Multidisciplinary Analysis of a Hypersonic Engine

ISTAR Flowpath

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Outline

• Overview & Motivation
• Description of Component Simulations
• Consistent Multidisciplinary Solutions
• Code Coupling Issues
• Benefits & Costs of MD Analysis
ISTAR Multidisciplinary Simulation: Objectives

• Develop high fidelity tools that can influence ISTAR design

• In particular, tools for coupling Fluid-Thermal-Structural simulations

• RBCC/TBCC designers carefully balance aerodynamic, thermal, weight, & structural considerations; consistent multidisciplinary solutions reveal details (at modest cost)

• At Scram mode design point, simulations give details of inlet & combustor performance, thermal loads, structural deflections
Approach Flow: Mach Contours

• Full Navier-Stokes solution using *Overflow*.
• Simulation includes forebody, canard, & engine inlet—only forebody geometry that influences engine inflow
• Chimera five block structured grid with $9 \times 10^5$ cells.
• $k-\omega$ turbulence model with low-Reynolds number form—no compressibility correction
• Equilibrium chemistry
• Sets Combustor inflow
• Yields heat & pressure loads for thermal & structural analysis
Combustor Solution:
Fuel mass fraction iso-surface colored by temperature

• Full Navier-Stokes plus finite-rate chemistry solution using *Vulcan*.
• Composite five block grid with $1.9 \times 10^5$ cells.
• 6-species 3-step finite-rate gaseous Ethylene model
• Inflow profile from Approach solution.
• $k-\omega$ turbulence model with wall functions; Compressibility correction
• Each injector modeled as a single triangular slot with equivalent area, massflow, and momentum. (normal injection).
• Flame holding cavity included.
• Yields heat & pressure loads for thermal & structural analysis
Combustor Solution: 1-D Averaged Quantities

- ANSYS—commercial finite element solver.
- 3-D unstructured grid with $1.3 \times 10^5$ nodes and $8.6 \times 10^4$ tetrahedra
- Temperature dependent material properties for Inconel 625, Titanium β21S
- Coolant passages modeled as a bi-layer material

- Neglects details of heat conduction around coolant passages, plus structural effects
- Some modeling of coolant circuit.
- Thermal model yields temperatures from heat loads, coolant system, and material properties
- Structural model yields deflections & stresses from pressure & temperature loads
Deflections Exaggerated

Multidisciplinary Coupling Procedures

- Fluid-Fluid Coupling
- Fluid-Thermal Coupling
- Fluid-Structural Coupling
- Aerodynamic Analysis
- Combustion Analysis
- Thermal Solid Analysis
- Structural Analysis
Consistent Multidisciplinary Solutions

- **Fluid-Fluid Coupling**: Flow quantities are the same where the Fluid codes meet.

- **Fluid-Thermal Coupling**: Heat fluxes & Temperatures are the same where Fluid & Thermal codes meet.

- **Fluid-Structural Coupling**: Deflected walls are the same as the Fluid boundaries.

ISTAR Multidisciplinary Simulation: Interpolation & Consistency

- Interpolation transfers inflow profiles, thermal & pressure loads, displacements from code-to-code.

- **One-pass:**
  
  \((\text{Fluid} \Rightarrow \text{Thermal} \Rightarrow \text{Structural})\)

  Boundary conditions often inconsistent.

- **Consistency achieved with multiple passes:**

  \((\text{Fluid} \Leftrightarrow \text{Thermal} \Leftrightarrow \text{Structural})\)
Fluid-Thermal Iteration

In engine case, L2 Norm of: \( \Delta T = 500 \, ^{\circ}R \).

Challenging Issues in Coupling: Toolkit Specific

- Robust interpolation between codes on wetted surface
  - Accept all types of grids and formats.
  - Some tolerance for out of plane target points.
  - Subsetting of source grids.
  - Extrapolation at boundaries.

- Update fluid grids to include surface deflections
  - Difficult when deformations, particularly shear deformations, exceed the grid spacing.
Challenging Issues in Coupling: Code Specific

- Noisy heat fluxes from fluid codes
- Code compatibility w.r.t coupling (turbulence models, wall functions?)

Calculation of Accurate Heat Fluxes
Benefits & Costs
(Single Discipline vs. Multidisciplinary)

- Cooling system design potentially aided by thermal/fluid calc.
- Computational cost: MD adds 100% of single discipline
- Cost of Setting up MD problem: a toolkit would help (Interpolation++)
- Disparate turn around times:
  thermal & structural time is <1% of fluid & combustion

Summary

- Single discipline simulations coupled into Multidisciplinary simulation.
- Application is Scram design point of ISTAR concept vehicle
- Reveal some code coupling issues and obstacles, costs and benefits