrix} \rightarrow \begin{bmatrix} 9 + \sqrt{65} & 0 \\ 0 & 9 - \sqrt{65} \end{bmatrix} \approx \begin{bmatrix} 17 & 0 \\ 0 & 1 \end{bmatrix}$$

Condition number: $17/1 = 17$
What if this were
$$\begin{bmatrix} 1e - 16 & 0 \\ 0 & 1 \end{bmatrix}$$
?
d you trust matrix operations to not lose precision?

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REAL WORLD EXAMPLES!

- HFSS = High Frequency Structure Simulator
- Pioneered by Jin-Fa Lee, sold to Ansys (currently on version ~R19)
- Has many features I don't know/understand you are encouraged to explore all of its features!
- Examples:
 - [My example] Microstrip transmission line
 - [Your turn] Shorted transmission line



Follow along screenshots

MICROSTRIP TRANSMISSION LINE

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GETTING STARTED

BLUE: Insert new project

RED: Insert (L to R) HFSS FEM | HFSS MoM | Maxwell

GREEN: Select your design here





BEN MUNK CONSIDERATIONS

- What do we expect? Simulation from 5 GHz 15 GHz, L \sim 10 mm
- For $\epsilon_r \approx 9$, quasi-TEM mode Fabry-Perot oscillations every...

$$\frac{\epsilon_r + 1}{2} \frac{c_{vacuum}}{L} \approx 6 \ GHz$$

- High transmission coefficients, low reflection coefficients
- Electric field/magnetic field/Poynting's vector riding down the TRL
- Anything else?



MAKE YOUR DESIGN [1]

| D 2 | New Open Open Examples Close | Ctrl+N Ctrl+O | |
|--------|---|------------------|--|
| | Save Save As Save As Technology File | Ctrl+S | N5 |
| | Archive Restore Archive | | |
| | Page Setup Print Preview | | |
| | Import Export | • | EDB |
| | 1 ZL/personal//Waveguide_sandbox.aedt 2 E\DocumentS//Waveguide_sandbox.aedt 3 C\Users\lab\DocumentS/Sinouse seport test.aedt 4 F\DocumentS/\Sinouse seport test.aedt 6 F\DocumentS/\Sowlie_test.aedt 6 F\DocumentS/\Sowlie_C.aedt 7 F\DocumentS/bowTie_C.chokAllowed.aedt 8 C\Users\lab\DesktoplelectrostaticTest.aedt | | SM2 AutoCAD GDSIII ODB++ Cadence APD/Allegro/SiP IPC2S3I AVR. Microwave Office Lead frame Ys |
| | Exit | | ANX |



BLUE: Import file from other SW

RED: Insert basic geometric shapes, can also extrude 2D objects to 3D

GREEN: Select your design here



MAKE YOUR DESIGN [2]



BLUE: To edit geometric parameters of the box, click here

RED: origin of one of the corners [X,Y,Z]

GREEN: Dimensions depending on the geometric shape, can be negative or variables



MAKE YOUR DESIGN [3]

| | Properties | | | <u>ዋ</u> | × | Select Definition |
|------------|--------------------------|------------|------|-----------------|---|---|
| 🖻 🍪 Model | Name | Value | Unit | Evaluated Value | | Materials Material Filters Search Parameters |
| ⊡ 🖉 Solids | Name | Substrate | | | | Search by Name |
| Substrate | Material Solve Inside | "sapphire" | | "sapphire" | | |
| | Orientation | Global | | | | copper copper |
| Planes | Model | ~ | | | | coming_glass cyanate_ester |
| | Group Dieplay Wi | Model | | | | diamond diamond_hi_pres diamond_pl_cvd |
| | Color | | | | | Dupont Type 100 HN F Duroid (tm) |
| · · · · · | Transparent | 0.5 | | | | femite |
| | 1 | | | | | View/Edit Materials |

| search | Search Crite | ernia e ermittivity | C by Property | Libraries [sys] AmoldMag [sys] China Stee [sys] HitachiMe | Show Project definitions gnetics I tals | Show all librarie |
|------------------------------|--------------|---------------------------|---------------|--|--|---------------------------------------|
| / Name | | Location | Origin | Relative | Relative | B ^ |
| | | - | | | 1 | |
| copper | | Project | Materials | 1 | 0.999991 | 58000000sie |
| copper | | SysLibrary | Materials | 1 | 0.999991 | 5800000sie |
| coming_glass | | SysLibrary | Materials | 5.75 | 1 | 0 |
| cyanate_ester | | SysLibrary | Materials | 3.8 | 1 | 0 |
| diamond | | SysLibrary | Materials | 16.5 | 1 | 0 |
| diamond_hi_pres | | SysLibrary | Materials | 5.7 | 1 | 0 |
| diamond_pl_cvd | | SysLibrary | Materials | 3.5 | 1 | 0 |
| Dupont Type 100 HN Film (tm) | | SysLibrary | Materials | 3.5 | 1 | 0 |
| Duroid (tm) | | SysLibrary | Materials | 2.2 | 1 | 0 |
| epoxy_Kevlar_xy | | SysLibrary | Materials | 3.6 | 1 | 0 |
| ferrite | | SysLibrary | Materials | 12 | 1000 | 0.01siemens. |
| | | | | - | | · · · · · · · · · · · · · · · · · · · |

BLUE: To edit EM properties of the box, click here

RED: *always* rename parts of the model to be physically relevant

GREEN: Click here to change the material

ORANGE: Color-code and 50% transparency always helps me track me track the model

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PARAMETRIZING THE DESIGN

| | | Project Manager $\Psi \times$ |
|--|---------------------|---|
| Properties: Project1 - HFSSDesign1 - Modeler | | Project1* HFSSDesign1 (DrivenModal)* Project1* Model |
| Name Value Unit Evaluated Value Description | Add Variable | |
| Command CreateBox | Name I | Excitations |
| | | Hybrid Regions |
| Position -L/2, -W/2, 0 mm 0.5mm , -0.5mm | Unit Type None | analysis |
| XSize -1.5 mm -1.5mm | | Optimetrics |
| YSize U.9 mm U.9mm | | Results |
| ZSize 0.2 mm 0.2mm | Value () | Port Field Display |
| | Type Local Variable | → Tag Held Overays |
| Show Hidden | OK Cancel | Properties 7 × |
| OK Cancel | Apply | Name Value Unit Evaluated Value Type L 1 mm 1mm Design W 1 mm 1mm Design No.bs. 0.2 mm 0.2mm Design |
| | | Louds U.2 mm U.2mm Design |

BLUE: good to make the design symmetric about the origin, if possible

RED: always add units to parameters (they can be expressions of other parameters too) GREEN: Change parameters from this menu



PARAMETRIZING THE DESIGN

| | | Project Manager $\Psi \times$ |
|--|---------------------|---|
| Properties: Project1 - HFSSDesign1 - Modeler | | Project1* HFSSDesign1 (DrivenModal)* Project1* Model |
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RED: always add units to parameters (they can be expressions of other parameters too) GREEN: Change parameters from this menu





SIMULATION BOUNDARY CONDITIONS [1]





BLUE: Add a radiation box around the design. For TRLs, I pad 100% in \pm Z. Generally want $> \frac{\lambda}{4}$ padding from radiating edges. Be sure to change the bounday condition to "rad" RED: check the radiation box to see if it looks right, then hide it (it looks annoying!) GREEN: Change object visibility, incl. the radiation boundary

UC SANTA BARBARA PHYSICS THE WORLD GETS CHANGED HERE.

SIMULATION BOUNDARY CONDITIONS [2]

| Properties: Project1 - HFSSDesign1 - Modeler |
|---|
| Name Value Unit Evaluated Value Description Coordinate Sys Global |
| Show Hidden OK Cancel Apply |

BLUE: Add a plane for excitation. Copy and paste it to make the second one

RED: take advantage of your parametrization

GREEN: Alter the axis as needed (defaults to Z, not good for us!)



SIMULATION BOUNDARY CONDITIONS [3]

| | Wave Port : General | Wave Port : Post Processing |
|--|--|---|
| Select Groups G C+ C+ C | Name: | |
| Select Vertices V | Number of Modes: 4 | |
| Select Multi M Next Behind B All Object Faces Faces On Plane | 1 Defined Zpi 2 Defined Zpi | Impedance ::= resistance + 1i * reactance |
| Go to History Measure | 3 Defined Zpi 4 Defined Zpi | Renormalize Specific Modes Edit Mode Impedances |
| View > Edit > Group > | Mode Alignment and Polarity: | Deembed Settings Deembed Distance: 0 mm |
| Assign Material Create Array | Set mode polarity using integration lines Align modes using integration lines | Positive distance will deembed the port into the model. Get Distance Graphically |
| Create Open Region Update Open Region Padding Assign Boundary | C Align modes analytically using coordinate system U Axis Line: Undefined Reverse V Direction | |
| Assign Excitation Assign Mesh Operation Plot Fields | Filter modes for reporter Use Defaults | I lost two weeks on this feature |
| Plot Mesh Incident Wave Plot Mesh Uniked Field Copy Image Voltage Current. | / Back Next > Cancel | < Back Finish Cancel |
| Magnetic Bias | | |

BLUE: Select the appropriate object or face (>>F to select a face)

RED: assigned boundary values or a make a port

GREEN: defines the field integration pathway

Note: wave ports excite a wave mode on a surface and lumped port excites a node or a single point. Try to replicate the physics as you can



PREPARING THE SIMULATION [1]





MAKING A SIMULATION

| HFSS Tools Window Help | gir modeley | |
|---|---|--|
| Solution Type Solution Type Solution Type Solution Type Solution Type Solution The Characteristic Solution The Characteristic Solution The Characteristic Solution The Characteristic Solution Solution Solution Solution Solution Solutions Hybrid Mech Operations | | General Options Advanced Hybrid Expression Cache Derivatives Defaults Setup Name Setup 1 Image: Solution Setup 1 Image: Solution Setup 2 Solution Prequency: Solution Frequencies C Broadband Frequency Image: Solution Frequency: Image: Single Multi-Frequencies C Broadband Frequency Image: Solution Frequency |
| Fields Radiation Results | List Revert to Initial Mesh Apply Mesh Operations | Use Defaults |
| Boundary Display (Solver View) Design Properties Design Datasets | Clear Linked Data | HPC and Analysis Options |

BLUE: Prepare a simulation

RED: frequency used in adaptive meshing solutions

GREEN: adaptive meshing success criterion, lower is better but usually takes longer



ADD A FREQUENCY OR PARAMETRIC SWEEP

| Project1* | E Solias | 5 · · · · · | | |
|------------------------------------|------------------|-----------------------------|--|--------------------------------|
| HFSSDesign1 (DrivenModal)* | 🔁 🚍 gold | Project Manager 4 X | | |
| 3D Components | H Gnd | Project1* | | |
| Boundaries | 🖃 🚝 sapphire | | E 22 0 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 | |
| Excitations | 🕀 🖉 Substrate | - Trospesigni (Drivenhodal) | : 🖻 🐶 🖏 🖅 🗜 | |
| - 🔐 Hybrid Regions | 🖻 🚝 vacuum | | | |
| Mesh Operations | E P radBound | | | - • |
| ⊡ | Sheets | | | |
| Optime 🗈 Copy | Ctrl+C Eeed1 | Boundaries | Validation Check: Project1 - HFSSDesign1 | × |
| Result 🕮 Paste | Ctrl+V I Feed2 | 庄 📲 Excitations | | |
| End C Rename | F2 inate Systems | 🚽 🛃 Hybrid Regions | | 🖌 🛙 esian Settinas |
| Radiat X Delete | Delete | | HFSSDesign1 | 🖌 🕄 Model |
| Definitions Properties | | 🖃 🔊 Analysis | | 🖌 🖌 Epundaries and Excitations |
| | | Setup 1 | Validation Check completed. | 🖌 🖌 Nesh Operations |
| Add Frequency Sweep | | TT FAI Optimatrics | | 🖌 🖌 Analysis Setup |
| Analyze | | | | 🖌 🗸 Cotimetrics |
| Submit Job | | Results | | 🖌 Fadiation |
| Revert to Initial Mesh | | 🕂 🕂 Port Field Display | | |
| Add Mesh Linked Solution Set | tup E | Field Overlays | | |
| Properties Apply Mesh Operations | | | | |
| Name Value Clear Linked Data | | | Abort Close | |
| Enabled Create Quick Report | | | | |
| Passes 10 Perform FFT on Report | | | | |
| Percent R 30 Perform TDR on Report | | | | |
| Deta S 0.02 Profile | | | | |
| Solution Fr 10 Convergence | | | | |
| Max Refine 100000 Matrix Data | | | | |
| Use Max Mesh Statistics | | | | |
| Use ABC Network Data Explorer | | | | |
| Solver Type Direct | | | | |
| IE Solver Auto | | | | |

BLUE: sweep the frequency based on the center frequency mesh

RED: parametric sweep/optimizations... where a lot of the of the engineering is! **GREEN:** button used to check to make sure you're ready to simulate



WHILE IT RUNS



| Progress | | |
|--|---|--|
| Microstrip_unloaded_a1 - HFSSDesign1 | Setup1: Adaptive Pass #1 - Transfering adaptive r | esh field files on Local Machine - RUNNING |
| | | |
| Sending solution file: Setup1.sf_fld_1 | | |
| | | |
| | | |



BLUE: Simulate command

RED: status bar, simulation can be cancelled as needed on the RHS of this bar

GREEN: Check s matrix convergence/mesh statistics... etc. here. ALWAYS CHECK THIS!



INTERPRET THE RESULTS (BEN MUNK!)



BLUE: Insert 1 of a number of types of plots and select your desired output

RED: can animate fields as needed

GREEN: If the passivity is bad, decrease ΔS or the tolerated residue

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BLUE: Export CSV files of your data for prettier plotting

RED: status bar, simulation can be cancelled as needed on the RHS of this bar

GREEN: Save the convergence and some mesh statistics for the record



EXERCISE – STUDY A SHORT

- Use the previous design files
- Ben Munk considerations?
 - Standing wave instead of a propagating wave
 - High reflection coefficient
 - Low loss: trace should "hug" the Smith Chart border
- Modify the structure for one port
 - Suggestion: delete feed2 and add a gold short to ground
 - Measure S11
- Try for a couple different substrate thicknesses (parametric step)
- Try for very thin gold (100 nm) versus tall gold (100 microns)
- Try for narrow versus thick feed ports



TRY REPRODUCING SOMETHING LIKE THIS



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