HFSS OVERVIEW

User perspective on computational electromagnetics

Motivation | The basic problem | Demos
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

*Global Simulation & Analysis Software Market, 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
Complex-valued, spatially-varying tensors

Uniqueness of Maxwell’s equations in non-lossy regions?
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!
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
• \( \sigma(\omega_{\text{max}}^6 L^5) \)

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

\[
\mathcal{L}(\Phi) = -\frac{\partial_x \varepsilon_r \partial_x \Phi}{\varepsilon_0} = 1 \text{ with } \varepsilon_r = \begin{cases} 
\varepsilon_1 & 0 < x < \frac{1}{2} \\
\varepsilon_2 & \frac{1}{2} \leq x < 1
\end{cases}
\]

- Physical meaning: static dielectric interface between \( \varepsilon_1 \) and \( \varepsilon_2 \)

- How can we solve this?

\[
\begin{align*}
\Phi(0) &= 0 \\
\Phi(1) &= 0 \\
\varepsilon_1 &= 1 \\
\varepsilon_2 &= 4 \\
\frac{\partial_x \Phi(x)}{\varepsilon_0} &= 0 \\
x = \frac{1}{2}
\end{align*}
\]
**Ben Munk Approach to the Toy Model**

- Integrate twice and apply boundary conditions

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

- Physical meaning: static dielectric interface between \(\epsilon_1\) and \(\epsilon_2\)
- BCs: should go to zero at \(x = 0\) and gradient should vanish at \(x = 1\) [OK]

\[\partial_x \epsilon_r \partial_x \Phi = -\rho/\epsilon_0\]

\(\epsilon_1 = 1 \quad \epsilon_2 = 4\)
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

\[ \Phi(x) \approx \psi_1(x)a_1 + \psi_2(x)a_2 = [\psi_1(x) \quad \psi_2(x)] \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \]
**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

\[
a_1 \int_0^1 \varepsilon_\tau (\partial_x \phi_1)^2 dx + a_2 \int_0^1 \varepsilon_\tau (\partial_x \phi_2)^2 dx = \int_0^1 \psi_1 dx
\]

\[
a_1 \int_0^1 \varepsilon_\tau (\partial_x \phi_1)^2 dx + a_2 \int_0^1 \varepsilon_\tau (\partial_x \phi_2)^2 dx = \int_0^1 \psi_1 dx
\]

- For us:

\[
\begin{bmatrix}
10 & -8 \\
-8 & 8 \\
\end{bmatrix}
\begin{bmatrix}
a_1 \\
a_2 \\
\end{bmatrix}
= \begin{bmatrix}
1/2 \\
1/4 \\
\end{bmatrix} = \hat{M} |a > = |b > \Rightarrow a_1 = \frac{3}{8}, a_2 = \frac{13}{32}
\]
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 \( \begin{bmatrix}
1e-16 & 0 \\
0 & 1 \\
\end{bmatrix} \)?
Would you trust matrix operations to not lose precision?
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
**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~ 10 mm
• For $\varepsilon_r \approx 9$, quasi-TEM mode Fabry-Perot oscillations every...

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

• High transmission coefficients, low reflection coefficients
• Electric field/magnetic field/Poynting’s vector riding down the TRL
• Anything else?
**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
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
PARAMETRIZING THE 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
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
BLUE: Add a radiation box around the design. For TRLs, I pad 100% in ±Z. Generally want $\frac{\lambda}{4}$ padding from radiating edges. Be sure to change the boundary 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
Simulation Boundary Conditions [2]

**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]**

**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

VERY IMPORTANT!!!
I lost two weeks on this feature
PREPARING THE SIMULATION [1]

Transmission Lines
Antennas
Just like the name sounds
Resonators and metamaterials
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**

**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

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!

11/28/2018
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
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