Thermal and Mechanical Coupling with HFSS
“Closing the loop”

Anders Edquist, ANSYS Nordic
Outline

- **Introduction to Multi-Physics Simulations**
- **Enabling Technologies**
  - EM, Thermal, Structural Mechanics and fluid flow & conjugate heat transfer
  - ANSYS Workbench
- **Thermal and Mechanical Coupling with HFSS:**
  - “Closing the Loop”, Waveguide Diplexer Example
  - Waveguide Termination Example
Introduction

• High performance RF/microwave systems and components design often requires consideration of operation in a real-world multi-physics environment.

• Understanding the interaction between multiple coupled physics is essential for an accurate system analysis.

• ANSYS offers a comprehensive solution capable of performing bi-directional coupled analysis between EM, thermal, structural mechanics and fluid flow.
• **Overview of multi physics capabilities**
  – ANSYS Workbench gives users the ability to easily couple multiple physics into a single workflow.
  – Users not experienced in all engineering disciplines can conduct a study across multiple physics by monitoring input and output parameters.
  – Powerful software packages
    • Electromagnetic Simulation using **HFSS, Q3D, Maxwell, Simpler**
    • Thermal/Stress using **ANSYS Mechanical**
    • Computation Fluid Dynamics using **Fluent, CFX, Icepack**
Overview ANSYS EM Capabilities (HFSS)

- FEM, IE, PO, Hybrid, and Transient Solvers
- Adaptive Meshing Technology
- Higher and mixed order basis functions
- Direct and Iterative Matrix Solvers
- Analytical Derivatives
- Domain Decomposition Methods
Overview Thermal/Stress Capabilities (ANSYS Mechanical)

- Steady State/Transient
- Explicit Solvers (Bird Strike)
- Solid, Shell, Beam, and Point Mass Elements
- Convection/Conduction/Radiation/Advection
- Layered Composite Shells and Solids
- Automatic Contact Setup (Thermal and Structural)
- HPC for large model support
Overview of CFD Capabilities (Fluent)

- Incompressible/Compressible Flow
- Extensive Turbulence Models
- Multi-Species & Reacting Flow
- Conjugate Heat Transfer
- Fluid Structure Interaction – 1 way & 2 way
- Dynamic, moving & sliding meshes
ANSYS Workbench

• ANSYS Workbench for multi-physics simulation and design exploration

• Ansoft products integrated into ANSYS Workbench platform
  – HFSS,
  – Maxwell
  – Designer
  – Q3D Extractor

• Analysis Systems
  – Thermal
  – Stress
  – CFD
  – EM
  – Design Exploration
“Closing the Loop”

- **Multi-Physics Simulations**
  - EM Solution using HFSS
  - Losses passed to ANSYS Mechanical or Fluent/CFX/Icepack for thermal analysis
  - Thermal loading applied to structural solution along with any external loads to calculate deformation

- **Complete Two-Way Coupling**
  - Electrical properties in HFSS can include a temperature dependency determined by the thermal solution
  - Deformed mesh results from structural analysis returned to HFSS for additional analysis
  - Iteration of simulation process to reach steady state

- **Multiple physics analysis completed using ANSYS Workbench**
Setting up the Project Environment

1. Add the HFSS analysis block
Waveguide Diplexer Example

35 GHz

100W

37 GHz

Enable Stress and/or Thermal Feedback

Solution Type...
Edit Options...
Deformation of Objects

Check Mark Box

Enable Stress Feedback

Object Name | Material | Deformation Dependent
--- | --- | ---
wg_inter | vacuum | False
wg_outer | aluminum | True
Waveguide Diplexer Example

Define/test different thermal boundary conditions

Example:
10 W/m², 2.7e-3 m² → approx 0.03 W!
0.1 W, 10 W/m² → 0.01 m² → 0.1 x 0.1 m

Exporting Surface Loss Density With Scaling...

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Total Loss</th>
<th>Scaling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>silversurf</td>
<td>3.34541W</td>
<td>1.03396</td>
</tr>
</tbody>
</table>
Waveguide Diplexer Example
Waveguide Diplexer Example

![Waveguide Diplexer Diagram]

x 100 000

s-parameters

Current Info
- s11 swept
- s21 swept
- s12 swept
- s22 swept
- s11 ref. imported
- s21 ref. imported
- s12 ref. imported

HFSS Design1

[Graph showing s-parameters]
Waveguide Termination

- **Waveguide Termination Geometry**
  - Perfect termination would result in nearly all input power absorbed by lossy material
  - Power absorbed in lossy material is realized in the form of heat
  - Power handling of termination depends on how well heat is transferred away from metal housing

- **Analysis**
  - HFSS is used to calculate the RF losses in waveguide termination
  - Thermal analysis using Icepak calculates temperatures using fluid dynamics
Introduction to Icepak

- ANSYS Icepak delivers powerful technology for electronics thermal management using computational fluid dynamics
- Based on ANSYS FLUENT solver
- Fast and accurate thermal results for electronics cooling applications
- Libraries of standard electronic components
  - Material Data, heat sinks, thermal interface materials, filters, packages, and fan and blower data.
Waveguide Termination – Thermal Management Configurations

1. **Aluminum housing**
   - Heat dissipation through natural convection on housing

2. **Heat Sink**
   - Increase surface area for natural convection and conduction away from thermal source

3. **Fan and Cabinet**
   - Forced air convection to increase heat flow away from thermal source
Power Handling of Waveguide Termination

Temperature vs. Input Power

• From this analysis we can identify cost savings by selecting an appropriate cooling method for the application power requirements.
Summary

• Using ANSYS Workbench, multiple physics simulations can be coupled to gain a better understanding of entire system performance

• With ANSYS Release 14.5, both stress and thermal feedback into HFSS from ANSYS Mechanical now give engineers the tools for more complete analysis and understanding of designs

• Coupling between HFSS and Icepak shows how the interaction between EM and fluid dynamics can be used for thermal management analysis
Extra
• Benefits of Integration
  – Utilizes intuitive multi-physics layout
    – Automated data exchange
    – Coupled physics solutions
  – Efficient system design exploration
  – Streamlined geometry handling
    – CAD integration in ANSYS Workbench provides bi-directional link to 3rd party CAD
    – Multiple physics can share the common geometry
  – Integration with EKM, Team Center and other PLM tools
  – Extensive Material Library
The Workbench Environment

- CAD Geometry
  - Coupled Physics Solutions
  - Automated geometry transfer and data exchange of solution shown by connections

Available Physics

Parameter Set
- Controls inputs and views outputs of each simulation, i.e. Input = Antenna Scan Angle, Output = Max Radome Deformation

Design Exploration
• Bi-direction Coupled Full-Wave EM to Thermal Stress Simulation of diplexer component
• High power RF input can result in cavity deformations large enough to shift response
  • External thermal and structural loads can also be applied to see impact on electrical performance
Application Examples

• Application Examples

  – Dielectric Resonator Filter
    • Filters need to meet stringent design specifications which often include operating environment and power handling
    • Analysis of electrical performance due to thermal and structural loads is achieved with bi-directional coupling between HFSS and ANSYS Mechanical

  – Connector
    • Electrical performance may easily be met while not able to meet thermal limits
    • It is important to understand design tradeoffs in more than one physics domain

  – Waveguide Termination
    • High power absorption by waveguide terminations can produce many thermal design considerations
    • Icepak allows accurate thermal modeling using computational fluid dynamics coupled to HFSS
      – Library of heat sinks and fans allow for simplified thermal analysis setup
Dielectric Resonator Filter Analysis

• Example filter
  – Dielectric resonator TE-mode filter.
  – Typically used in the high power applications where low loss and good power handling are needed
  – One major design challenge is how to account for effects on performance due to high temperature

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return Loss</td>
<td>&gt; 18 dB</td>
<td>2561 – 2579 MHz</td>
</tr>
<tr>
<td>Insertion loss</td>
<td>&lt; 0.35 dB</td>
<td>2561 – 2579 MHz</td>
</tr>
<tr>
<td>Attenuation</td>
<td>&gt; 15 dB</td>
<td>&lt; 2553 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 2588 MHz</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>-5 to +45°C</td>
<td></td>
</tr>
<tr>
<td>Average Power</td>
<td>200 W</td>
<td></td>
</tr>
</tbody>
</table>
• Temperature Compensation
  - The temperature drift of the resonators can be compensated by carefully selecting dielectric material with suitable temperature coefficient ($\tau_f$).
  - Two-way EM-Thermal/Stress analysis makes it possible to evaluate the effect of different ($\tau_f$) on filter performance.
    • Temperature dependent material properties
    • Geometry deformation
Simulation Design Flow

- **EM Analysis**
  - Temperature dependent material properties
  - Full HFSS analysis with Ansoft Designer for virtual filter tuning

- **Thermal Analysis**
  - Boundary conditions for convection and other thermal properties applied
  - Temperature feedback to HFSS

- **Structural Analysis**
  - Structural boundary conditions and thermal stresses
  - Mesh deformation feedback to HFSS
Temperature Drift and Temperature Compensation

\[ f \approx \frac{1}{\text{size} \sqrt{\varepsilon_r}} \]

\[ T \uparrow \Leftrightarrow \text{size}_{\text{general}} \uparrow \Leftrightarrow f \downarrow \quad \text{temperature drift} \]

\[ \text{size}_{\text{puck}} \downarrow \Leftrightarrow f \uparrow \]

\[ T \uparrow \Leftrightarrow \text{size}_{\text{cavity}} \uparrow \Leftrightarrow \text{size}_{\text{puck}} \downarrow \Leftrightarrow f \uparrow \quad \text{“mechanical” compensation} \]

\[ T \uparrow \Leftrightarrow \varepsilon_r \downarrow \Leftrightarrow f \uparrow \quad \text{“electrical” compensation} \]
Understanding Temperature Compensation

- Two-Way Thermal Analysis
  - Only including temperature feedback into HFSS
  - Material properties are temperature dependent
  - Electrical compensation
    - $\tau_f$

- Two-Way Structural Analysis
  - Only including deformed mesh feedback into HFSS
  - Material properties are temperature independent
  - Mechanical compensation

Temperature compensation uses electro-thermal properties of material to offset effect of deformations caused by thermal stresses

Effects can be studied individually or combined
Dielectric Resonator Filter Analysis – Choosing Materials

Dielectric Resonator Data Sheet

<table>
<thead>
<tr>
<th>Material Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric constant: ( \varepsilon_r )</td>
</tr>
<tr>
<td>Temperature coefficient of resonant frequency (( \tau_f ) ppm/°C)</td>
</tr>
<tr>
<td>Q (1/tanδ) min</td>
</tr>
<tr>
<td>Thermal expansion (ppm/°C) (20–200°C)</td>
</tr>
<tr>
<td>Thermal conductivity (cal/cm/sec°C) @ 25°C</td>
</tr>
</tbody>
</table>

• Dielectric resonator available with temperature coefficient, \( \tau_f = -6 \) to \(+6\) ppm/°C
  • Temperature compensation achieved with appropriate material characteristics

• Using ANSYS Workbench and coupled physics, we will:
  • Determine ideal \( \tau_f \) for optimal filter performance
  • Test design trade-offs for materials
  • Validate specifications are met while also including operating environment conditions
Dielectric Resonator Filter Analysis

$\tau_f = +6 \text{ ppm/}^{\circ}\text{C}$

Ambient Temperature = 45 $^{\circ}\text{C}$, Input Power = 200 W
Dielectric Resonator Filter Analysis

\[ \tau_f = 0 \text{ ppm/}^\circ\text{C} \]

Ambient Temperature = 45 \(^\circ\text{C}\), Input Power = 200 W
Dielectric Resonator Filter Analysis

\[ \tau_f = -6 \text{ ppm/°C} \]

Ambient Temperature = 45 °C, Input Power = 200 W

Minimized frequency shift with available dielectric resonator materials
Dielectric Resonator Filter Analysis

Material outside of data sheet specification can achieve best temperature compensation at possibly higher cost and/or time tradeoff

\( \tau_f = -9 \text{ ppm/}^\circ\text{C} \)

Ambient Temperature = 45 °C, Input Power = 200 W
• TRU Corporation Right Angle Adaptor
  – Type N to SC connector

• Maximum Power Handling
  – 1kW @ 2.5 GHz

• Design Tradeoffs
  – Important to understand how material choices can effect both electrical and thermal performance
  – Material that may meet electrical specifications may not meet thermal specifications

*Model courtesy of TRU Corporation
**Design Consideration: Dielectric Supports**

- Material choice will affect electrical performance and also mechanical performance
  - Electrical performance requires controlled 50 ohm impedance transition
  - Mechanical performance requires operating within thermal limits at rated input power

**Dielectric Supports/Insulators**
- Compare two materials
  - Teflon
    - Cheapest solution
    - Low thermal conductivity
  - Fluoroloy H
    - Higher thermal conductivity
Thermal Performance: Teflon

• Input Power - 1kW @ 2.5 GHz

• Operating Environment
  – 22 °C
  – Natural Convection

• Dielectric Supports
  – Teflon
  – Thermal Conductivity: 0.25 W/(m·K)
  – Melting Point: 327°C

• Conductors
  – Tri metal plating defined by layered impedance boundary condition

• Peak temperature: 404.41°C
  – Based on the thermal analysis results, dielectrics would melt and the part will fail
  – Cheapest material choice would not meet thermal requirements even though it would meet all electrical requirements
Input Power - 1kW @ 2.5 GHz

Operating Environment
- 22 °C
- Natural Convection

Dielectric Supports
- Fluoroloy H
- Thermal Conductivity: 1.21 W/(m·K)
- Melting Point: 327°C

Conductors
- Tri metal plating defined by layered impedance boundary condition

Peak temperature: 199.27°C
- Well within thermal limits
- Electrical and thermal performance requirements are met
Connector Thermal Performance

![Graph showing Input Power Vs. Max Temperature for Teflon Insulators, Fluoroloy H Insulators, and Melting Point.](image)

- Temperature Reduction with Fluoroloy H insulators