Performance and Robustness Tradeoffs for Scramjet-Powered Hypersonic Vehicles

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NASA FAP Annual Meeting - Hypersonics Project
October 7-9, 2008

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Vibroacoustics Solutions: Dr. A. Kelkar, Dr. J. Vogel
Mission Critical Technologies: J. Benavides
Other: Dr. P. Voulgaris (UIUC), Dr. B. Ridgely (Raytheon), D. Soloway (NASA)
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Outline

• Motivation

• State-of-the-Art: Prior and Current Efforts

• Fundamental Issues and Challenges

• Sample Engineering Longitudinal Model for Generic Hypersonic Vehicle
  – Model Description
  – Static and Dynamic Analysis
  – Control Design Tradeoffs
  – Nonlinear Issues

• Summary and Conclusions
Motivation

Air-breathing hypersonic vehicles represent next critical step toward achieving reliable affordable access to space and global reach vehicles.

- Rocket-based systems must carry oxygen - more expensive (limits payload), less reliable. Airbreathing... need not carry oxygen - less expensive (reduce TOGW), more reliable, offers increased $I_{sp}$ and lower cost-per-pound-to-orbit.

- NASA Emphasis: two-stage-to-orbit (TSTO) concepts; e.g. NASA reference vehicle (RV)

Dr. J. Robinson, et. al.

- Issue: Significant aero-thermo-elastic-propulsion interactions and uncertainty – requires control-relevant integrated multidisciplinary (IM) MAD approach.

NOTES: 1. To suitably limit scope, we focus on scramjet-powered vehicles (Mach 5-16) and a single vehicle

2. Final IM-MAD approach will be applicable to TSTO.
STATE OF THE ART
State of the Art: Programs

- **1986-1993 - NASP X-30**: $3B SSTO effort involving DOD and NASA; No flights
- **1996 - Hyper-X Program**: Initiated to advance hypersonic air-breathing propulsion
- **2002 - Scramjet**
  Supersonic combustion of scramjet in flight first demonstrated July 30, 2002 by Univ of Queensland Centre for Hypersonics (HyShot program)
- **2004 - X-43A Flights**
  Hyper-X program culminated with historic (March 27, November 16) 2004 Mach 7, 10 X-43A scramjet-powered flights (McClinton, 2007)

  ...ushered in era of airbreathing hypersonic flight

- **Hypersonic International Flight Research Experimentation (HIFIRE)**
  Ongoing collaboration between NASA, AFRL, Australian Defence Science and Technology Organization (DSTO), Boeing Phantom Works, University of Queensland Will involve 10 flights over 5 years

- **X-51A Scramjet Engine Demonstrator - WaveRider (SED-WR)**
  AFRL, Boeing, Pratt & Whitney, Rocketdyne single HC-fueled scramjet, fixed-geometry inlet, air-launched expendable missile, to be launched by B-52 at ∼35Kft, accelerated by solid-propellant rocket motor (MGM-140) to Mach 4.5 scramjet ignition speed, target speed: ∼Mach 6-7, first flight: ∼ Aug 2009
Aero-Thermo Interactions (Anderson, 2006)

- Drag can be reduced by making body more slender (increased fineness); this increases structural heating, reduces flexible mode frequencies...can degrade control system performance...may cause instability!

- Hypersonic vehicle design is heat-driven, not drag-driven
  Reason: within hypersonic regime ($M > 5$) heating varies as $V^3$; drag as $V^2$

Scramjet Propulsion (Heiser & Pratt, 1994)

- Airbreathing systems need not carry oxidizer - significantly reduces TOGW
  - for given payload $W_{payload}$: $\frac{W_{rocket}}{W_{payload}} \approx 25 >> \frac{W_{airplane}}{W_{payload}} \approx 6.5$ (4% vs 15.4%)
  - offers potential for significantly (vis-a-vis rockets)
    - increased specific impulse $I_{sp} \overset{\text{def}}{=} \frac{\text{Impulse}}{W_{propellant}}$ ($I_{sp}$ for H $>> I_{sp}$ for HC fuels $\Rightarrow$ Much higher Mach numbers for H - larger volume)
    - lower cost-per-pound-to-orbit (currently $10K/lb$ for rocket based systems)
Integrated Airframe and Engine - “Engineframe”

- Entire underbelly part of flowpath - long forebody provides compression lift, mass capture
- Will fly at highest allowable $\bar{q}$ (structure permitting) to maximize mass capture
- Aft body expansion nozzle recovers thrust
- May require tight AOA control for proper operation (particularly at off-design conditions)
- Aft situated c.g. results in instability - requires minimum BW to stabilize

Trajectories within Airbreathing Corridor (Heiser & Pratt, 1994)

- About 30kft wide (vertically); dynamic pressure: $\bar{q} \in [500, 2000]$ psf
  - lower bd dictated by available lifting area; upper bd by structural limits
  - At Mach 16, lower bd requires flight below 150kft

Need for Flight Path Angle (FPA) Control

- Assume corridor-centered flight at Mach 10. If FPA deviates by $\sim 2.9^\circ$ for 30 sec, vehicle will leave corridor! (Static calculation; doesn’t capture dynamical issues!)
- Can be disastrous - particularly in presence of uncertain low-frequency flexible modes
- Issue: RHP zero (elevator to FPA) may limit FPA BW...may require additional control surface to follow rapid FPA commands; e.g. a canard (beware severe thermal issues)
Prior and Ongoing Work

- 1994, Chavez-Schmidt (Arizona State University)
  - 3DOF longitudinal (plus flexing) model
  - simple scramjet engine
    - isentropic diffuser, internal-external nozzles, 1D Rayleigh flow combustor
    - thermal choking (unity combustor exit Mach)
    - convenient plume assumption
  - FEM based structural model (based on similar full scale vehicle)

  - engineering and CFD methods, 6DOF, winged cone

- 2004-2008, Bolender, Doman, Oppenheimer, et. al.
  - builds on 1994 Chavez-Schmidt model (overview given below)

- 2008, VSI-Control3D; Univ. Michigan-OSU
  - Two Ongoing NASA (collaborative) Modeling NRAs
  - engineering and CFD methods, 6DOF
  - general vehicle configurations; e.g. NASA RV, etc.
SAMPLE ENGINEERING MODEL

Bolender, Doman, Oppenheimer
Overview of Model

- 3DOF longitudinal + structural (Bolender, Doman, Oppenheimer, et. al, 2005-2008)

- Model components
  - inviscid compressible oblique-shock and Prandtl-Meyer expansion theory
  - unsteady effects: linear piston theory
  - viscous drag effects: Eckerts temperature reference method (turbulent)
  - structural: assumed modes method (free-free beam)
  - propulsion: 1994 Chavez, Schmidt
  - 4 possible controls - elevator, fuel equivalence ratio (FER), diffuser area ratio, canard

- Propulsion improvement: GNC2008 Torrez, Driscoll, Bolender, Doman, Oppenheimer.

- For this paper, 2 controls (elevator, FER) model, diffuser area ratio = 1, canard removed
Fundamental Questions Asked

- Where can vehicle be trimmed (altitude, Mach)?...focus on level-flight

- How do trim properties change over trimmable region?

- How do dynamic properties change over trimmable region?
  - poles, zeros, right half plane zero-to-pole ratio
  - frequency response, control coupling

- What control design tradeoffs do we expect?
  - closed loop bandwidth vs. reference command magnitude
  - robustness with respect to uncertain flexible dynamics

- How do nonlinear issues impact control design tradeoffs?
Contributions of Work

Model Used: Bolender, Doman, Oppenheimer, et. al. (3 DOF + flexing) longitudinal model (2004-2008)

Publications
“Modeling & Control of Scramjet-Powered Hypersonic Vehicles: Challenges, Trends, & Tradeoffs,” Published and presented at AIAA GNC Conference and Exhibit, Honolulu, Hawaii, Aug. 18-21, 2008

“Constraint Enforcement for Scramjet-Powered Hypersonic Vehicles with Significant Aero-Elastic-Propulsion Interactions,” Submitted for publication to American Control Conference, St. Louis, Missouri, June 10-12, 2009

Trim (Static) Properties

• Trimmable Region: \( \sim \) Mach 5-12, 70-115 kft
  (subset of airbreathing corridor, Mach 5-16, 70-120 kft, \( \bar{q} \in [500, 2000] \) psf [Heiser and Pratt, 1993])

• Show importance of FER Margin

\[
FERM \overset{\text{def}}{=} \min(\text{Thermal Choking FER}, 1) - \text{TrimFER}
\]

and how it depends on Mach, altitude, flow turning angle (AOA+forebody deflection).

\( FERM_{TC} \) decreases with decreasing Mach, increasing altitude, increasing FTA (AOA+forebody deflection).

\( FERM_{unity} \) decreases with increasing Mach, increasing altitude (independent FTA).

Dynamic Properties

• Pitch-up instability due to forward cp (long forebody compression ramp) and rear shifted cg.

• Requires minimum bandwidth (BW) for stabilization
  – More unstable at lower altitudes and higher Machs
  – Instability (and poles) invariant along constant dynamic pressure profiles
Contributions of Work

Dynamic Properties

- Right half plane (non-minimum phase) zero associated with elevator-FPA map; vehicle initially loses altitude prior to climbing when elevator is deflected upwards.

- Limits maximum achievable (FPA tracking) BW
  - RHP zero decreases with increasing altitude and decreasing Mach (like RHP pole).
  - RHP zero monotonically (albeit slightly) along constant dynamic pressure profiles.

Control Design Tradeoffs (LQR)

- While state feedback can be used to eliminate minimum BW constraint at error, acceptable command following and disturbance attenuation requirements require a minimum BW (at error); also, still require minimum BW at controls.

- FPA BW limited by RHP zero (inverse response) effects and flexible dynamics
  - Elevator+FER allows for decrease in FPA settling time by 3% (5.15 sec to 5.0 sec).
  - Elevator+canard (no FER) allows for 23% decrease (5.15 sec to 3.97 sec)...but canard may burn off!

- FPA robustness with respect to uncertainty in flexibility
  - Elevator alone allows for 11.2% decrease in flexility (EI) before instability.
  - Elevator+FER allows for 17.1% decrease in flexibility (52% improvement).
  - Elevator+FER+canard allows for 19.5% decrease of flexibility.

Nonlinear Issues

- Methods Used: LQR, Generalized Predictive Control.

- FER Margin limits controller BW and/or reference command magnitudes (mainly velocity; FPA to much lesser extant).

- Elevator saturation can induce instability for large controller BW/reference FPA command magnitudes
  - Constraint enforcement methodologies needed to ensure stability and best possible tracking.
TRIMMABLE REGION AND STATIC TRIM PROPERTIES
Airbreathing corridor: $\bar{q} \in [500, 2000] \text{ psf}$ [Heiser and Pratt, 1993]

Trimmable region - subset of airbreathing corridor (approx Mach 5-12, 70-115 kft)

Structural Constraint: $\overline{\tau} = 2000 \frac{\text{lbs}}{\text{ft}}$ (not absolute!)

- Nominal flight condition: Mach 8, 85 kft, $\bar{q} = 2076 \text{ psf}$, (to facilitate comparison with prior research)

FER Constraints:
- FER = 1, (model does not capture thrust reduction for FER > 1)
- Thermal choking (combustor exit Mach = 1)
Trim Analysis

Both AOA and elevator deflection decreases monotonically with increasing Mach, and increases monotonically with increasing altitude.

Left endpoints: thermal choking.

Right endpoints:
- $\bar{q} = 2000 \text{ psf}$ for 70-104 kft
- FER = 1 for 104-115 kft

Figure 2: Trim AOA and Elevator Deflection: Level Flight, Unsteady-Viscous Flow, 2 Control Flexible Vehicle
Trim Analysis

Figure 3: Trim FER and Flexing Deflection Angles: Level Flight, Unsteady-Viscous Flow, 2 Control Flexible Vehicle

- FER increases monotonically with ↑Mach and ↑altitude.
- Fore/aft deflection angle is always negative/positive, and relatively constant.
DYNAMIC ANALYSIS: LINEAR
Dynamic Analysis

Figure 4: Right Half Plane Pole: Level Flight, 2 Control Flexible Vehicle

- RHP pole fairly constant along constant dynamic pressure profiles;
  - increases with increasing dynamic pressure (greater BW for stabilization)
- RHP pole increases linearly with increasing mach
- RHP pole decreases monotonically with increasing altitude
Dynamic Analysis

- RHP zero decreases with decreases dynamic pressure
- RHP zero increases linearly with increasing mach
- RHP zero decreases monotonically with increasing altitude

Figure 5: Right Half Plane Zero: Level Flight, 2 Control Flexible Vehicle
DYNAMIC ANALYSIS: FREQUENCY RESPONSE
Figure 6: Plant Bode Magnitude Response, Mach 8, 85 kft: Level Flight, 2 Control Flexible Vehicle
Figure 7: Plant Bode Phase Response, Mach 8, 85 kft: Level Flight, 2 Control Flexible Vehicle
DYNAMIC ANALYSIS: LQR SERVO METHODOLOGY


LQR Servo Methodology

\[
\dot{x}_p = A_p x_p + B_p u \quad y = C_p x_p
\]

- \( y = [v \gamma]^T \) is the output vector
- \( u = [FER \, \delta_c]^T \) is the control vector
- \( x_p = [y^T \, x_r^T]^T = [v \, \gamma \, \alpha \, q]^T \) is the plant state vector
- \( x_r = [\alpha \, q]^T = [0_{2 \times 2} \, I_{2 \times 2}] x_p = C_r x_p \) denotes the rest of the states in \( x_p \) (i.e. states in \( x_p \) excluding those in \( y \))

The sensitivities are defined as follows:

Sensitivity @ output (\( r \to e \)): \( S_o = [I + L_o]^{-1} \)

Comp. sensitivity @ output (\( r \to y \)): \( T_o = L_o [I + L_o]^{-1} \)

Open loop @ output (\( e \to y \)): \( L_o = PK \)

Input disturbance to output: \( S_o P = [I + L_o]^{-1} P \)

Sensitivity @ input (\( d_i \to u_p \)): \( S_i = [I + L_i]^{-1} \)

Comp. sensitivity @ input (\( d_i \to u \)): \( T_i = [I + L_i]^{-1} \)

Open loop @ input (\( u_p \to u \)): \( L_i = KP \)

Reference to control: \( KS_o = K [I + L_o]^{-1} \)
DYNAMIC ANALYSIS:
CLOSED LOOP SENSITIVITY STUDIES
(Using only $\delta_e$ on FPA)
Sensitivity Magnitude Response (Elevator Only)

Figure 9: LQR Closed Loop Sensitivity (Mach 8, 85 kft)

- Min BW @ controls $T_i, \omega_g = 6.28$ ($\sim 2$ times the unstable pole) to get $< 10$ dB peak in $S_o$
  - Attempts to decrease BW @ the input yields peaking in $S_o$ before $S_i$
- Min BW @ error $S_o \approx 0$ given large enough BW @ $T_i$
- Max BW @ error $S_o, \omega_g = 1.47 \ll$ RHP Zero $= 8.5$
  - Limited by the RHP Zero and low frequency flexible modes ($\sim 20 \frac{rad}{s}$)
  - $\omega_g$ limited by the simplicity of K, (PI like structure)
  - Adding FER as an input will allow for an increase in $\omega_g$ beyond 1.47 (not shown)
• Controls can grow unrealistically large before maximum BW issues are seen
• Minimum BW dictated by 10 dB response in $S_oP$ (input disturbance to plant output)
• Min BW @ controls $T_i$, $\omega_y = 6.28$ ($\sim$ 2 times the unstable pole) to get $< 10$ dB peak in $S_o$
  - Attempts to decrease BW @ the input yields peaking in $T_o$ before $T_i$
Figure 12: LQR Closed Loop Frequency Response, Open Loop (Mach 8, 85 kft)

- Min BW @ controls \( L_i, \omega_g = 5.98 \)
Figure 13: LQR Closed Loop Time Response, Flight Path Angle Command (Mach 8, 85 kft)

- Slowest BW design settles in 360 seconds (not shown)
- Fastest BW design begins to excite flexible modes as seen in the control response
- Fastest BW design settles in 2.15 seconds
DYNAMIC ANALYSIS:
CLOSED LOOP LQR
TWO INPUT, TWO OUTPUT (TITO)
Time Response (TITO System)

Figure 14: LQR Closed Loop Time Response, Velocity Command (Mach 8, 85 kft)

- Output and control response to velocity commands for the three designs (referred to as fast, nominal, slow)
- Control responses show equilibrium control + small signal control
- Thermal choking occurs at FER = 0.92 (for a turning angle equal to the trim turning angle)
- As the controller bandwidth increases, the transient values of the FER control increases
- Transient responses for the elevator are similar for all three designs
• Output and control response to flight path angle commands for the three designs
• For the slow and nominal designs, the elevator deflection transient increases while the FER transient remains small
• As the controller bandwidth is further increased, a noticeable jump in the FER transient is observed

Figure 15: LQR Closed Loop Time Response, Gamma Command (Mach 8, 85 kft)
Figure 16: LQR Frequency Response, Sensitivity at Error Signal (Mach 8, 85 kft)

- Sensitivity at the input and output
- The maximum sensitivity is located at 1 rad/s and has a value of 2.5 dB for fast design, and 0.5 dB for the slow design
• Complentary sensitivity at the input and output
• The maximum sensitivity at the input is located at 1 rad/s and has a value of 5.98 dB for all 3 designs.
Singular Value Response (TITO System)

Figure 18: LQR Frequency Response, Control Sensitivity and Input Disturbance to Output (Mach 8, 85 kft)

- Control sensitivity and input disturbance to output properties for the closed loop response
- Control sensitivity values increase with increasing controller bandwidth
- Input disturbance rejection properties improve as controller bandwidth is increased
NONLINEAR ISSUES: FER MARGIN
• Thermal Choking FER Margin

\[ FERM_{TC} = \text{Thermal Choking FER} - \text{Trim FER} \]

• Thermal Choking FER almost independent of altitude (not shown) for the above Mach ranges.

• Unity FER Margin

\[ FERM_{Unity} = 1 - \text{Trim FER} \]

• \( FERM_{TC} \) decreases with decreasing Mach, increasing flow turn angle, decreasing altitude

• \( FERM_{Unity} \) decreases with increasing mach & altitude

\[ \text{FER Margin} = \min(FERM_{TC}, FERM_{Unity}) \]

• \( \left( \frac{L}{D} \right)_{\text{max}} \) at Mach 6.6, 100 kft, but results in FER Margin = 0!!!
NONLINEAR SIMULATIONS:
GENERALIZED PREDICTIVE CONTROL
Figure 20: Nonlinear and Lin-Sat Responses to 3°, 6° FPA Commands - No Constraint Enforcement

- Nonlinear and lin-sat responses
- No constraint enforcement is included
- For the large FPA commands, the lin-sat responses go unstable while the nonlinear responses do not go unstable.
Nonlinear and lin-sat responses

Constraint enforcement included

Lin-sat response no longer unstable
Figure 22: Nonlinear and Lin-Sat Responses to 2000, 4000 ft/s Velocity Commands - With Constraint Enforcement

- Nonlinear and lin-sat responses
- Constraint enforcement included
- FER is observed to hit and stay at the rails - resulting in maximum acceleration.
Summary and Conclusion

**Trim (Static) Properties**
- Trimmable Region: ~Mach 5-12, 70-115 kft
- Show importance of FER Margin and how it depends on mach, altitude, flow turning angle (AOA+forebody deflection).
  \[ FERM_{TC} \] decreases with decreasing Mach, increasing altitude, increasing FTA (AOA+forebody deflection).
  \[ FERM_{unity} \] decreases with increasing Mach, increasing altitude (independent FTA).

**Dynamic Properties**
- More unstable at lower altitudes and higher Machs
- Instability (and poles) invariant along constant dynamic pressure profiles

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- While state feedback can be used to eliminate minimum BW constraint at error, acceptable command following and disturbance attenuation requirements require a minimum BW (at error); also, still require minimum BW at controls
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