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Technical Notes

The simulation technique used to calculate the full 3D electromagnetic field inside a structure is based on <u>the finite element method.</u> Although its implementation is largely transparent, a general understanding of the method is useful in making the most effective use of Ansoft HFSS.

This section provides an overview of the finite element method and its implementation in Ansoft HFSS. It also describes how modal S-parameters are computed from the simulated electric and magnetic fields and how they can be converted to "nodal" or "voltage" based pseudo-S-parameters used in circuit theory.

Information is included on the following:

- The Finite Element Method
- Software Modules
- Derivation of Wave Equation
- Implementation

- S-Parameters
- Radiated Fields
- Modes to Nodes Conversion

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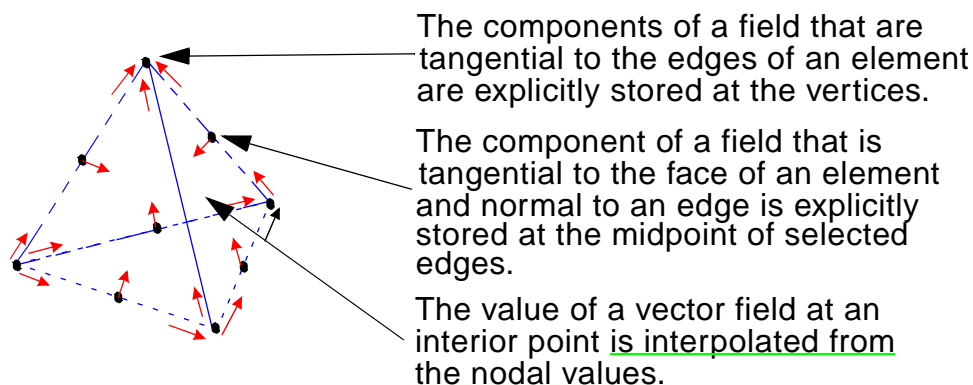
The Finite Element Method

In order to generate an electromagnetic field solution, Ansoft HFSS employs the finite element method. In general, the finite element method divides the full problem space into thousands of smaller regions and represents the field in each sub-region (element) with a local function.

In Ansoft HFSS, the geometric model is automatically divided into a large number of tetrahedra, where a single tetrahedron is basically a four-sided pyramid. This collection of tetrahedra is referred to as the finite element mesh.

Representation of a Field Quantity

The value of a vector field quantity (such as the H-field or E-field) at points inside each tetrahedron is interpolated from the vertices of the tetrahedron. At each vertex, Ansoft HFSS stores the components of the field that are tangential to the three edges of the tetrahedron. In addition, the system can store the component of the vector field at the midpoint of selected edges that is tangential to a face and normal to the edge (as shown below). The field inside each tetrahedron is interpolated from these nodal values.

The components of a field that are tangential to the edges of an element are explicitly stored at the vertices.

The component of a field that is tangential to the face of an element and normal to an edge is explicitly stored at the midpoint of selected edges.

The value of a vector field at an interior point is interpolated from the nodal values.

By representing field quantities in this way, the system can transform Maxwell's equations into matrix equations that are solved using traditional numerical methods.

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Basis Functions

Various interpolation schemes (basis functions) can be used to interpolate field values from nodal values.

- A 1st order tangential element basis function interpolates field values from both nodal values at vertices and on edges.
  1st order tangential elements have 20 unknowns per tetrahedron.
- A 0th order basis function makes use of nodal values at vertices only — and therefore assumes that the field varies linearly inside each tetrahedron.
  0th order tangential elements have six unknowns per tetrahedron.

Size of Mesh Versus Accuracy

There is a trade-off between the size of the mesh, the desired level of accuracy, and the amount of available computing resources.

The accuracy of the solution depends on how small each of the individual elements (tetrahedra) is. Generally speaking, solutions based on meshes using thousands of elements are more accurate than solutions based on coarse meshes using relatively few elements. To generate a precise description of a field quantity, each element must occupy a region that is small enough for the field to be adequately interpolated from the nodal values.

However, generating a field solution involves inverting a matrix with approximately as many elements as there are tetrahedra nodes. For meshes with a large number of elements, such an inversion requires a significant amount of computing power and memory. Therefore, it is desirable to use a mesh fine enough to obtain an accurate field solution but not so fine that it overwhelms the available computer memory and processing power.

To produce the optimal mesh, Ansoft HFSS uses an iterative process in which the mesh is automatically refined in critical regions. First, it generates a solution based on a coarse initial mesh. Then, it refines the mesh in areas of high error density and generates a new solution. When selected parameters converge to within a desired limit, the system breaks out of the loop.

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Field Solutions

During the iterative solution process, the S-parameters typically stabilize before the full field solution. Therefore, when you are interested in analyzing the field solution associated with a structure, it may be desirable to use convergence criteria that are tighter than usual.

In addition, for any given number of adaptive iterations, the magnetic field (H-field) is less accurate than the solution for the electric field (E-field) because the H-field is computed from the E-field using the relationship:

$$H = \frac{\nabla \times E}{-j\omega\mu}$$

Eigenmodes

Eigenmodes are the resonances of the structure. The eigenmode solver finds the resonant frequencies of the structure and the fields at those resonant frequencies.

For a Driven Solution, Ansoft HFSS solves the following matrix equation (for a lossless case):

$$Sx + k_o^2 Tx = b$$

where:

- S and T are matrices that depend on the geometry and the mesh.
- x is the electric field solution.
- k_o is the free-space wave number.
- b is the value of the source defined for the problem.

However, in order to find the resonances of the structure, the eigenmode solver sets b to zero, and solves the equation:

$$Sx + k_o^2 Tx \equiv 0$$

for sets of (ko, x), one ko for every x. The variable x is still the electric field solution, and ko is the free space wave number corresponding to that mode. The wave number ko is related to the frequency of the resonant modes through the following:

$$f = \frac{k_o c}{2\pi}$$

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where c is the speed of light.

The Ansoft HFSS eigenmode solver can find the eigenmodes of lossy as well as lossless structures, and can calculate the unloaded Q of a cavity. Q is the quality factor, and is a measure of how much energy is lost in the system. Unloaded Q is the energy lost due to lossy materials. Because ports and other sources are restricted for eigenmode problems, the Q calculated does not include losses due to those sources.

In addition to calculating the unloaded Q, the eigenmode solver can calculate the loaded Q of structures only for power lost through PML structures.

Note: Like the driven solution, the eigenmodes tend to converge long before the field solutions.

Peak vs. RMS phasors

This section concerns how field quantities are represented within Ansoft HFSS. Some users will not need this information, such as those who wish to know port S-parameters or relative amplitudes of field solutions. Those that wish to find absolute field values, for example, will need to review the difference between the two types of field representation, peak and RMS.

HFSS solves in the frequency domain and obtains a phasor representation of the steady-state finite element field solution. Physical quantities such as the instantaneous (time domain) electric field are then obtained as derived quantities from the phasor representation.

If E_x is the x-component of a "peak" phasor quantity representing a time-harmonic electric field, the physical electric field x-component at time t, denoted $E_x(t)$, is computed from:

$$E_x(t) \equiv \Re[E_x e^{j\omega t}]$$

where:

- $\Re$ is the real part of a complex number or function.
- ω is angular frequency, $2\pi f$.
- j is the imaginary unit, $\sqrt{-1}$.
- t is the time.

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On the other hand, if E_x is an "RMS" phasor, an additional factor of $\sqrt{2}$ is required:

$$E_x(t) = \Re[\sqrt{2}E_x e^{j\omega t}]$$

As a consequence of these equations, the peak physical field, max ($E_x(t)$) observed over a full time cycle is $max(E_x(t)) = |E_x|$ for peak phasors and $max(E_x(t)) = \sqrt{2}|E_x|$ for RMS phasors.

Additionally, given field phasors $\mathbf{E}$ and $\mathbf{H}$, to compute the time-averaged power flow through a surface, the normal component of the real part of the complex Poynting vector is integrated over the surface. The correct form of the complex Poynting vector $\mathbf{S}$ depends on which phasor representation is used. For peak phasors:

$$\mathbf{S} \equiv \tfrac{1}{2}\mathbf{E} \times \mathbf{H}^*$$

For RMS phasors:

$$\mathbf{S} \equiv \mathbf{E} \times \mathbf{H}^*$$

While using Ansoft HFSS, the conventions are as follows:

- Each propagating mode incident on a port contains 1 watt of time-averaged power.
- Circuit gap sources are specified in a peak sense. That is, if a voltage gap source magnitude is 5 volts, then the time domain circuit source behaves as v(t) = 5cosωt. Likewise for a current gap source.
- Plane-wave sources are specified in a peak sense. That is, if the plane wave magnitude is 5 V/m, then the plane wave incident field magnitude is $E(t) = 5\cos(\mathbf{k} \cdot \mathbf{r} + \omega t)$.
- Radiated power, as computed in the 3D Post Processor, is a time-averaged quantity computed using the complex Poynting vector.
- Phasors in the Data Calculator are peak phasors. The Poynting vector button in the calculator therefore implements the Poynting vector for peak phasors, **S** = 1/2**E** x **H***. Calculations that compute either average or instantaneous time domain quantities must adhere to the peak phasor conventions.

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Implementation

To calculate the S-matrix associated with a structure, the system does the following:

- Divides the structure into a finite element mesh.
- Computes the modes on each port of the structure that are supported by a transmission line having the same cross-section as the port.
- Computes the full electromagnetic field pattern inside the structure, assuming that one mode is excited at a time.
- Computes the generalized S-matrix from the amount of reflection and transmission that occurs.

The final result is an S-matrix that allows the magnitude of transmitted and reflected signals to be computed directly from a given set of input signals, reducing the full 3D electromagnetic behavior of a structure to a set of high frequency circuit parameters.

Solution Process

There are four variations to the solution process:

- Single frequency solution
- Fast frequency sweep
- Discrete frequency sweep
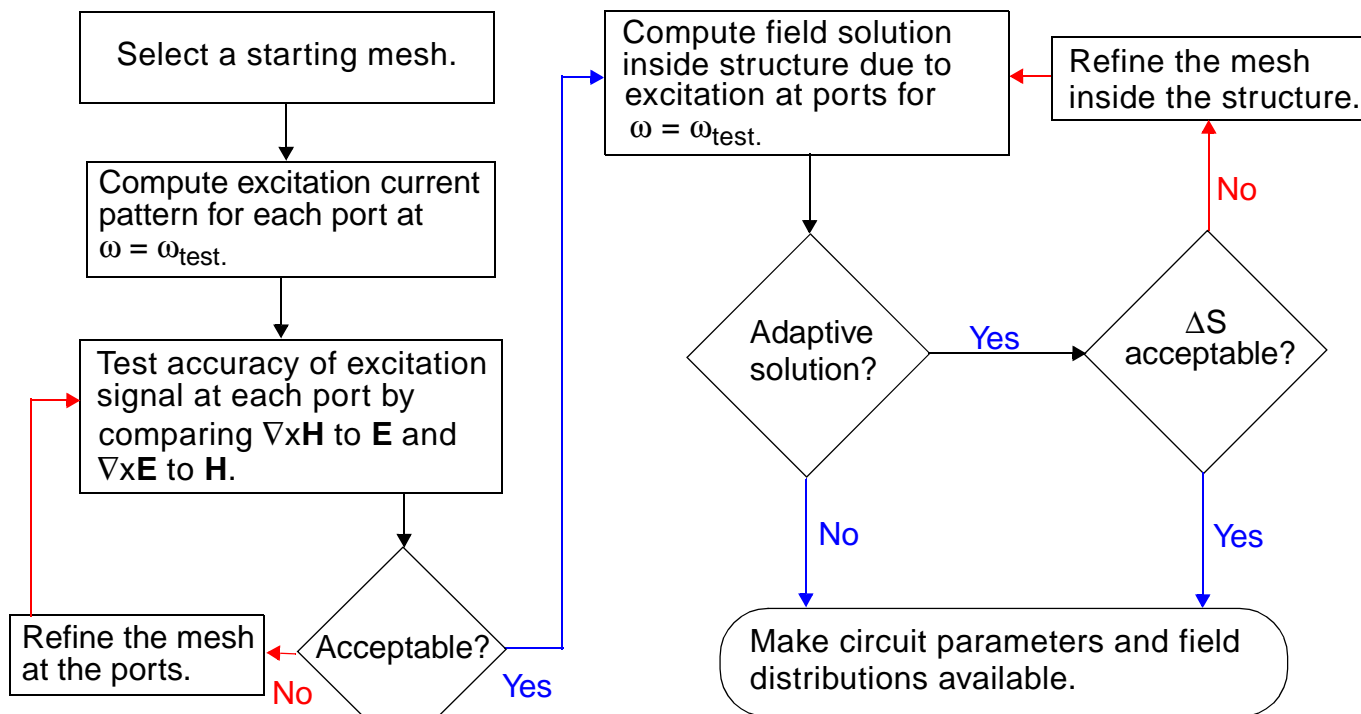- Interpolating frequency sweep

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Single Frequency Solution

A single frequency solution generates an adaptive or non-adaptive solution at a single frequency and is often the first step in performing a frequency sweep. An adaptive solution is one in which a finite element mesh is created and automatically refined in the areas of highest error — increasing the accuracy of succeeding adaptive solutions. The procedure for performing a single frequency solution is shown below:

Select a starting mesh.

Compute excitation current pattern for each port at $\omega = \omega_{test}$.

Test accuracy of excitation signal at each port by comparing $\nabla \times \mathbf{H}$ to $\mathbf{E}$ and $\nabla \times \mathbf{E}$ to $\mathbf{H}$.

Refine the mesh at the ports.

Acceptable? No / Yes

Compute field solution inside structure due to excitation at ports for $\omega = \omega_{test}$.

Refine the mesh inside the structure.

Adaptive solution? Yes / No

ΔS acceptable? No / Yes

Make circuit parameters and field distributions available.
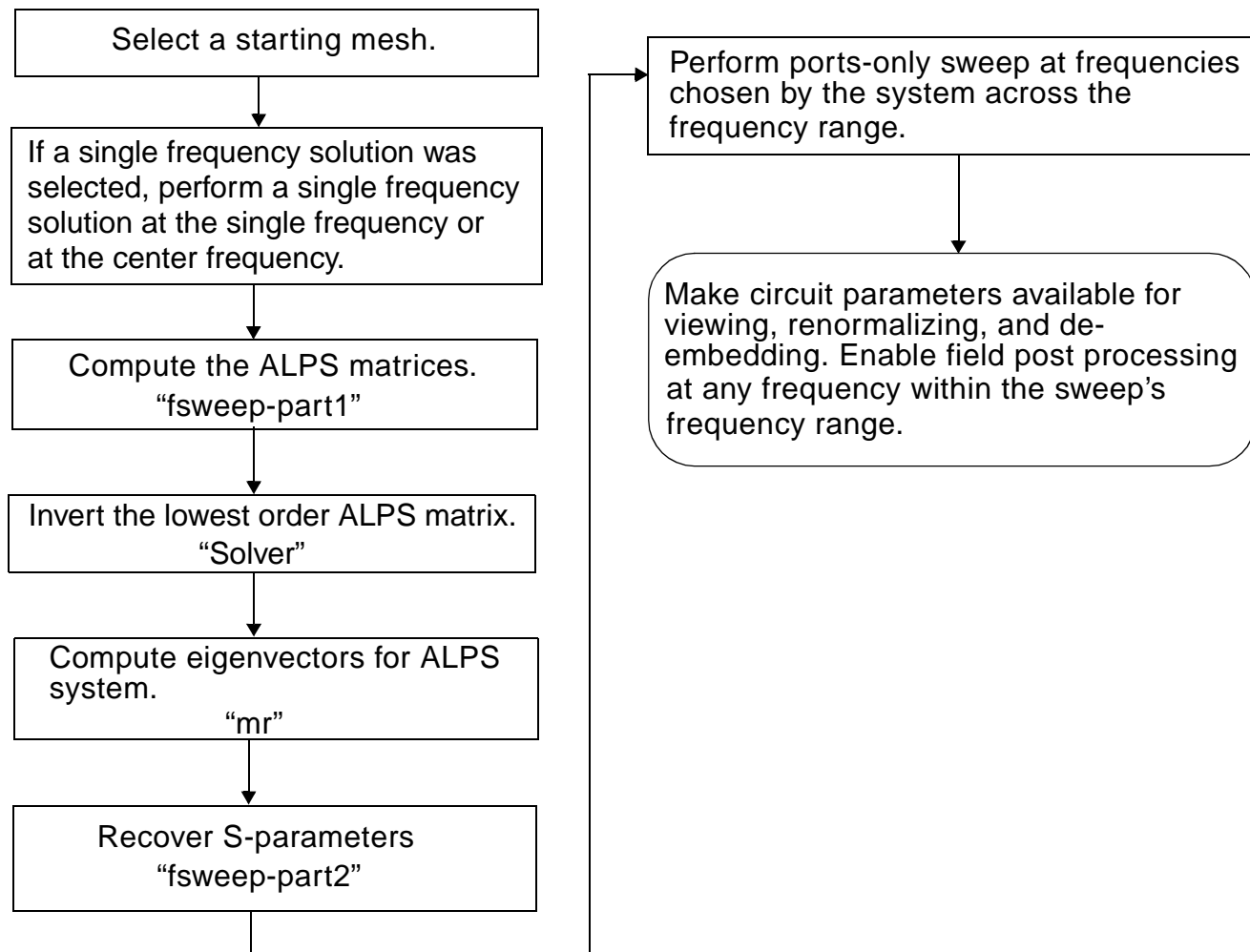
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Fast Frequency Sweep 💬

This type of solution uses an existing mesh to generate a solution over a range of frequencies. The system uses an Adaptive Lanczos-Padé Sweep (ALPS)-based solver to extrapolate an entire bandwidth of solution information. You specify the starting and ending frequencies and the interval at which new solutions are generated. The same mesh is used for each solution, regardless of the frequency. While solutions can be computed and viewed at any frequency, the solution at the center frequency is the most accurate. The procedure for a fast frequency sweep is shown below:

Select a starting mesh.

If a single frequency solution was selected, perform a single frequency solution at the single frequency or at the center frequency.

Compute the ALPS matrices.
"fsweep-part1"

Invert the lowest order ALPS matrix.
"Solver"

Compute eigenvectors for ALPS system.
"mr"

Recover S-parameters
"fsweep-part2"

Perform ports-only sweep at frequencies chosen by the system across the frequency range.

Make circuit parameters available for viewing, renormalizing, and de-embedding. Enable field post processing at any frequency within the sweep's frequency range.
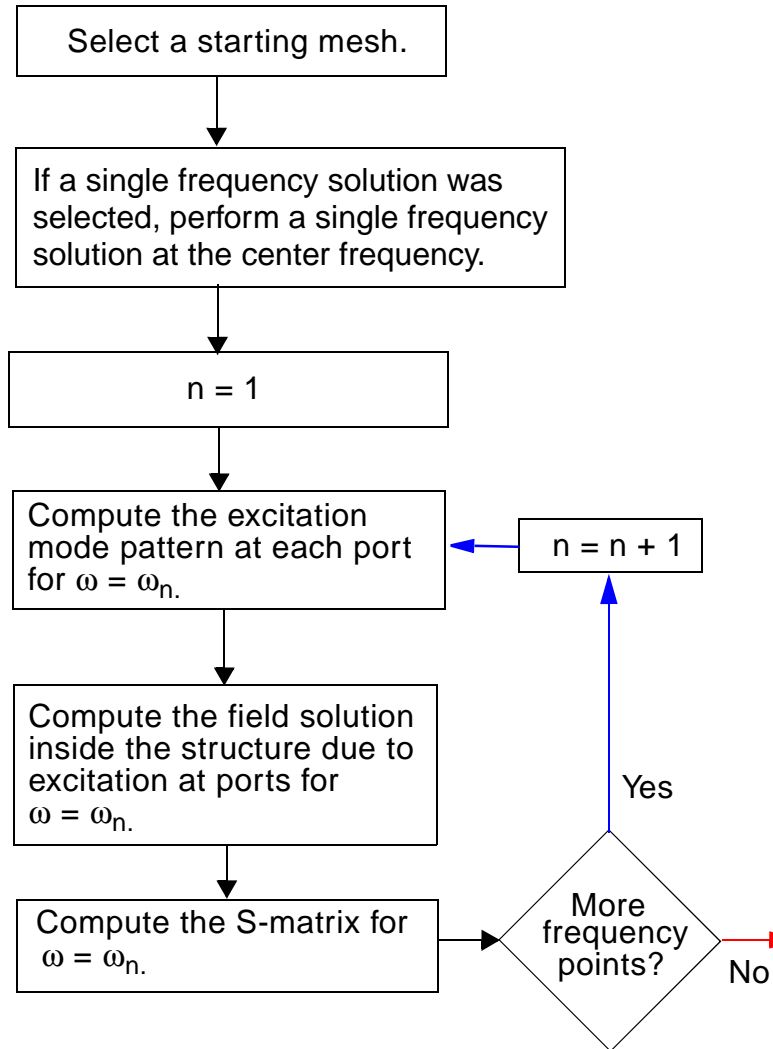
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Discrete Frequency Sweep

To perform a discrete frequency sweep, the system uses an existing mesh to generate a solution over a range of frequencies. You specify the starting and ending frequencies and the interval at which new solutions are generated. The same mesh is used for each solution, regardless of the frequency. The procedure for a discrete frequency sweep is shown below, where n equally spaced frequencies are included in the sweep:

Select a starting mesh.

If a single frequency solution was selected, perform a single frequency solution at the center frequency.

n = 1

Compute the excitation mode pattern at each port for $\omega = \omega_n$.

n = n + 1

Compute the field solution inside the structure due to excitation at ports for $\omega = \omega_n$.

Compute the S-matrix for $\omega = \omega_n$.

More frequency points?

Yes

No

Make circuit parameters available for viewing, renormalizing, and de-embedding. Enable field post processing at the single frequency or at the center frequency. (Field post processing is only available for the single frequency or the center frequency.)

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Interpolating Frequency Sweep

To perform an interpolating frequency sweep, the system uses an existing mesh to interpolate solutions over a range of frequencies. You specify the starting and ending frequencies and solutions are generated at frequency points chosen by the system. The same mesh is used for each solution, regardless of the frequency. A uniform error tolerance exists throughout the entire solution. The procedure for an interpolating frequency sweep is shown below, where n frequencies determined by the system are included in the sweep:

Select a starting mesh.

If a single frequency solution was selected, perform a single frequency solution at the center frequency.

$n = 1$

Obtain the next interpolation frequency ω_n.

$n = n + 1$

Compute the excitation mode pattern at each port for $\omega = \omega_n$.

All parameters (S-, Zpi, etc.) converge?

No

Yes

Make circuit parameters available for viewing, renormalizing, and de-embedding. Enable field post processing at the single frequency or at the center frequency. (Field post processing is only available for the single frequency or the center frequency.)

Compute the field solution inside the structure due to excitation at ports for $\omega = \omega_n$.

Compute the S-matrix for $\omega = \omega_n$.

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Software Modules

In the process of generating a solution, Ansoft HFSS calls various software modules to execute specialized tasks. The role of each module is listed in the following table:

Module	Function
Executive	Performs all executive functions.
3D Modeler	Provides the interface for drawing geometric models.
Material Manager	Provides the interface for assigning materials to objects.
3D Boundary Manager	Provides the interface for assigning boundaries and sources.
Mesh3d	Generates the initial mesh and refines existing meshes. Also provides the interface for manually refining the mesh.
wave	Determines the excitation field pattern at each port.
abc3d	Computes the full 3D solution inside the structure.
solver	Inverts the matrix associated with the finite element mesh.
eigen	Calculates real or complex eigenmodes.
Post Processors	Provide the interface for analyzing the data calculated during the solution process. Three Post Processors are available.

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The Executive Module

Choose the Maxwell Control Panel **Projects** command to access the Project Manager. From there, you must create a project, classify its type as **Ansoft High Frequency Structure Simulator 8**, and then open it to start the Executive software module.

The Executive module is responsible for all executive level tasks. It controls the Executive Commands menu, and provides access to the 3D Modeler, the Material Manager, the 3D Boundary Manager, the Meshmaker, and the Post Processors. It also coordinates the solution process by calling the modules **wave** and **abc3d** as necessary.

Files

The following files created by Ansoft HFSS are stored in the directory containing the current project:

File Name	Extension	Contents
projectname	**.adp**	Stores the adaptive refinement points.
projectname	**.szg**	Stores the contents of S-matrices.
projectname	**.tst**	Stores the emissions test information.
projectname	**.kvc**	*(Fast frequency sweeps only.)* Stores the eigen-vectors of the reduced matrices.
projectname	**.hsf** **.msf**	*(Ferrite problems only.)* Stores the magnetostatic field information.

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The 3D Modeler Module

When you choose the **Draw** command to create or modify the geometry for a structure, Ansoft HFSS passes control to the 3D Modeler. The 3D Modeler screen appears.

Files

Geometric objects are written to the following file:

File Name	Extension	Contents
projectname	**.sm3**	Stores objects for use in the final geometric model.

The Material Manager Module

When you choose the **Setup Materials** command to assign materials to objects or define new materials, Ansoft HFSS passes control to the Material Manager. The **Material Manager** window appears.

Files

Material information is written to the following file:

File Name	Extension	Contents
projectname	**.mat**	Stores material definitions.
projectname	**.asn**	Stores material assignments.

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The 3D Boundary Manager Module

When you choose the **Setup Boundaries/Sources** command to define boundary conditions and sources, Ansoft HFSS passes control to the 3D Boundary Manager. The 3D Boundary Manager window appears.

Files

Boundary and source information is written to the following file:

File Name	Extension	Contents
projectname	**.bnd**	Stores information about ports and boundaries.

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The Meshmaker Module

To create the initial finite element mesh and to refine an existing mesh, Ansoft HFSS passes control to the Meshmaker software module. You may also access the Meshmaker interface to manually refine the mesh.

Initial Mesh

Initially, the Meshmaker automatically divides the structure's geometry into a number of relatively coarse tetrahedra, each having four triangular faces. The Meshmaker uses the vertices of objects as the initial set of tetrahedra vertices. Other points are added to serve as the vertices of tetrahedra only as needed to create a robust mesh.

Automatic Mesh Refinement

After the initial field solution has been created and areas of high error density have been located, the Meshmaker is called again to refine the mesh in those areas. After refining the mesh in the selected region, the Meshmaker updates the mesh files.

Files

The finite element mesh is written out to the following files:

File Name	Extension	Contents
projectname	**.hyd**	Specifies the location of tetrahedra.
projectname	**.fac**	Specifies the location of tetrahedra faces.
projectname	**.lin**	Specifies the location of tetrahedra edges.
projectname	**.pnt**	Specifies the location of tetrahedra vertices.

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The 2D Wave Module

Before the full 3D electromagnetic field inside a structure can be calculated, it is necessary to determine the excitation field pattern at each port. To calculate the excitation pattern at each port, the system calls the **wave** software module. This module calculates the natural field patterns (or modes) that can exist inside a transmission structure with the same cross-section as the port. The resulting 2D field patterns serve as boundary conditions for the full 3D problem.

Excitation Fields

The assumption is that each port is connected to a uniform waveguide that has the same cross-section as the port. Therefore, the excitation field is the field associated with traveling waves propagating along the waveguide to which the port is connected:

$$\boldsymbol{E}(x, y, z, t) \ = \ \Re[\boldsymbol{E}(x, y)e^{j\omega t - \gamma z}]$$

where:

- $\Re$ is the real part of a complex number or function.
- $\boldsymbol{E}(x,y)$ is a phasor field quantity.
- $\gamma = \alpha + j\beta$ is the complex propagation constant, where:
  - α is the attenuation constant of the wave.
  - β is the propagation constant associated with the wave that determines, at a given time t, how the phase angle varies with z.
- ω is angular frequency, $2\pi f$.
- j is the imaginary unit, $\sqrt{-1}$.

In this context, the x- and y-axes are assumed to lie in the cross-section of the port; the z-axis lies along the direction of propagation.

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Wave Equation

The field pattern of a traveling wave inside a waveguide can be determined by solving Maxwell's equations. The following equation that the **wave** module solves is derived directly from Maxwell's equation:

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times \boldsymbol{E}(x, y) \right) - k_0^{\ 2} \varepsilon_r \boldsymbol{E}(x, y) = 0$$

where:

- **E**(x,y) is a phasor representing an oscillating electric field.
- k_0 is the free space wave number, $\omega \sqrt{\mu_0 \varepsilon_0}$.
- ω is the angular frequency, $2\pi f$.
- $\mu_r(x, y)$ is the complex relative permeability.
- $\varepsilon_r(x, y)$ is the complex relative permittivity.

When the **wave** module solves this equation, it obtains an excitation field pattern in the form of a phasor solution, **E**(x,y). It also solves independently for **H**(x,y) using the corresponding wave equation in **H**. These phasor solutions are independent of *z* and *t*; only after being multiplied by $e^{-\gamma z}$ do they become traveling waves.

Also note that the excitation field pattern computed by **wave** is valid only at a given frequency. A different excitation field pattern is computed for each frequency point of interest.

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2D Mesh Refinement

The **wave** module treats its computation of the excitation field pattern as a 2D finite ele-ment problem. The mesh associated with each port is simply the 2D mesh of triangles corresponding to the face of tetrahedra that lie on the port surface. The **wave** module per-forms an iterative refinement of this 2D mesh without calling the Meshmaker.

The refinement procedure is as follows:

1. Using the triangular mesh formed by the tetrahedra faces of the initial mesh, **wave** calculates solutions for both the magnetic field, **H**, and the electric field, **E**.
2. To determine if the 2D solution is accurate, **wave** uses the following equations:

$$\nabla \times \boldsymbol{H} = \sigma \boldsymbol{E} + j\omega\varepsilon\boldsymbol{E}$$
$$\nabla \times \boldsymbol{E} = -j\omega\mu\boldsymbol{H}$$

where **H**(x,y) and **E**(x,y) are phasors.
3. The module first calculates **E** and **H** independently using the appropriate wave equations. Next, it computes $\nabla \times \boldsymbol{H}$ and compares the results to the solved **E**. It then computes $\nabla \times \boldsymbol{E}$ and compares the results to the solved **H**.
4. If the reciprocal comparison falls within an acceptable tolerance, the solution is accepted. Otherwise, the 2D mesh on the port face is refined and **wave** performs another iteration.

Any mesh points that have been added to the face of a port are read out to the existing mesh files. These points are incorporated into the full 3D mesh the next time the Mesh-maker is called.

For a detailed understanding of the theory which the **wave** module implements, refer to the following:

Jin-Fa Lee, Din-Kow Sun, and Zoltan J. Cendes, "Full-Wave Analysis of Dielectric Waveguides Using Tangential Vector Finite Elements," *IEEE Transactions on Microwave Theory and Techniques*, vol. 39, No 8, August 1991.

Modes

For a waveguide or transmission line with a given cross-section, there is a series of basic field patterns (modes) that satisfy Maxwell's equations at a specific frequency. Any linear combination of these modes can exist in the waveguide. By default, the system instructs **wave** to compute only the dominant mode field pattern.

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Mode Conversion

In some cases it is necessary to include the effects of higher order modes because the structure acts as a mode converter. For example, if the mode 1 (dominant) field at one port is converted (as it passes through a structure) to a mode 2 field pattern at another, then it is necessary to obtain the S-parameters for the mode 2 field.

Modes, Reflections, and Propagation

It is also possible for a 3D field solution generated by an excitation signal of one specific mode to contain reflections of higher order modes which arise due to discontinuities in the structure. If these higher order modes are reflected back to the excitation port or transmitted to another port, the S-parameters associated with these modes should be calculated.

If the higher order mode decays before reaching any port — either because of attenuation from losses or because it is a non-propagating evanescent mode — there is no need to obtain the S-parameters for that mode. Therefore, one way to avoid the need for computing the S-parameters for a higher order mode is to include a length of waveguide in the model that is long enough for the higher order mode to decay in. For example, if the mode 2 wave associated with a certain port decays to near zero in 0.5 mm, then the "constant cross-section" portion of the geometric model leading up to the port should be at least 0.5 mm long. Otherwise, for accurate S-parameters, the mode 2 S-parameters must be included in the S-matrix. The length of the constant cross-section segment that has to be included in the model depends on the value of the mode's attenuation constant, α.

Frequency

The field patterns associated with each mode generally vary with frequency. However, the propagation constants and impedances always vary with frequency. When performing frequency sweeps, be aware that as the frequency increases, the likelihood of higher order modes being propagating modes also increases.

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Multiple Ports on the Same Face

Visualize a port face on a microstrip that contains two conducting strips side by side as two separate ports. If the two ports are defined as being separate, the system simulates the case in which the two ports are connected to uncoupled transmission structures. It is as if a conductive wall separates the excitation waves. However, in actuality, there will be electromagnetic coupling between the two strips.

To model this coupling accurately, analyze the two ports as a single port with multiple modes. In general, if there are N disconnected conductors in the port cross-section, at least N - 1 modes are required for an accurate solution. For example, if the port consists of two adjacent microstrip lines surrounded by a conducting enclosure, $N = 3$; therefore at least two modes should be defined on the port. Assign an equal number of terminals as modes. Refer to Defining Terminals for more information.

If the multi-conductor port plane is near discontinuities within the 3D model, additional modes beyond N - 1 may be necessary. However, if you define terminals on a multi-con-ductor port, the presence of non-quasi transverse electromagnetic (TEM) modes will adversely affect the entries of any computed terminal matrices. Therefore, rather than increase the number of modes beyond the required N - 1, extend the port outward until any higher-order modes have sufficient attenuation to be omitted from consideration.

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Files

The **wave** module writes out a set of files for each port. For example, the files associated with port 1 are shown in the following table. A similar set of files is produced for each port.

File Name	Extension	Contents
port	**.frq**	Contains the mapping of port solution numbers to frequency.
port1	**.ref**	Stores the status of the adaptive refinement process.
port1	**.apt**	Contains the point list for the 2D mesh at port 1.
port1	**.i1**	Contains the coordinates of the impedance line for port 1. A set of .i*n* files is created only if an impedance line has been defined for at least one port in the structure.
port1	**.nvc**	Specifies vectors that are normal to the port.
port1	**.sat**	Specifies the material parameters of the 2D object.
port1	**.sln**	Contains boundary information for the 2D field pattern.
port1	**.sob**	Specifies the objects in which the 2D triangular elements lie.
port1	**.spt**	Specifies the location of vertices in the 2D mesh for port 1.
port1	**.sti**	Specifies the location of triangular faces in the 2D mesh.
*port1*_0	**.e1**	Contains the field solution for the electric field at port 1.
*port1*_0	**.h1**	Contains the field solution for the magnetic field at port 1.
*port1*_0	**.imp**	Contains characteristic impedances for port 1.
*port1*_0	**.spc**	Specifies the frequency and number of modes for port 1.
port1_1	**.tvc**	Specifies vectors that are tangential the port.

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Multiple Modes

If multiples modes have been requested, additional files are created. For example, if two modes have been requested, the following files are created:

- The file **port1_1.tvc** is replaced with **port1_1.tvc** and **port1_2.tvc**.
- The file **port1_0.e1** is replaced with **port1_0.e1** and **port1_0.e2**.
- The file **port1_0.h1** is replaced with **port1_0.h1** and **port1_0.h2**.
- The file **port1.i1** is replaced with **port1.i1** and **port1.i2**.

Frequency Sweeps

If a frequency sweep has been performed, additional files are created. For example, a discrete frequency sweep containing two frequency points for the dominant mode only yields the following:

- The file **port1_0.e1** is replaced with **port1_0.e1** and **port1_1.e1**.
- The file **port1_0.h1** is replaced with **port1_0.h1** and **port1_1.h1**.
- The file **port1_0.imp** is replaced with **port1_0.imp** and **port1_1.imp**.
- The file **port1_0.spc** is replaced with **port1_0.spc** and **port1_1.spc**.

Note: ☞ The **.tvc** files are the only **wave** files for which the _n specifies the mode. Mode numbering starts at 1. That is, the file for mode 1 is **port1_1.tvc** while the file for mode 2 is **port1_2.tvc**. For all other files, the _n indicates the frequency point. Frequency-point numbering starts at 0. That is, the file for the first frequency point is **port1_0.e1,** while the file for the second frequency point is **port1_1.e1**.

Ports-Only Solutions

If a ports-only solution has been requested, other additional files are created. For example, a frequency sweep containing two frequency points for the dominant mode only yields the following:

- The file **port1.sln** is replaced with **port1_0.sln** and **port1_1.sln**.
- The file **port1.sob** is replaced with **port1_0.sob** and **port1_1.sob**.
- The file **port1.sti** is replaced with **port1_0.sti** and **port1_1.sti**.

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The 3D Field Solver Module

To calculate the full 3D field solution, Ansoft HFSS calls the **abc3d** module. This module solves the following wave equation:

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times E(x, y, z) \right) - k_0{}^2 \varepsilon_r E(x, y, z) = 0$$

where:

- **E**(x,y,z) is a complex vector phasor representing an oscillating electric field.
- k_0 is the free space phase constant, $\omega \sqrt{\mu_0 \varepsilon_0}$.
- ω is the angular frequency, $2\pi f$.
- $\mu_r(x, y)$ is the complex relative permeability.
- $\varepsilon_r(x, y)$ is the complex relative permittivity.

This is the same equation that the **wave** module solves for in calculating the 2D field pattern at each port. The difference is that **abc3d** does not assume that the electric field is a traveling wave propagating in a single direction. It assumes that the phasor **E** is a function of x, y, and z. The physical electric field, **E**(x,y,z,t), is the real part of the product of the phasor, **E**(x,y,z), and $e^{j\omega t}$:

$$E(x, y, z, t) = \Re[E(x, y, z)e^{j\omega t}]$$

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Boundary Conditions

Ansoft HFSS imposes boundary conditions at all surfaces exposed to the edge of the meshed problem region — which includes all outer surfaces and all surfaces exposed to voids within the structure. The following boundary conditions are recognized by **abc3d**:

- Port
- Incident wave
- Voltage drop
- Current Source
- Perfect **E**
- Perfect **H**/Natural
- Finite conductivity
- Impedance
- Lumped RLC
- Radiation
- Symmetry
- Master
- Slave

Evanescent Modes and Attenuation

It is possible for a 3D field solution generated by an excitation signal of one specific mode to contain reflections consisting of higher-order modes.

- If these higher-order reflections propagate to the ports, request that the S-parameters associated with these modes be calculated.
- If these higher-order modes decay before reaching the ports — either because of losses or because they are non-propagating evanescent modes — there is no need to obtain the S-parameters for that mode.

A small length of the waveguide or transmission line that is connected to each port must be included in the structure. For example, if one port is connected to a coaxial cable, then the portion of the model leading up to the port must have the cross-section of the cable.

The required length of the port section depends on the value of the attenuation constant, α, associated with each higher-order mode. For example, if the mode 2 wave associated with a certain port decays to near zero in 0.5 millimeters, then the constant cross-section portion of the geometric model leading up to the port should be 0.5 millimeters long. Otherwise you should include the effect of a mode 2 wave in the S-matrix.

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Files

After a solution has been calculated, **abc3d** writes the solution to the following set of files:

File Name	Extension	Contents
projectname	**.bsp**	Specifies the nodes at which explicit values are stored.
projectname	**.btn**	Specifies the field solution of **E** at specific nodes.
projectname	**.bst**	Specifies interpolation data for the field solution.

Post Processor Modules

When you select one of the three Post Processors from the **Post Process** menu, Ansoft HFSS passes control to the selected Post Processor. The following Post Processors are available from the **Post Process** menu:

Fields   Accesses the 3D Post Processor, which allows you to display contour, shaded, vector, value vs. distance, and animated plots of fields. Also allows you to import and export solution files and access the field calculator.

Matrix Data   Accesses the Matrix Data Post Processor, which allows you to view matrices computed for the S-parameters, impedances, and propagation constants during each adaptive solution.

Matrix Plot   Accesses the Matrix Plot Post Processor, which allows you to plot a variety of parameters versus time or frequency.

The selected Post Processor screen appears.

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S-Parameters

A generalized S-matrix describes what fraction of power associated with a given field excitation is transmitted or reflected at each port.

The S-matrix for a three-port structure is as follows:

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

where:

- All quantities are complex numbers.
- The magnitudes of a and b are normalized to a field carrying one watt of power.
  - $|a_i|^2$ represents the excitation power at port i.
  - $|b_i|^2$ represents the power of the transmitted or reflected field at port i.
- The full field pattern at a port is the sum of the port's excitation field and all reflected/transmitted fields.
- The phase of a_i and b_i represent the phase of the incident and reflected/transmitted field at t=0.
  - $\angle a_i$ represents the phase angle of the excitation field on port i at t = 0. (By default, it is zero for lossy port modes and lossless propagating modes. For lossless cut-off modes, it is 90.)
  - $\angle b_i$ represents the phase angle of the reflected or transmitted field with respect to the excitation field.
- S_{ij} is the S-parameter describing how much of the excitation field at port j is reflected back or transmitted to port i. For example, S_{31} is used to compute the amount of power from the port 1 excitation field that is transmitted to port 3. The phase of S_{31} specifies the phase shift that occurs as the field travels from port 1 to port 3.

Note: ☞ When **wave** computes the excitation field for a given port, it has no information indicating which way is "up" or "down." Therefore, if the port mode has not been calibrated, the calculated S-parameters may be 180 degrees out of phase with the expected solution.

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Higher Order Modes

By default, Ansoft HFSS only computes the S-parameters associated with the dominant mode at each port. However, the system can account for higher order modes if it is specifically requested to do so. Each additional mode at each port represents another entry in the S-matrix. For example, in a three-port structure in which the two most dominant modes are analyzed, a 6x6 S-matrix would be required to describe the behavior of the structure. The full S-matrix required in such a case is:

$$
\begin{bmatrix}
b_1^1 \\
b_1^2 \\
b_2^1 \\
b_2^2 \\
b_3^1 \\
b_3^2
\end{bmatrix}
=
\begin{bmatrix}
S_{11}^{11} & S_{11}^{12} & S_{12}^{11} & S_{12}^{12} & S_{13}^{11} & S_{13}^{12} \\
S_{11}^{21} & S_{11}^{22} & S_{12}^{21} & S_{12}^{22} & S_{13}^{21} & S_{13}^{22} \\
S_{21}^{11} & S_{21}^{12} & S_{22}^{11} & S_{22}^{12} & S_{23}^{11} & S_{23}^{12} \\
S_{21}^{21} & S_{21}^{22} & S_{22}^{21} & S_{22}^{22} & S_{23}^{21} & S_{23}^{22} \\
S_{31}^{11} & S_{31}^{12} & S_{32}^{11} & S_{32}^{12} & S_{33}^{11} & S_{33}^{12} \\
S_{31}^{21} & S_{31}^{22} & S_{32}^{21} & S_{32}^{22} & S_{33}^{21} & S_{33}^{22}
\end{bmatrix}
\begin{bmatrix}
a_1^1 \\
a_1^2 \\
a_2^1 \\
a_2^2 \\
a_3^1 \\
a_3^2
\end{bmatrix}
$$

where:

- All quantities are complex numbers.
- The magnitudes of a and b are normalized to fields that carry one watt of power.
  - $\left| a_i^m \right|^2$ represents the power of the mode m excitation field at port i.
  - $\left| b_i^m \right|^2$ represents the transmitted/reflected component's power of the mode m field at port i.

The full field pattern of a mode at a port is the sum of the excitation fields at that mode and all reflected/transmitted fields of the same mode.

- The phases of a and b are the phase angles of the transmitted and reflected fields.
  - $\angle a_i^m$ represents the phase angle (at t=0) of the incoming mode m field at port i. (By default, it is zero for lossy port modes and lossless propagating modes. For lossless cut-off modes, it is 90.)
  - $\angle b_i^m$ represents the phase angle of the reflected or transmitted field of mode m at port i with respect to the excitation fields.

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- S_{ij}^{mn} is the S-parameter that describes how much of a mode n excitation field at port j is transmitted (or reflected) as a mode m field at port i.

To simplify how you view the data, the system displays an S-matrix involving higher order modes as a series of smaller mode-to-mode matrices.

For example, when you request a display of the S-parameters relating a "port 1, mode 2" field to a "port 2, mode 1" field, the following mode-to-mode S-matrix is displayed:

$$\begin{bmatrix} b_1^2 \\ b_2^1 \end{bmatrix} = \begin{bmatrix} S_{11}^{22} & S_{12}^{21} \\ S_{21}^{12} & S_{22}^{11} \end{bmatrix} \begin{bmatrix} a_1^2 \\ a_2^1 \end{bmatrix}$$

Frequency Points

The S-parameters associated with a structure are a function of frequency. Therefore, separate field solutions and S-matrices are generated for each frequency point of interest. Ansoft HFSS supports three types of frequency sweeps:

- Fast frequency sweeps, in which an Adaptive Lanczos-Padé Sweep (ALPS)-based solver is used to extrapolate, from a single solution at a center frequency, solutions for a range of frequencies. Fast frequency sweeps are useful for analyzing the behavior of high Q structures. For large frequency ranges, they are much faster than solving the problem at individual frequencies.
- Discrete frequency sweeps, in which a solution is generated for the structure at each frequency point you specify. Discrete frequency sweeps support any single frequency solution.
- Interpolating frequency sweeps, in which a solution is interpolated for the structure based upon solved frequency points. Interpolating frequency sweeps are useful for analyzing the behavior of scatterer or wideband structures or structures with ferrite materials, highly lossy materials, master and slave boundaries, or cut-off frequencies. This type of sweep is much faster than a discrete sweep because an accurate solution can be obtained by calculating a field solution from a minimal number of frequency points.

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Renormalized S-Matrices

Before a structure's generalized S-matrix can be used in a high frequency circuit simulator to compute the reflection and transmission of signals, it must be normalized to the appropriate impedance. For example, if a generalized S-matrix has been normalized to 50 ohms, it can be used to compute reflection and transmission directly from signals that are normalized to 50 ohms.

To renormalize a generalized S-matrix to a specific impedance, the system first calculates a unique impedance matrix Z, associated with the structure defined as follows:

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

where:

- S is the *nxn* generalized S-matrix.
- I is an *nxn* identity matrix.
- Z_0 is a diagonal matrix having the characteristic impedance (Z_0) 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 the desired impedance and admittance as diagonal values. For example, if the matrix is being renormalized to 50 ohms, then Z_Ω would have diagonal values of 50.

Visualize the generalized S-matrix as an S-matrix that has been renormalized to the characteristic impedances of the structure. Therefore, if a diagonal matrix containing the characteristic impedances of the structure is used as Z_Ω in the above equation, the result would be the generalized S-matrix again.

For information about renormalized terminal S-matrices, please see the section in these Technical Notes entitled Terminal-Based Models for Circuit Analysis.

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Z-Matrix

The impedance matrix, Z, is calculated from the S-matrix as follows:

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

where:

- S is the *nxn* generalized S-matrix.
- I is an *nxn* identity matrix.
- Z_0 is a diagonal matrix having the characteristic impedance (Z_0) of each port as a diagonal value.

Y-Matrix

The admittance matrix, Y, is simply the inverse of the impedance matrix, Z.

To display the unique impedance and admittance matrices (Z and Y) associated with a structure, use the Matrix Data Post Processor.

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Characteristic Impedances

Ansoft HFSS needs to calculate the characteristic impedance of each port in order to compute a renormalized S-matrix. The system computes the characteristic impedance of each port in three ways — as Z_{pi}, Z_{pv}, and Z_{vi} impedances.

You have the option of specifying which impedance is to be used in the renormalization calculations.

PI Impedance

The Z_{pi} impedance is the impedance calculated from values of power (P) and current (I):

$$Z_{pi} = \frac{P}{I \bullet I}$$

The power and current are computed directly from the simulated fields. The power passing through a port is equal to the following:

$$P = \oint_{s} E \times H ds$$

where the surface integral is over the surface of the port.

The current is computed by applying Ampere's law to a path around the port:

$$I = \oint_{l} H \bullet dl$$

While the net current computed in this way will be near zero, the current of interest is that flowing into the structure, I^{-}, or that flowing out of the structure, I^{+}. In integrating around the port, the system keeps a running total of the contributions to each and uses the average of the two in the computation of impedances.

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PV Impedance

The Z_{pv} impedance is the impedance calculated from values of power (P) and voltage (V):

$$Z_{pv} = \frac{V \bullet V}{P}$$

where the power and voltage are computed directly from the simulated fields. The power is computed in the same way as the Z_{pi} impedance. The voltage is computed as follows:

$$V = \oint_l E \bullet dl$$

The path over which the system integrates is referred to as the impedance line — which is defined when the ports are set up. To define the impedance line for a port, select the two points across which the maximum voltage difference occurs. The system has no way of knowing where the maximum voltage difference will be unless you define an impedance line.

VI Impedance

The Z_{vi} impedance is given by:

$$Z_{vi} = \sqrt{Z_{pi}Z_{pv}}$$

For TEM waves, the Z_{pi} and Z_{pv} impedances form upper and lower boundaries to a port's actual characteristic impedance. Therefore, the value of Z_{vi} approaches a port's actual impedance for TEM waves.

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Impedance Multiplier

If a symmetry plane has been defined (allowing the model of a structure to be cut in half), the impedance computations have to be adjusted by specifying an impedance multiplier. The need for this multiplier can be understood by looking at how the use of symmetry affects the computation of Z_{pv}.

In cases where a perfect E plane of symmetry splits a structure in two, only one-half of the voltage differential and one-half of the power flow can be computed by the system. Therefore, since the Z_{pv} impedance is given by:

$$Z_{pv} = \frac{V \bullet V}{P}$$

the computed value is one-half the desired value. An impedance multiplier of 2 must be specified in such cases.

In cases where a perfect H plane of symmetry splits a structure in two, only one-half of the power flow is seen by the system but the full voltage differential is present. Therefore, structures split in half with perfect H symmetry planes result in computed impedances that are twice those for the full structure. An impedance multiplier of 0.5 must be specified in such cases.

If multiple symmetry planes are used or if only a wedge of a structure is modeled, you must adjust the impedance multiplier accordingly.

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Choice of Impedance

When the system is instructed to renormalize the generalized modal S-matrix, you must specify which value to use in the computations — Z_{pi}, Z_{pv}, or Z_{vi}.

- For TEM waves, the Z_{vi} impedance converges on the port's actual impedance and should be used.
- When modeling microstrips, it is sometimes more appropriate to use the Z_{pi} impedance.
- For slot-type structures (such as finline or coplanar waveguides), Z_{pv} impedance is the most appropriate.

For more information on the computation of impedances, refer to the following:

Bruno Bianco, Luigi Panini, Mauro Parodi, and Sandro Ridella, "Some Considerations about the Frequency Dependence of the Characteristic Impedance of Uniform Microstrips," *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-26 No. 3, March 1978.

Edward F. Kuester, David C. Chang, and Leonard Lewin, "Frequency-Dependent Definitions of Microstrip Characteristic Impedance," *International URSI Symposium on Electromagnetic Waves*, Munich, 26-29 August 1980, pp. 335 B/1-3.

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De-embedding

If a uniform length of transmission line is added to (or removed from) a port, the S-matrix of the modified structure can be calculated using the following relationship:

$$\begin{bmatrix} S' \end{bmatrix} = \begin{bmatrix} e^{\gamma l} \end{bmatrix} \begin{bmatrix} S \end{bmatrix} \begin{bmatrix} e^{\gamma l} \end{bmatrix}$$

where:

- $\begin{bmatrix} e^{\gamma l} \end{bmatrix}$ is a diagonal matrix with the following entries:

$$\begin{bmatrix} e^{\gamma_1 l_1} & 0 & 0 \\ 0 & e^{\gamma_2 l_2} & 0 \\ 0 & 0 & e^{\gamma_3 l_3} \end{bmatrix}$$

- $\gamma = \alpha + j\beta$ is the complex propagation constant, where:
  - α is the attenuation constant of the wave.
  - β is the propagation constant of the uniform transmission line at port i.
- l_i is the length of the uniform transmission line that has been added to or removed from the structure at port i. A positive value indicates that a length of transmission line has been removed from the structure.

The value of γ for each port is automatically calculated by the **wave** module.

Evanescent Modes and S-Parameters

In structures containing only propagating modes, conservation of power implies that:

$$\sum_{j=1}^{n} \left| S_{ij} \right|^2 \le 1$$

However, in structures containing evanescent (non-propagating) modes, this relationship

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is not necessarily true. The propagation constant, β, of these modes is zero, which intro-duces a term for the reactive power in the structure into the calculation of S-parameters — increasing the structure's apparent power. The S-parameters for evanescent modes should be considered to represent the field strength associated with these modes on the port(s).

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Derivation of Wave Equation

The **wave** and **abc3d** modules both solve the following wave equation:

$$\nabla\times\left(\frac{1}{\mu_r}\nabla\times\boldsymbol{E}\right) - k_0{}^2\varepsilon_r\boldsymbol{E} = 0$$

where:

- **E**(x,y,z) is a phasor representing an oscillating electric field.
- k_0 is the free space wave number, $\omega\sqrt{\mu_0\varepsilon_0}$, where ω is the angular frequency, $2\pi f$.
- μ_r is the complex relative permeability.
- ε_r is the complex relative permittivity.

The difference between **wave** and **abc3d** is that **wave** assumes that the electric field is a traveling wave with this form:

$$\boldsymbol{E}(x, y, z, t) = \Re[\boldsymbol{E}(x, y)e^{j\omega t - \gamma z}]$$

while **abc3d** assumes that the phasor **E** is a function of x, y, and z:

$$\boldsymbol{E}(x, y, z, t) = \Re[\boldsymbol{E}(x, y, z)e^{j\omega t}]$$

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Maxwell's Equations

The wave equation solved by **wave** and **abc3d** is derived from Maxwell's equations, which in their time-domain form are:

$$\nabla \times \boldsymbol{H}(t) = \boldsymbol{J}(t) + \frac{\partial}{\partial t}\boldsymbol{D}(t)$$

$$\nabla \bullet B(t) = 0$$

$$\nabla \times \boldsymbol{E}(t) = -\left(\frac{\partial}{\partial t}\right)(\boldsymbol{B}\,t)$$

$$\nabla \bullet D(t) = \rho$$

where:

- **E**(t) is the electric field intensity.
- **D**(t) is the electric flux density, ε**E**(t), and ε is the complex permittivity.
- **H**(t) is the magnetic field intensity.
- **B**(t) is the magnetic flux density, μ**H**(t), and μ is the complex permeability.
- **J**(t) is the current density, σ**E**(t).
- ρ is the charge density.

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Phasor Notation

Because all time-varying electromagnetic quantities are oscillating at the same frequency, they can be treated as phasors multiplied by $e^{j\omega t}$ (in **abc3d**) or by $e^{(j\omega t - \gamma z)}$ (in **wave**).

In the general case which **abc3d** solves, the equations become:

$$\nabla \times \boldsymbol{H} e^{j\omega t} = \boldsymbol{J} e^{j\omega t} + \frac{\partial}{\partial t} \boldsymbol{D} e^{j\omega t}$$

$$\nabla \times \boldsymbol{E} e^{j\omega t} = -\frac{\partial}{\partial t} \boldsymbol{B} e^{j\omega t}$$

$$\nabla \bullet \boldsymbol{D} e^{j\omega t} = \rho e^{j\omega t}$$

$$\nabla \bullet \boldsymbol{B} e^{j\omega t} = 0$$

By factoring out the quantity $e^{j\omega t}$ and using the following relationships:

$$\frac{\partial}{\partial t} \boldsymbol{E} e^{j\omega t} = j\omega \boldsymbol{E} e^{j\omega t}$$

$$\frac{\partial}{\partial t} \boldsymbol{H} e^{j\omega t} = j\omega \boldsymbol{H} e^{j\omega t}$$

Maxwell's equations in phasor form reduce to:

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + j\omega \boldsymbol{D}$$

$$\nabla \times \boldsymbol{E} = -j\omega \boldsymbol{B}$$

$$\nabla \bullet \boldsymbol{D} = \rho$$

$$\nabla \bullet \boldsymbol{B} = 0$$

where **B**, **H**, **E**, and **D** are phasors in the frequency domain.

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Now, using the constitutive relationships $B = \mu H$, $D = \varepsilon E$, and $J = \sigma E$, Maxwell's equations in phasor form become:

$$\nabla \times H = j\omega\left(\varepsilon + \frac{\sigma}{j\omega}\right)E = j\omega\varepsilon_c E$$

$$\nabla \times H = j\omega\varepsilon E$$

$$\nabla \times E = -j\omega\mu H$$

$$\nabla \bullet \varepsilon E = \rho$$

$$\nabla \bullet \mu H = 0$$

where **H** and **E** are phasors in the frequency domain, μ is the complex permeability, and ε is the complex permittivity.

H and **E** are stored as phasors, which can be visualized as a magnitude and phase or as a complex quantity.
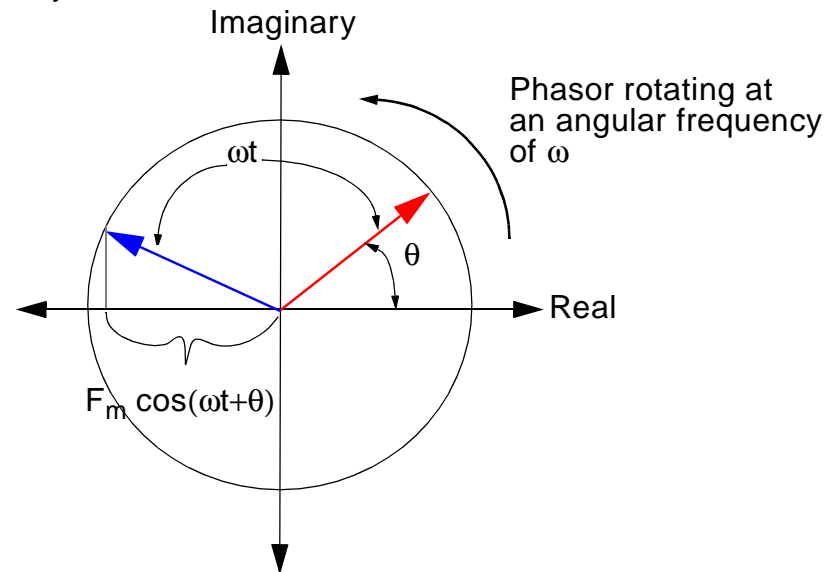
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Assumptions

To generate the final field equation, place **H** in the $\nabla \times E$ equation in terms of **E** to obtain:

$$H = -\frac{1}{j\omega\mu}\nabla \times E$$

Then, substitute this expression for **H** in the $\nabla \times H$ equation to produce:

$$\nabla \times \left(-\frac{1}{j\omega\mu}\nabla \times E \right) = j\omega\varepsilon E$$

Conductivity

Ansoft HFSS is capable of including conductivity in the model either as a bulk material loss factor, similar to dielectric loss tangent, or as an impedance boundary condition applied to the outer surfaces of the object.

Note: ☞ The choice between the bulk material loss and the boundary condition is made using **Solve Inside** in the Material Manager. The boundary condition can also be applied when setting boundaries in the boundary manager.

The choice between bulk material loss and the surface boundary condition is problem dependent. The boundary condition should be applied whenever the conductor is much thicker than the skin depth at the solution frequency. In this case, the unknowns within the conductor are not included in the unknown vector, resulting in a smaller matrix and a faster solution. However, if the conductor is not thick relative to the skin depth, the bulk material conductivity must be used to arrive at an accurate solution. With this assumption, the wave equation reduces to:

$$\nabla \times \left(\frac{-1}{j\omega\mu}\nabla \times E \right) = (j\omega\varepsilon + \sigma)E$$

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Dielectric Loss Tangent

Dielectric losses can be modeled by assuming that the relative permittivity, $\hat{\varepsilon}_r$, is complex:

$$\hat{\varepsilon} = \varepsilon' - j\varepsilon''$$

Expressed in terms of the dielectric (electric) loss tangent, $\tan\delta_e = \varepsilon_r''/\varepsilon_r'$, the complex relative permittivity, $\hat{\varepsilon}_r$ becomes:

$$\hat{\varepsilon}_r = \varepsilon_r' - j\varepsilon_r'\tan\delta_e$$

Magnetic Loss Tangent

Losses in magnetic materials can be modeled by assuming that μ_r is complex.

$$\hat{\mu}_r = \mu_r' - j\mu_r''$$

Expressed in terms of the magnetic loss tangent, $\tan\delta_m = (\mu_r''/\mu_r')$, the complex relative permeability becomes:

$$\hat{\mu}_r = \mu_r'\left(1 - \frac{j\mu_r''}{\mu_r'}\right) = \mu_r'(1 - j\tan\delta_m)$$

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Definition of Freespace Wave Number

Using the relationships $\varepsilon = \varepsilon_0 \varepsilon_r$ and $\mu = \mu_0 \mu_r$, the wave equation being solved can be placed in this form:

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times \boldsymbol{E} \right) - \omega^2 \mu_0 \varepsilon_0 \varepsilon_r \boldsymbol{E} = 0$$

Now, if the freespace phase constant (or wave number) is defined as $k_0^2 = \omega^2 \mu_0 \varepsilon_0$, the above reduces to:

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times \boldsymbol{E} \right) - k_0^2 \varepsilon_r \boldsymbol{E} = 0$$

which is the equation that the modules **abc3d** and **wave** solve.

When materials with finite conductivities are included, the wave equation takes the form:

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times \boldsymbol{E} \right) - (k_0^2 \varepsilon_r - j k_0 Z_0 \sigma) \boldsymbol{E} = 0$$

where:

- Z_0 is the characteristic impedance of free space:

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$$

For more information on the wave equation and how it is solved using finite elements, refer to the following:

Zoltan J. Cendes and Jin-Fa Lee, "The Transfinite Element Method for Modeling MMIC Devices," *IEEE Transactions on Microwave Theory and Techniques*, vol. 36, pp. 1639-1649, Dec. 1988.

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Radiated Fields

When calculating radiation fields, the values of the fields over the radiation surface are used to compute the fields in the space surrounding the device. This space is typically split into two regions — the near-field region and the far-field region. The near-field region is the region closest to the source. In general, the electric field **E**(x,y,z) external to the region bounded by a closed surface may be written as:

$$\boldsymbol{E}(x, y, z) = \int_s (j\omega\mu_0\boldsymbol{H}_{tan}\, G + \boldsymbol{E}_{tan} \times \nabla G + \boldsymbol{E}_{normal}\nabla G\,)ds \qquad (1)$$

where:

- s represents the radiation boundary surfaces.
- j is the imaginary unit, $\sqrt{-1}$.
- ω is the angular frequency, $2\pi f$.
- μ_0 is the relative permeability of the free space.
- $\boldsymbol{H}_{tan}$ is the component of the magnetic field that is tangential to the surface.
- $\boldsymbol{E}_{normal}$ is the component of the electric field that is normal to the surface.
- $\boldsymbol{E}_{tan}$ is the component of the electric field that is tangential to the surface.
- G is the free space Green's function, given by:

$$G = \frac{e^{-jk_0|\boldsymbol{r} - \boldsymbol{r}'|}}{|\boldsymbol{r} - \boldsymbol{r}'|}$$

where:

- k_0 is the free space wave number, $\omega\sqrt{\mu_0\varepsilon_0}$.
- $\boldsymbol{r}$ and $\boldsymbol{r}'$ represent, respectively, field points and source points on the surface.

In the far field where r>>r' (and usually r>>λ_0), the Green's function can be approximated by:

$$G \approx \frac{e^{-jk_0 r}\, e^{jk_0\hat{r}\cdot r'}}{r}$$

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When this form of G is used in the far-field calculations, the fields that result have an r dependence in the form of:

$$\frac{e^{-jkr}}{r}$$

This *r* dependence is characteristic of a spherical wave, which is a key feature of far fields. The far field is a spherical TEM wave with the following equation:

$$\boldsymbol{E} = \eta_0 \boldsymbol{H} \times \hat{\boldsymbol{r}}$$

where η_0 is the intrinsic impedance of free space.

When you choose **Radiation/Compute/Near Field**, Ansoft HFSS uses the general expressions given in (**eq. 1**). For this command, you must specify the radial coordinate *r*. Because it can be used to compute fields at an arbitrary radius from the radiating structure, this command can be useful in EMC applications.

Note: ☞ If you are using **Radiation/Compute/Near Field** to calculate the fields in a problem containing an incident wave, the radius at which the fields are calculated is very important. If the radius is within the solution region, then the fields calculated are either the total fields or the scattered fields depending upon which is selected using **Data/Edit Sources**. If the radius is outside the solution region, then the fields calculated are only the scattered fields.

When you choose **Radiation/Compute/Far Field**, the previously discussed far-field approximations are used, and the result is valid only for field points in the far-field region.

Antenna Properties

Generally, when dealing with radiated fields, you are also interested in the antenna properties of the radiated bodies. Ansoft HFSS calculates the following antenna properties:

beam area   accepted power
directivity   radiation efficiency
gain   maximum intensity
radiated power   polarization
axial ratio   polarization ratio

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Polarization

At each aspect angle in the far field of a radiating source, the electric and magnetic field vectors lie in a fixed plane. Over time, the instantaneous electric field vector traces out a figure or shape in this plane. This figure defines the polarization state of the field.

In general, this figure is an ellipse and is called the *polarization ellipse*. The wave is said to be *elliptically polarized* when the instantaneous electric field traces out an ellipse. As a special case, the polarization ellipse may be a circle, in which case the wave is *circularly polarized*. Elliptical and circular polarization have two different states, *left* and *right*, distinguished by the sense of rotation of the electric field vector. Some of these figures, or states, are shown below. In each case the direction of propagation is out of the screen.

Circular

Right-hand circular polarization   Left-hand circular polarization

Elliptical

Right-hand elliptical polarization   Left-hand elliptical polarization
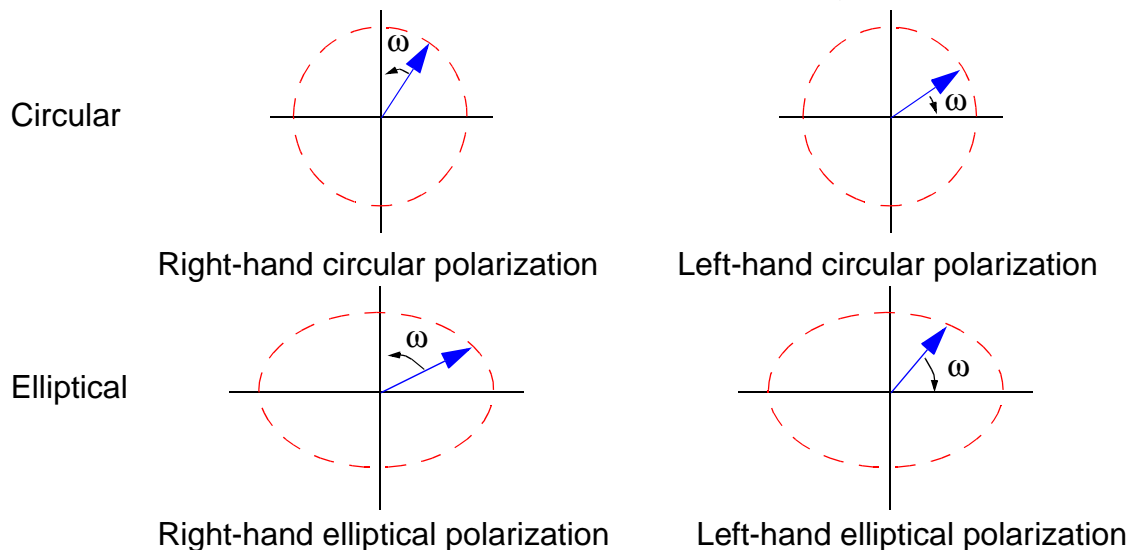
ω is the rotation radian frequency.

A second special case occurs when the polarization ellipse degenerates to a straight line. In this case the wave is *linearly polarized*.

To completely describe the polarization state of a radiated field, two independent components are required. Ansoft HFSS supports three types of descriptions:

- Spherical polar
- Ludwig-3
- Circular

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Spherical Polar

The most fundamental description is spherical polar, which is the electric field phasor resolved in the directions of unit theta and phi vectors of the reference coordinate system. In this description, the field may be written as $E = (E_\theta, E_\phi)$.

Ludwig-3

Arthur C. Ludwig wrote a classic paper ≡ the definition of cross polarization. In particular, his third definition is often used since it describes the field components that are typically measured on a far-field antenna test range. Using his definition, the field may be written as $E = (E_x, E_y)$ where:

$$E_x = E_\theta \cos\phi - E_\phi \sin\phi$$
$$E_y = E_\theta \sin\phi + E_\phi \cos\phi$$

and phi is the usual azimuthal angle in the reference spherical coordinate system.

Circular

For antennas designed to receive or transmit circularly polarized fields, a meaningful description is in terms of pure left and right circular states. In this description, the field may be written as $E = (E_R, E_L)$ where:

$$E_R = \frac{1}{\sqrt{2}}(E_\theta - jE_\phi)$$
$$E_L = \frac{1}{\sqrt{2}}(E_\theta + jE_\phi)$$

Axial Ratio

Axial ratio is defined as the ratio of the major to the minor axis of the polarization ellipse. By definition, the axial ratio has the following range:

$$1 \leq |AR| \leq \infty$$

Here an axial ratio of one indicates that the electric field is circularly polarized and an axial ratio of infinity indicates that the electric field is linearly polarized.

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Polarization Ratio

The IEEE defines the (complex) polarization ratio as, "For a given field vector at a point in space, the (magnitude of the) ratio of the complex amplitudes of two specified orthogonally polarized field vectors into which the given field vector has been resolved." [Ref]
Ansoft HFSS computes the following six polarization ratios at each selected aspect angle:

$$Circular/LHCP = \left|\frac{E_L}{E_R}\right|$$

$$Circular/RHCP = \left|\frac{E_R}{E_L}\right|$$

$$Spherical/Phi = \left|\frac{E_\phi}{E_\theta}\right|$$

$$Spherical/Theta = \left|\frac{E_\theta}{E_\phi}\right|$$

$$Ludwig \quad 3/X = \left|\frac{E_x}{E_y}\right|$$

$$Ludwig \quad 3/Y = \left|\frac{E_y}{E_x}\right|$$

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Beam Area

This is the solid angle through which all power emanating from the antenna would flow if the maximum radiation intensity is constant for all angles over the beam area. It is measured in steradians and is represented by:

$$\Omega_A = \frac{P_{rad}}{U_{max}}$$

where:

- Ω_A is the solid angle in steradians.
- P_{rad} is the radiated power in watts.
- U_{max} is the maximum radiation intensity in watts per steradian.

Directivity

The directivity of an antenna is commonly defined as the ratio of the radiation intensity in a given direction to the radiation intensity averaged over all directions. It is a dimensionless quantity represented by:

$$directivity = \frac{4\pi U}{P_{rad}}$$

where:

- U is the radiation intensity in watts per steradian in the direction specified.
- P_{rad} is the radiated power in watts.

Note: ☞ The directivity given in the **Far Field Parameters** panel is the directivity in the direction of maximum radiation intensity, U_{max}.

For a lossless antenna, the directivity will be equal to the gain. However, if the antenna has inherent losses, the directivity is related to the gain by the radiation efficiency of the antenna.

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Gain

Gain is 4π times the ratio of an antenna's radiation intensity in a given direction to the net power accepted by the antenna from a connected transmitter. In Ansoft HFSS the connected transmitter is a surface that has been defined as a port.

The following equation is used to calculate gain in Ansoft HFSS:

$$gain = 4\pi \frac{U}{P_{acc}}$$

where:

- U is the radiation intensity in watts per steradian in the direction specified.
- P_{acc} is the accepted power in watts entering the antenna.

Gain can be confused with directivity, since they are equivalent for lossless antennas. Gain is related to directivity by the radiation efficiency of the antenna. If the radiation efficiency is 100%, they are equal.

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Radiated Power

Radiated power is the amount of time-averaged power (in watts) exiting a radiating antenna structure through a radiation boundary.

For a general radiating structure in HFSS, radiated power is computed as:

$$P_{rad} = \Re \int_s E \times H^* \cdot ds$$

where:

- P_{rad} is the radiated power in watts.
- $\Re$ is the real part of a complex number.
- s represents the radiation boundary surfaces.
- E is the radiated electric field.
- H^* is the conjugate of **H**.
- ds is the local radiation-boundary unit normal directed out of the 3D model.

Note: The accuracy of the computed radiated power depends on the accuracy of **E** and **H**. In some cases it is possible that the computed radiated power may deviate slightly from the actual radiated power.

Because the radiated power is calculated from the output signal at the port, a port must be defined for this quantity to be displayed.

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Accepted Power

The accepted power is the amount of time-averaged power (in watts) entering a radiating antenna structure through one or more ports. For antennas with a single port, accepted power is a measure of the incident power reduced by the mismatch loss at the port plane.

For a general radiating structure in HFSS, accepted power is computed as:

$$P_{acc} = \Re \int_A \boldsymbol{E} \times \boldsymbol{H}^* \cdot ds$$

where:

- P_{acc} is the accepted power in watts.
- $\Re$ is the real part of a complex number.
- A is the union of all port boundaries in the model.
- $\boldsymbol{E}$ is the radiated electric field.
- $\boldsymbol{H}^*$ is the conjugate of **H**.
- ds is the local port-boundary unit normal directed into the 3D HFSS model.

For the simple case of an antenna with one lossless port containing a single propagating mode, the above expression reduces to:

$$P_{acc} = |a|^2 (1 - |s_{11}|^2)$$

where:

- a is the complex modal excitation specified using the **Data/Edit Sources** command.
- s_{11} is the single-entry generalized scattering matrix (without renormalization) computed by HFSS.

Note: Because the accepted power is calculated from the input signal at the port, a port must be defined for this quantity to be displayed.

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Radiation Efficiency

The radiation efficiency is the ratio of the radiated power to the accepted power given by:

$$e = \frac{P_{rad}}{P_{acc}}$$

where:

- P_{rad} is the radiated power in watts.
- P_{acc} is the accepted power in watts.

Since the radiation efficiency is calculated from the accepted power, a port is required for the radiation efficiency.

Max U

The radiation intensity, U, is the power radiated from an antenna per unit solid angle. Ansoft HFSS calculates the radiation intensity in the direction in which it has the maximum value. The maximum intensity of the radiation is measured in watts per steradian and is calculated by:

$$U(\theta,\phi) = \frac{|\boldsymbol{E}|^2}{\eta_0} r^2$$

where:

- $U(\theta,\phi)$ is the radiation intensity in watts per steradian.
- $|\boldsymbol{E}|$ is the magnitude of the E-field.
- η_0 is the intrinsic impedance of free space — 376.7 ohms.
- r is the distance from the antenna, in meters.

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Modes to Nodes Conversion

This section describes the conversion of modal S-parameters, computed using Ansoft HFSS's full-wave field solver, into nodal or voltage-based pseudo-S-parameters used in circuit theory.

The S-matrix solutions in HFSS express their results in terms of the incident and reflected powers of waveguide modes. This description is mathematically and physically rigorous, but does not lend itself to problems where several different modes can propagate simultaneously. Examples of such situations include coupled transmission lines on printed circuit boards, multi-conductor cables, and many common types of electrical connectors. For these types of structures, which generally support multiple, quasi-transverse electromagnetic (TEM) modes of propagation, it is difficult to excite and measure a single mode. In any practical, or laboratory-like, measurement situation:

- measurements (e.g. of voltage) contain contributions from several modes
- the applied stimuli excite several modes simultaneously

Nodal or "terminal" support was added to HFSS to enable the simulation of terminal currents and voltages directly, without requiring engineers to determine the needed linear combinations of waveguide modes.

Background

Recall from electromagnetic field theory that the solutions for the transverse components of the electric and magnetic fields in a waveguide with a uniform cross-section can be written as:

$$\vec{E}_t = \sum_n a_n \vec{e}_n(x, y)e^{-\gamma z} + \sum_n b_n \vec{e}_n(x, y)e^{\gamma z}$$

$$\vec{H}_t = \sum_n a_n \vec{h}_n(x, y)e^{-\gamma z} - \sum_n b_n \vec{h}_n(x, y)e^{\gamma z}$$

Here the a_n and b_n are the intensities of the forward and backward traveling modal waves, and $\vec{e}_n$ and $\vec{h}_n$ are the transverse electric and magnetic field patterns. Note that the a_n and b_n are considered to be dimensionless quantities here, while $\vec{e}_n$ and $\vec{h}_n$ have the normal units for electric and magnetic fields. For this discussion's purpose, assume that each port is defined at z=0; this permits the removal of exponential terms in the above equations.

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Nodal Voltages and Currents

It is possible to define a set of voltages for a port by establishing a number of different integration paths across the port. If a port supports N quasi-TEM modes of propagation, one can set up N different open contours of integration, C_1, C_2, ..., C_N, and define N different voltages, v_1, v_2, ..., v_N according to the integral formulas:

$$v_k = - \int_{C_k} \vec{E}_t \cdot \vec{dl}$$

These integration paths are set in the **3D Boundary Manager**, when you define the terminal voltage lines on a port.

Alternatively, one can define a set of currents $\{i_k\}$ using a set of closed contours of integration $\{D_k\}$:

$$i_k = \oint_{D_k} \vec{H}_t \cdot \vec{dl}$$

Ansoft HFSS does not require you to set up the current integration contours separately. The software automatically infers the current contours from the chosen voltage contours using a power conservation relationship.

Each definition produces a set of relationships between the modal intensities and the voltages or currents. Since the total transverse fields can be expanded as a linear combination of modes, we can rewrite the previous equations as:

$$v_k = - \sum_n a_n \int_{C_k} \vec{e}_n(x, y) \cdot \vec{dl} - \sum_n b_n \int_{C_k} \vec{e}_n(x, y) \cdot \vec{dl}$$

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$$i_k = \sum_n a_n \int_{D_k} \vec{\bar{h}}_n(x, y) \cdot \vec{dl} - \sum_n b_n \int_{D_k} \vec{\bar{h}}_n(x, y) \cdot \vec{dl}$$

To simplify, introduce the terms:

$$t_{kn} = -\int_{C_k} \vec{\bar{e}}_n(x, y) \cdot \vec{dl}$$

$$u_{kn} = \int_{D_k} \vec{\bar{h}}_n(x, y) \cdot \vec{dl}$$

Now v_k and i_k become:

$$v_k = \sum_n a_n t_{kn} + \sum_n b_n t_{kn}$$

$$i_k = \sum_n a_n u_{kn} - \sum_n b_n u_{kn}$$

Since there are N possible voltage definitions and N quasi-TEM modes, there are NxN

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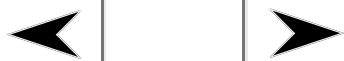
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matrices that relate the nodal voltages and currents to the modal intensities:

$$[v_k] = [t_{kn}]([a_n] + [b_n])$$

$$[i_k] = [u_{kn}]([a_n] - [b_n])$$

Now introduce the matrices $T = [t_{kn}]$ and $U = [u_{kn}]$ to represent these transformations. Note that the units of T are volts, while the units of U are amperes.

In summary, the **3D Post Processor** could be used to load different modal field patterns and manually perform the integrals defined previously over each terminal contour line. This would be a tedious and error-prone process, which HFSS's modes-to-terminals conversion feature alleviates.

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Terminal-Based Models for Circuit Analysis

It is possible to use the transformations developed above to compute terminal-based admittance (Y), impedance (Z) and pseudo-S-matrices (S_p). First consider the admittance case. A relationship of the form $i = Yv$ is needed that gives the vector of terminal currents $i = [i_k]$ as a function of the vector of terminal voltages $v = [v_k]$. It is known that:

$$v = T(a + b)$$

and:

$$i = U(a - b)$$

It is also known that the incident and scattered modal powers are related by $b = Sa$, where S is the modal S-matrix computed by HFSS. Therefore:

$$v = T(a + Sa) = T(I + S)a$$
$$i = U(a - Sa) = U(I - S)a$$

Here I denotes an identity matrix of the same size as S. i can then be solved for in terms of v by eliminating the incident wave variable a:

$$a = (I + S)^{-1}T^{-1}v$$
$$i = U(I - S)(I + S)^{-1}T^{-1}v$$

The terminal-based (or nodal) admittance matrix Y is identified from the above expression as

$$Y = U(I - S)(I + S)^{-1}T^{-1}$$

A similar relationship can be developed for the terminal-based impedance matrix:

$$Z = T(I + S)(I - S)^{-1}U^{-1}$$

It is also possible to convert the terminal-based admittance and impedance matrices into a terminal-based "pseudo-S-matrix" S_p. To do this, a reference impedance Z_k must be defined for each terminal k. Then standard formulas are used to convert the terminal impedance matrix Z into the terminal S-matrix:

$$S_p = Z_{\text{ref}}^{1/2}(Z + Z_{\text{ref}})^{-1}(Z - Z_{\text{ref}})Z_{\text{ref}}^{-1/2}$$

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Here $Z_{\text{ref}} = \text{diag}(Z_k)$ is a diagonal matrix whose entries are the reference impedances Z_k.

The terminal S-matrix S_p relates the intensities of the incident and reflected pseudo-waves at the terminals:

$$[\beta_k] = S_p[\alpha_k]$$

These pseudo-waves are defined by:

$$\alpha_k = \frac{1}{2}Z_k^{-1/2}(v_k + Z_k i_k)$$

$$\beta_k = \frac{1}{2}Z_k^{-1/2}(v_k - Z_k i_k)$$

Here α_k is the incident pseudo-wave at terminal k, and β_k is the reflected pseudo-wave at the same terminal. Note that the units of α_k and β_k are watts$^{1/2}$. The terminal voltages and currents can also be written in terms of the pseudo-waves:

$$v_k = Z_k^{1/2}(\alpha_k + \beta_k)$$
$$i_k = Z_k^{-1/2}(\alpha_k - \beta_k)$$

Unlike true waveguide modes, the pseudo-waves α_k and β_k have no associated propagation constant. The pseudo-waves represent linear combinations of several modes, which may all have differing propagation constants. HFSS is still capable of performing de-embedding on the terminal-based S-matrix, but this is accomplished by first de-embedding the modal S-matrix and then performing the transformation back to a terminal-based S-matrix.

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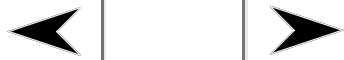
Terminal Characteristic Impedance Matrix

Consider the situation illustrated below: A 3D structure with one multi-mode waveguide port is loaded by an *N*-port matrix impedance *Z*. The structure contains internal sources, which generate outgoing waves that exit through the waveguide port and strike the impedance *Z*. If *Z* does not match the impedance of the waveguide in some sense, a reflection will occur from this load and will return to the 3D structure, where it is interpreted as an incident wave.
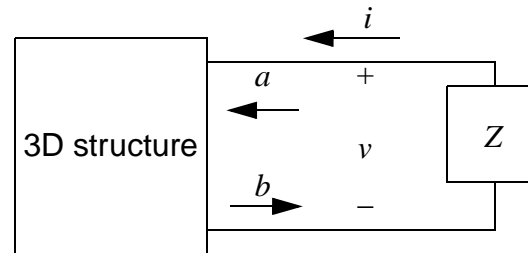
An optimal choice of *Z* will prevent any reflections from the load returning as an incident wave *a*. Note that the circuit equations at the load are $v = -Zi$ (the minus sign is due to the sense of the current i.) By replacing the voltages and currents with their modal expansions, the voltage becomes:

$$v = T(a + b) = -ZU(a - b)$$

Rearranging this to isolate a and b, it is determined that:

$$(T + ZU)a + (T - ZU)b = 0$$

Now notice that if we select $T = ZU$; the incident wave a vanishes. Corresponding to this condition is an "optimal" choice Z_0 for the impedance Z:

$$Z_0 = TU^{-1}$$

Z_0 is the terminal characteristic impedance matrix for the multi-mode waveguide port. This value of impedance will completely absorb any linear combination of modal waves leaving the port. As such, it should be of interest to circuit designers wishing to control reflections. In the important, special case of a lossless waveguide, it can be shown that $Z_0 = TT^T$ is a real-valued, symmetric impedance matrix. It is then easy to synthesize a network of resistors with the specified matrix impedance.

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Exporting Terminal S-Matrices for Full-Wave Spice Analysis

Significant coupling that occurs in closely located circuits reaching frequencies above one GHz can now be included in circuit analysis. When terminal S-parameter data calculated by Ansoft HFSS is exported to PSpice, HSPICE, and Maxwell Spice software, transformation data between voltages and currents is constructed based on the S-parameter data. Therefore full-wave effects can be modeled in the circuit analysis.

When terminal S-parameter data is exported from HFSS to PSpice or HSPICE, HFSS creates an equivalent circuit, represented by a black box with input and output terminals, that includes the same frequency response behavior as the original device analyzed in HFSS. Frequency domain information from Ansoft HFSS is transferred to circuit simulators that operate in the time domain. Broadband matching of frequency responses is ensured while the full-wave solution accuracy is preserved. When terminal S-parameter data is exported from HFSS to Ansoft's Maxwell Spice software, HFSS creates a new "full-wave *N*-port subcircuit", also represented by a black box that includes the same frequency response behavior as the original device.

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