Hypersonic Vehicle (HSV) Modeling

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HSV Concentration

MACCCS Kickoff Meeting
Ann Arbor, 29 August 2007
Team

- U of M Faculty: Carlos Cesnik (PI), Jim Driscoll

- Current students: Nathan Falkiewicz, Torstens Skujins, Nathan Scholten, Sean Torrez, plus Post-doctoral fellow (TBD)

- AFRL collaborators: Mike Bolender, David Doman, Mike Oppenheimer
Overview

- Challenge: strong interactions among aerodynamics, elastic airframe and control effector deformations, heat transfer, and propulsion system (itself tightly integrated into the lifting body)

- Focus in two main areas:
  - development and validation of simple (low-order) control models that can characterize the main aerothermoservoelastic effects coupled with propulsion in a 6 DOF flight dynamics simulation of HSV; and
  - determination on how to appropriately modify vehicle configuration to improve its dynamic controllability without compromising vehicle performance.

- All done in close collaboration with AFRL/VACA researchers who will provide primarily the control design and modeling expertise as part of the Collaborative Center.
Sample Relevant Work at UM
Very Flexible HALE Aircraft (Sensorcraft-class)

• Aeroservoelastic formulations at different complexity levels
  – Target preliminary vehicle and control design and more detailed analysis
  – Able to simulate 6-DOF with fully flexible vehicle
• Numerically investigate aeroelastic response under nonlinear effects
• Model different vehicle configurations

![Diagram of aircraft dynamics and control](image)

**Case 3 Heavy Weight**
- Rigid
- Linearized
- Nonlinear
TIME = 0

**Mission Profile**
- Nonlinear
TIME = 0
Disciplinary Components of HSV

- Four main component areas to be addressed in the study:
  - Modal representation in 3D
  - Variable mass
  - Heat flow
  - 3D shocks, viscous effects
  - Inlet spillage
  - Elevon-canard interaction
  - 6 DOF
  - High altitude/speed effects
  - Stability and control derivatives
  - Combined cycle, dual mode engine
  - Isolator losses
  - Dissociation losses
Thermo-structural Dynamics Modeling

- Structures defined by flexibility and inertia effects
  - different options to characterize deformations
- Heat issues:
  - thermo effects on the elastic characteristics of the vehicle
    - Dependent on the structural layout and material stacking sequence
      → need detailed model of the structure to assess impact on vehicle response
  - temperature gradients in the structure will impact
    - the reference vibration modes and static deflections of the control surfaces and possibly of the entire vehicle (mainly due to thermal stresses and material property degradation with temperature)
    - fuel temperature in the tanks (which can define optimum flight trajectories).

McNamara and Friedmann, 2006
Unsteady Aerodynamics Modeling

- Complex environment of unsteady, viscous, non-equilibrium, reacting flow
- Current models limited to longitudinal dynamics
  - Stead state shock/expansion geometry determined based on the Oblique Shock Theory
  - Superimposed unsteady aero effects based on piston theory
- Several issues—AFRL has identified needed improvements in the following areas:
  - Unsteady pressure over the entire wetted surface area, including lateral aerodynamics,
  - Spillage effects caused by the location of the bow shock with respect to the inlet during vehicle bending,
  - Coupling of the aerodynamics and the heat transfer,
  - Control surface aerodynamics, including elevon, canard, and elevon-canard interactions,
  - Viscous effects.
Propulsion Model

- Combined cycle engine as an integral part of the vehicle structure
- Model must contain (AFRL):
  - engine forces & moments related to bow shock/engine spillage, pressures on aft underbody
  - forces depend on fuel/air ratio, diffuser area ratio, cowl leading edge
- We will work with AFRL to improve modeling of:
  - inlet/isolator shock losses,
  - scramjet dissociation / frozen flow losses
  - real gas effects, finite-rate chemistry
  - how pressure varies with distance inside engine
  - thermal choking limitations to fuel-air ratio
  - RBCC (or TBCC) cycle analysis, ram-scram transition
  - boundary layer effects (effective duct shape change)

Driscoll will discuss more about it next
Flight Dynamics Model

• Free flight simulation of the flexible HSV is the ultimate goal
  – Lateral dynamics will bring new modes that may couple with the longitudinal ones (short-period mode; phugoid-like mode, although independent of speed; and a height mode, typically not seen in conventional subsonic vehicles)
• Development of the nonlinear rigid 6 DOF model based on AFRL’s current planar (2D) formulation
• Solution of combined flight dynamics/aerothermoelasticity problem
  – numerical stability for long term simulations
  – integration of the disciplines and models
Vehicle Configuration and Sensitivities for Dynamic Controllability

• Issue: How to appropriately modify the vehicle’s configuration to improve its dynamic controllability without compromising its performance?

• Create 6 DOF Simulation:
  – Simulate open-loop couplings among different disciplines
  – Quantify the effects of coupled physics coming from the different disciplinary areas
  – Determine stability derivatives and overall root locus characteristics by linearization at different mission segments
  – Serve as the representation of the HSV for testing control laws
Overview of Modeling Approach

- Two main thrusts for HSV modeling:
  - (Low-order) control models
  - (High-fidelity) reference models along with a control evaluation model.
(Low-order) Control Models

• Guiding principle: *represent the important physics that will drive the controllability of the HSV with the lowest number of states possible* (suitable for control studies)

• Approach: create *representative* low-order models for the thermo-structural dynamics, unsteady aerodynamics, engine dynamics, flight dynamics, and all their couplings from combination of:
  – (Direct) fundamental models
  – Reduced-Order Models (ROM) from high-fidelity models

and then assess the validity of the models
(High-fidelity) Reference Models

• High-fidelity computational models will be used to:
  – create the “truth” model for accuracy assessment of the control models
  – serve the basis for creating ROMs directly from its results

• Approach: codes (and models when available) will be used for this study and no code development effort is expected
  – MSC.Nastran for thermo-structural dynamics
  – FUN3D for unsteady aerodynamics
  – VULCAN for engine dynamics
Example: High-fidelity Aerothermoelastic Model

(a) Aerothermoelastic Solution Procedure.

(b) Finite Element Analysis.

McNamara and Friedmann, 2006
Example: ROM based on Volterra Series

- Impulse response method for (linear or nonlinear) time-invariant systems

- Successfully applied as Aerodynamic Impulse Response method for different flight regimes and different codes, including CFL3D (Silva, 1997, 2007; Guendal and Cesnik, 2001)

- Core of the process is based on discrete system identification

\[
y(i) = h_0 + \sum_{k=0}^{N} h_1(k)u(i - k) + \sum_{k_1=0}^{N} \sum_{k_2=0}^{N} h_2(k_1, k_2)u(i - k_1)u(i - k_2)
\]

- Applicability to the other disciplines and to the combined coupled problem will be investigated
Proposed Modeling Approach

Components

Ref. Models
- H.F. Struct
- H.F. Therm
- H.F. Aero
- H.F. Prop

Control Design Models
- F.M. Struct
- F.M. Therm
- F.M. Aero
- F.M. Prop

ROM Struct
ROM Therm
ROM Aero
ROM Prop

HSV System

ROM Struct
ROM Therm
ROM Aero
ROM Prop

Control Evaluation Model
- System ROM
- 6 DOF

Controllers

Component Accuracy Assessment

6 DOF System

Parametric Studies

C.D. Struct
C.D. Aero
C.D. Prop
C.D. Therm
## Schedule

<table>
<thead>
<tr>
<th>Fundamental Models</th>
<th>Year 1</th>
<th>Year 2</th>
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<tbody>
<tr>
<td>Unsteady aerodynamics</td>
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<td>add real gas properties, boundary layer to 2D model</td>
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<td>extend AFRL model to lateral aerodynamics</td>
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<td>add real gas properties, boundary layer to 3D model</td>
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<td>Thermo-structures</td>
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<td>1D heat flow and connection to planar beams</td>
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<td>consider dynamics of more complex beams</td>
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<td>spatial variation of thermal properties</td>
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<td>Propulsion</td>
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<td>add 2D engine efficiency factors for shock</td>
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<td>Component Accuracy Assessment</td>
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<td>Unsteady aerodynamics FUN3D</td>
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<td>Propulsion: VULCAN</td>
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<td>Component ROMs</td>
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<td>System ROM</td>
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<td>Control Evaluation Model</td>
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<td>System C.D.</td>
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<td>Integration of System C.D. and 6 DOF</td>
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<td>New 6DOF + aerothermoelastic + propulsion</td>
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First Year Activities

- **Fundamental model development**
  - extend AFRL’s piston theory-based aero model to include B.L.’s displacement thickness effects
  - model elevator-canard interaction (started over the summer, Skujins and Oppenheimer)
  - model 1D thermo-structural response to extract parameter corrections for HSV structure
  - add realistic efficiency factors to propulsion model

- **Reference models**
  - setup codes and input files for reference case
  - define fundamental information flow between components and define key I/O for ROM generation
  - create baseline structural layout for 1D thermo analysis
  - run 2-D propulsion model to identify critical issues

- **Select baseline vehicle**
  - stretched X-43A (to 100-ft length) with NASP-based interior structural layout (info needs to be accessible)
Initial Task Assignments

• Graduate students:
  – Torstens Skujins (MS/PhD): unsteady aerodynamics modeling (canard-elevon interaction, steady CFD coupled with piston theory, boundary layer effects) and flight dynamics
  – Nate Falkiewicz (MS/PhD): thermo-structural modeling (1D heat flow through the thickness and its connection with structural dynamics model parameters, FEM modeling of representative structure)
  – Nate Scholten (MS): High-fidelity aerodynamics and propulsion modeling
  – Sean Torrez (MS/PhD): propulsion modeling (1D efficiency factor corrections, engine cycle code reference modeling)
  – TBD: Aerothermoelastic ROM generation and system integration for controls applications

• Post-doctoral fellow (TBD):
  – Baseline 3D vehicle definition
  – H.F. code and input setup
Concluding Remarks

• Highly coupled multidisciplinary problem modeling effort for control design and simulation
• Several specific challenges lay ahead—group is highly motivated and bring disciplinary expertise and prior experience in similar issues
• Good start with student summer activity (Torstens Skujins) at AFRL—more is expected in the following summers
• Initial activities will focus on extending current 2D AFRL models for potentially important effects
• New initiatives in high-fidelity modeling will provide reference cases for error assessment and initial validation of the models