Control-Oriented Model of a Hypersonic Vehicle (MASTRIM) -

Containing an Integrated, Advanced Propulsion Sub-Model (MASIV)

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Outline

A. Motivation

B. Results prior to last year

C. Results for last year

D. Next year’s plans
A. Motivation

Develop an improved “control-oriented” model by significantly modifying Doman-Bolender model

- hypersonic vehicle (MASTRIM) with integrated propulsion (MASIV)
- compute lift, drag, thrust, moments in 1 sec on PC using ROMs

- including realistic shock interactions in the inlet,
- combustor finite rate chemistry, 3-D mixing
- nozzle expansion waves to compute lower edge shear layer
- add operability limits: ram-scram, unstart, flame-out
B. Motivation

Ascent trajectory of MAX-1 trimmed vehicle
1. Optimization study - how to minimize fuel?
2. MDO study – optimize geometry (surrogate vs. collocation)
3. Delivered to MIT - linearized A, B matrices, poles and zeros

Operability Limits

4. When does ram-scram occur?
5. How much do forces jump at ram-scram? controllability?
6. When does unstart occur?
7. Can a “better” trajectory avoid unstart?

Generic hypersonic vehicle geometry (GHV, HiFIRE6)
8. Add 3-D shock interactions to inlet (3-D Riemann problem)
9. Add ethylene fuel “lookup tables”
Motivation

A Reduced Order Model (ROM) is required

Suppose vehicle ascends along a constant dynamic pressure path

We ask: when does ram-scram transition occur?

To generate this plot: lift, drag, thrust, moments were computed 1500 times = (guess 15 AoA’s to trim) X 5 (q values) X 20 altitude values / curve
Motivation

ROM is best when thousands of force computations are needed

- when optimizing the trajectory
- when generating operating maps
- for geometry optimization (MDO)

ROM provides understanding of Operability Limits

- Unstart Margin - understand what factors help or hurt
- Ram-scram transition - estimate large jump in forces
- Engine Flameout - need finite rate chemistry

ROM is useful for a “first look” at the design space

- First identify a small number of problem cases
- Understand what the problem is
- Run high fidelity CFD just for those cases
Motivation: Operability Limits – when does **unstart** occur?

\[
\text{Unstart Margin} \quad = \quad \frac{L_1}{L_2}
\]

- \(L_1\) = distance between leading edge of shock train and entrance to isolator
- \(L_2\) = total length of isolator

1. First must properly compute the thermally-choked (ram) case
2. Then MASIV predicts isolator back pressure \(p_{\text{back}}\)
3. Length of shock train then computed from experimental relation

\[
\frac{L_2 - L_1}{H} = \text{function} \left( \frac{p_{\text{back}}}{p_{\text{inlet}}} \right)
\]
MASIV tells us one way to avoid unstart!

For a short isolator, MASTRIM shows that as you accelerate too fast (2 m/s²) → you unstart before you reach ram-scram!

Unstart Margin

Flight Mach Number

MASIV predicts the proper acceleration path = lower ER path

→ reduce acceleration to 1 m/s² for the predicted time period
Motivation: Operability Limits = Unstart, Flameout, Ram-Scram Issues
B. Results Prior to Last Year

1. **MASTRIM** - Developed a 6-DOF Flight Dynamics Model of a Hypersonic Vehicle - based on Doman-Bolender trim code

2. Completed Propulsion/Vehicle integration
   
a. **SAMURI** - reduced order inlet & nozzle code
      added realistic inlet losses from multiple shock/expansion interactions. rapidly computes lower edge of exhaust plume
   
b. **MASIV** - reduced order code for combustor
      method: lookup tables from high fidelity 3-D combustion, 3-D mixing added: finite-rate chemistry of hydrogen and ethylene fuel, gas dissociation losses

3. **Operability Limits - began methodology**
   - ram-scram transition, engine unstart, flame out at low pressure
B. Prior to last year (con’t)

4. Published three examples:
   a) Level Flight       Generic X-43, Mach 8
   b) Ascent             Operating maps ($\delta_{CE}$, $\alpha$, ER) vs. ($M_\infty$, h)
   c) Turn               Poles, zeros, time to double amplitude

5. Disseminated the MASTRIM code
   Delivered MASTRIM to AFRL
   Demos to AFRL Air Vehicles and Propulsion
     Boeing (Bowcutt) Huntington Beach March 11
     NASA AMES (Soloway)
     Ohio State
   Demos at MIT and NASA Glenn are planned
     Michael Smart UQ @ HyTASP Conference

6. Validation tests vs. high-fidelity 3-D CFD & some experiments (6-10%)
   reduced run time to ~ 1 sec
Developed a 6-DOF Flight Dynamics Model

MASTRIM control parameters:

1. $\delta_{CE}$ elevon combined deflection angle
2. $\delta_{ER}$ equivalence ratio change
3. $\Delta x_c$ cowl lateral translation distance
4. $\Delta y_c$ cowl transverse translation distance
5. $\Delta \theta_c$ cowl flap angle
6. $\varepsilon_{FUEL}$ fraction of fuel injected at location 2

for a turning trajectory:
7. $\delta_{DE}$ elevon differential deflection angle
8. $\delta_{CR}$ rudder combined deflection angle
9. $\delta_{DR}$ rudder differential deflection angle

Trims the vehicle
Computes poles, zeros, time to double amplitude
Prior to Last Year – SAMURI inlet ROM

Track discrete waves, no CFD grid used

Shocks: exact 2-D oblique shock relations with real gas properties
Expansions: discretize continuous fan into 2-4 waves

Wave interactions: exact Riemann jump conditions
Boundary layers: displace wall by displacement thickness

\[ M_\infty = 10, \quad \alpha = 0, \quad q = 2040 \text{ lbf/ft}^2 \]

inlet losses: \[ \text{PRF} = \text{(stagnation) pressure recovery factor} \approx 60\% \]
inlet compression ratio: \[ p_2/p_\infty = 40 \]

Dalle, J. of Propul. & Power, 2010
Prior to last year: for nozzle, SAMURI predicts lower edge

Riemann solver - interaction of many expansion waves

engine flow

Plume lower edge

Dalle, sub. to J. of Propul. & Power, 2011
Pre-computed lookup tables of finite-rate chemistry of jet-in-cross flow mixing

15 species, 22 reactions ethylene or hydrogen fuel

Fuel can be added anywhere

Area is variable

Wall friction, heat transfer

Real gas properties

Torrez, J. of Propul. & Power, 2011
Prior to last year – flight dynamics of climbing flight

acceleration from Mach 7 to Mach 11, constant q & mass flow air
trajectory minimizes total fuel consumption

stable – to – unstable transition at Mach 9.5 due to increased $\alpha$
 Publications, Awards

Sean Torrez won AIAA Airbreathing Propulsion Graduate Student Award at San Diego AIAA JPC

Prior to last year = one journal paper, 12 AIAA conference papers


Last year = 4 journal papers, 5 AIAA conference papers

   “Ram-Scram Transition...on Ascent Trajectory”, to be submitted, 2012.

“Design of ...Flowpaths ...”, AIAA 2011-2380
“Turn Performance of a ....Hypersonic Vehicle”, AIAA 2011-6300
“Hypersonic Vehicle Flight Dynamics... ”, AIAA 2010-7930
C. Last Year - Results

Ascent trajectory of MAX-1 trimmed vehicle
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C. Last Year: Ascent trajectory – optimization - minimize fuel

surrogate method: \( q = \text{constant} \)
compute operating maps of:
\((\text{ER}, \dot{m}_f, \alpha, \delta_{CE}, \ldots) = \text{fcn} \ (M, \dot{V})\)

minimum fuel trajectory:
\( q = 1 \text{ atm.} \)
acceleration varies as:

\[
\begin{align*}
\text{Acceleration, } \dot{V} [\text{m/s}^2] & \quad \text{Mach number, } M \\
0 & \quad 7 \quad 8 \quad 9 \quad 10 \quad 11 \quad 12 \quad 13 \\
0 & \quad 1 \quad 2 \quad 3 \quad 4
\end{align*}
\]

24 km 32 km Altitude

\[
\begin{align*}
\text{Altitude} & \quad 24 \text{ km} \quad 32 \text{ km} \\
\dot{V} & \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10 \quad 11 \quad 12 \quad 13
\end{align*}
\]

Dalle, Torrez, Driscoll, Bolender, Bowcutt, sub. to JSR
Minimize fuel along a constant $q = 1$ atm. path

Study #1: vary
location of fuel injection,
angle of wall divergence
location of wall divergence

Torrez, Dalle, Driscoll, AIAA 2011-5757

<table>
<thead>
<tr>
<th>Variable</th>
<th>baseline value</th>
<th>1 var. optimized</th>
<th>2 var. optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{inj}$</td>
<td>0.166 m</td>
<td>0.036 m</td>
<td>0.058 m</td>
</tr>
<tr>
<td>$\alpha_{div}$</td>
<td>3.99°</td>
<td>3.99°</td>
<td>3.04°</td>
</tr>
<tr>
<td>$x_{div}$</td>
<td>0.831 m</td>
<td>0.831 m</td>
<td>0.831 m</td>
</tr>
<tr>
<td>$\Delta m_{fuel}$</td>
<td>1299 kg</td>
<td>1252 kg</td>
<td>1242 kg</td>
</tr>
<tr>
<td>% improvement</td>
<td>0</td>
<td>3.5</td>
<td>4.4</td>
</tr>
</tbody>
</table>
Last Year: MDO study - optimize geometry

Study #2:
Displace cowl vertically ($\Delta y$) – change compression ratio
Displace cowl horizontally ($\Delta x$) – change spillage, mass flow
Rotate cowl lip ($\Delta \theta$) – shift shock interaction locations

What geometry provides best compression? Lowest fuel required?
Result for optimization study: optimize flowpath


Varied:
\[ \delta x_{\text{cowl}} \quad M_{\infty} \]
\[ \delta y_{\text{cowl}} \quad \alpha \]
\[ \delta \Theta_{\text{flap}} \]

Maximized:
Inlet recovery factor \( \left( p_{02}/p_{01} \right) \)


Varied: fuel injector location
Maximized: thrust

Thrust (normalized)

\[ p_3 \text{ in } 10^5 \text{ Pa} \]
Last year: Operability Limits: added ram-scram transition

Where is the thermal choking location?
How to solve ODEs near the singular point?

\[
\frac{1}{M^2} \frac{dM^2}{dx} = \frac{F(M)}{1 - M^2} \frac{1}{A} \frac{dA}{dx} + \frac{G(M)}{1 - M^2} \frac{1}{T_0} \frac{dT_0}{dx}
\]

L’Hospital’s Rule:
choking is where:
\[
\frac{1}{A} \frac{dA}{dx} = \frac{1 + \gamma}{2} \frac{1}{T_0} \frac{dT_0}{dx}
\]

area change (given)  \( \sim \) heat added by combustion

Torrez, S., AIAA 2011-2380
Last Year: Operability Limits – when does Ram-Scram occur?

If you require larger acceleration – you need larger ER

- stay thermally choked longer
- so: larger Flight Mach Number at ram-scram transition
Last Year: Derivatives of performance curves are discontinuous

- at ram-scram, affecting controllability
Last Year – how large are the sudden jumps in forces at ram-scram?

A challenge to the control system

Before ram-scram

Wall pressure (atm)

After ram-scram

Inlet shocks jump during ram-scram

Wall pressure jumps down during ram-scram
Last Year: Operability Limits – when does \textit{unstart} occur?

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Last year: added the flame-out limit

Our finite-rate chemistry goes “out” if:

- combustor gas pressure or temperature is too low
- combustor gas velocity is too large (scalar dissipation rate)
- inlet provides insufficient compression ratio
- lookup tables: chemical reaction rate = function (dissipation rate)
D. Next Year

1. Add Generic Hypersonic Vehicle:

2. Add 3-D inlet: 3-D Riemann wave interactions, inward-turning add Tyler’s AFRL Vehicle Model Generator

3. Ethylene fuel: run GHV on ethylene fuel, speed up code

4. Uncertainty: apply uncertainty analysis to compute data needed by Anu’s adaptive control model

5. Integration of Cesnik’s aero thermo elastic model with: MASTRIM – trim code, external forces MASIV – propulsion code
D. Next Year (continued)

6. Interaction: with Anu Annaswamy’s Active-Adaptive Control Laboratory at MIT to couple MASTRIM to her adaptive control model

7. Optimization of more of the control variables (cowl displacement, elevon size, fuel type)

8. Operability limits - flame out limits

9. Validation: determine uncertainty of our unstart, ram-scram predictions

10. MDO: optimize inlet panels, elevon size, combustor length for GHV
Next Year - Provide Uncertainty - to MIT for adaptive control


\[
\dot{x} = A\ x + B \ \Lambda \ (R_s (u) + d)
\]

\[\Lambda = \text{effect of thrust uncertainties on the B matrix}\]
\[R_s = \text{rectangular saturation function } = u_i \ (\text{if } u_i < u_{\text{max}})\]
\[d = \text{disturbance term}\]
\[u = \text{control input} \quad \delta_{\text{thrust}}, \delta_{\text{elevon}}\]
Next Year: 3-D Inlet - wave interactions for GHV

“Compound Compressible Flow” and “Streamline Tracing”

Discrete stream tubes;
Shapiro influence coefficients;
Enforce cons. mass, mom, energy
+ surface tracing of 3-D shocks

“Compound Compressible Flow for Hypersonic Inlets”, Mark Lewis, AIAA 2009-7304
“…Hypersonic Inlet Rectangular to Elliptical…”, M. Smart, C. Trexler, JPP 20 2004
Integration with Cesnik’s aero thermo elasticity model

- Begin with X-43-like MAX-1 vehicle

- Revisit Doman-Bolender problem – effect of longitudinal bending on inlet shocks, spillage, loss of thrust

- Add more complex geometry and thermo elasticity model

- Add multiple shock interactions that were omitted in Doman-Bolender

- Consider intense heat transfer where bow shock reflects from engine cowl
Next year: compute controllability

*At ram-scram limit: thermal choking b.c. suddenly disappears,
Sudden change in wall pressures, forces, moments
Derivatives of thrust performance curves are discontinuous

Metric: Time-to-double amplitude, which varies along trajectory
Flight Dynamics of a High Speed Turn Trajectory

Increasing the Mach number shortens the period of each mode

<table>
<thead>
<tr>
<th>Pole</th>
<th>Time to Double</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.24</td>
<td>0.31</td>
</tr>
<tr>
<td>1.84</td>
<td>0.38</td>
</tr>
<tr>
<td>-0.0058</td>
<td>120.0</td>
</tr>
</tbody>
</table>
Long term impact

MASTRIM is a validated flight dynamics platform upon which to build an adaptive control law

Anu Annaswamy (MIT): adaptive control methods to avoid unstart, flame out, and issues during ram-scram transition

- needs a validated flight dynamics model
- needs uncertainty analysis
- flight dynamics model must be sufficiently fast, robust, and have sufficient control variables
- “fundamental” aspect of our model is important – we can explain why the control system adapts in a certain way
Payoffs to the Air Force

• Research addresses important component of control design and analysis development

• Novel modeling approaches to support G&C design and analysis beginning in the vehicle conceptual design phase

• State-of-the art techniques in reduced-order and first-principles modeling

• Codes have been transitioned to NASA AMES, AFRL, Boeing, and Raytheon