HFSS Hybrid Finite Element and Integral Equation Solver and Savant for Large Scale Electromagnetic Design and Simulation

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Agenda

• Overview of Simulation Trends and Technologies
• ANSYS Simulation Technologies Overview
• ANSYS Electromagnetic Simulation Techniques
  • HFSS-FEM
  • HFSS-IE
  • Hybrid FE-BI
  • Hybrid IE-Regions
• Physical Optics
• Savant
• Examples
The Problem: Installed Antenna Performance

- Antennas often designed in isolation or under ideal conditions
- Mounting antennas on realistic platforms changes performance
- Impacts overall RF system performance
  - Need to know installed performance early in the design cycle!
ANSYS EBU Product Portfolio

Geometry and Material Complexity

Electrical Size

Savant: Shooting Bouncing Ray

HFSS-IE: Fast Method of Moments

HFSS: Finite Elements

The HFSS Solution

ANSYS Domain Decomposition Method

Geometry and Material Complexity
Advantages

• **Complementary Technology**
  – HFSS: Antenna Design
  – Savant: Installed Performance

• **Extremely Fast**
  – Multicore, GPU and MPI
  – Consumer or Scientific grade GPUs

• **Low Memory Requirements**
  – Most jobs require < 8 GB of RAM

• **Accuracy**
  – Physics models not found in other ray tracing tools

• **Intuitive**
  – Powerful GUI with thorough Help/Tutorials
ANSYS Simulation Technologies

• Finite Element Method
  • HFSS
  • Efficiently handles complex material and geometries
  • Volume based mesh and field solutions
  • Fields are explicitly solved throughout entire volume

• Integral Equations
  • HFSS-IE
  • Efficient solution technique for open radiation and scattering
  • Currents solved only on surface mesh
  • Efficiency is achieved when structure is primarily metal
Hybrid Finite Element – Integral Equations

- Finite Element Method
- HFSS
  - Efficiently handles complex geometries

Integral Equations
- HFSS-IE
  - Efficient solution technique for open radiating and scattering of metallic objects

- Hybrid Finite Element - Integral Equations
  - FE-BI
  - IE-Regions

- Hybrid method invoked inside of HFSS Design using IE-Regions or FE-BI boundary conditions
- Hybrid method takes advantage of features from both methods to allow for more efficient simulations
ANSYS Simulation Technologies

- **Physical Optics**
  - HFSS-IE
  - High frequency approximation
  - Ideal for electrically large, smooth objects
  - Currents are approximated in illuminated regions and set to zero in shadow regions
  - 1st order interactions

- **Ray Tracing**
  - Savant
  - Extends physical optics (PO) to multiple bounces with GO ray tracing
  - Asymptotic technique
    - Complimentary capability to full-wave solvers
    - Electrically large platforms (i.e., many wavelengths in dimension)
High Frequency Technique: Physical Optics

High frequency asymptotic solver available inside of HFSS-IE designs

- Currents are approximated in illuminated regions and set to zero in shadow regions
- First order interaction only, single bounce
- Source excitation from HFSS Far Field Data-Link of incident plane wave

Usage

- Applications include
  - Electrically large - RCS, Antenna Placement, Reflector Analysis
- Quickly estimate performance of electrically large problems
- Full wave solution is beyond computation resources
Savant’s Methodology: SBR+

• **Shooting and Bouncing Rays**
  – Asymptotic technique
    • Complimentary capability to full-wave solvers
    • Electrically large platforms (i.e., many wavelengths in dimension)
  – Extends physical optics (PO) to multiple bounces with GO ray tracing
  – Material Modeling: Dielectric/Magnetic stacks, Fresnel table import

• **SBR+ ?**
  – Build on traditional SBR with additional physics
    • Physical Theory of Diffraction (PTD) Edge Correction
    • Uniform Theory of Diffraction (UTD) Edge Rays
    • Creeping Wave
  – Driving philosophy
    • Use full array of GTD/UTD methods to “paint” currents on platform body
    • Radiate painted currents to field observers, Rx antennas
    • All models/mechanisms work together to improve accuracy
Hybrid Methods

FE-BI

IE-Regions
Finite Element – Boundary Integral

- Mesh truncation of infinite free space into a finite computational domain
  - Alternative to ABC or PML radiation boundary conditions

- Hybrid solution of FEM and IE
  - IE solution on outer faces
  - FEM solution inside of volume

- FE-BI Advantages
  - Arbitrary shaped boundary
    - Conformal and discontinuous to minimize solution volume
  - Reflection-less boundary condition
    - High accuracy for radiating and scattering problems
  - No theoretical minimum distance from radiator
    - Reduce simulation volume and simplify problem setup
Finite Element – Boundary Integral: Example Problem

- FE-BI can be used to significantly reduce required computer resources
- Large volume of air inside of radome can be removed from the FEM solution domain
  - Air volume would be required if using PML or ABC
- Two FE-BI surfaces will be applied
  - Conformal to radome
  - Conformal to horn antenna (10 GHz)

<table>
<thead>
<tr>
<th>10 GHz</th>
<th>RAM (GB)</th>
<th>Elapsed Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABC</td>
<td>15</td>
<td>70min</td>
</tr>
<tr>
<td>FE-BI</td>
<td>7</td>
<td>30min</td>
</tr>
</tbody>
</table>
IE-Regions

In a hybrid FEM-IE solution, IE Regions allow uniform regions of free space or dielectric to be removed from the FEM solution

• Metal objects can be solved directly with an IE solution applied to surface
  • Removes need for air box to surround metal objects
• Dielectric regions can be replaced with an IE Region on the boundary of uniform dielectric material
  • Solution inside of dielectric is solved using IE
IE-Regions: Example Problem

IE-Region Applied to RCS of Electrally Large Dielectric Sphere

- Hybrid FEM-IE solution of scattering from dielectric sphere using IE-Regions
- Uniform volume of dielectric removed by applying IE-Region to surface of dielectric sphere

Radius = 900mm, $\varepsilon_r = 4$, $F = 1GHz$

<table>
<thead>
<tr>
<th></th>
<th>1 GHz</th>
<th>RAM (GB)</th>
<th>Elapsed Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM Only</td>
<td></td>
<td>33.4</td>
<td>222min</td>
</tr>
<tr>
<td>Hybrid FEM-IE</td>
<td>3.2</td>
<td></td>
<td>35min</td>
</tr>
</tbody>
</table>

10X Less 7X Faster
Hybrid Solution

- With the addition of IE regions, a fully hybridized solution of FEM and IE is capable of solving electrically large problems more efficiently

- FEM and IE

- FE-BI
  - Truncate an FEM solution space with any arbitrary surface using a boundary integral

- IE-Regions
  - When used along with FE-BI, conducting objects outside of FEM solution space can be solved directly with IE, eliminating the need for conducting objects to be enclosed in an air volume
  - Homogenous dielectric volumes can be removed from the FEM solution and replaced with the equivalent IE solution in the region, useful when dielectric regions are electrically large requiring large FEM solution volume
Examples

Finite Element - Boundary Integral
IE-Region
Physical Optics
Savant
Array on Spacecraft Using FE-BI

- 7 Element Helix Antenna Array integrated on satellite platform
  - Dielectric solar panels and antenna supports do not make this problem ideal for HFSS-IE

- Inclusion of solar panels create an electrically large model
  - 64λ wide at 3.5 GHz

- Using ABC or PML boundary would require an Airbox equal to 21k λ³

- FE-BI can reduce the required Airbox to 1.2k λ³
Array on Spacecraft Using FE-BI: Results

- Array platform integration simulated with conformal FE-BI
  - RAM requirements reduced by 10x
  - RAM reduction as a result of removing the surrounding free space

- Only possible using FE-BI

<table>
<thead>
<tr>
<th>Boundary Type</th>
<th>Airbox Volume</th>
<th>Number of Domains</th>
<th>Total RAM (GB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABC</td>
<td>21k $\lambda^3$</td>
<td>34</td>
<td>210</td>
</tr>
<tr>
<td>FE-BI</td>
<td>1.2k $\lambda^3$</td>
<td>12</td>
<td>21</td>
</tr>
</tbody>
</table>

10X Less
Reflector Analysis Using IE-Regions

- Multiple techniques have been developed to analyze reflector antennas using HFSS
  - Full HFSS Solution - Model entire solution space using only HFSS
    - High level of fidelity also requires most computer resources
  - Data Link Solutions – Source feed excitation modeled separately from reflector
    - Data link solutions only include 1 way coupling from source excitation to reflector
  - Hybrid Solutions
    - Efficient, high fidelity solution using hybrid FEM-IE techniques

Full HFSS solution requires large air box (~37k \(\lambda^3\))
Reflector Analysis Using IE-Regions: Setup

• Analysis of electrically large reflector antennas may benefit from multi-step design approach utilizing several simulation methodologies

HFSS to HFSS-IE or PO Data-link:
• Source excitation solved in HFSS
• Used as data linked excitation into a Physical Optics or HFSS-IE simulation

Hybrid Solution - FE-BI and IE-Region
• Full wave simulation performed using a hybrid solution in HFSS
  • IE-Region applied to reflector
  • FE-BI applied around feed
Reflector Analysis Using IE-Regions: Results

• **Full wave solution possible using hybrid FEM-IE solution, enabled with FE-BI and IE-Regions**
  • Agreement between methods only show small difference in peak and side lobe levels

• **Offset fed reflector**
  • Backscatter and blockage not fully included in either data-linked simulation – effects would be more significant for center fed reflector
Reflector Analysis Using IE-Regions: Results

<table>
<thead>
<tr>
<th>Boundary Type</th>
<th>Airbox Volume</th>
<th>Total RAM (GB)</th>
<th>Elapsed Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full HFSS solution (FEM Only, DDM)</td>
<td>37k $\lambda^3$</td>
<td>163.5 (1st pass)</td>
<td>2.7 (1st pass)</td>
</tr>
<tr>
<td><strong>Full Wave Hybrid FEM-IE</strong></td>
<td><strong>8.6 $\lambda^3$ (Feed Only)</strong></td>
<td><strong>&gt;32X Less</strong></td>
<td><strong>&gt;10X Faster</strong></td>
</tr>
<tr>
<td>HFSS to IE Data-Link</td>
<td>NA</td>
<td>3.4</td>
<td>0.2</td>
</tr>
<tr>
<td>HFSS to PO Data-Link</td>
<td>NA</td>
<td>0.4</td>
<td>1 minute</td>
</tr>
</tbody>
</table>
Hybrid Solution for Antenna Placement Analysis Using IE-Regions

- Antenna performance modeled with placement in proximity to human head
  - Cell phone platform and antenna with complex material properties and geometry are ideally modeled using FEM solution
  - The uniform, high dielectric properties of the head are ideally modeled using IE solution

- Hybrid Solution
  - An internal dielectric IE Region can be applied to head geometry to reduce computational size and improve efficiency
  - FEM solution is applied remaining volume

Human Head Material Properties:

\[ \varepsilon_r = 79, \ \sigma = 0.47 \text{siemens/m} \]
Hybrid Solution for Antenna Placement Analysis Using IE-Regions: Results

IE-Region Boundary Condition Applied

Hybrid FEM-IE Solution 1.8 GHz
FEM Only Solution 1.8 GHz

<table>
<thead>
<tr>
<th>Solution Type</th>
<th>Total RAM (GB)</th>
<th>Elapsed Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM Only</td>
<td>6.2</td>
<td>1</td>
</tr>
<tr>
<td>Hybrid Solution</td>
<td>3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

2X Faster  2X Less
Hybrid Solution for Antenna Placement Analysis Using IE-Regions

- **Antenna performance modeled with placement in proximity to human head inside vehicle**
  - Cell phone platform and antenna with complex material properties and geometry are ideally modeled using FEM solution
  - The uniform, high dielectric properties of the head are ideally modeled using IE solution
  - The car is ideally modeled using IE-Region

- **Hybrid Solution Setup**
  - An internal dielectric IE-Region can be applied to head geometry to reduce computational size and improve efficiency
  - An exterior metallic IE-Region is applied to car model
  - FEM solution is applied remaining volume
Hybrid Solution for Antenna Placement Analysis Using IE-Regions: Results

<table>
<thead>
<tr>
<th>Solution Type</th>
<th>Total RAM (GB)</th>
<th>Elapsed Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full FEM Solution</td>
<td>160 GB (DDM)</td>
<td>8</td>
</tr>
<tr>
<td>Hybrid FEM-IE Solution</td>
<td>11</td>
<td>2.7</td>
</tr>
</tbody>
</table>

15X Less 3X Faster
Physical Optics (PO) for Electrically Large Simulations

High frequency asymptotic solver

- Scattering and antenna placement of electrically large objects

RCS of PEC Sphere

- Highlights capabilities and limitation of physical optics
- Creeping wave effects not accounted for by PO
- When electrical size of sphere becomes large, full wave solution converges with physical optics solution

<table>
<thead>
<tr>
<th>Solution @ High Freq.</th>
<th>Total RAM (GB)</th>
<th>Elapsed Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Wave (HFSS-IE)</td>
<td>1.4</td>
<td>87</td>
</tr>
<tr>
<td>Physical Optics</td>
<td>0.1</td>
<td>14</td>
</tr>
</tbody>
</table>
**Physical Optics for RCS of Electrically Large Structures**

Good correlation between full wave solution and physical optics solution for RCS of electrically large cone-sphere

- Creeping wave effects not accounted for in physical optics solution
- Apparent as incident angles approach tip and sphere side of cone-sphere

<table>
<thead>
<tr>
<th>Solution @ High Freq.</th>
<th>Total RAM (GB)</th>
<th>Elapsed Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Wave (HFSS-IE)</td>
<td>6.6</td>
<td>2 hours</td>
</tr>
<tr>
<td>Physical Optics</td>
<td>4.8</td>
<td>16 minutes</td>
</tr>
</tbody>
</table>
International Space Station (ISS): Antenna Placement and Blockage Simulations

Multiple antenna and communication channels operating on and around the ISS are subject to blockage due to the large structure
• Physical Optics allows us to model important navigational and communications challenges
  • Degradation of communications due to adjusting solar panels on ISS
  • Blockage of GPS signals used by docking vehicles
Physical Optics for S-Band Communications on ISS Antenna Blockage

<table>
<thead>
<tr>
<th>Solution @ 2GHz</th>
<th>Total RAM (GB)</th>
<th>Elapsed Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Optics</td>
<td>47</td>
<td>57</td>
</tr>
</tbody>
</table>

Source location
Savant
Antenna Models

• From HFSS
  – Far-field radiation patterns
  – Current sources

• Built in parametric models
  – Dipoles, monopoles, loops, slots
  – Pyramidal and Conical horns
  – Parametric Beam

• Array Design Tool
  – Linear, Rectangular, Elliptical & By File
  – Weighting and phasing of elements

• Near-Field to Current Sources
  – Third Party CEM tools
  – Measured Data (Microwave Vision Group)
Accuracy: Creeping Wave

1 GHz monopole mounted on Global Hawk

Creeping Wave is very important for this problem! Savant is the only SBR tool with this capability.
Accuracy: UTD Diffraction Rays

1 GHz monopole

UTD Is Very Important For This Problem! Savant is the only SBR tool with this capability

SBR Rays + UTD Rays
HFSS & Savant Integrated Workflow

- **Isolated Antenna Element Solved in HFSS**
- **250 MHz Monopole**
- **HFSS Currents Used by Savant**
- **Simulation Time for Installed Antenna**
  - **Savant**: 12 minutes
  - **HFSS**: 195 minutes

**42λ x 17λ x 3.75λ**

- **Savant Quickly Simulates the Large Installed Environment**

(Elevation Cut (Azimuth = 0°) and Elevation Cut (Azimuth = 90°))
HFSS & Savant Integrated Workflow

Complete Installed Antenna Pattern in Savant
Value Proposition

- Extend the capabilities of HFSS users to address much larger problems
- Enhance the investment in HFSS and other ANSYS tools
- Rapid simulations allow for many iterations during design cycle
- Optimize amount of testing required
- Advanced diagnostic features help users to understand results
- Recognized as best-in-class ray tracing technology
  - Shooting and Bouncing Rays (SBR)
GPU and MPI Examples

- CPU and GPU
  - Monopole on 737-800
    - 40,000 angular samples
    - 3 to 4 GHz, 40 MHz steps
    - 747,820 rays hit CAD

- CPU, GPU and MPI
  - 94 GHz Antenna on UH-60

- Computer hardware costs $20K

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Time</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 CPU Core</td>
<td>12 hrs, 18 min</td>
<td></td>
</tr>
<tr>
<td>4 CPU Cores</td>
<td>3 hrs, 12 min</td>
<td>4x</td>
</tr>
<tr>
<td>1 CPU Core, 1 GPU</td>
<td>10.7 min</td>
<td>&gt;70x</td>
</tr>
<tr>
<td>4 CPU Cores, 2 GPU</td>
<td>6.2 min</td>
<td>&gt;118x</td>
</tr>
<tr>
<td>1 Node, 6 cores, 2 GPU</td>
<td>720 sec</td>
<td></td>
</tr>
<tr>
<td>5 Nodes, 30 CPU cores, 10 GPUs</td>
<td>143 sec</td>
<td>5x</td>
</tr>
</tbody>
</table>
Workflow + Hardware Acceleration

HFSS

UHF Blade Antenna
2.3 GHz

1,620 simulations to capture moving blades and engine assemblies

6 hours to compute all jobs on laptop!
Summary

- Data Link Savant
- Data Link IE Solutions
- HFSS-IE with HPC/MPI
- Hybrid HFSS (FE-BI/IE-Region)
- Full HFSS Solution

Model Electric Size

Model Material Complexity

Fidelity
Thank You!