Mode Transition Design Considerations for an Airbreathing Combined-Cycle Hypersonic Vehicle

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Mode Transition Basics

- Why?
  - Turbine Based Combined Cycle (TBCC) systems are a means to accelerate a reusable hypersonic vehicle from takeoff to staging and return to land
- What?
  - The transition from a low-speed system (turbine engine) to a high-speed system (ram/scramjet)
- When?
  - Somewhere between M3 – M4 (some want to go lower … ~M2.5)
  - Significant design consequences to transition MN
- What's the problem?
  - Need seamless transition of propulsive forces/moments
  - Both turbine engine and ram/scramjet will be operating at their operability margins
  - Common inlet flowpaths
  - Transition performance losses could impact mission
  - Upsets could be catastrophic!!

Mode Transition Control Issues

- Controls Task
  - **Need to seamlessly (relatively) blend two propulsive systems through highly nonlinear phases of their operation**
    - Turbine Engine
      - Max operating conditions to shutdown/cocooning
      - Operability (aerodynamic/thermal stability)
    - Ram/Scramjet
      - Startup condition to full propulsive operation
      - Stability
    - Vehicle
      - Keep it flying
      - Keep it flying in an optimum trajectory
- Modeling
  - **Need integrated vehicle/turbine engine/ram/scramjet dynamic models of sufficient fidelity to capture important control tasks**
  - **Controls analysis/design models do not exist**

Hypersonic Vehicle & Propulsion Models

Hypersonic Vehicle Models	
Linear	CAUTION
Nonlinear	CAUTION
Fidelity	CAUTION
Dynamic	CAUTION
6DOF	DANGER
3DOF	✓
Controls	CAUTION
Tractability	CAUTION

+

Turbine Engine Models	
Linear	✓
Nonlinear	✓
Fidelity	✓
Dynamic	✓
High Mach	CAUTION
Controls	CAUTION
Tractability	CAUTION

+

Ramjet Engine Models	
Linear	DANGER
Nonlinear	✓
Fidelity	✓
Dynamic	CAUTION
Controls	DANGER
Tractability	DANGER

=

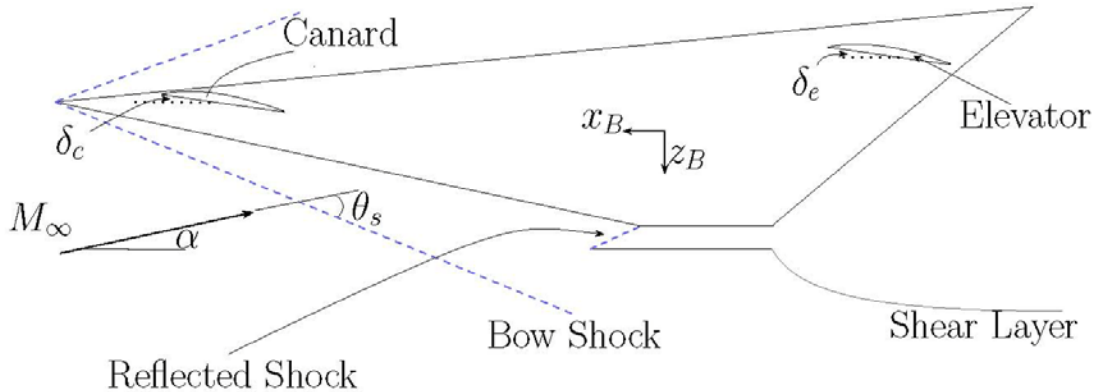
Integrated Models	
Linear	DANGER
Nonlinear	DANGER
Fidelity	DANGER
Dynamic	DANGER
Controls	DANGER
Tractability	DANGER

✓	Models exist w/desired characteristics, integration straightforward
CAUTION	Models exist, limited desired characteristics, integration challenging
DANGER	Models do not exist in useable form for mode transition studies

Modeling is the REAL Challenge

AFRL Hypersonic Vehicle Model

Bolender et al (2004-2007)



Longitudinal Equations of Motion

$$\dot{V}_t = \frac{T\cos\alpha - D}{m} - g\sin(\theta - \alpha)$$

$$\dot{\alpha} = \frac{-L - T\sin\alpha}{mV_t} + Q + \frac{g}{V_t}\cos(\theta - \alpha)$$

$$\dot{Q} = \frac{M}{I_{yy}}$$

$$\dot{\theta} = Q$$

$$\dot{h} = V_t\sin(\theta - \alpha)$$

$$\ddot{\eta}_i = -2\zeta_i\omega_i\dot{\eta}_i - \omega_i^2\eta_i + N_i,\ i = 1, \ldots, n$$

States		Controls	
V_t	Horizontal Velocity (ft/s)	δ_e	Elevator angle (deg)
α	Angle of Attack (deg)	δ_c	Canard angle (deg)
Q	Pitch rate (deg/sec)	Φ	Fuel Equivalence Ratio
h	Altitude (ft)		
Θ	Pitch Angle (deg)		
η	Generalized modal coordinate		
η_{dot}	Generalized modal coordinate velocity		

Ramjet Propulsion Model

- **RAMSCRAM**
- **1-D Steady-state thermodynamic design and off-design performance of rocket-based combined cycles, ejector ramjets, ramjets and scramjets**
- **Real gas effects, multiple fuels and/or oxidizers**
- **FORTRAN legacy code (circa 1990) ☹**
- **Forebody (oblique shock), Inlet, Mixer, Combustor, Nozzle**

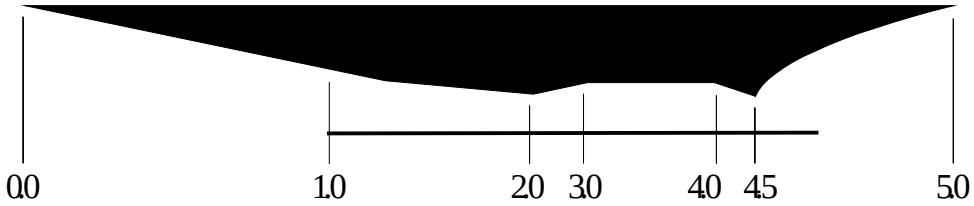


Fig 1 - Ramjet station locations

Ramjet Propulsion Model

(as implemented)

- **RAMSCRAM - Cannibalized**
- **1-D Steady-state thermodynamic design and off-design performance of ~~rocket-based combined cycles, ejector ramjets,~~ ramjets and scramjets**
- **Real gas effects, ~~multiple fuels and/or oxidizers~~**
- **~~FORTRAN legacy code~~ ☹**
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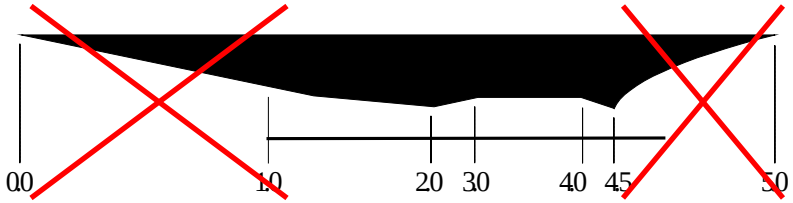
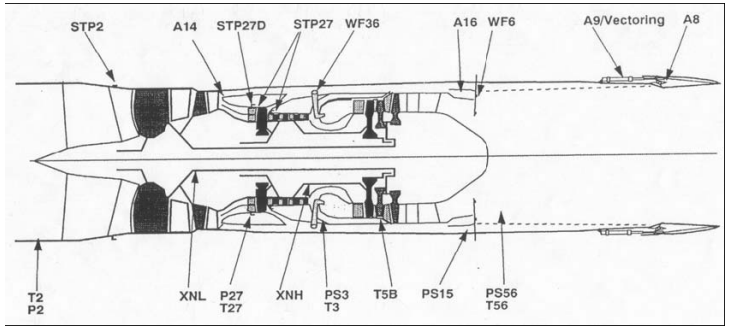


Fig 1 - Ramjet station locations

Modular Aero-Propulsion System Simulation MAPSS

- **MATLAB Simulink model of turbofan engine (Parker & Melcher, NASA/TM 2004-212968)**
  - **Based upon GE32**
  - **Three states: Fan Speed (XNL), Core Speed (XNL), Hot section metal temperature (TMPC)**
  - **Three controls: Main Fuel Flow (WF36), Nozzle area (A8), Bypass Exit Area (A16)**
  - **Added augmentor fuel flow schedule (WF6) to match trim thrust**
  - **High update rate of engine physics model to balance equations significant impact on simulation time**



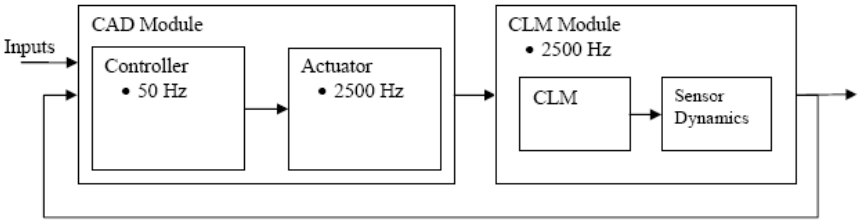


Figure 1: Basic block diagram of MAPSS.

Propulsive System(s) Mode Transition Approach

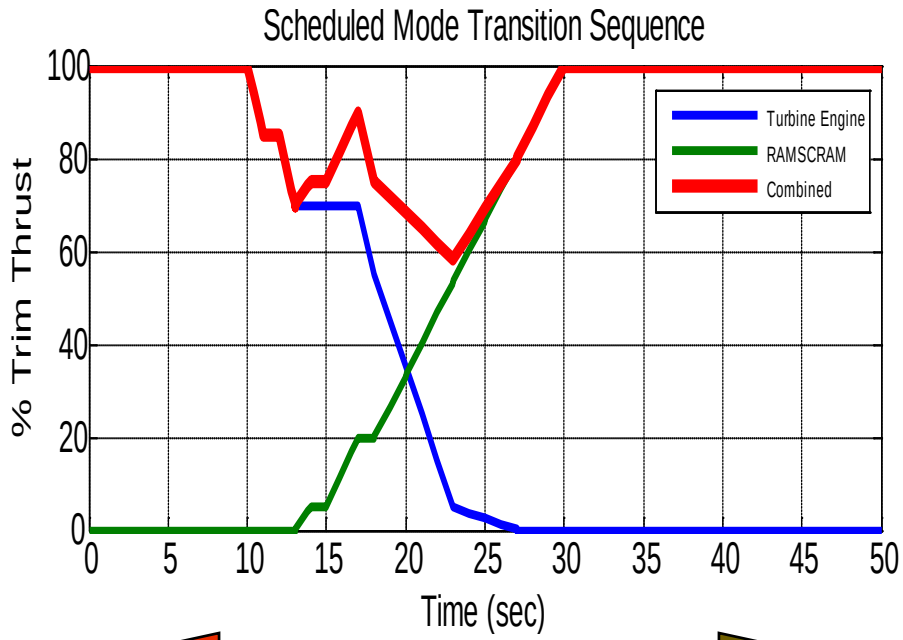
No Thrust Blending

- Simplest
- Safest
- Min impact on propulsion systems

Total Thrust Blending

- Complex
- Riskiest
- Max impact on propulsion systems

Impact on Propulsion Systems



- Slowest
- Max Impact on Vehicle Flight Dynamics

- Fastest
- Min Impact on Vehicle Flight Dynamics

Impact on Vehicle Flight Dynamics

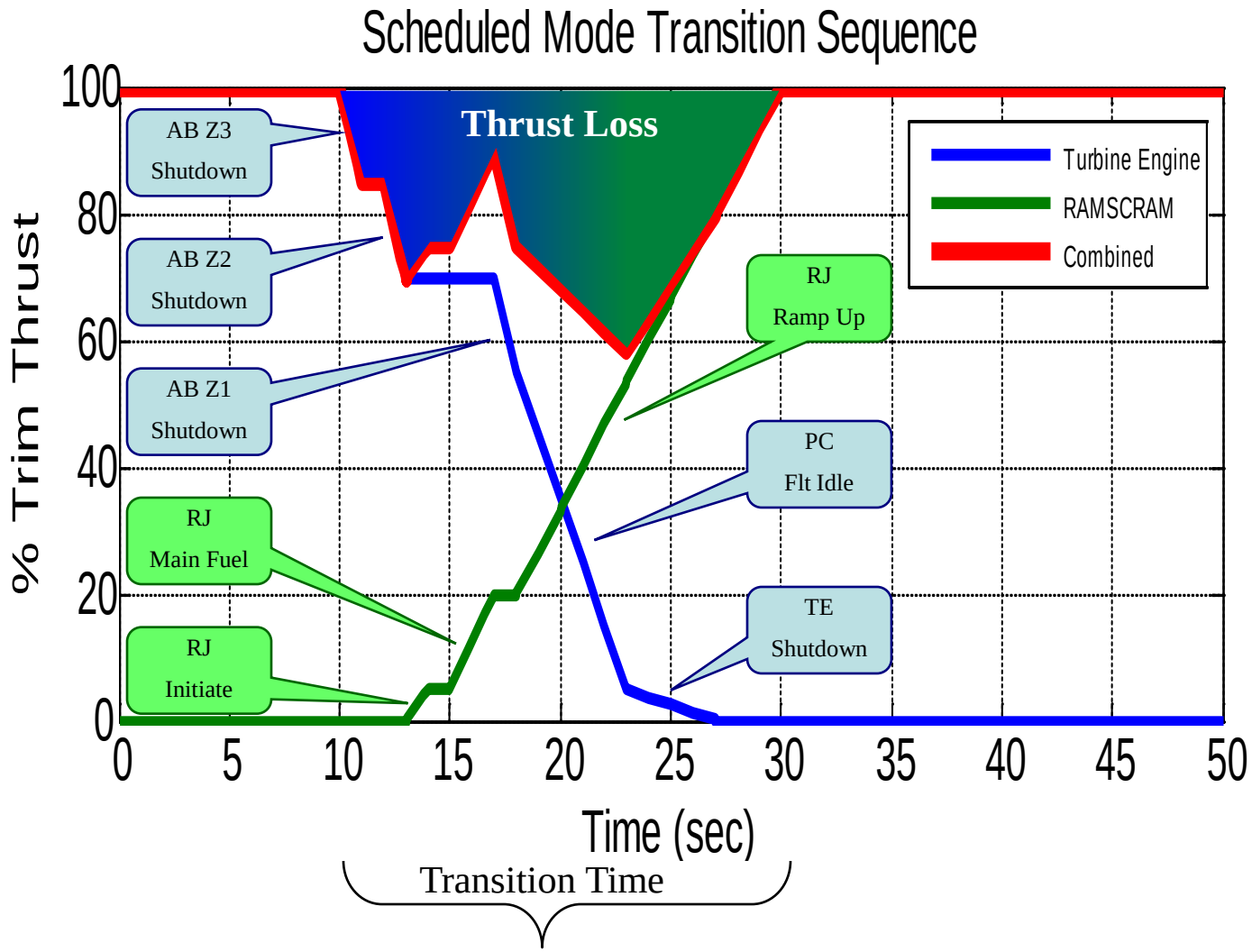
This is the Mode Transition Design Space

Mode Transition Control Design Approach

- **During mode transition, propulsive thrust dictated by process of transition from turbine engine to ramjet**
  - "Normal" flight control not possible
  - Must decide what to control (or what to give up)
- **Consider holding forebody flow structure (nearly) constant**
  - Constant unit corrected airflow
  - May simplify flow transition between flowpaths
  - Implies holding V and α constant
    - "Give up" on altitude
    - Trade potential energy for kinetic energy
    - Trajectory analysis to validate this is a "good" thing
- **Nominal Controller**
  - V, α, h controlled variables
  - δ_e, δ_c, Φ control effectors
- **Mode Transition Controller**
  - V, α controlled variables
  - δ_e, δ_c control effectors

Linear Blending of Controls in/out of Mode Transition

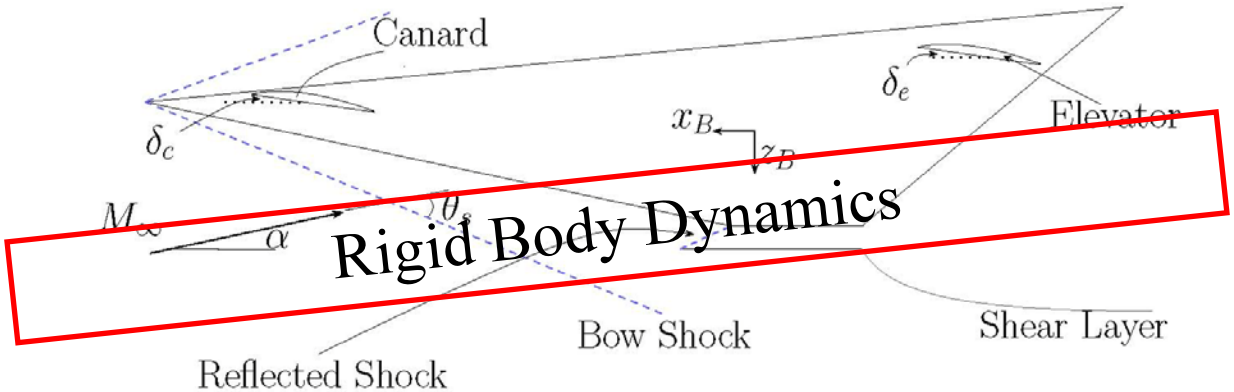
Mode Transition Sequence



Key Parameter Integrated Thrust Loss (= f(transition time, max thrust loss))

AFRL Hypersonic Vehicle Model

(as implemented)



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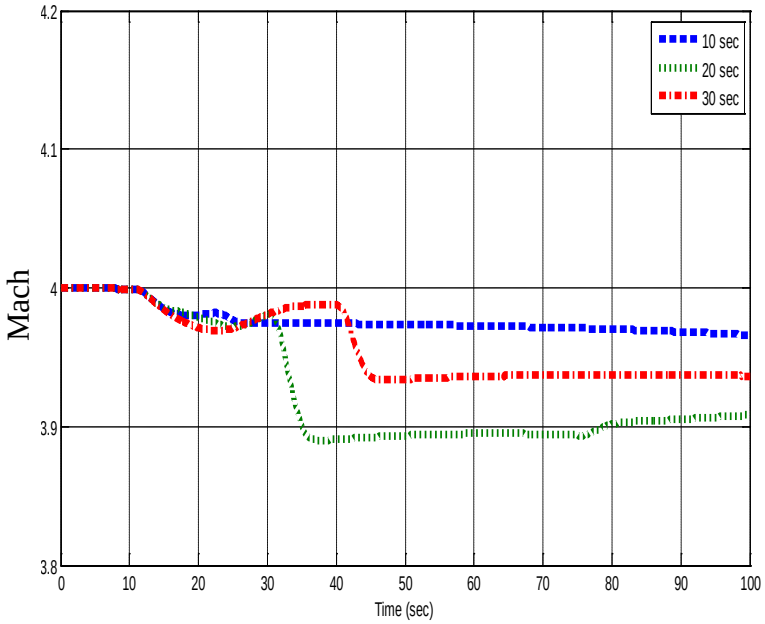
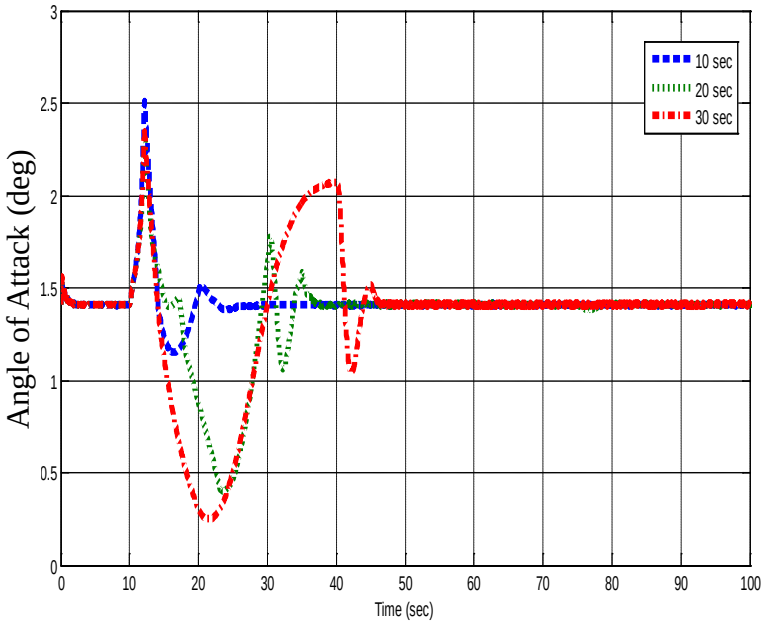
Example Mode Transition Results
Controlled Variables

Vehicle Mach Number



Angle of Attack

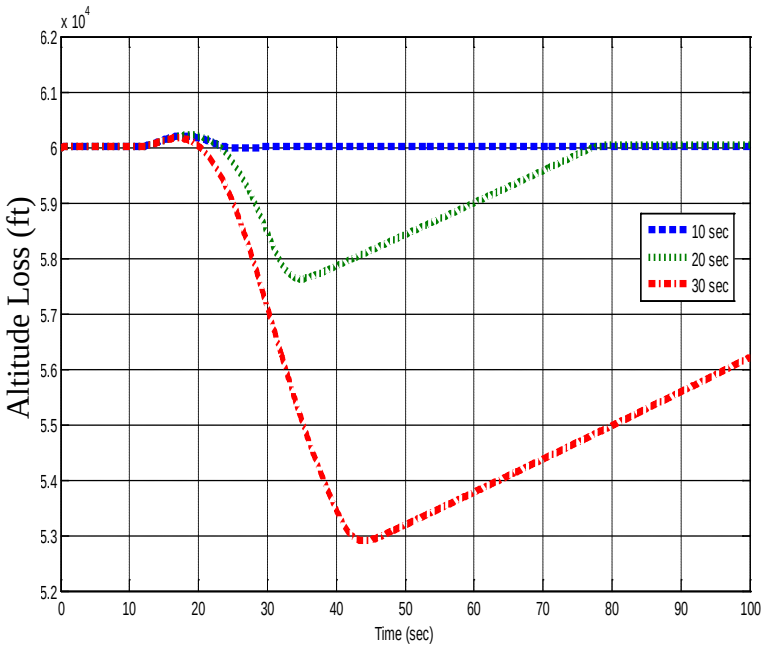


Control Objective

Hold Mach & α to keep inlet flow conditions constant

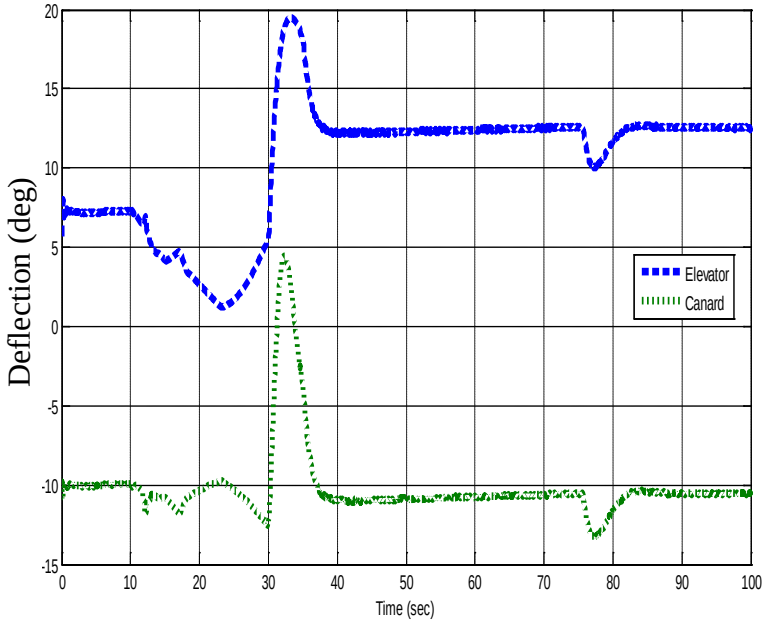
Example Mode Transition Results
Impact

Altitude Loss



Altitude *Loss* is the Transition Metric

Control Effectors



Actuators within limits
(20 sec transition case)

Example Mode Transition Sequences

Results

Sequence Time (sec)	Maximum Thrust Loss (%)	Propulsive Energy Loss (lbf*sec) (normalized)	Velocity Change (fps)	Angle of Attack Variation (deg)	Altitude Change (ft)
10	40	**-0.24**	-32	+0.5 / -0.8	**-20**
	60	**-0.41**	-66	+0.2 / -1.5	**-567**
20	20	**-0.16**	-60	+0.6 / -0.7	**-170**
	40	**-0.49**	-79	+0.5 / -1.4	**-1862**
	40 (zoned)	**-0.67**	-106	+0.3 / -1.6	**-2374**
30	20	**-0.40**	-68	+0.5 / -0.8	**-2103**
	40	**-1.00**	-64	+0.3 / -1.7	**-7102**

Greater Propulsive Energy Loss → Greater Altitude Loss

What's Next
(i.e., how to make this better!!)

- **Use flexible vehicle model**
  - Flexibility impact on angle of attack significant
- **Tune turbine engine model**
  - More suited to acceleration to high Mach task
- **Incorporate more RAMSCRAM capability**
  - Multiple fuel stations, variable geometry, design feature
- **Investigate vehicle trajectory impacts**
  - Does diving make sense?
- **Incorporate flow dynamics results from hardware experiments**
  - NASA GRC Large-Scale Mode Transition Inlet (L-IMX)
  - Other government/industry activities
- **Investigate more sophisticated control objectives**
  - Tailoring objectives to ease transition
- **Investigate better control methods**
  - Non-linear control approaches
  - Control allocation approaches

Summary

- **First-cut integrated hypersonic vehicle-turbine engine-ramjet engine model built**
- **Candidate mode transition approach selected and evaluated**
- **Nominal & Mode Transition controllers designed**
- **Example propulsion system transition schedules tested**
  - Survivable given limits on net thrust loss
  - Able to hold ~constant forebody flow structure
  - May be an trajectory optimization problem
- **Next Steps**
  - Use flexible vehicle model
  - Tune propulsion system models
  - Incorporate results of mode transition flowpath experiments
  - Develop control objectives
  - Develop control methods

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