SUP/Integrated Inlet/Engine Control

Propulsion Control and Diagnostics Research Under NASA Aeronautics Research Mission Programs Workshop at Ohio Aerospace Institute, Cleveland OH Nov. 6-7, 2007

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NASA Fundamental Aeronautics - Supersonics Project:
Aero-Propulso-Servo-Elasticity (APSE)

Outline

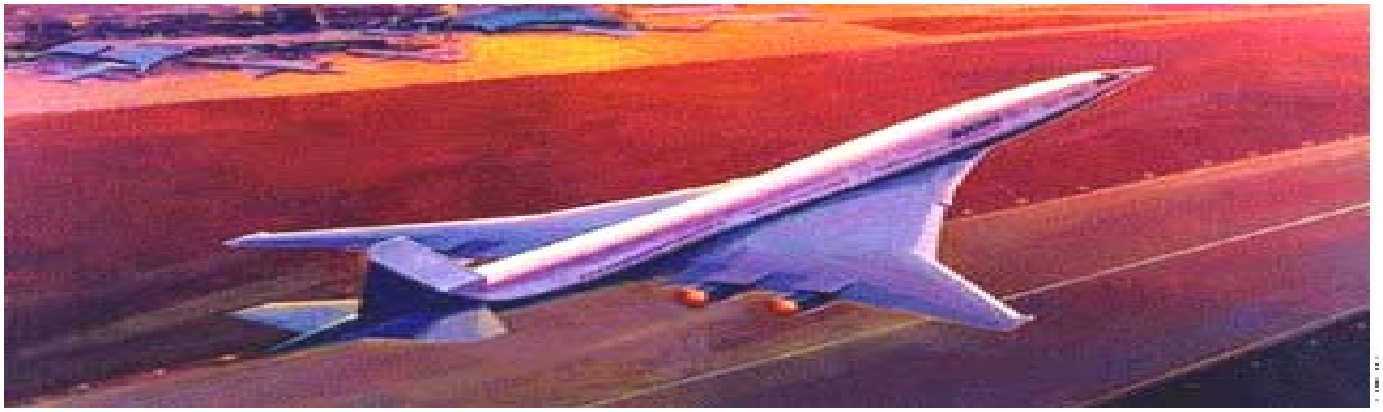
- Program Challenges
- Approaches
- Engine Modeling
- Controls Design
- Conclusion/Future Work

Program Challenges

The Supersonics Project has identified a set of key technical challenges that are barriers to success for these vehicles

- **Performance challenges**, including Aero-Propulso-Servo-Elastic (APSE) analysis and design

- **Efficiency challenges**, including supersonic cruise efficiency ….



Modeling Approach/Propulsion

- High Fidelity 1D Flow Models – Based on Component Performances and Volume Gas dynamics
- Some old FORTRAN computer Codes Exist

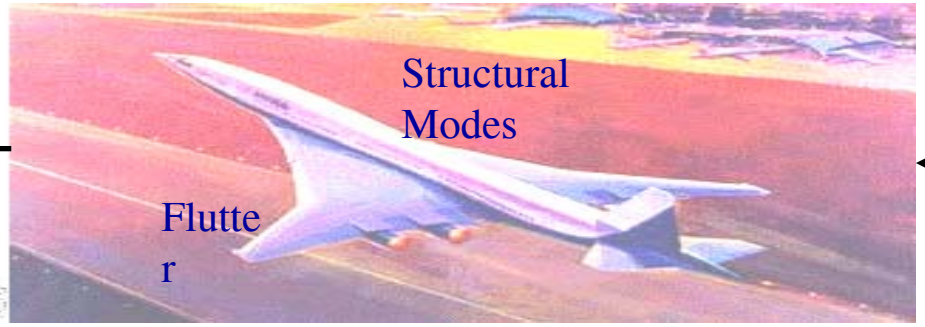
  -- Develop codes on state-of-the-art platforms due to analysis, complexity, commonality, and configuration control issues

  -- Research done more effectively by also being involved in simulation development.

Controls Approach/Propulsion

- Mainly Classical Feedback Control
- Control Methodologies extended to relate hardware designs and performance requirements to control design limitations for stability, time response, and disturbance rejection.

Aero-Propulso-Servo-Elastic (APSE)

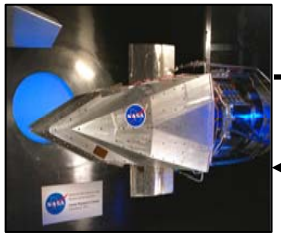


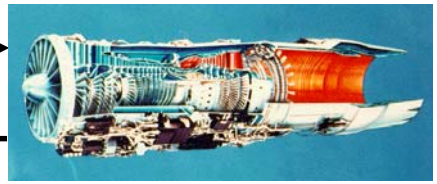
Aero-Servo-Elastic

Thrust
Variations

APSE Flow
Disturbances

External Flow
Disturbances





Propulsion

- Integrated Modeling &Controls Design
- Vehicle Stability
- Ride quality
- Cruise Efficiency

Integrated APSE Model

Design and Analysis

Engine Model

Engine Components Modeled Separately (performance & Volume dynamics)

Compressor

$$\frac{d}{dt}(\rho_{sv,n}) = \frac{1}{V_n}(\dot{W}_{c,n} - \dot{W}_{c,n+1} - \dot{W}_{b,n})$$

$$\frac{d}{dt}(\dot{W}_{c,n}) = \frac{A_n g}{l_n}(P_{tc,n} - P_{tv,n})\left(1 + \frac{\gamma_{cp}-1}{\gamma_{cp}} M_n{}^2\right)^{\frac{\gamma_{cp}}{\gamma_{cp}-1}}$$

$$\frac{d}{dt}(T_{tv,n}) = \frac{\gamma_{cp}}{\rho_{sv,n} V_n}(T_{tc,n}\dot{W}_{c,n} - T_{tv,n}\dot{W}_{c,n+1} - T_{tv,n}\dot{W}_{b,n})$$

$$P_{tv,n} = \left(1 + \frac{\gamma_{cp}-1}{2} M_n{}^2\right)^{\frac{1}{\gamma_{cp}-1}} \rho_{sv,n} R T_{tv,n}$$

$$M_n = \frac{\dot{W}_{c,n}}{\rho_{sv,n} A_n \sqrt{\gamma_{cp} R T_{s,n}}}$$

$$T_{s,n} = T_{tv,n} - \frac{\dot{W}_{c,n}^2}{2\rho_{sv,n}^2 A_n^2 c_{p,n}}$$

$$\dot{W}_{b,n} = K_b A_{b,n} \frac{P_{tv,n}}{\sqrt{T_{tv,n}}}$$

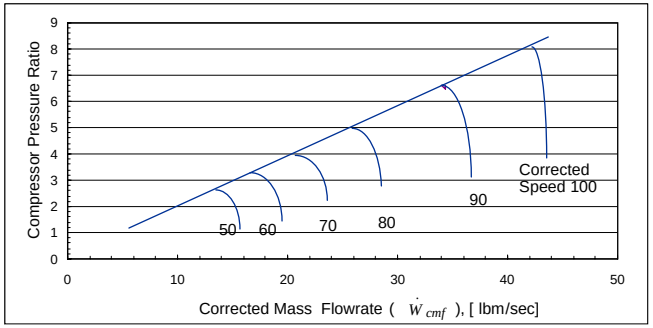
$$\dot{W}_{cmf,n} = \frac{\dot{W}_{c,n}\sqrt{T_{tv,n-1}/T_{ref}}}{P_{tv,n-1}/P_{ref}}$$

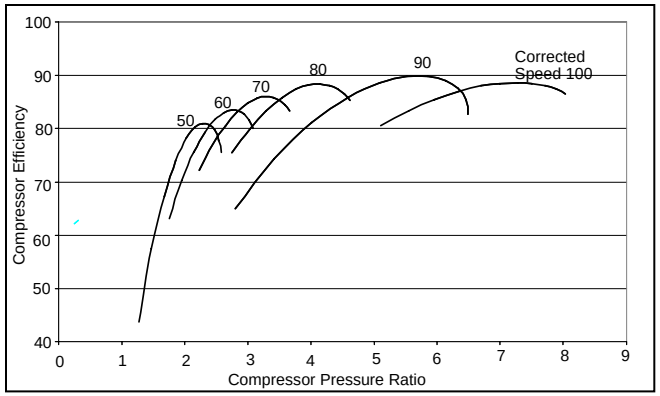
$$N_{c,n} = \frac{N}{N_{d,n}}\sqrt{T_{d,n}/T_{tv,n-1}}$$

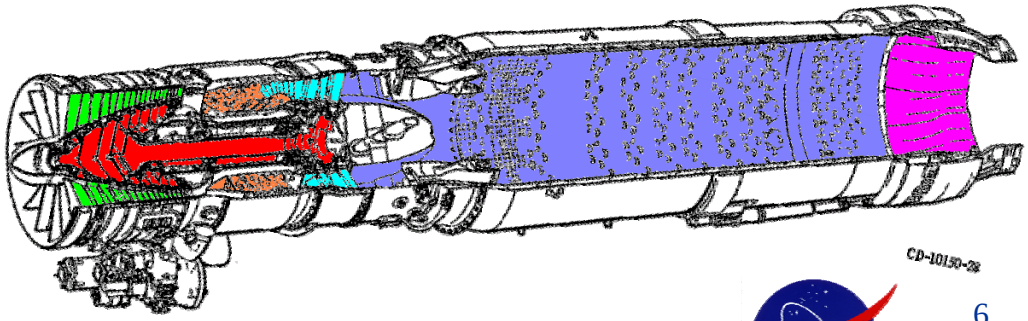
$$P_{tc,n} = P_{r,n} * P_{tv,n-1}$$

$$T_{tc,n} = T_{tv,n-1}\left[1 + \frac{P_{r,n}^{(\gamma_{cp}-1)/\gamma_{cp}} - 1}{\eta_{cp}}\right]$$

$$A_n = 4\pi r_n (r_{Tn} - r_n)$$

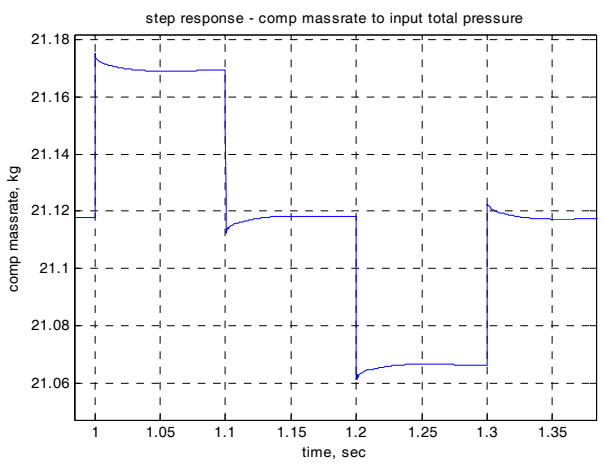


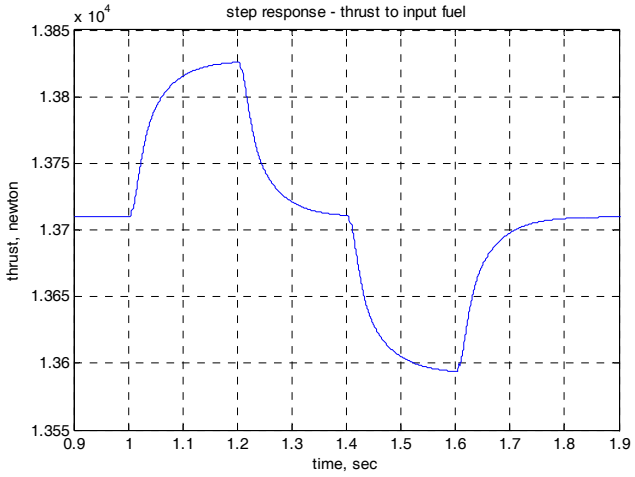


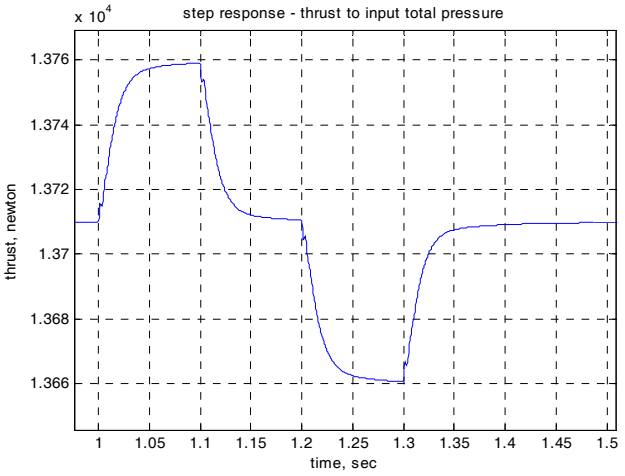


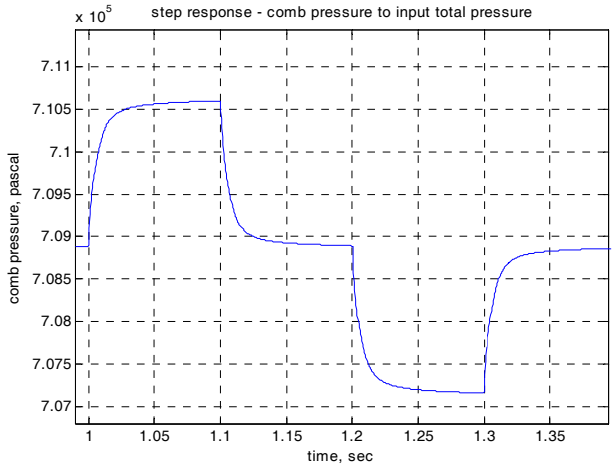
Engine Modeling Results

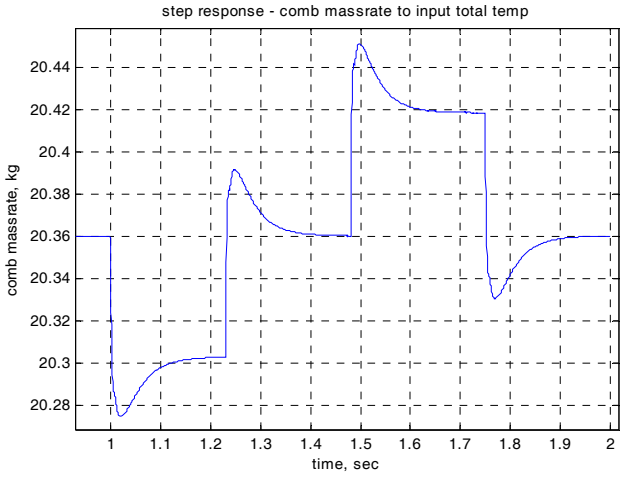
Step Responses

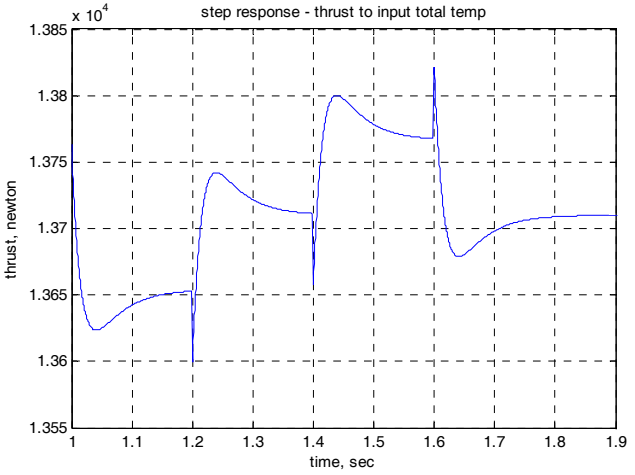






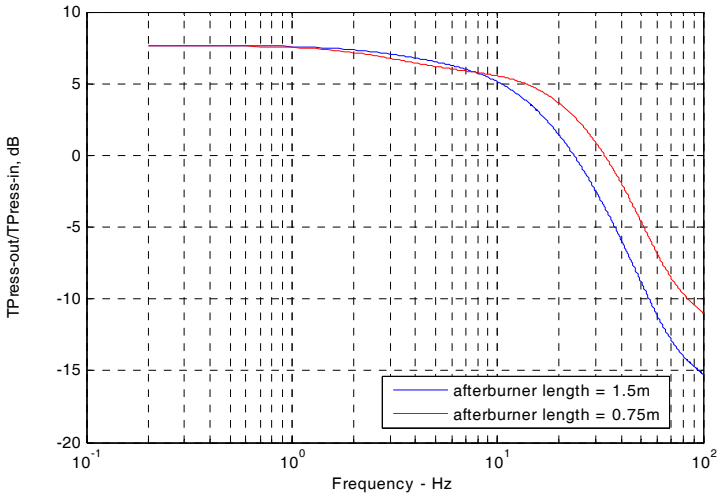


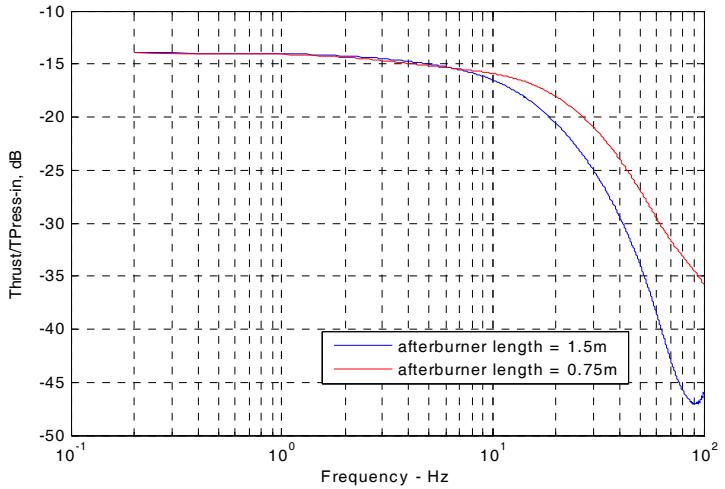


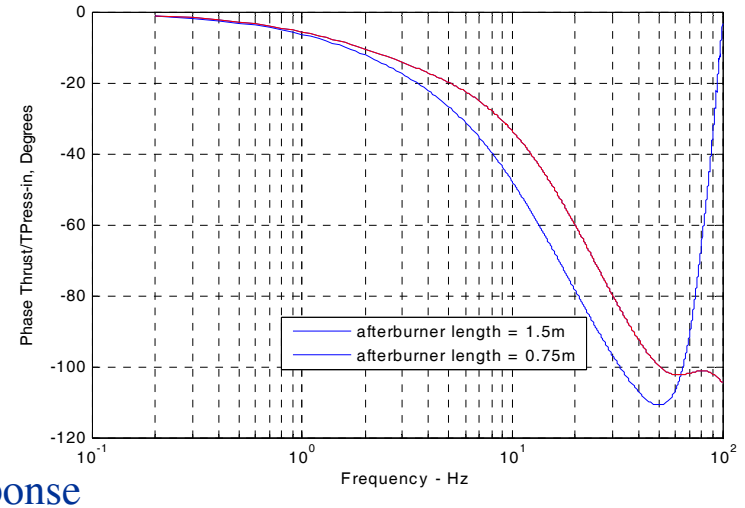


Engine Modeling Results

Frequency Responses







Component Volumes

V_afterb = 0.2408

V_comp = 0.0369

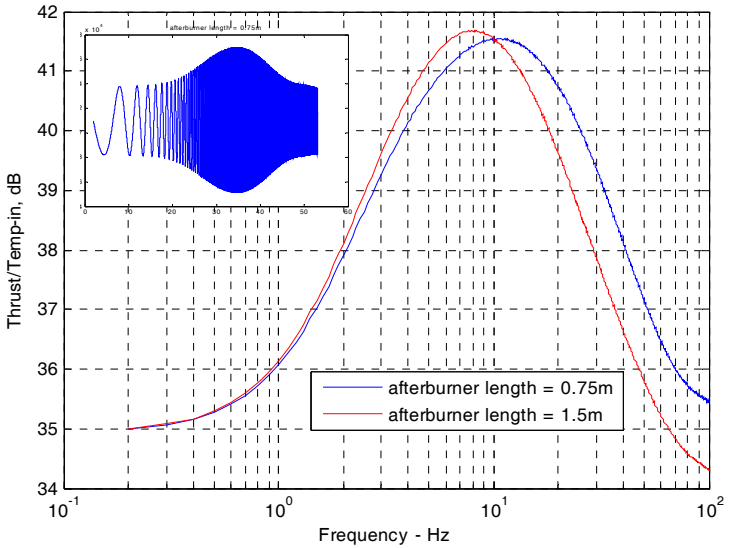
V_comb = 0.0149

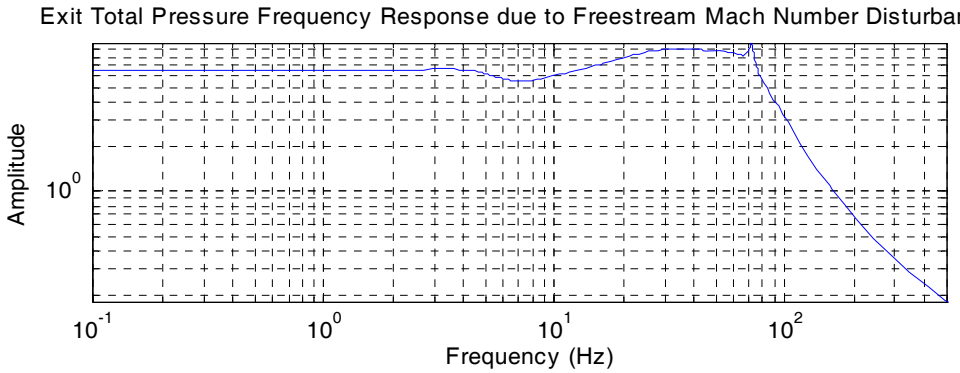
V_turb = 0.0133

-- Afterburner Volume dominates Frequency Response

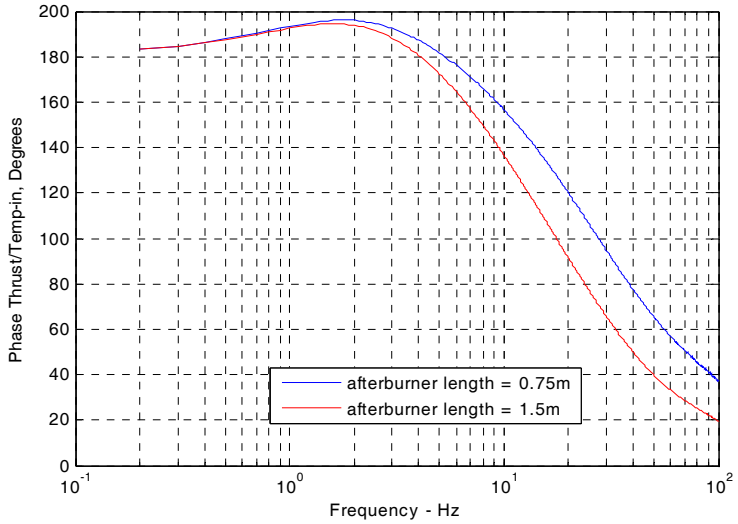
-- Fuel actuation speed ~38 rad/sec (~6 Hz) ➡ Control system, no disturbance attenuation above 6 Hz

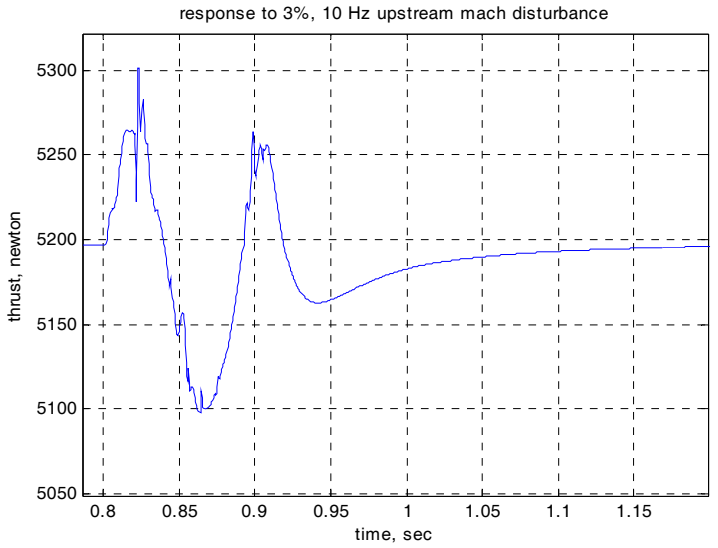
Engine Modeling Results





Inlet Response

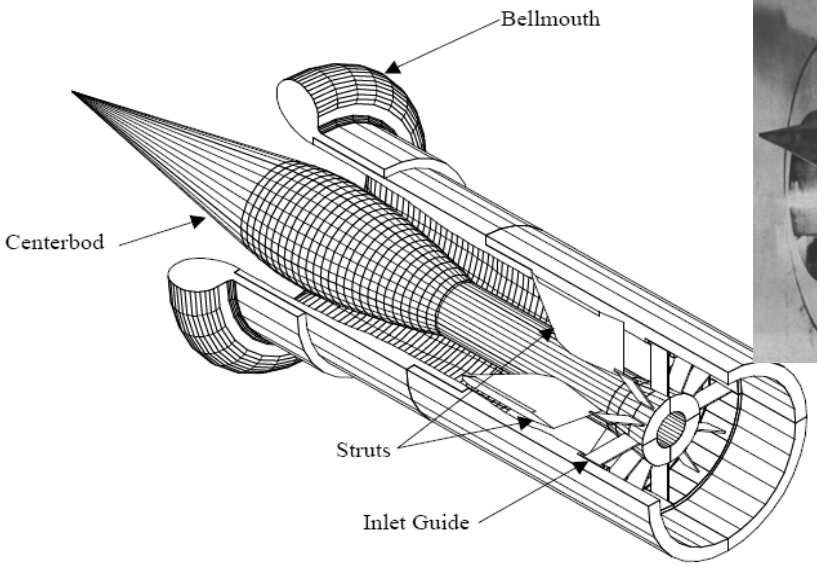


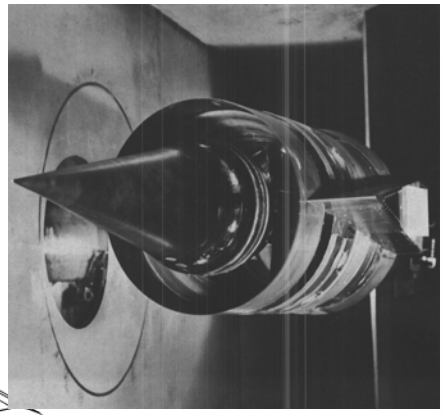


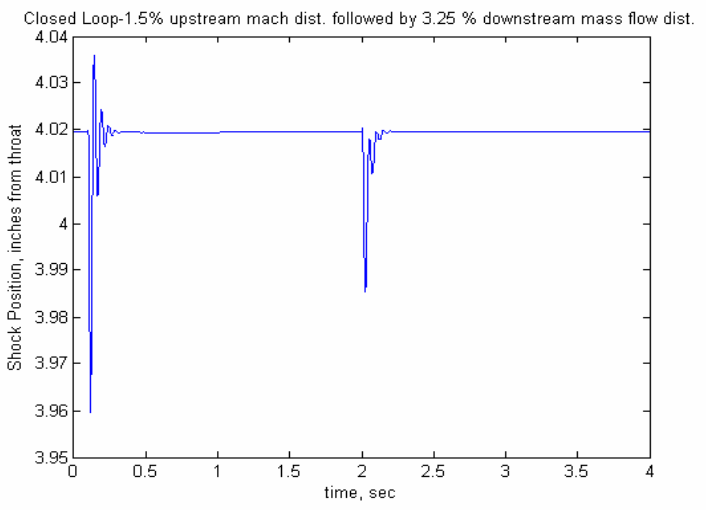
Thrust Response to 3% mach disturbance at the inlet input

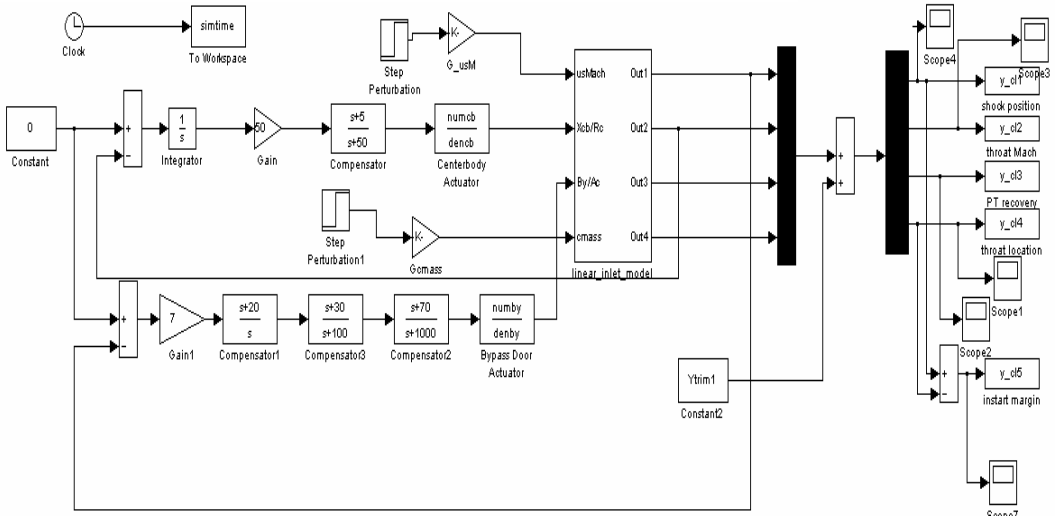
Kopasakis, G.; Connolly, J; Ma P.: "Volume Dynamics Propulsion System Modeling and Analysis for Supersonics Vehicle Research," ASME Turbo Expo, 2008 - Pending

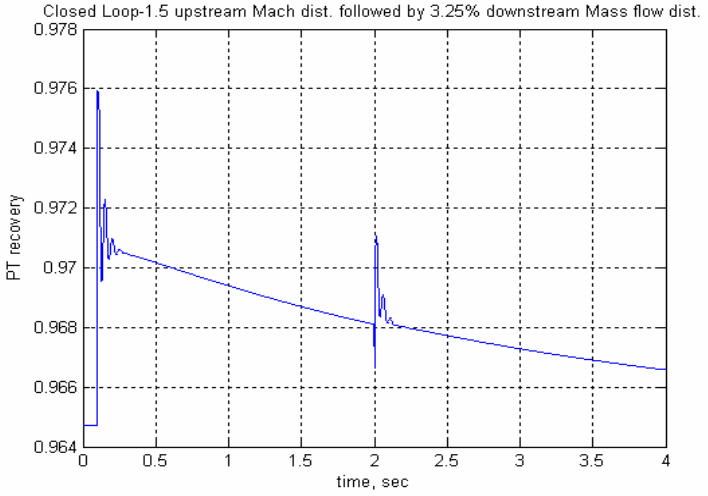
Axisymetric Inlet Shock Position Control Exercise



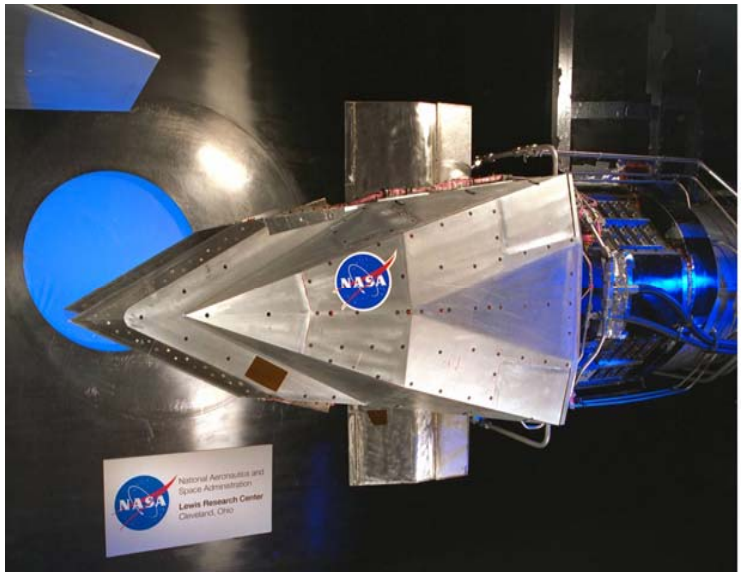


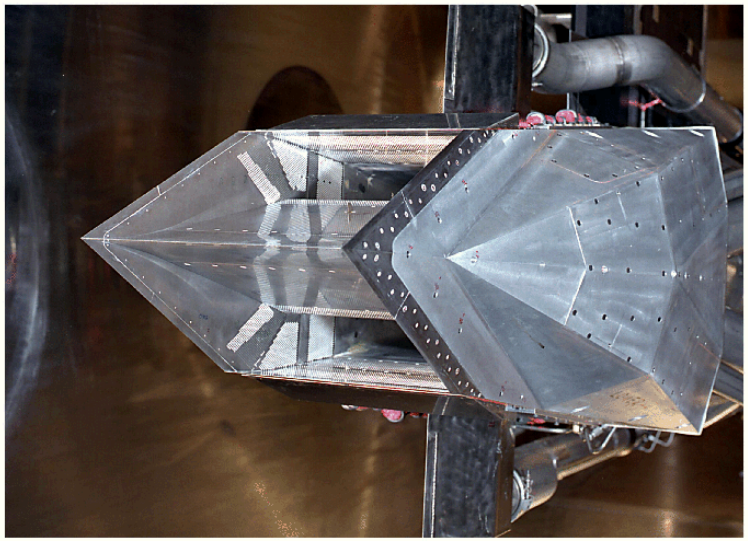


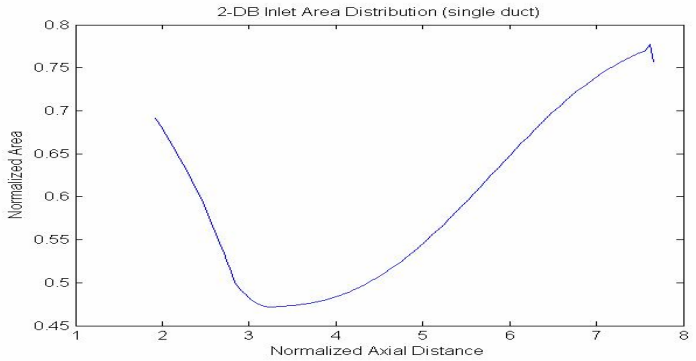


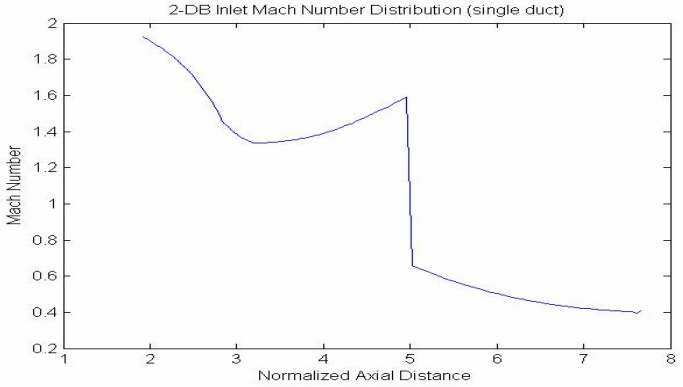


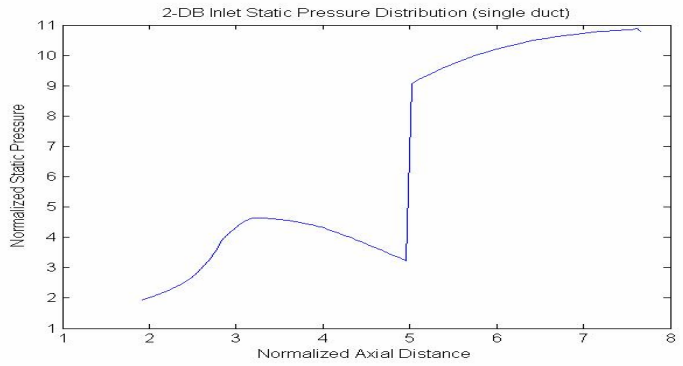
2D Bifurcated Inlet Simulations











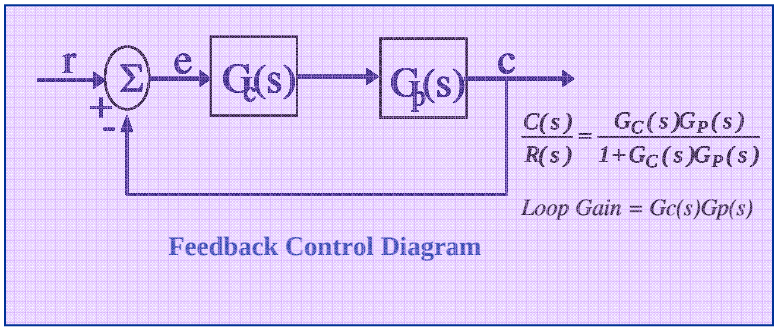
Controls Design Approach

- Controls approach involves a methodical Loop Shaping Design Methodology.
- Extended classical control design to directly relate hardware designs like actuator speeds, and performance requirements to control design and it's limitations.
- This is done in order to establish a design vehicle to increase performance and enable reduction of design margins.

Loop Shaping Controls Design

- Given Control Performance Requirements

Disturbance Attenuation 20 dB at 100 rad/sec
Phase Margin $\geq 45^{o}$ *, Gain Margin* ≥ 10
Response time 0.05 sec, 2% Settling time 0.2 sec
Actuator rate limit 1000 rad/sec



Feedback Control Diagram

- Method to shape the control system Loop Gain to meet requirements

- Given plant transfer function then calculate the controller transfer function to satisfy the desired Loop Gain

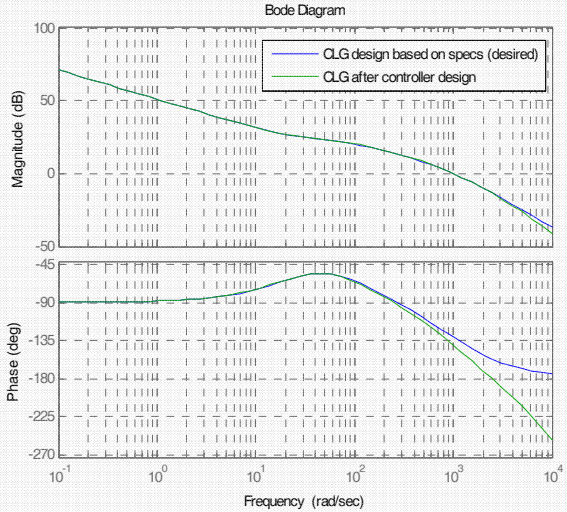
- Methodology also addresses control design limitations based on hardware designs and requirements; shows how to achieve best control design and facilitates requirements negotiation or justifying hardware design changes

Kopasakis, G.: "Feedback Control Loop Shaping Design with Practical Considerations," NASA/TM-2007-215007, Oct. 2007.

Loop Shaping Controls Design

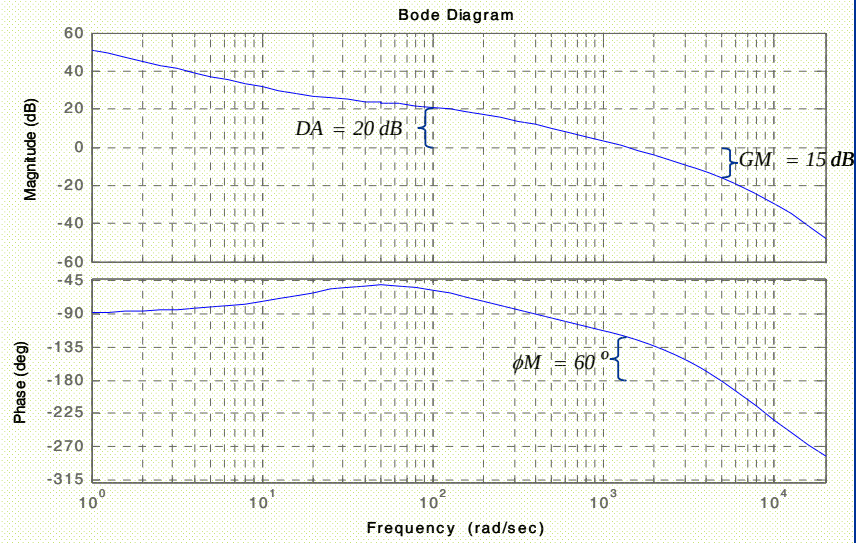
Plant Transfer Function
+
System Requirements

Design closed loop gain & calculate controller gain to match desired closed loop gain

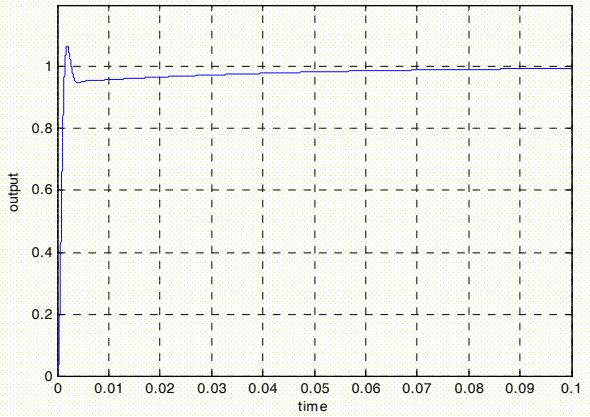


Comparison of Desired LG –vs- LG Based on the Controller Design

Perform final adjustments to max. design effectiveness



Loop Gain Design to Meet Requirements



Closed Loop Step Response

Potential Collaboration Opportunities

- SUP program has gone through few rounds of NRA's
- Next round is expected to be in January
- So far no NRA's have been awarded in APSE

Conclusion/Future Work

- Work on engine modeling validation and enhancements continues
- Inlet 1D CFD model in SIMULINK will start in FY08
- Engine Feedback controls work and Closed loop thrust variations in FY08
- Bounding upstream flow field disturbances: ASE, atmospheric, pitch and yaw – FY08-09
- Integrated APSE model in late FY08 and FY09
- Models and controls validation/testing?
- Out years possible areas – Parallel propulsion process modeling
  Advanced Controls to optimize performance