HFSS Hybrid Finite Element and Integral Equation Solver 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 *New in v12*
- Hybrid FE-BI *New in v13*
- Hybrid IE-Regions *New in v14*
- Physical Optics *New in v14*

High Performance Computing

- HFSS with Domain Decomposition Method (DDM) *New in v12*
- HFSS-IE with industry standard Message Passing Interface (MPI) *New in v14*

Examples
Simulation Trends

Full System Simulations
• Require simulation of more complicated and electrically large problems
• Efficient simulations

Types of problems to solve
Ansoft 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

• Physical Optics new in v14
  • 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
Hybrid Finite Element – Integral Equations

Finite Element Method
• HFSS
  • Efficiently handles complex material and geometries

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

• Hybrid Finite Element - Integral Equations
  • FE-BI New in v13
  • IE-Regions New in v14

  • 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

IE-Regions
High Frequency Technique: Physical Optics

Physical Optics
• HFSS-IE
• Ideal for electrically large, conducting and smooth objects

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
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: Boundary Condition Setup

Enabled with HFSS-IE license feature inside of an HFSS Design

Setup is similar to ABC boundary condition

• Enabled by selecting “Model exterior as HFSS-IE domain”

Radiation surface must enclose entire geometry

• 1 infinite ground plane allowed

Direct vs. Iterative Matrix Solver

• Direct Matrix Solver
  – Preferred method with FE-BI
  – Quickest solution

• Iterative solver
  – Uses the least amount of RAM
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 New in v14

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: Boundary Condition Setup

IE-Regions can be applied to metal or dielectric objects inside of an HFSS Design

- Metal Objects
  - Typically exterior to air box region with FE-BI outer radiation boundary or
  - Internal to dielectric IE Region

- Dielectric Objects
  - Must be interior to air box region

Assignment:

- Select Object

  - HFSS → IE Regions → Assign As IE Region

IE Solution Applied to Metal outside of air box and dielectric inside of air box

Air Volume truncated with FE-BI radiation boundary condition

![IE Region Visualization](image)
IE-Regions: Example Problem

IE-Region Applied to RCS of Electrically 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, $\varepsilon_r = 4$, $F = 1\text{GHz}$

<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 using IE Regions</td>
<td></td>
<td>3.2</td>
<td>35min</td>
</tr>
</tbody>
</table>

10X Less

7X Faster
Hybrid Solution

With the addition of IE regions to HFSS v14, 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
High Performance Computing Applied to Hybrid Methods

HPC with HFSS using Domain Decomposition

HPC with HFSS-IE using MPI New in v14
High Performance Computing

Increase simulation capacity using High Performance Computing (HPC)

Domain Decomposition Method (DDM) for HFSS

- HFSS only
- HFSS using FE-BI and IE-Regions *New in v14*

Distributed Memory Parallel for HFSS-IE *New in v14*

- Uses industry standard Message Passing Interface (MPI)
- Perform HFSS-IE simulation by distributing solution across machines in a cluster or network
High Performance Computing with HFSS using DDM

- Distributes mesh sub-domains to network of processors
  - FEM volume can be subdivided into multiple domains
  - IE Domains that are discontinuous will be distributed to separate nodes when they become large
- Significantly increases simulation capacity
- Multi-processor nodes can be utilized
High Performance Computing with HFSS-IE using MPI

- The HFSS-IE solver in HFSS v14 uses the industry standard Message Passing Interface (MPI) and can perform solutions that distribute memory use across machines in a cluster or network.
- Simulation capacity is only limited by available computer resources.
  - Enables simulation of electrically large problems.
New features in HFSS v14 enabling large scale electromagnetic design and simulation

**Hybrid FEM and IE Solution**
- FE-BI and IE-Regions
  - Requires HFSS and HFSS-IE license

**Distributed Memory Hybrid HFSS and HFSS-IE**
- For Hybrid HFSS and HFSS-IE
  - HFSS, HFSS-IE and HPC License
- For HFSS-IE Only
  - HFSS-IE and HPC License

**Physical Optics**
- Requires HFSS-IE license
Examples
Finite Element - Boundary Integral
IE-Region
Physical Optics
High Performance Computing
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

- $64\lambda$ wide at 3.5 GHz

Using ABC or PML boundary would require an Airbox equal to $21k \lambda^3$

FE-BI can reduce the required Airbox to $1.2k \lambda^3$
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

![Diagram showing fidelity and computer resources vs. solution types](image)

- **Full HFSS solution requires large air box (~37k λ³)**
- **Hybrid Solution uses FEM for feed and IE applied to reflector**
Analysis of electrically large reflector antennas may benefit from a 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

![Graphs showing θ-pol Gain (dBi) for different analysis methods](image)

### Table: Analysis 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 λ³</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 λ³ (Feed Only)</strong></td>
<td><strong>5</strong></td>
<td><strong>&lt;32X Less</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>

>32X Less  >10X Faster
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: 
\[ \varepsilon_r = 79, \ \sigma = 0.47 \text{simems/m} \]
Hybrid Solution for Antenna Placement Analysis Using IE-Regions: Results

### Solution Types

<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 Less** RAM and **2X Faster** Elapsed Time compared to FEM Only.
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>

Incident Wave

- Full Wave Solution
- Physical Optics Solution
**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>
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

733 \lambda
Distribute HFSS-IE Using MPI

Full wave solution using HFSS-IE of electrically large structures

RCS of fighter aircraft at 5GHz

250\lambda

175\lambda
Distributed HFSS-IE Solution: Fighter Aircraft

Full wave solution

Scattering of fighter aircraft at 5GHz

Large scale simulation possible by using compute cluster of 10 networked machines

Solution only possibly using distributed computing resources

<table>
<thead>
<tr>
<th>Distributed HFSS-IE Solution</th>
<th>Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Memory</td>
<td>32 GB</td>
</tr>
<tr>
<td>Total Memory (10 nodes)</td>
<td>325 GB</td>
</tr>
<tr>
<td>Total Time</td>
<td>33.5 Hours</td>
</tr>
</tbody>
</table>