Microwave Cavity Simulation Using Ansys HFSS

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Abstract. The design of microwave cavity detectors for axion dark matter research is often accomplished using advanced full-wave electromagnetic simulation software tools. These tools provide a cost-effective approach to evaluate a wide variety of cavity configurations, frequency tuning mechanisms, and conductive or dielectric materials and coatings. One simulation software package used for this application is Ansys High Frequency Structure Simulator (HFSS), which is based upon the well-established finite element method. HFSS includes numerous features useful for microwave cavity design such as parametric geometry modeling, adaptive meshing algorithm, curvilinear mesh elements, driven modal and eigenmode matrix solvers, and optimization algorithms. This paper describes the use of the HFSS software to simulate microwave cavities for axion haloscope detectors, with an example tutorial for a cylindrical cavity. Excellent agreement between the simulated and analytical results is shown for the resonant frequency, quality factor, and form factor.

Keywords: Ansys HFSS, Cavity Simulation, Finite Element Modeling.

1 Overview of HFSS

1.1 General Capabilities

Ansys HFSS [1] is a full-wave frequency-domain three-dimensional electromagnetic field solver which uses the finite element method to solve Maxwell's equations. It offers industry-standard accuracy, adaptive meshing of arbitrary geometries, fully parametric modeling, multiple optimization engines, high-performance computing capabilities, and multi-physics integration via the Ansys Workbench environment. HFSS has been commercially available for approximately 30 years and is widely used to design antennas, filters, waveguides, connectors, transitions, and electronic packages.

Multiple numerical solvers are available within the HFSS software, each targeted for different applications. A license allows the use of the frequency-domain finite element solver, frequency-domain finite element eigenmode solver, time-domain finite element solver, frequency-domain integral equation solver, frequency-domain finite element boundary integral hybrid solver, frequency-domain planar integral equation solver, or a linear circuit solver. A license allows the solver to use a maximum of four processor cores. Additional high-performance computing (HPC), optimization, and distributed solver licenses are available to increase computing capabilities.

1.2 User Interface

The HFSS user interface is integrated into the Electronics Desktop environment which is part of the Electromagnetics Suite. Fig. 1 shows the user interface of HFSS Release 19 within the Electronics Desktop. The user interface consists of multiple window panes with a menu and ribbon toolbar along the top, project manager and properties windows on the left, 3D model editor tree window in the center, graphics window on the right, and message manager and progress windows along the bottom.

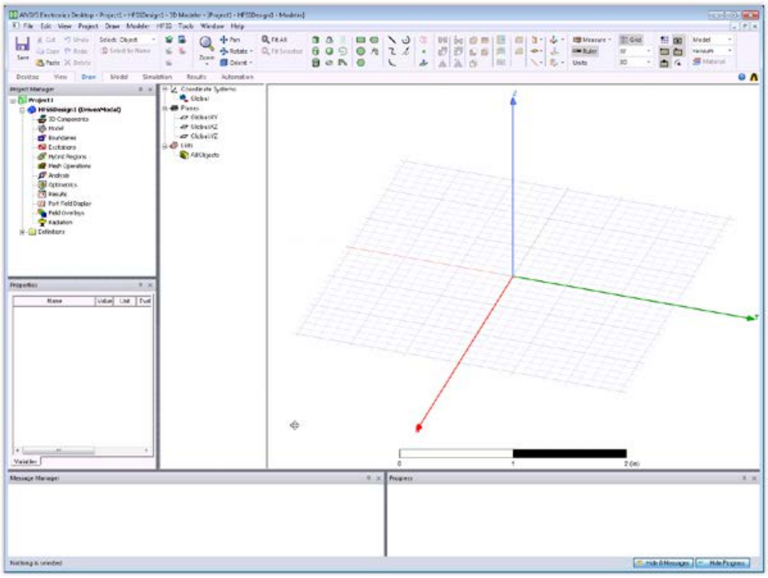

Fig. 1. HFSS Release 19 user interface within the Electronics Desktop environment.

1.3 Solution Types for Cavity Simulation

Two solution types applicable to microwave cavity design are the frequency-domain eigenmode and frequency-domain driven modal solvers. The eigenmode solver calculates the natural resonances of the cavity based upon the geometry, materials, and boundary conditions. It calculates modal frequencies, unloaded quality factors, and electromagnetic field solutions for up to 20 modes simultaneously. This solver can be used to study the modal behavior of a resonant structure, generate mode maps for tuned cavities, and calculate field-based quantities such as the cavity form factor.

The driven modal solution uses one or more ports to excite the cavity structure and provides network parameters (SYZ parameters) and electromagnetic field solutions. A wave port is a cross-section of a transmission line used to calculate the characteristic impedance and complex propagation constant of the excitation mode. The driven modal solver can be used to include antenna feed probes to predict transmission and reflection coefficients and study how to achieve critical coupling to a cavity mode. Multiple frequency sweep types are available to obtain SYZ matrix and electromagnetic field results over a user-specified bandwidth.

1.4 Meshing Technologies for Cavity Simulation

The creation of a robust, efficient mesh which accurately represents the model geometry is a critical step required to obtain accurate results from a finite element method solver. HFSS generates a tetrahedral element mesh using an iterative algorithm which refines the element size and distribution until a user-defined convergence criteria is reached. This method produces a graded mesh with fine discretization in locations required to accurately represent the field behavior, effectively tuning the mesh to the electromagnetic performance of the structure. The convergence parameter used in mesh generation is typically the modal frequency for an eigenmode solution and S-parameters for a driven modal solution.

In addition to the automatic meshing algorithm, the user can manually influence the initial mesh density. These optional controls can further focus mesh elements in critical areas to reduce the number of adaptive passes needed to converge to the specified criteria, but are not required to achieve accurate results. Both rectilinear and curvilinear tetrahedral mesh elements are available to optimally represent the model geometry. Curvilinear mesh elements are recommended for the simulation of cylindrical or curved cavity structures.

1.5 Boundary Conditions for Cavity Simulation

The electromagnetic solver requires boundary conditions to define material properties for geometry surfaces. These surface definitions also can be used to simplify geometries or make the meshing process more efficient. By default, any object surface that contacts the background is automatically defined as a perfectly conducting boundary. Cavity models often include finite conductivity boundaries to model good conductors such as copper.

Other applicable boundary conditions include absorbing or perfectly matched layer boundaries to model open regions, impedance boundaries for resistive materials, layered impedance boundaries for thin coatings, periodic boundaries for repeating structures, and symmetry plane boundaries to reduce model size. Frequency-dependent properties can be included for the driven modal solver. Effects such as surface roughness and anisotropy can also be included as appropriate.

1.6 Electromagnetic Fields Calculator

HFSS includes a calculator which can access field data to perform a wide variety of mathematical operations. The calculator can use geometric, complex, vector, and scalar data to create numerical, graphical, or exportable results. Additionally, frequently used expressions can be created and loaded into any project. The fields calculator is used to obtain the cavity form factor which is a value between 0 and 1 representing the axion coupling to a cavity mode in a haloscope detector. Although it is provided directly with the eigenmode solver results, the quality factor can also be calculated using the magnetic field data if desired.

2 Resonant Cavity Example

2.1 Creating the Model

The example model described here is a cylindrical copper cavity with a radius of 21 cm and height of 100 cm. The TM_{010} mode is expected to resonate at 546.42 MHz with an unloaded quality factor of 61,391 [2] and form factor of 0.692 [3].

Create HFSS Project. Insert project into Electronics Desktop using *File > New*.

Set Eigenmode Solution Type. Select *HFSS > Solution Type* and select Eigenmode.

Set Model Units. Select *Modeler > Units* and select cm.

Set Dialog Data Entry Mode. Select *Tools > Options > General Options* and then *3D Modeler > Drawing > Dialog*.

Set Default Transparency Value. Select *Tools > Options > General Options* and then *3D Modeler > Display > Rendering*. Enter a value of 0.7.

Create Parameterized Cavity. Select *Draw > Cylinder*. Enter “cavity_rad” in radius value and then 21 cm. Enter “cavity_height” in height value and then 100 cm.

Assign Cavity Wall Conductivity. Select the cavity in the 3D Modeler Editor tree. Select *Edit > Extend Selection > All Object Faces*. Select *HFSS > Boundaries > Assign > Finite Conductivity*. Enter “cavity_walls” in the name field.

Apply Curvilinear Mesh Elements. Select the cavity in the 3D Modeler Editor tree. Select *HFSS > Mesh Operations > Assign > Apply Curvilinear Meshing* and enter “Cavity” in the name field.

2.2 Solving the Model

Add Solution Setup. Select *HFSS > Analysis Setup > Add Solution Setup*. Enter minimum frequency = 540 MHz, number of modes = 3, maximum number of passes = 12, maximum delta frequency per pass = 2%, and minimum passes = 4.

Save Project. Select *File* > *Save* and enter “cavity.aedt” as the file name.

Perform Validation Check. Select *HFSS* > *Validation Check* and confirm a check mark appears beside each step.

Solve Model. Select *HFSS* > *Analyze All* in the menu bar.

2.3 Viewing the Results

View Solution Data. Select *HFSS* > *Results* > *Solution Data*. Select Eigenmode Data tab to view modal frequencies and quality factors for each requested mode. The first mode is TM_{010}, the second mode is TM_{011}, and the third mode is TE_{113}. The Mode 1 frequency should be 546.42 MHz and quality factor should be 61,378. The simulated frequency exactly agrees with the analytical value and the unloaded quality factor agrees within 0.02%. Select the Convergence tab to view adaptive pass information including the number of mesh elements and frequency convergence value for each pass. Select Profile tab to view the log file for the simulation.

View E-Field Phase Animation. Select XZ and YZ planes in the 3D Modeler Editor tree. Select *HFSS* > *Fields* > *Plot Fields* > *E* > *Mag_E*. Right-click on Mag_E1 plot in the Field Overlays section of the Project Manager tree. Select Phase as the swept variable with start value of 0 degrees, stop value of 170 degrees, and step value of 17.

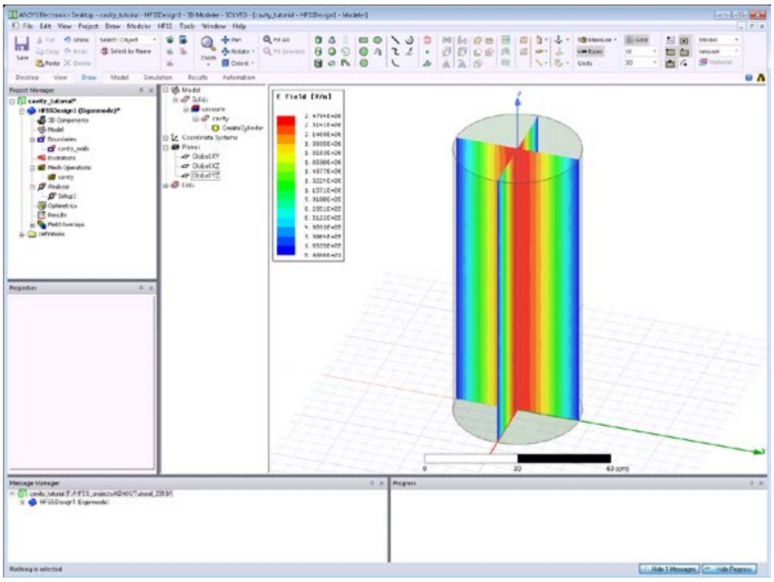

Fig. 2. Plot of TM_{010} mode electric field magnitude in two vertical planes.

View E-Field Vector Animation. Select XZ and YZ planes in the 3D Modeler Editor tree. Select *HFSS > Fields > Plot Fields > E > Vector_E.*

Active Mode of Interest. Select *HFSS > Fields > Edit Sources*. Enter a magnitude of 1 J for the desired mode and magnitude of 0 J for the other two modes. This will activate the desired mode for all field plots and post-processing calculations.

Calculate Form Factor. Select *HFSS > Fields > Calculato*r. Due to space limitations, the detailed steps used to calculate form factor are not included here. The simulated value should be 0.692 which agrees exactly with the analytical calculation.

3 Summary

This paper has described several key features of the Ansys HFSS software which is used to design microwave cavities for axion dark matter research. Effective use of advanced simulation software allows researchers to efficiently investigate concepts for a wide variety of cavity designs and obtain detailed insights into the electromagnetic behavior of the structure. A step-by-step procedure for an example cylindrical cavity was also given showing excellent agreement with analytical calculations for the resonant frequency, quality factor, and form factor.

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