Control-Oriented Model of the Propulsion System

J. F. Driscoll

University of Michigan

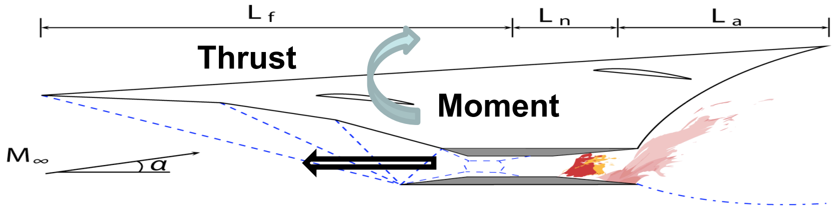
Sean Torrez, Derek Dalle, Matt Fotia (NASA)

AFRL collaborators: Mike Bolender, David Doman,
Mike Oppenheimer

Control of flight dynamics

Pitching moment ($\boldsymbol{M}$) in vehicle equations
requires improved prediction of thrust ($\mathcal{T}$)

100 ft long
X-43 geometry
Doman, AFRL



Moment:
$$\mathrm{M} = \mathrm{M}_{\mathrm{aero}} + \mathcal{T} \cdot \mathrm{z}_{\mathrm{T}}$$

$$\begin{bmatrix}\Delta\dot{\alpha}\\ \Delta\dot{q}\end{bmatrix} = \begin{bmatrix} Z_\alpha/U & 1\\ M_\alpha & M_q\end{bmatrix}\begin{bmatrix}\Delta\alpha\\ \Delta q\end{bmatrix} + \begin{bmatrix} Z_{\delta_e}/U & Z_{\delta_T}/U \\ M_{\delta_e} & M_{\delta_T}\end{bmatrix}\begin{bmatrix}\Delta\delta_e\\ \Delta\delta_T\end{bmatrix}$$

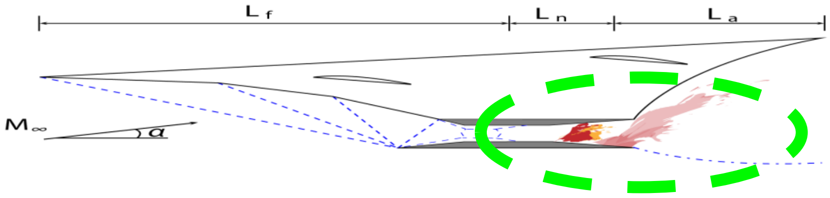
Elevator deflection
Throttle setting

Previous models: not control-oriented, too slow, too many variables,
did not include control parameters,
ignored inlet shock interactions, real gas dissociation & chemistry

MASIV: “Michigan-AFRL Scramjet-in-Vehicle” model:
control-oriented (fast, reduced order, min # of variables)
includes inlet shock interactions, real gas, finite rate chemistry
specifically identifies control variables

TASKS - Sean Torrez

Control-oriented model of combustor / nozzle



✓ 1. replace original AFRL propulsion model with first order ODEs of wall heat transfer, variable area: for SCRAM mode

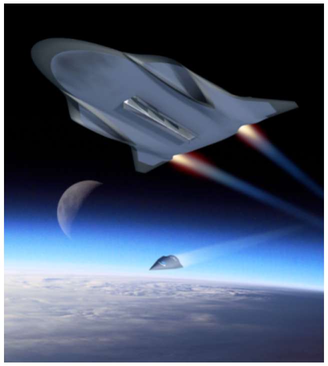
✓ 2. add ROM: reduced-order model of 3-D mixing, finite rate reaction, dissociation, : 1-D scaling laws derived from 3-D data

✓ 3. assess accuracy of MASIV – compare to CFD, experiments

✓ 4. changes to flight dynamics: poles, zeros, sensitivity coefficients

✓ 5. “drop in” MASIV into existing AFRL HSV code by Nov 30, 2009

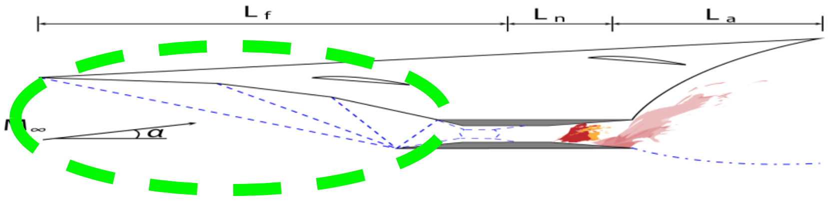
TASKS - Sean Torrez (continued)



6. minimize run time by optimizing ROM
7. vary combustor control variables: two fuel locations, ER
8. add RAM mode, add isolator shocks, ram-scram transition
9. flight dynamics (AFRL HSV code) during ram-scram transition
10. optimization study of engine design

TASKS - Derek Dalle

Control-oriented model of inlet and plume



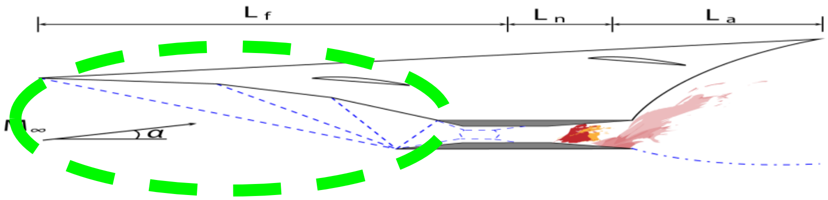
✓ 1. replace original AFRL inlet model with Riemann wave interaction solver
  - ROM = many shock- expansion interaction, for real gas
  - compute Pressure Recovery Factor (PRF) & spillage - vary M_∞, α
  - run time of a few seconds
  - include boundary layer displacement, rounded leading edges

✓ 2. determine optimum inlet geometry that is not too sensitive to off-design M_∞, α

✓ 3. assess validity of reduced order model: by comparison to CFD

✓ 4. “drop in” MASIV inlet code into existing AFRL HSV by Nov 30, 2009

TASKS - Derek Dalle (continued)



5. vary control variables: contraction ratio (CR),
   cowl flap deflection,
   boundary layer bleed

6. optimization study of inlet

TASKS Matt Fotia (NASA funded)

Assist Sean and Derek by providing CFD "truth" models

of combustor and inlet to assess their ROMs

- Inlet truth model: CFD++ for Mach 8, with wall boundary layers
- Combustor truth model: FLUENT with turbulent combustion flamelet chemistry

Publications to date:

1. "Shift of the Poles and Zeros of a Hypersonic Vehicle Due to Variations in the Scramjet Engine Model", SM Torrez, JF Driscoll, MA Bolender, DB Doman, M Oppenheimer, AIAA Paper 2008-4619
2. "A Scramjet Engine Model Including Effects of Precombustion Shocks & Dissociation", SM Torrez, D. Micka, J. F. Driscoll, MA Bolender, DB Doman, M Oppenheimer, AIAA Paper 2008-4619
3. "Flight Dynamics of Hypersonic Vehicles: Effects of Improved Propulsion Modeling", SM Torrez, JF Driscoll, MA Bolender, DB Doman, AIAA Paper 2009-6152
4. "Scramjet Engine Model MASIV: Role of Finite-Rate Chemistry and Combustor-Isolator Interactions", SM Torrez, JF Driscoll, D Dalle, DJ Micka, M Fotia, AIAA Paper 2009-4939
5. "Reduced-Order Modeling of Two-Dimensional Supersonic Flows with Applications to Scramjet Inlets", Derek J. Dalle, Matt L. Fotia, James F. Driscoll, submitted to J. of Propulsion & Power, 2009.

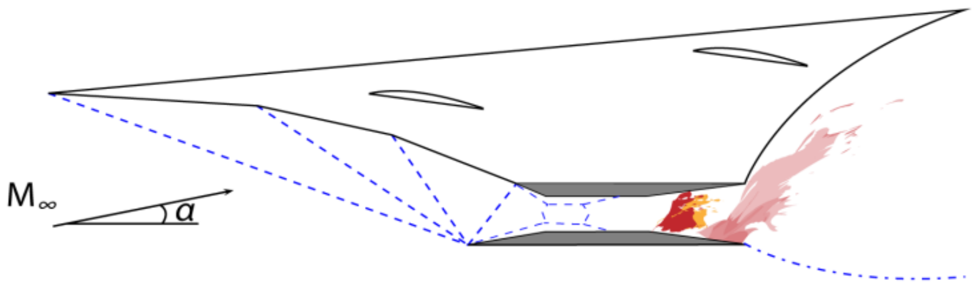
Publication in preparation:

"A Scramjet Model (MASIV) for Control-Oriented Applications", Torrez, Driscoll, Dalle, Fotia, present at AIAA Spaceplanes Meeting Bremen, submit to JPP

"Flight Dynamics of a Hypersonic Vehicle: Effect of Improved Propulsion Modeling", Torrez, Driscoll, Dalle, Fotia, Bolender, Doman, Journal TBD

MASIV Contains the Following Control Variables

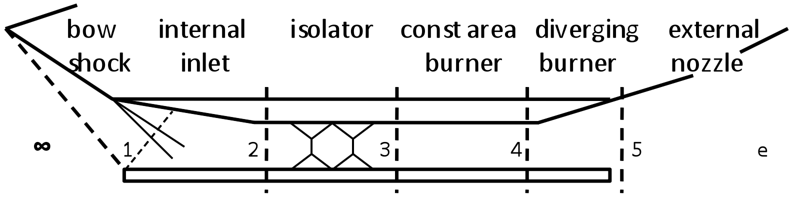
Engine
control
variables



1. cowl flap angle
2. inlet contraction ratio
3. fuel added station #1
4. fuel added station #2
5. plasma control of flame location
6. boundary layer bleed (to be added)

Previous models are not adequate: SRGULL, RJPA codes do not include:
- chemical kinetics, modern mixing data
- isolator boundary conditions, not control-oriented

MASIV: a Control – Oriented Propulsion Model



6 + N equations

6+ N unknowns:

$$\frac{1}{\rho}\frac{d\rho}{dx} = \frac{1}{\dot{m}}\frac{d\dot{m}}{dx} - \frac{1}{U}\frac{dU}{dx} - \frac{1}{A}\frac{dA}{dx} \qquad (1)$$

$$\frac{1}{U}\frac{dU}{dx} = \frac{-1}{\gamma\ M^2}\left(\frac{1}{p}\frac{dp}{dx} + \frac{2\gamma M^2 C_f}{D} + \frac{\gamma M^2(1-\varepsilon)}{\dot{m}}\frac{d\dot{m}}{dx}\right) \qquad (2)$$

$$\frac{1}{p}\frac{dp}{dx} = \frac{1}{\rho}\frac{d\rho}{dx} + \frac{1}{T}\frac{dT}{dx} - \frac{1}{\overline{MW}}\frac{d\overline{MW}}{dx} \qquad (3)$$

$$\frac{d\,\overline{MW}}{dx} = -\overline{\mathrm{MW}}^2 \sum_i\left(\frac{1}{MW_i}\frac{dY_i}{dx}\right) \qquad (4)$$

$$\frac{d\dot{m}}{dx} = \sum_i \frac{d\dot{m}_{i,added}}{dx} \qquad (5)$$

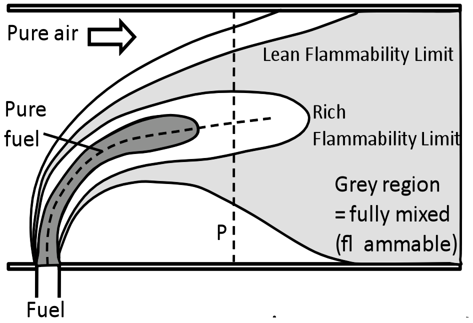
$$\frac{dT}{dx} = \frac{1}{c_p}\left\{\frac{dh_{RP}}{dx} + \left[h_{0,s,added} - h_{0,s}\right]\left[\frac{1}{\dot{m}}\frac{d\dot{m}}{dx}\right] - \frac{2C_f\, c_p\,(T_{aw} - T_w)}{\mathrm{Pr}^{2/3}\ A} - \mathrm{U}\,\frac{dU}{dx}\right\} \qquad (6)$$

$$\frac{dY_i}{dx} = \frac{\omega_i\, MW_i\, A}{\dot{m}} + \frac{1}{\dot{m}}\frac{d\dot{m}_{i,added}}{dx} - \frac{Y_i}{\dot{m}}\frac{d\dot{m}}{dx} \qquad (7)$$

Our ROM for Mixing / Combustion in MASIV

1. Add 3-D mixing, modern Turbulent Flamelet Combustion theory to the 1-D equations

2. First: rapidly compute 3-D fields for fuel, turbulence levels using measured scaling relations for jet in crossflow:



ρ_F = fuel gas density
U_A = air velocity

Fuel concentration along jet centerline

$$C_c = 0.9 \left(\frac{\rho_F}{\rho_A}\right)^{1/3} \left(\frac{U_F}{U_A}\right)^{-1/3} \left(\frac{x_c}{d_F}\right)^{-2/3}$$

Mixture fraction in radial direction

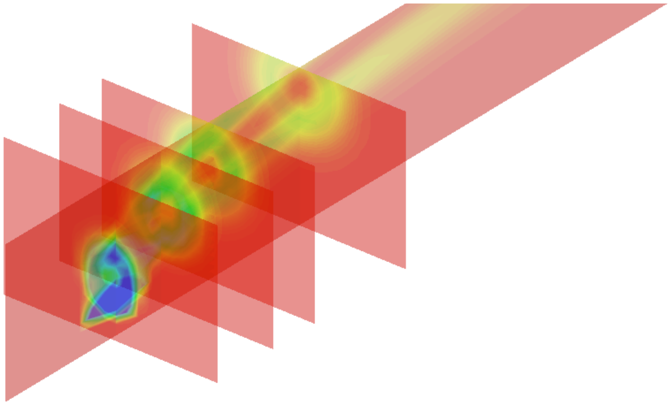
$$\bar{f}(s,r) = \bar{f}_c(s)\ exp\left(\frac{-r^2}{2b^2}\right)$$

Mixture fraction fluctuations

$$f' = 0.14 \left(\frac{r}{b}\right) \bar{f}_c\ exp\left(\frac{-r^2}{2b^2}\right)$$

3. Next: Compute “complex chemistry flamelet lookup tables”
   - solve 20+ chemical reactions with dissociation
   - apply modern PDF theory of flamelet statistics

4. Then use lookup tables to assign proper chemical reaction rates to each (x,y,z) location, to obtain 3-D reaction rates:



5. Integrate 3-D reaction rate field for each species over each (y,z) plane perpendicular to flow → to get 1-D reaction rate for each species

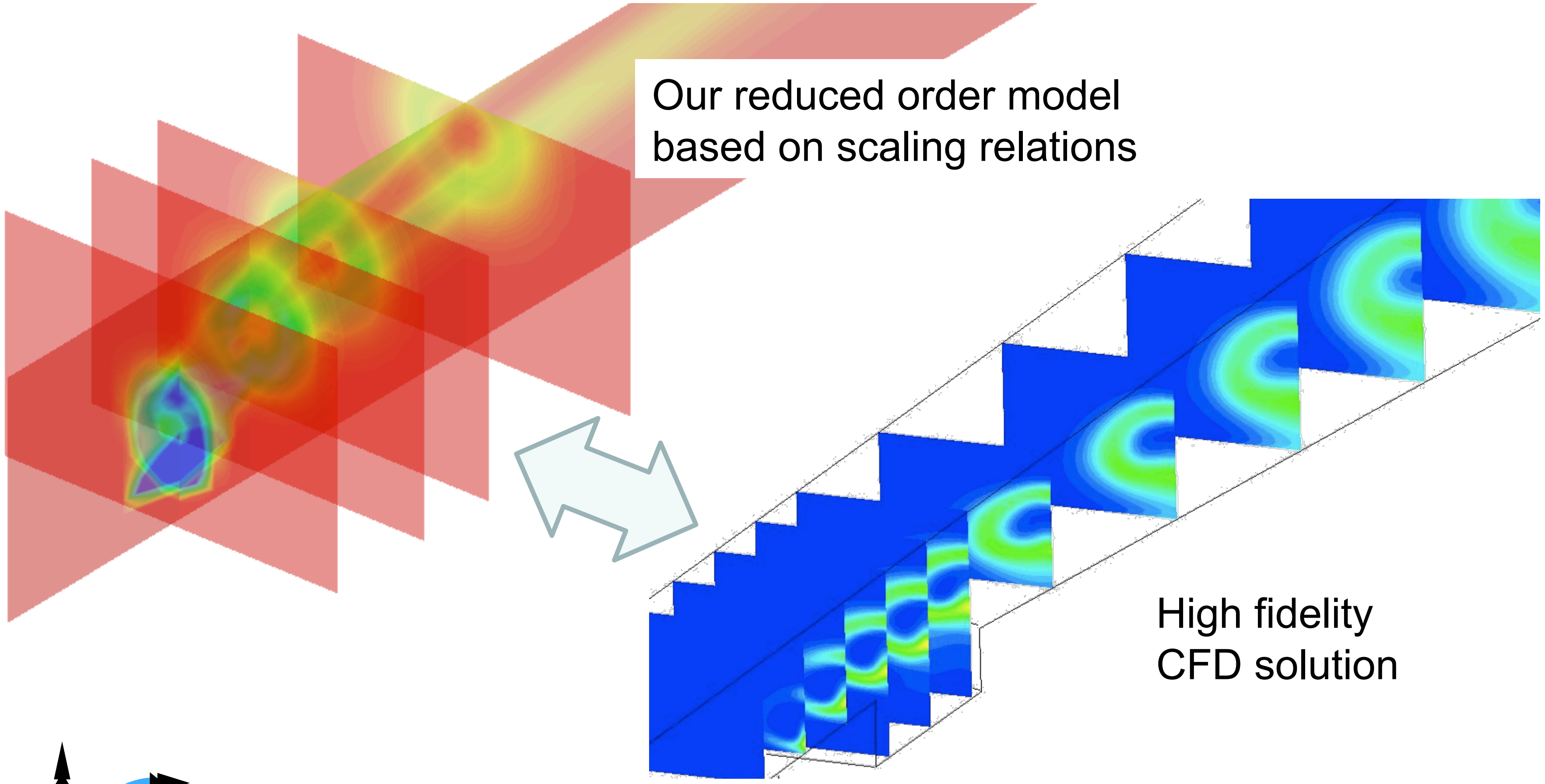
6. Add this 1-D reaction rate to the 1-D ODE’s in MASIV

Advantages of our ROM for mixing, combustion

1. Very fast
2. Accurate – validated by CFD and experimental data
   - providing that we always have fuel jet injected from wall
3. Contains modern Turbulent Combustion Theory
   – correctly simulates turbulence statistics with Beta function PDF,
   - correctly simulates combustion with modern flamelet lookup table
   - correctly simulates flameout due to high strain rate (scalar dissipation)
4. Contains full chemistry – correctly predicts flameout if pressure too low

Assess accuracy of our ROM

by comparison to CFD simulations

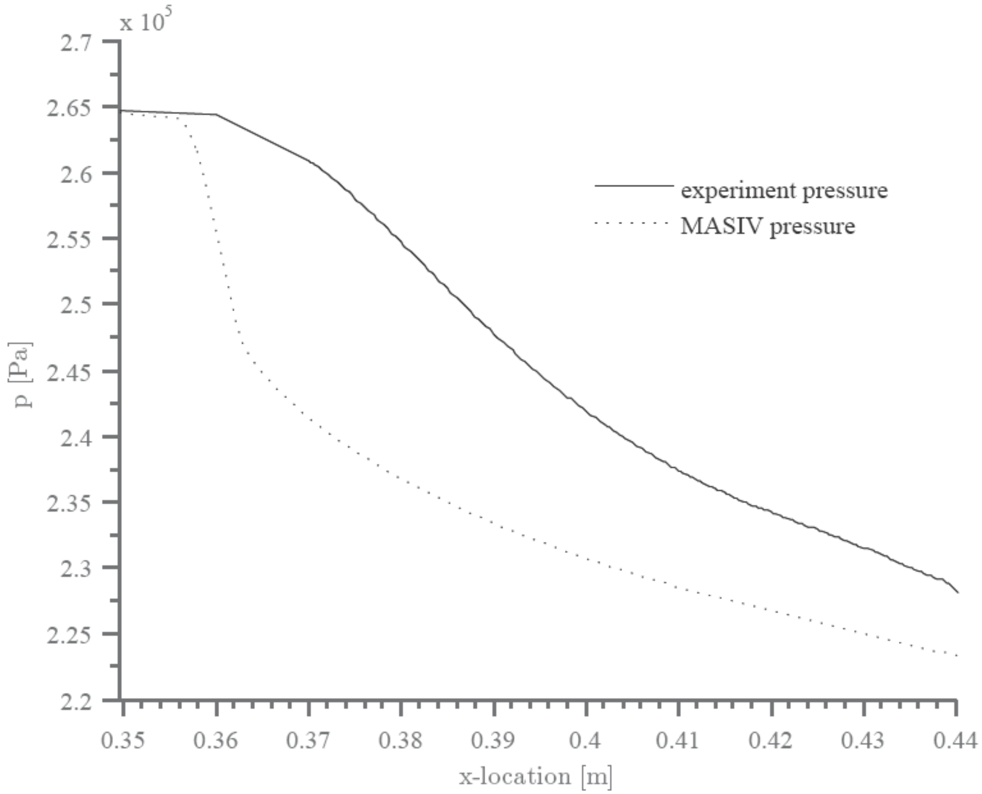


Our reduced order model based on scaling relations

High fidelity CFD solution

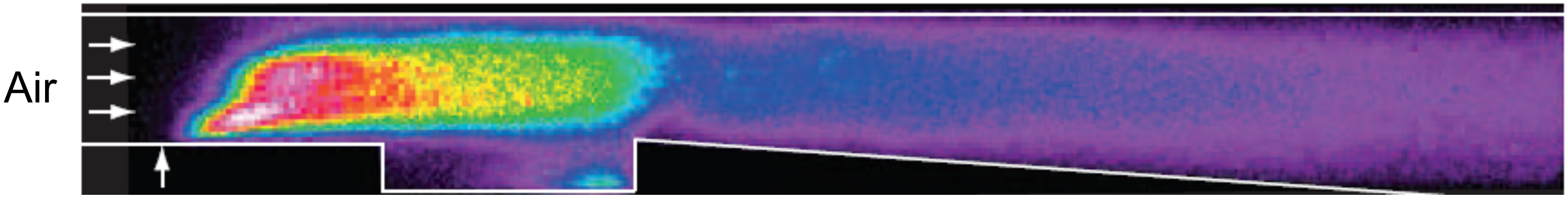
Assessment of our ROM of Mixing – Combustion

Wall pressures within 8% of experiment



Validate ROM of Mixing – Combustion using experimental data

- Insure that our ROM computes flame length, wall pressure distribution that are consistent with our own experimental data
  (leveraged funding from other sources)

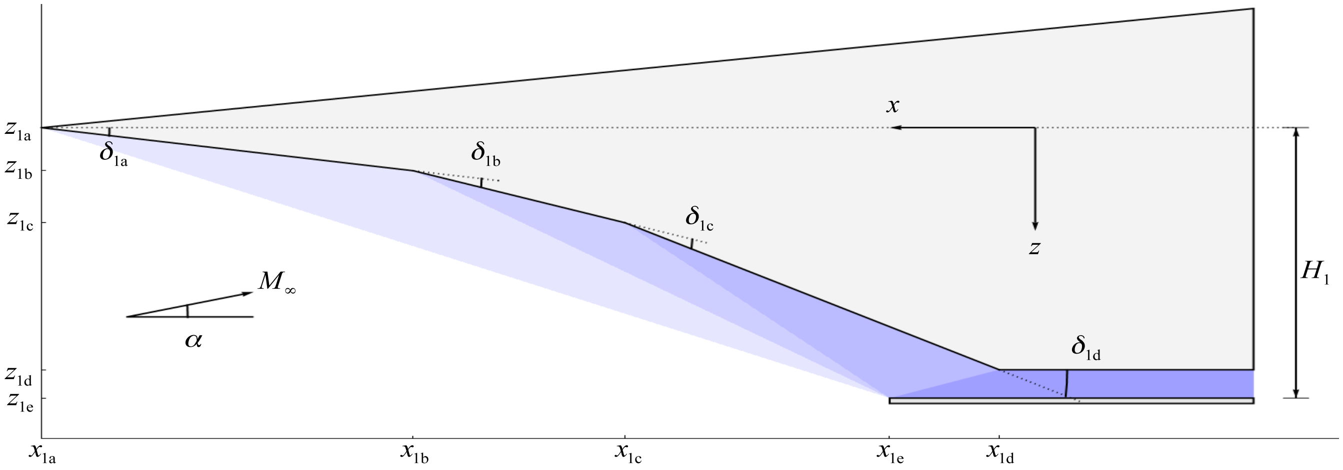


H2 – Air, $T_{o,i}$ = 1500 K, ϕ = 0.36

50% H2 / 50% C_2H_4 – Air, $T_{o,i}$ = 1470 K, ϕ = 0.42

Inlet Design

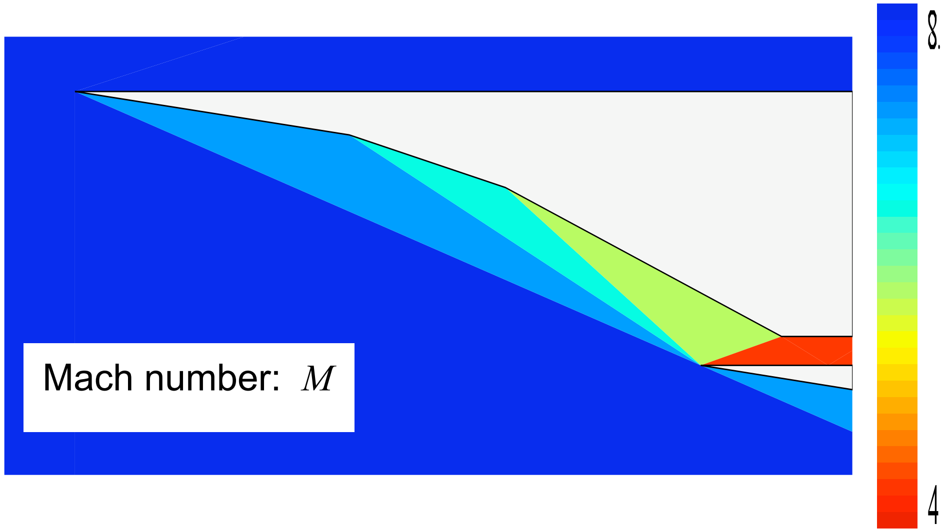
- Maximize pressure recovery factor (PRF) at one condition.
  - Zero spillage, single shock turns flow
  - Equal normal Mach numbers
  - Geometry depends on angle of attack
- Constraint on pressure at end of inlet: $p_2 \geq 0.5$ atm.
- Optimize to not have large losses for off-design

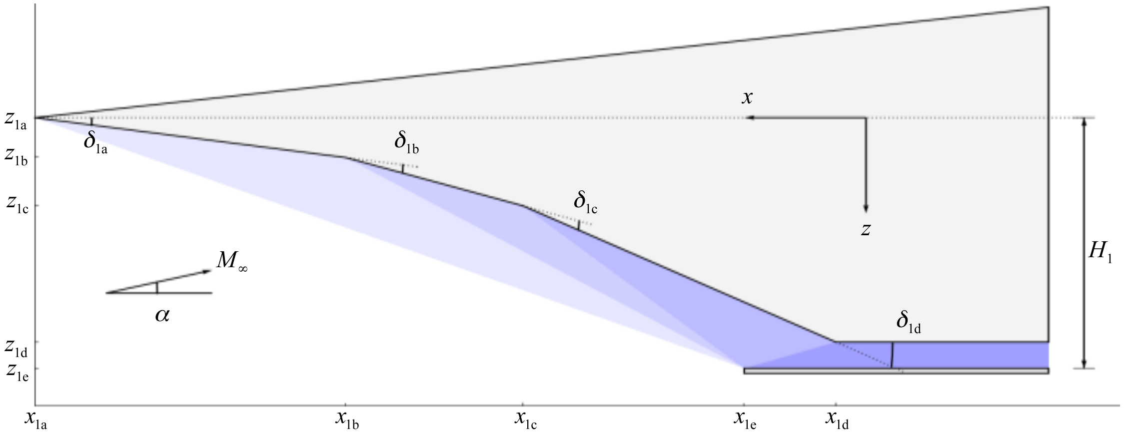


On-design Conditions: $M_\infty = 8, \alpha = 0$

- Freestream conditions:
  - $M_\infty = 8.0$
  - $p_\infty = 2.18$ kPa
  - $T_\infty = 223$ K

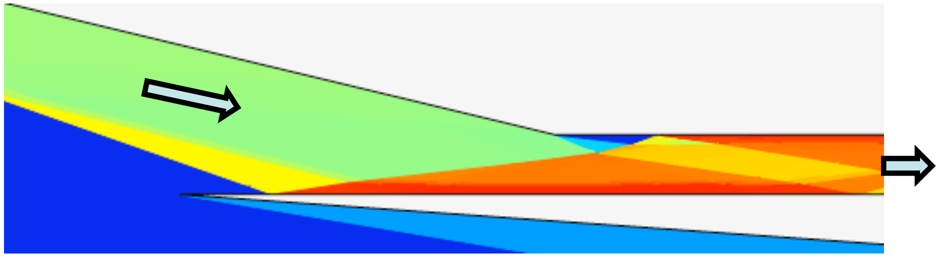
- Compression results:
  - $M_2 = 4.28$
  - $p_2 = 66.8$ kPa
  - $T_2 = 659$ K
  - prf = 0.682





Design optimum inlet for
one design condition
M_{oo} = 8, α = 0, q = 2040 lbf/ft^2

For off design condition: M_{oo} = 10, α = 0
model complex shock-expansion interactions, spillage



Compute inlet losses: PRF= stagnation pressure recovery factor ~ 60%

How to do it rapidly without CFD, yet maintain accuracy of within 10% ?

Validate by comparison to CFD++

Our ROM of the Inlet

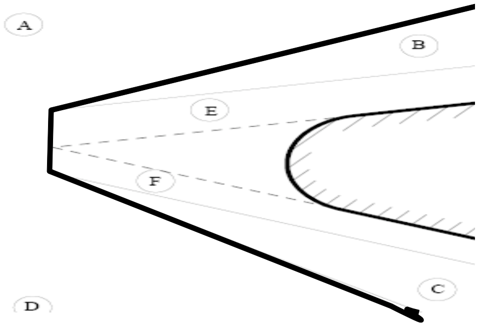
Shocks: assume 2-D, exact oblique shock relations with real gas properties
(c_p, γ not constant)

Expansions: discretize continuous fan into 2-4 waves

Use exact Riemann equations for each wave interaction (10 to 100 in each inlet)

Boundary layers: displace wall by displacement thickness computed by
standard supersonic formula

Rounded leading edges: replace curved shock with three straight shocks,
at locations given by Billig's empirical formula:



Weakest interactions identified and neglected

Validate using CFD++ truth solution

<u>Items not modeled:</u>
Mixing layer from wave interactions = small effect
Unsteady and 3-D effects

Consistent, accurate method to discretize the expansion

- First solve for the conditions after the expansion.

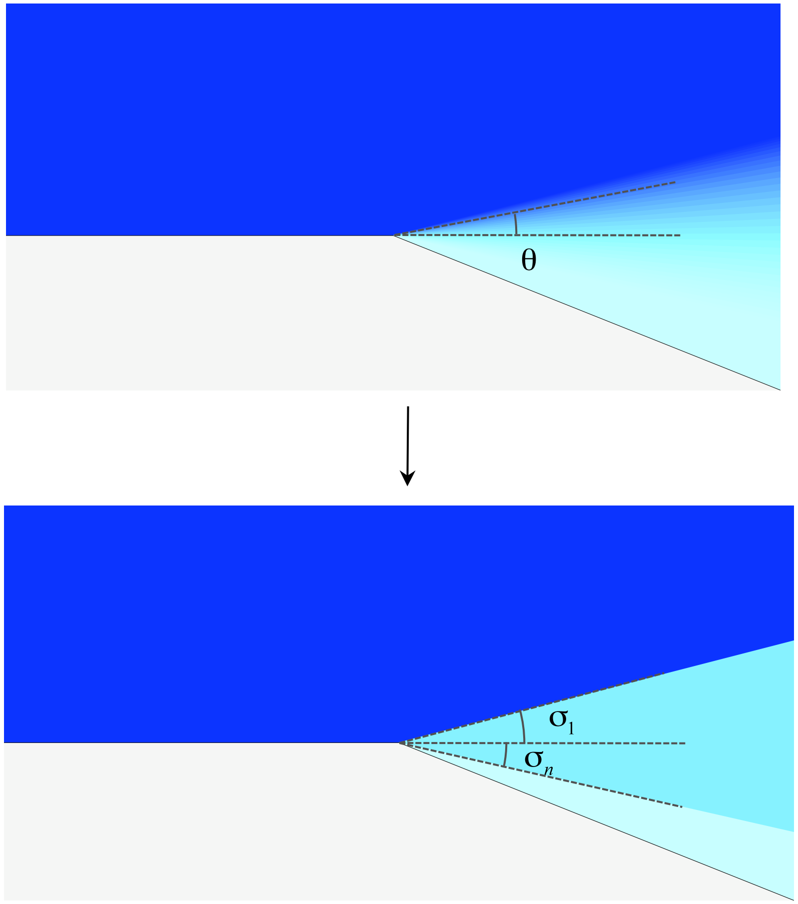
- Then solve for the Mach number as a function of θ.
  - $M(\theta) = \sqrt{1 + \frac{\gamma + 1}{\gamma - 1} \tan^2 \left(\sqrt{\frac{\gamma - 1}{\gamma + 1}} \left(\sigma_1 - \mu_1 + \frac{\pi}{2} - \theta \right) \right)}$
  -

- Form an approximate function $\tilde{M}(\theta)$ that is piecewise constant.
  - Pick several angles $\theta_1, \theta_2, \ldots, \theta_n$.
  - Find corresponding Mach numbers.
  - Use $\nu_1 + \varphi_1 = \nu_i + \varphi_i$ to find flowpath angles.
  - Isentropic relations give other parameters.

- Use Gaussian quadrature to minimize total error.

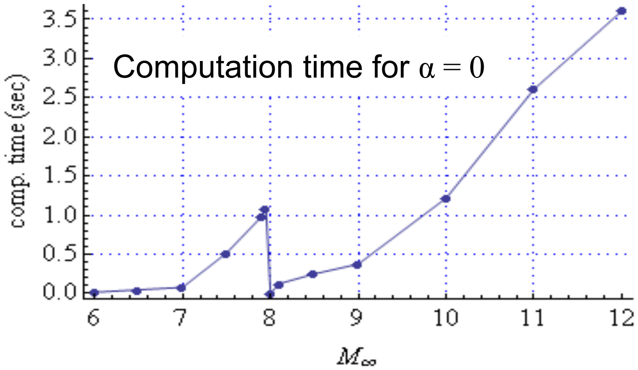
$$\varepsilon = \int_{\sigma_1}^{\sigma_n} \left(M(\theta) - \tilde{M}(\theta) \right)^2 d\theta$$

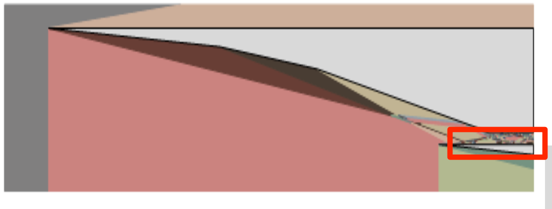
Example: $\delta = 21.8°$ deflection with $M_1 = 4$

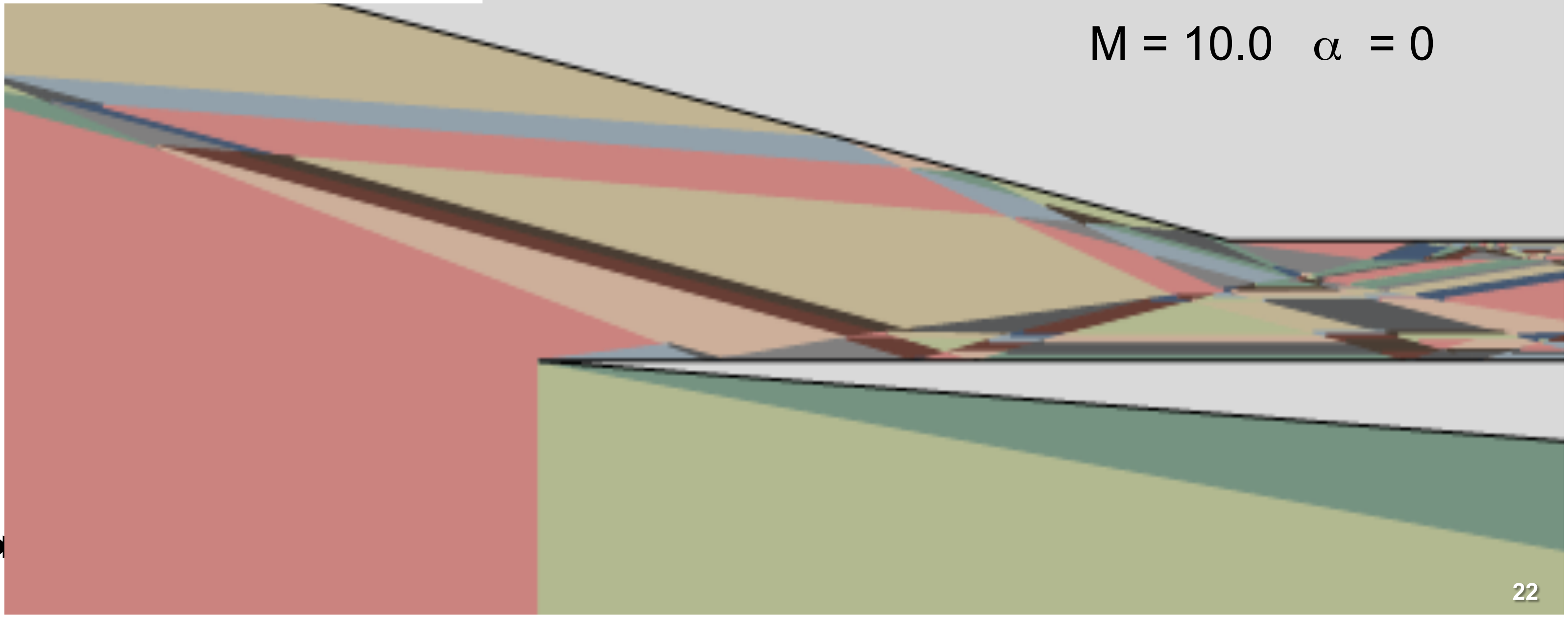


Our Inlet ROM - off design

- Computation time
  - around 0.6 seconds per solution
  - Will be made faster in MATLAB





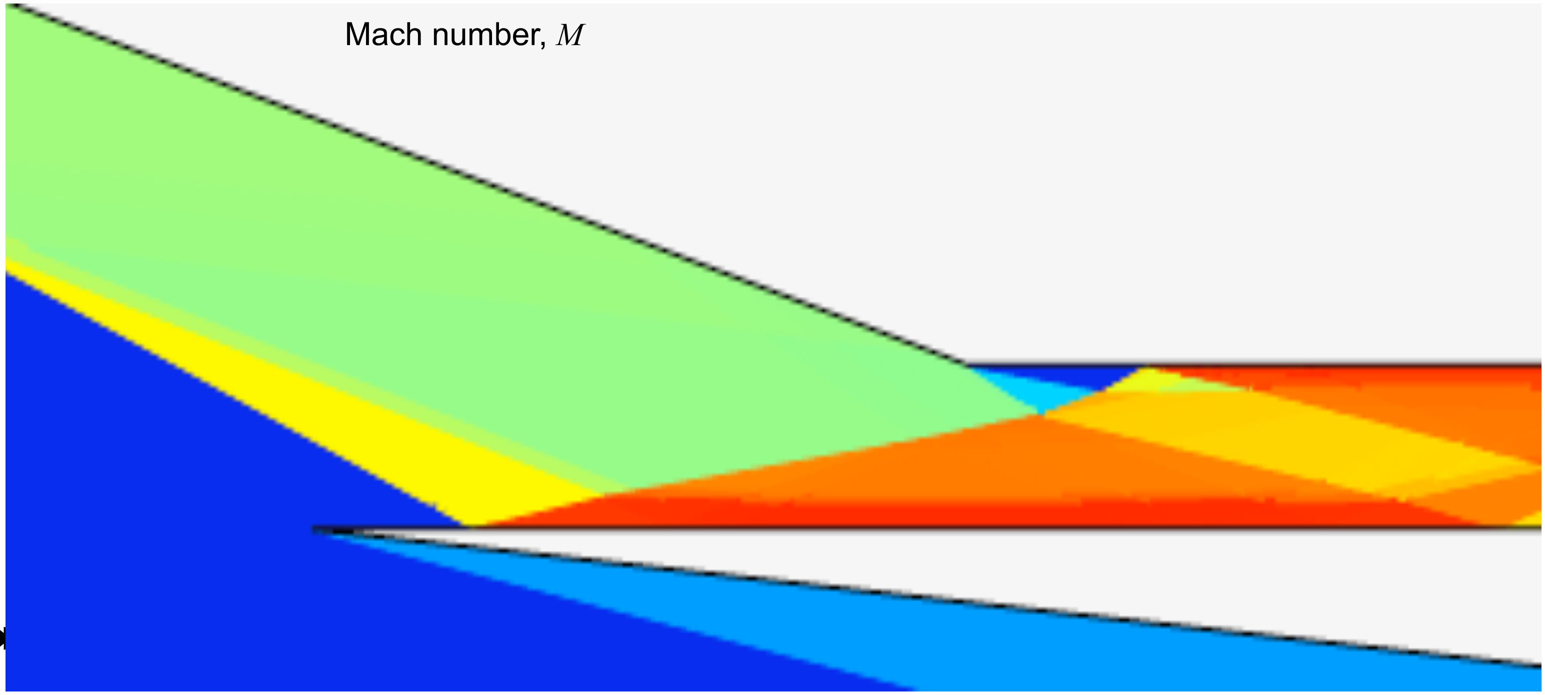


Off-design Example: $M_\infty = 10$, $\alpha = 0°$

Pressure recovery factor = 0.363　　Spillage fraction = 0

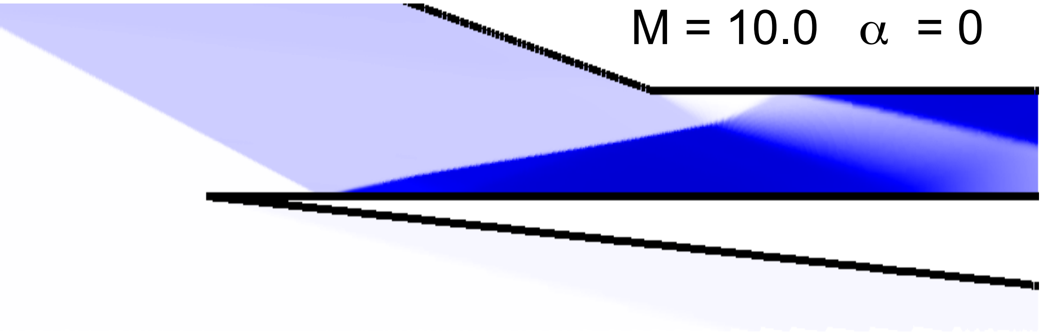
Thermodynamic variables

$p_2/p_\infty = 39.9$　　$\rho_2/\rho_\infty = 10.4$　　$T_2/T_\infty = 3.83$　　$M_2 = 4.73$

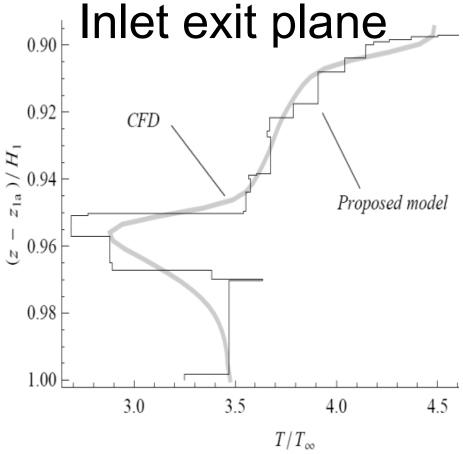


Assessment of our inlet ROM using CFD++

Viscous CFD using CFD++:

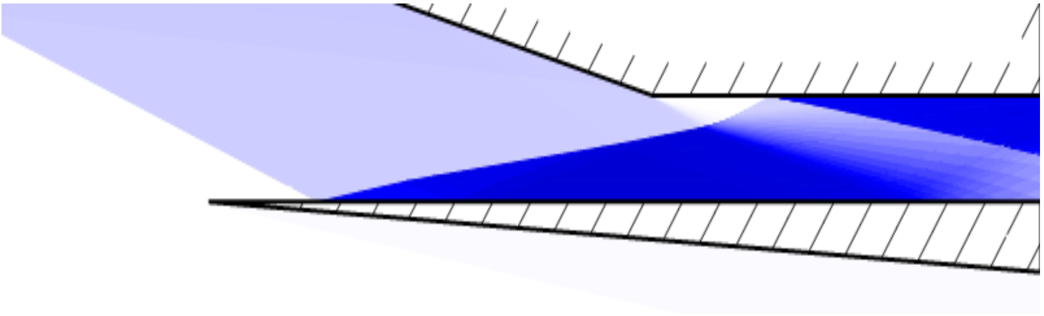


M = 10.0 α = 0



Inlet exit plane

Inlet ROM using 20 waves in expansion:



	CFD	proposed model	relative error
p_2/p_∞	34.70	35.39	0.0199
T_2/T_∞	3.603	3.645	0.0156
u_2/u_∞	0.9289	0.9302	0.0013
$p_{0,2}/p_{0,\infty}$	0.3331	0.3552	0.0664

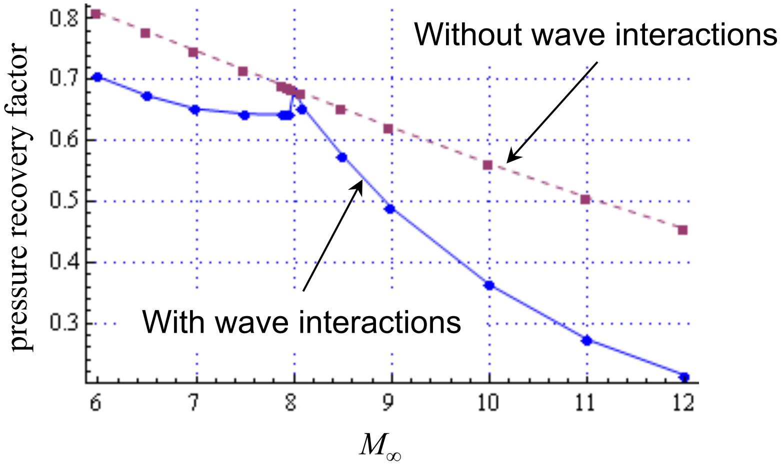
6.6% error in ROM

RESULTS: Off-Design Inlet

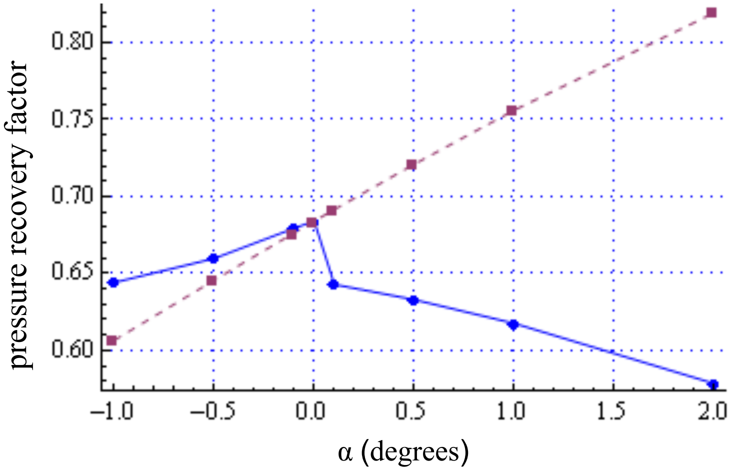
- Wave interactions cause dramatic inlet losses
- Sharp gradients in pressure loss near design condition
- Multi-objective optimization

  Optimize both design condition and reduce sensitivities to angle of attack and Mach number.

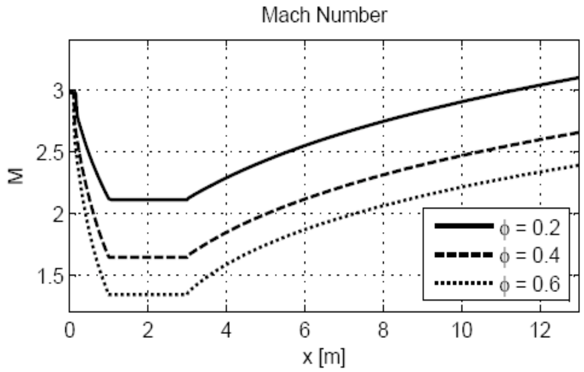
Response to Mach number at $\alpha = 0$



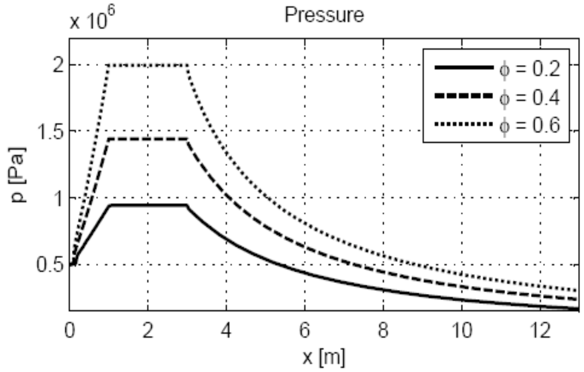
Response to angle of attack at $M_\infty = 8$



RESULTS: Real gas effects in combustor

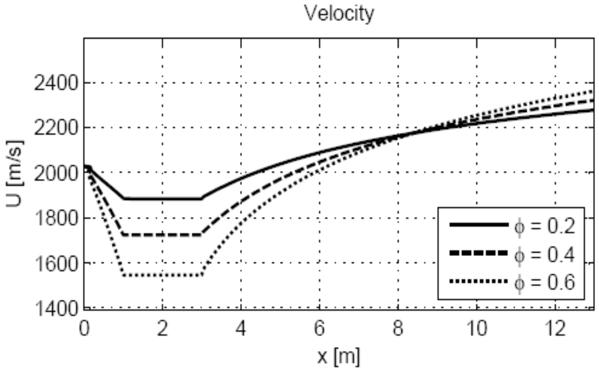


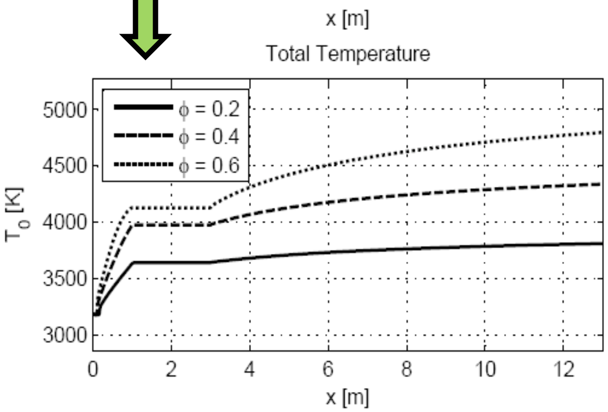
Adding more fuel drives Mach number toward one



Static pressure must exceed 0.5 atm or fuel will not burn

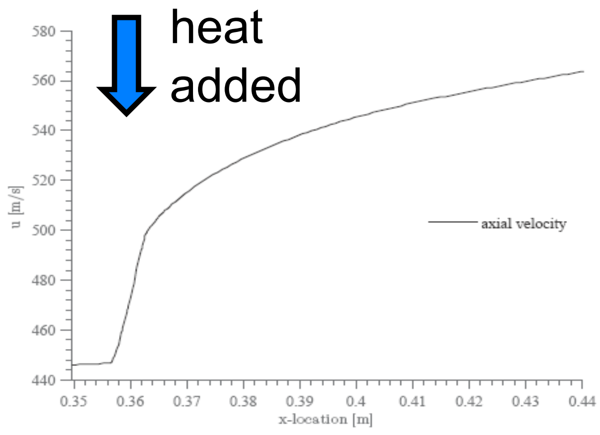
Total Temperature indicates where heat is added - by combustion and by recombination in nozzle



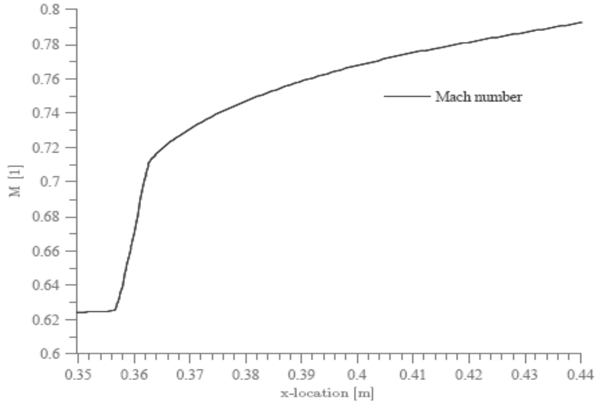


RESULTS: profiles of gas properties (in ram mode)

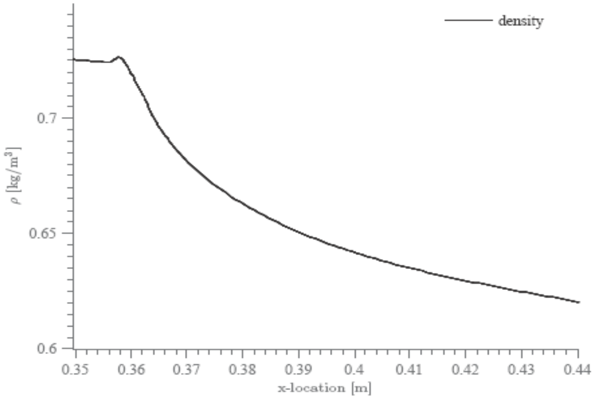
with flamelet chemistry, dissociation, heat loss to walls



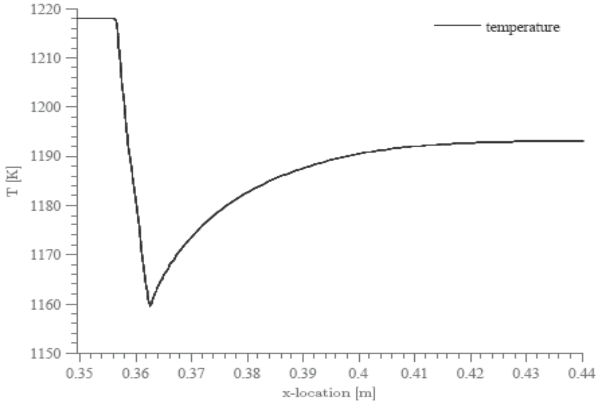
a) axial velocity



b) Mach number



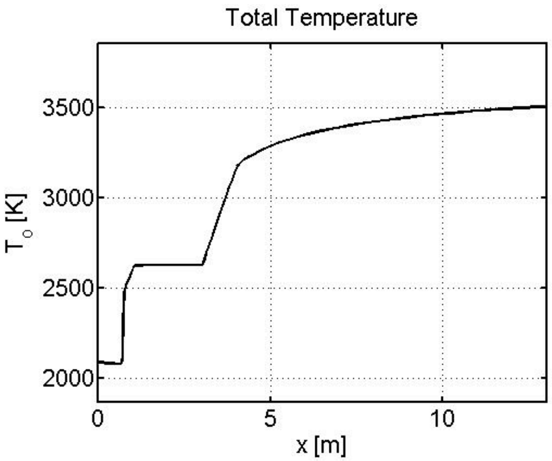
c) density

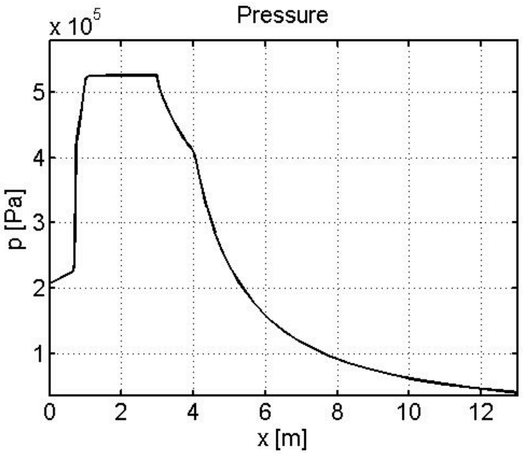


d) temperature

Results: Propulsion ROM (AIAA 2008-6386)

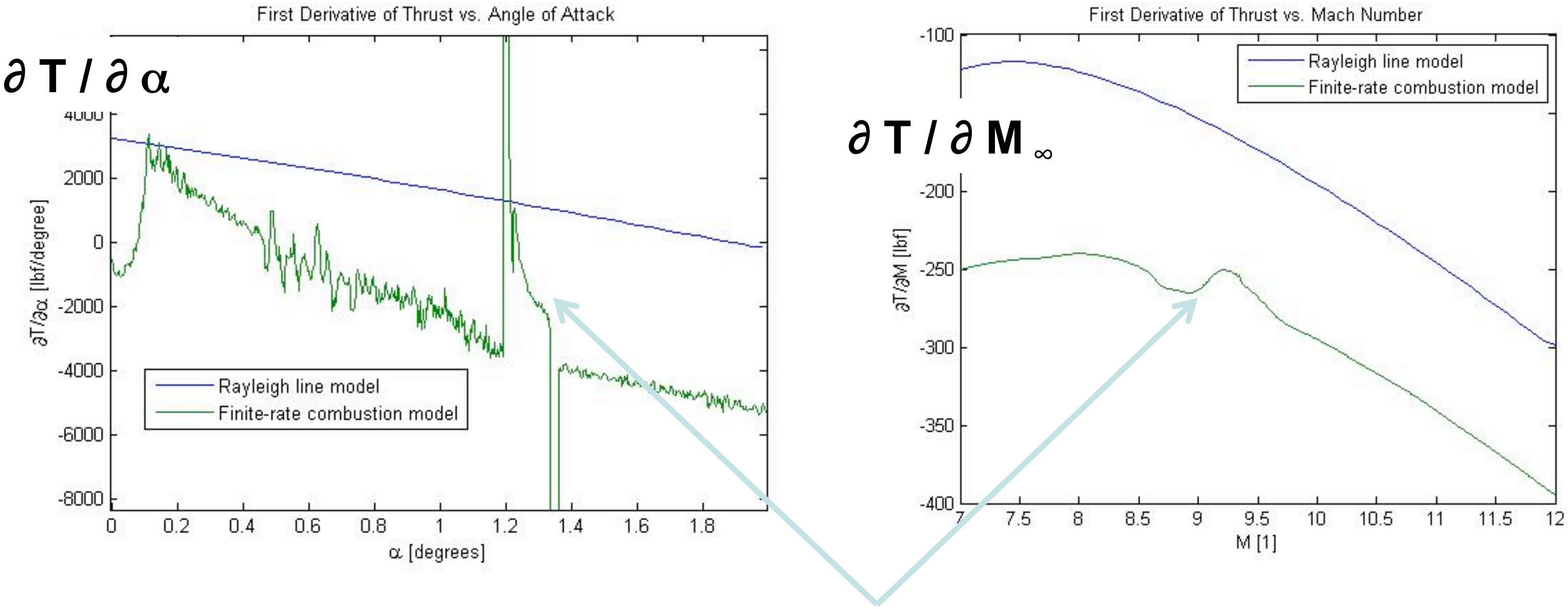
- Mixing model identifies realistic location where heat release by combustion occurs
- Finite rate chemistry model realistically identifies pressures, temperatures required (require 0.5 atm to burn)
- This sets realistic limits to operating envelope





RESULTS: Thrust Sensitivity to α, M_∞ (AIAA 2008-6386)

- With new propulsion model, engine thrust is more sensitive to changes in angle of attack, Mach number and fuel equivalence ratio



Shock-on-lip condition

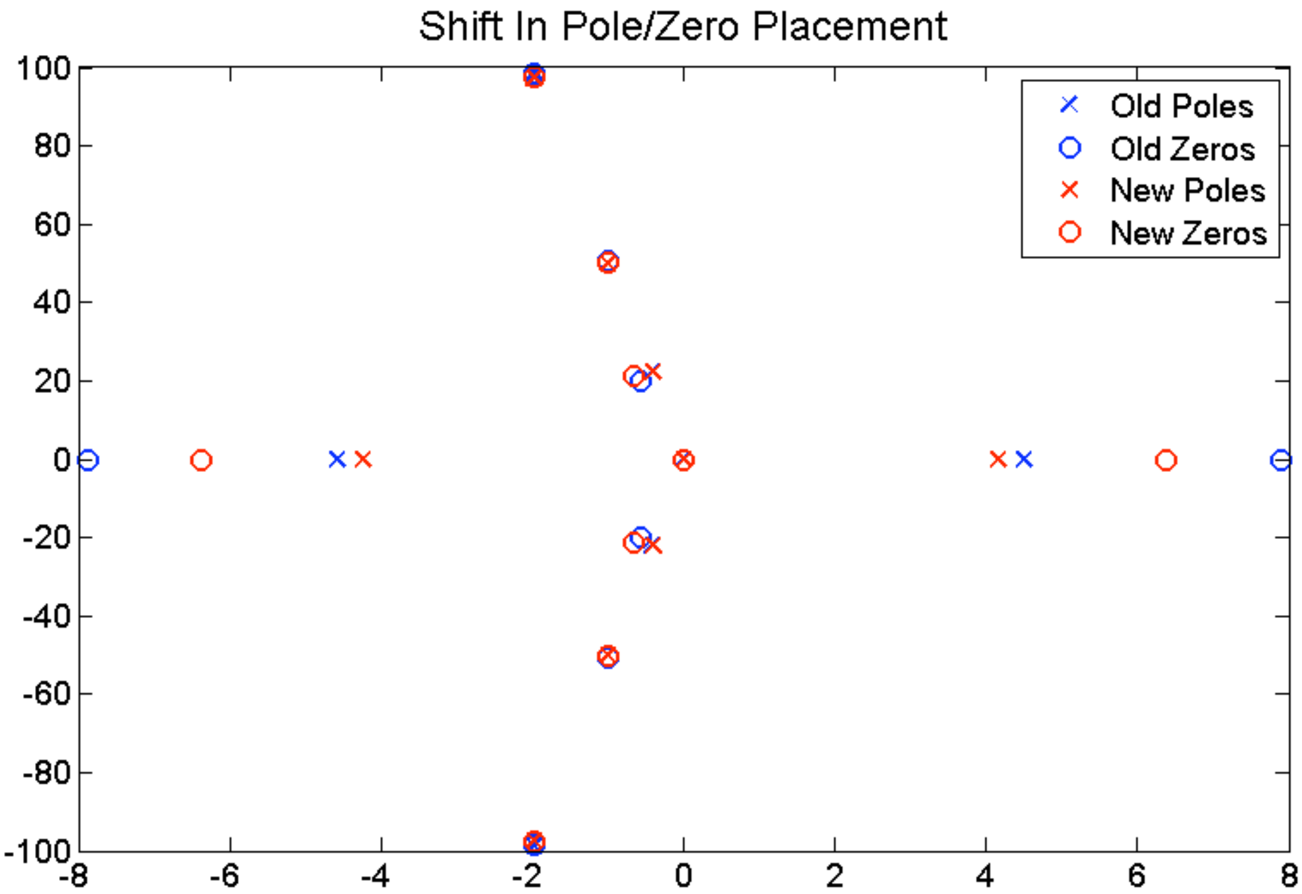
RESULTS: HSV Trim (AIAA 2008-6386)

- Engine sensitivity affects thrust, which affects trim conditions on AoA and control input (canard, elevator and fuel equivalence ratio)

	Rayleigh-line model (old)	**Finite-rate model (new)**
α	1.97°	0.919°
$\dot{m}_{air}$	4.19 lbm/s	3.80 lbm/s
T	1820 lbf	1530 lbf
$T/\dot{m}_{fuel}$	434 ft/s	403 ft/s
$\dot{m}_{fuel}$	0.0525 lbm/s	0.0558 lbm/s
I_{sp}	1080 s	857 s
δ_e	0.476°	6.75°
δ_c	-9.50°	-10.4°

RESULTS: Vehicle Stability (AIAA 2008-6386)

- New propulsion model: some vehicle modes less stable



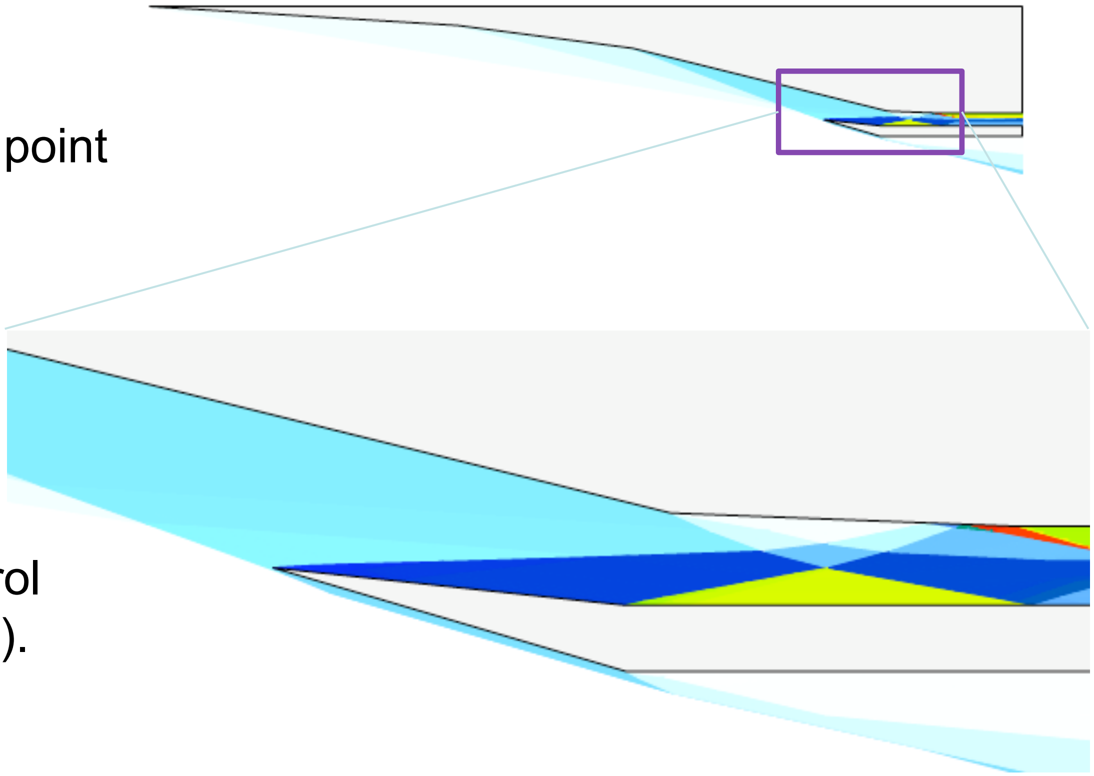
RESULTS: Robust Optimization of Inlet

- Current design:
  - Optimized for one condition
  - Poor performance at other conditions
  - Highly sensitive near design point

- Improved design:
  - Decrease sensitivities

$$\left.\frac{\partial(prf)}{\partial M_\infty}\right|_{M_\infty=8} \qquad \left.\frac{\partial(prf)}{\partial \alpha}\right|_{M_\infty=8}$$

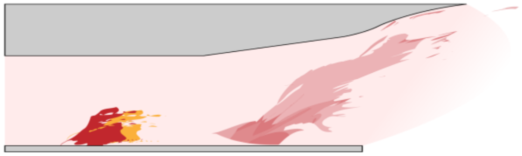
  - Possibly introduce inlet control variable (*e.g.* cowl deflection).



Example: $M_\infty = 8.5,\ \alpha = 0$

Plans for next year

Drop in MASIV into AFRL HSV code by Nov 30, 2009



Minimize run time

Vary control variables

inlet: contraction ratio (CR),
cowl flap deflection,
boundary layer bleed

combustor: two fuel locations, ER

Add ram mode, isolator shocks, ram-scram

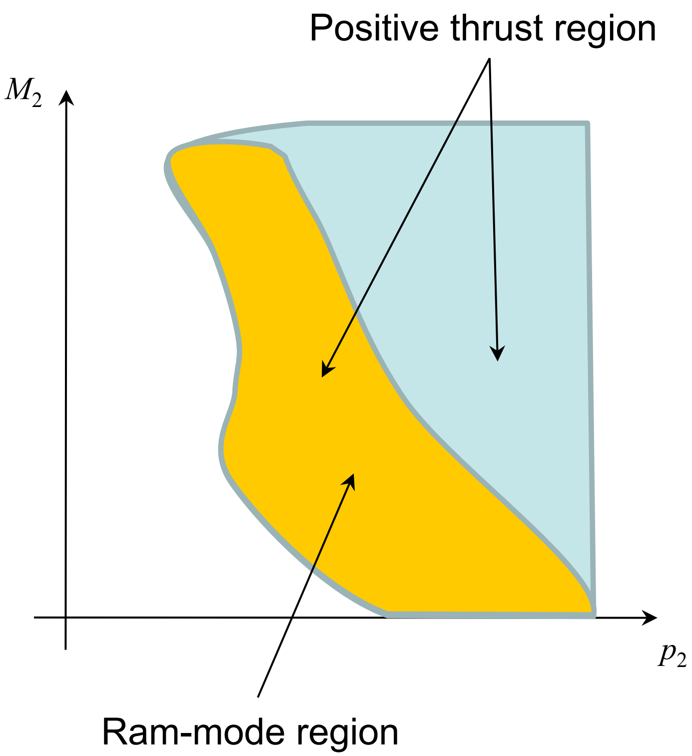
Compute flight dynamics during scram, ram, ram-scram transition

Optimization of combustor, inlet

Next year: Parameter Study of Engine

- Investigate control of MASIV propulsion model
  - Given M_∞, α
  - Design variables: fuel location, internal compression
  - Control variables: fuel scheduling, internal wall deflection
  - Re-optimize inlet for trim condition.

- Develop constraints for inlet
  - Given p_2, T_2, and M_2
  - Determine critical boundaries
  - *Ram/scram transition*
  - *Unstart, etc.*
  - Crucial for design of better inlets
  - Passive inlet for large range of M_∞ unlikely
  -



(*Drawing does not represent actual results.*)