Summary

AeroPropulsoServoElasticity: Dynamic Modeling of the Variable Cycle Propulsion System

This presentation was made at the 2012 Fundamental Aeronautics Program Technical Conference and it covers research work for the Dynamic Modeling of the Variable cycle Propulsion System that was done under the Supersonics Project, in the area of AeroPropulsoServoElasticity.

The presentation covers the objective for the propulsion system dynamic modeling work, followed by the work that has been done so far to model the variable Cycle Engine, modeling of the inlet, the nozzle, the modeling that has been done to model the affects of flow distortion, and finally presenting some concluding remarks and future plans.

National Aeronautics and Space Administration

Fundamental Aeronautics Program

Supersonics Project

AeroPropulsoServoElasticity: Dynamic Modeling of the Variable Cycle Propulsion System

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www.nasa.gov

Outline

- Objective
- Variable Cycle Engine (VCE) Propulsion System Modeling
  - -- Engine Modeling
  - -- Inlet modeling
  - -- Nozzle Modeling
- Parallel Flow Path Modeling
- Concluding Remarks/Future

Team

- **Team: All NASA GRC** (2FTE's)

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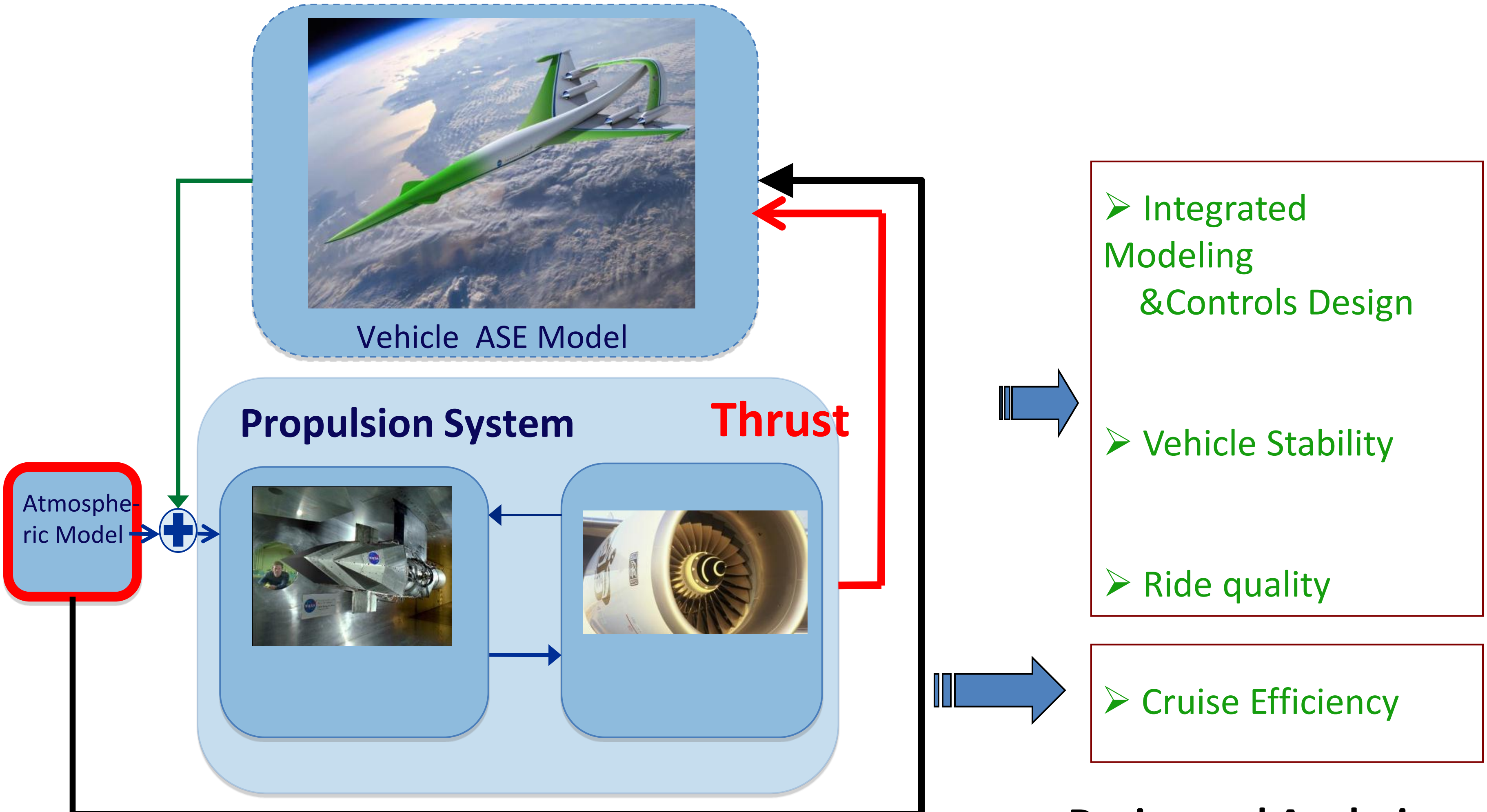
Objective

What is AeroPropulsoServoElasticity (APSE), Why?

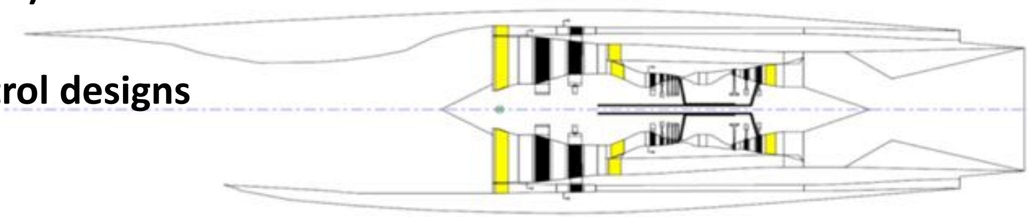


Integrated APSE Model
(NASA LaRC in collaboration with NASA GRC)

Design and Analysis

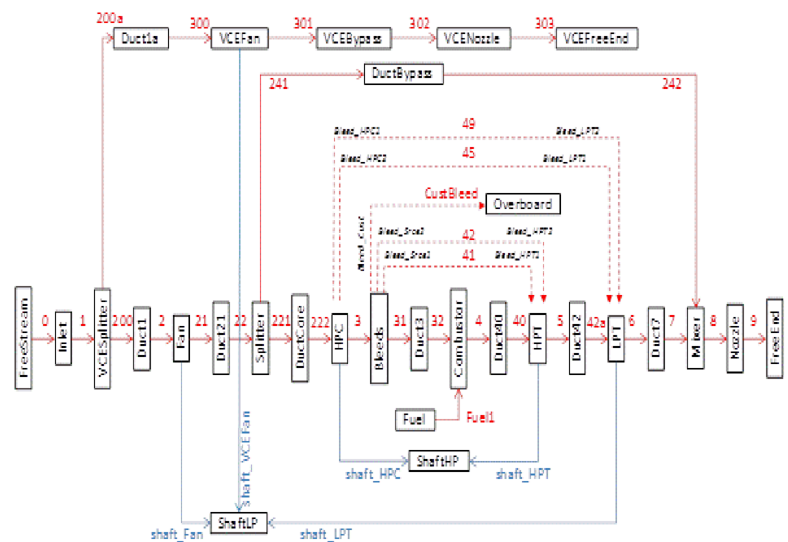
Key Milestone Progress
N+2/N+3 Propulsion System Modeling

Objective
- Develop concept Variable Cycle Engine (VCE) dynamic propulsion system model
- Develop propulsion system operation control designs



VCE Propulsion System Concept

Approach
- Modify prior developed engine models & develop additional component models
- Develop CFD inlet and nozzle models w/ variable geometries
- Generate linear models and feedback control designs
- Generate engine operation control schedules



VCE Component Model Diagram

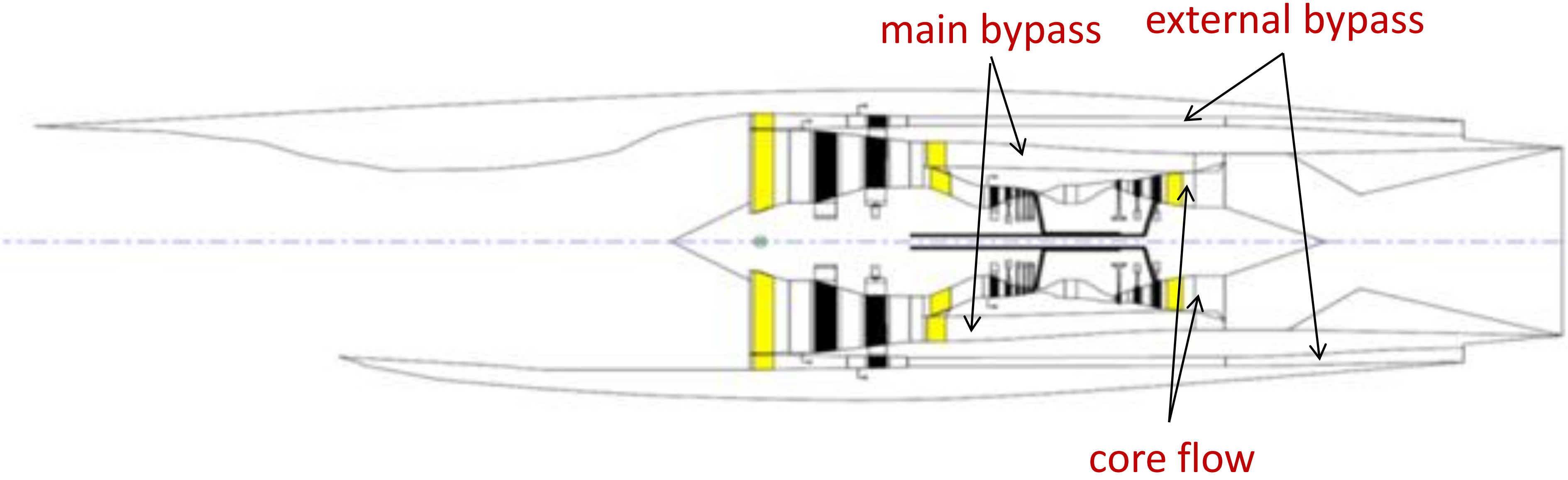
Significance
- Provides a valuable platform for controls design to improve performance & disturbance suppression
- Provides a platform for dynamically verifying propulsion system concept designs
- Provides propulsion system for ASE integration and for overall controls & vehicle performance studies

Variable Cycle Engine Model

- Dual Spool variable cycle – High bypass at low altitudes to low bypass high altitudes

- Noise abatement for overland flight
  -- Through external bypass & through nozzle design

- Cycle analysis conducted in NPSS – provided geometries and component performance characteristics for dynamic model



Component Modeling - Roadmap & Approach

Development Roadmap

1. **Original component models developed based on J85-13 engine**

2. **Many of J85-13 component models and methods directly utilized for VCE w/ the appropriate maps and geometries**

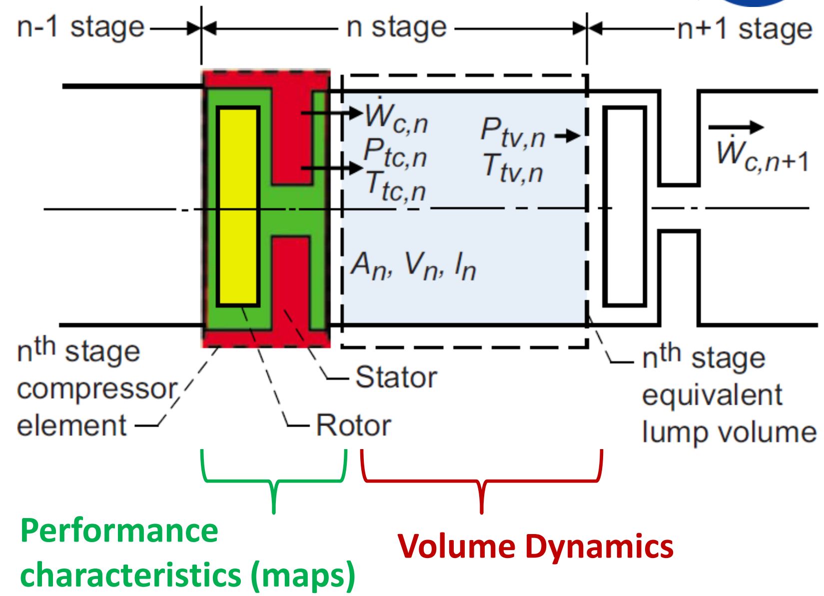
3. **Some new component models developed (ducts, mixers, splinters, dual core) - VCE V.1**

4. **For some components need to develop detailed models – like CFD for inlet & nozzles**

5. **Need to develop fully operational engine (control schedules) – Methodology developed w/ J85-13**

6. **Parallel flow paths for distortion & boundary layer effects**

7. **Propulsion & ASE integration – Interfaces, controls and performance studies**



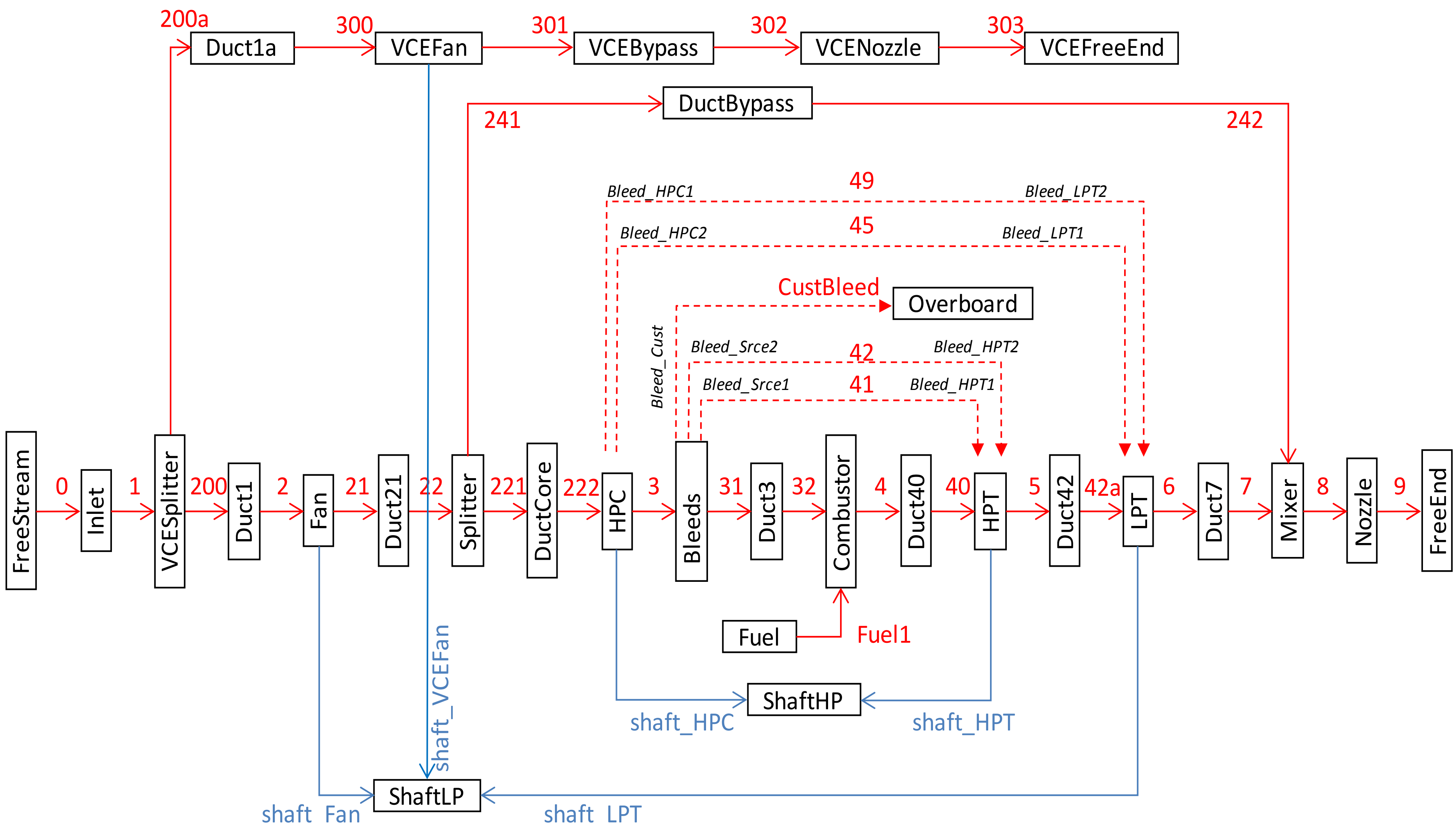
Continuity of mass, momentum & energy

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

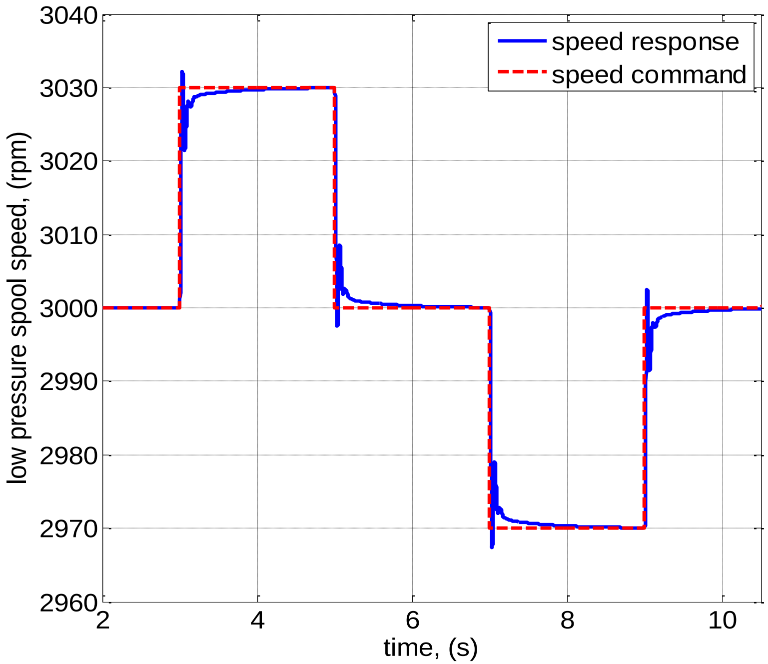
$$\frac{d}{dt}\dot{W}_{c,n} = \frac{A_n g}{l_n}(P_{\mathrm{tc},n} - P_{\mathrm{tv},n})\left(1 + \frac{\gamma_{\mathrm{cp}} - 1}{2}M_n^2\right)^{-\gamma_{\mathrm{cp}}/(\gamma_{\mathrm{cp}}-1)}$$

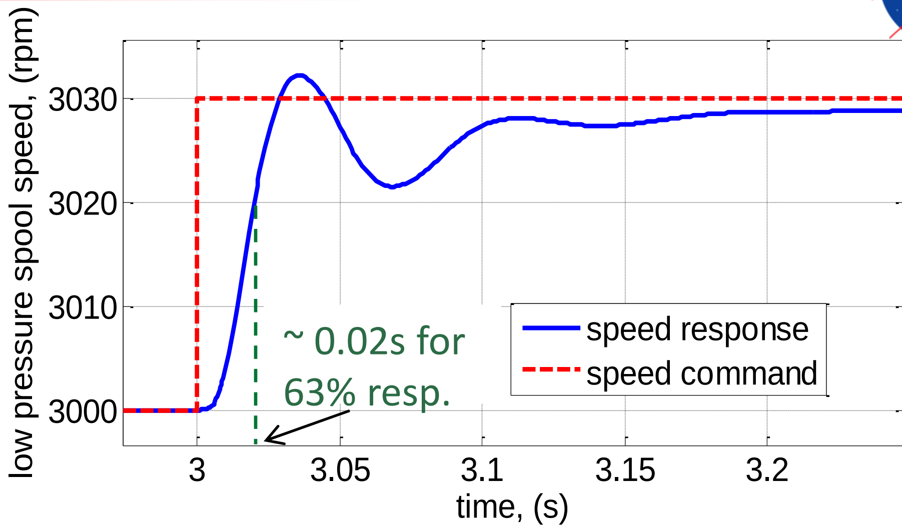
$$\frac{d}{dt}(\rho_{\mathrm{sv},n}, T_{\mathrm{tv},n}) = \frac{\gamma_{\mathrm{cp}}}{V_n}(T_{\mathrm{tc},n}\dot{W}_{c,n} - T_{\mathrm{tv},n}\dot{W}_{c,n+1} - T_{\mathrm{tv},n}\dot{W}_{b,n})$$

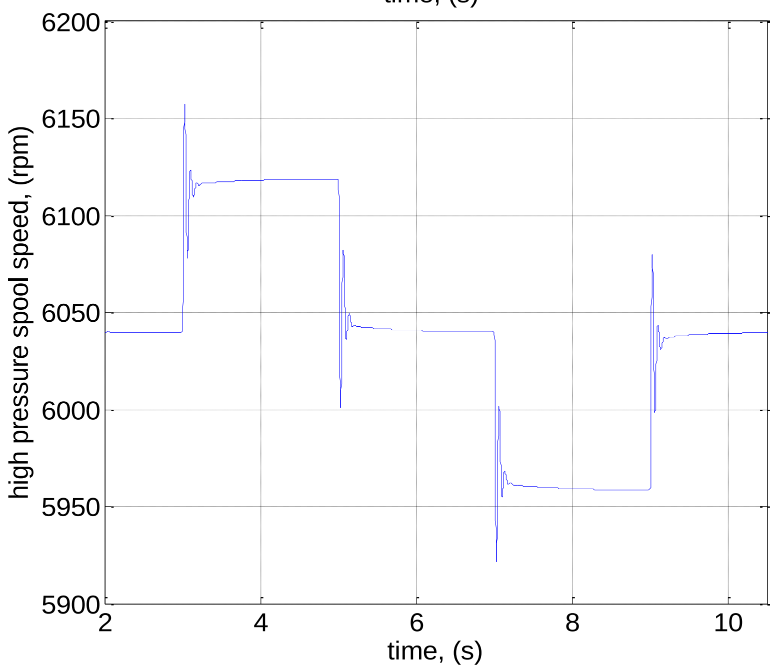
Variable Cycle Engine Model Components



VCE Engine Results







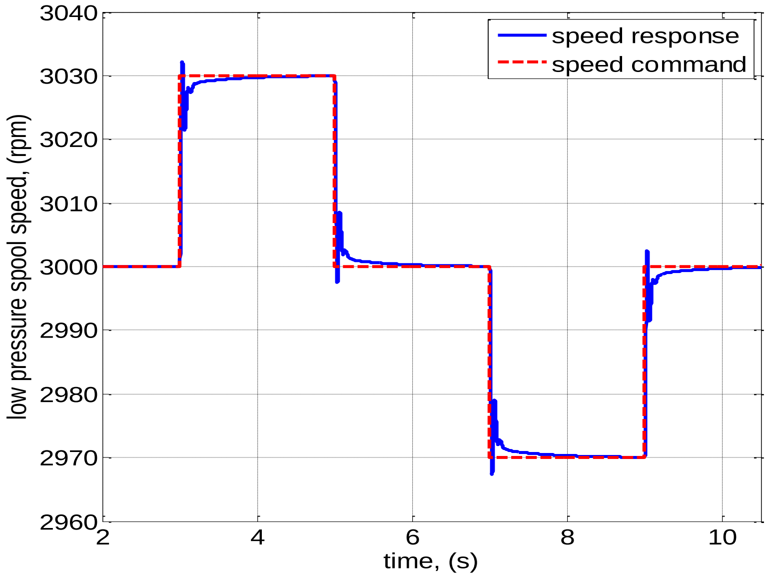
<u>Initial objective is VCE model development</u>

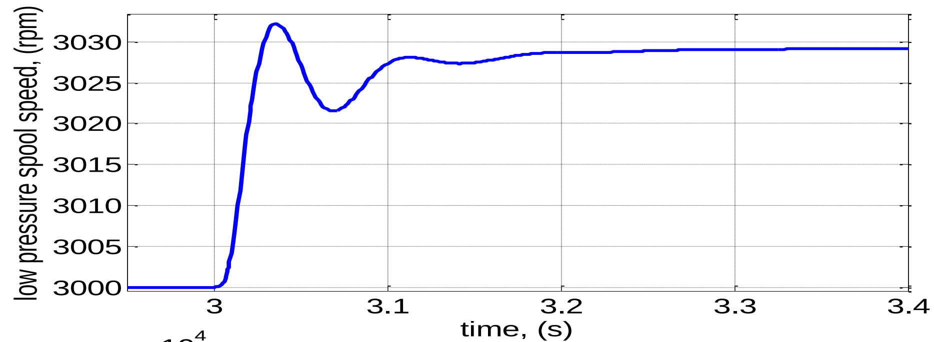
- Control design effort light; hold model together
  -- But designed for higher bandwidth controls for disturbance attenuation

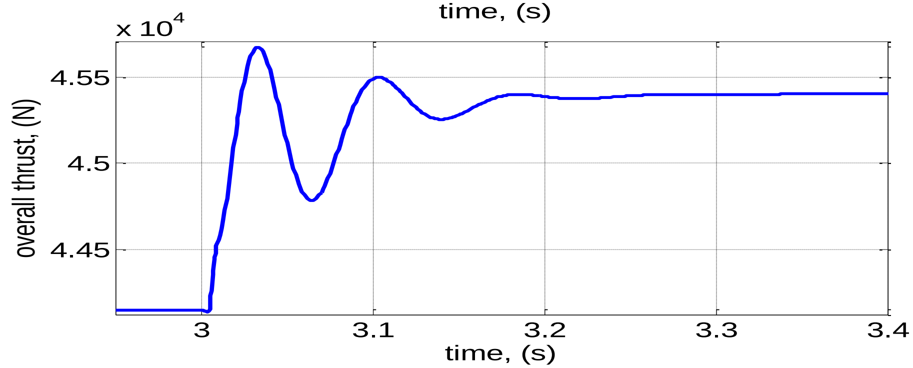
- Engine has higher response capability of ~ 70 rad/sec on high side (~40 rad/sec typically used)

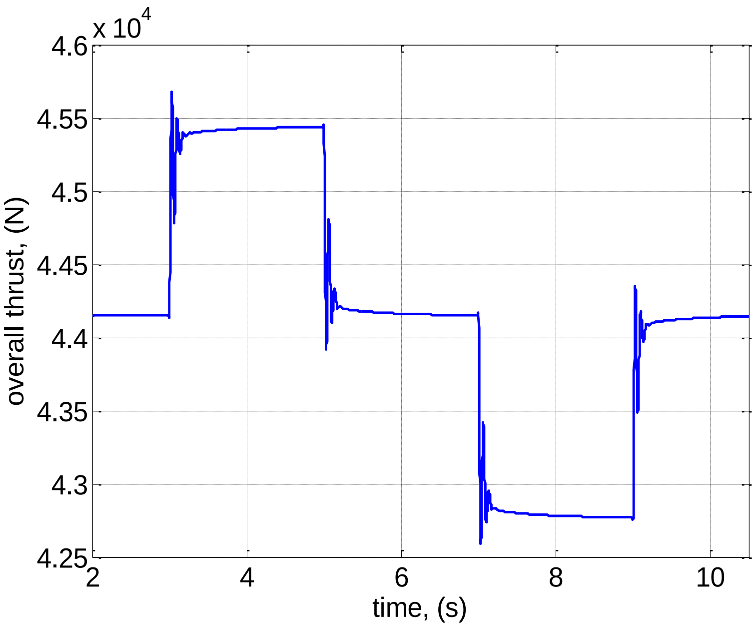
- Potential to use higher response capability to design for better disturbance attenuation, safety margins, and engine efficiency

VCE Engine Speed and Thrust









- Nominal VCE propulsion system thrust 44,100 N or 9,914 lbf
- A 1% change in fan speed causes 2.9% change in thrust
- Thrust response more underdamped – design of speed controller also needs to consider thrust response

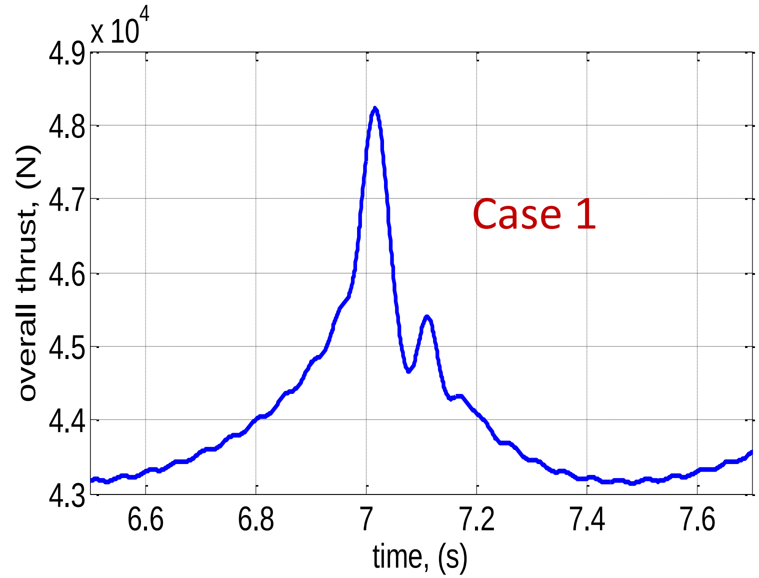
VCE Engine Atmospheric Disturbance and Thrust

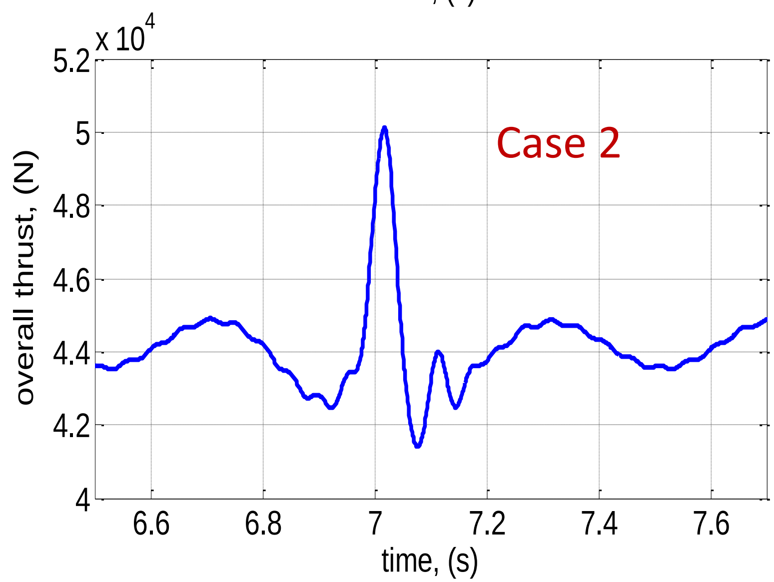
Thrust response w/ Atmospheric Disturbance

With no external compression inlet & no 1D CFD for nozzles

- Case 1; **eddy dissipation rate** 4x average of North Atlantic cruise altitudes; **integral length scale** typical (equivalent to atmospheric turbulence patch size of ~ 11 km); **max locally dissipating wind speeds** 80 mph
  -- Results in thrust variations up to ~ 5000 N or 1124 lb

- Case 2; eddy dissipation rate worst recorded; integral length scale typical; max dissipating wind speeds 150 mph
  -- Results in thrust variation up to ~ 9000N or 2024lb





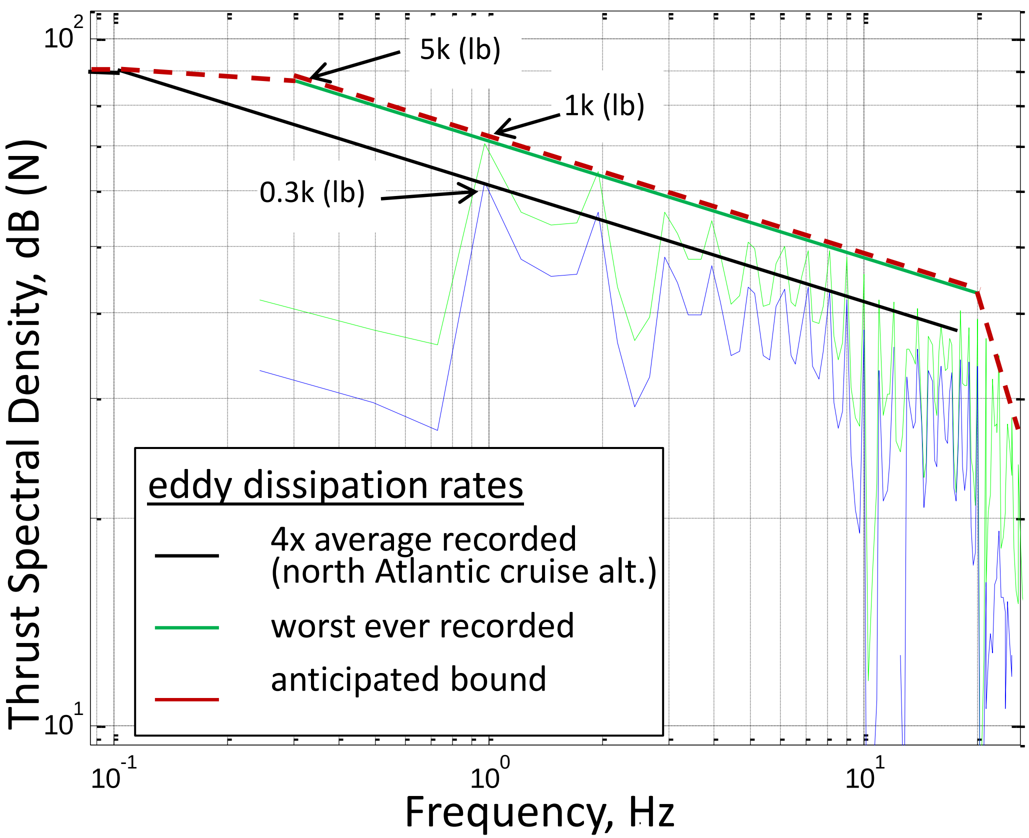
Variable Cycle Propulsion System Studies

<u>Preliminary</u> - Thrust Spectral for Coupling to AeroServoElastic (ASE) Modes

- Study based on V.1 initial variable cycle engine modeling

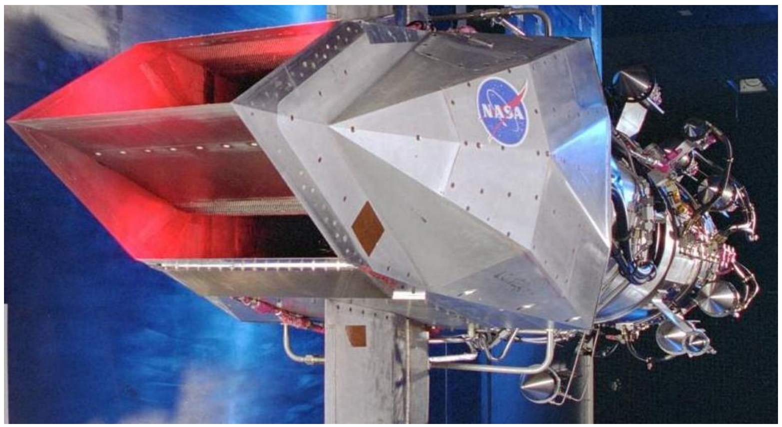
- Atmospheric turbulence model w/ eddy dissipation rates & momentary wind gusts up to 180 mph

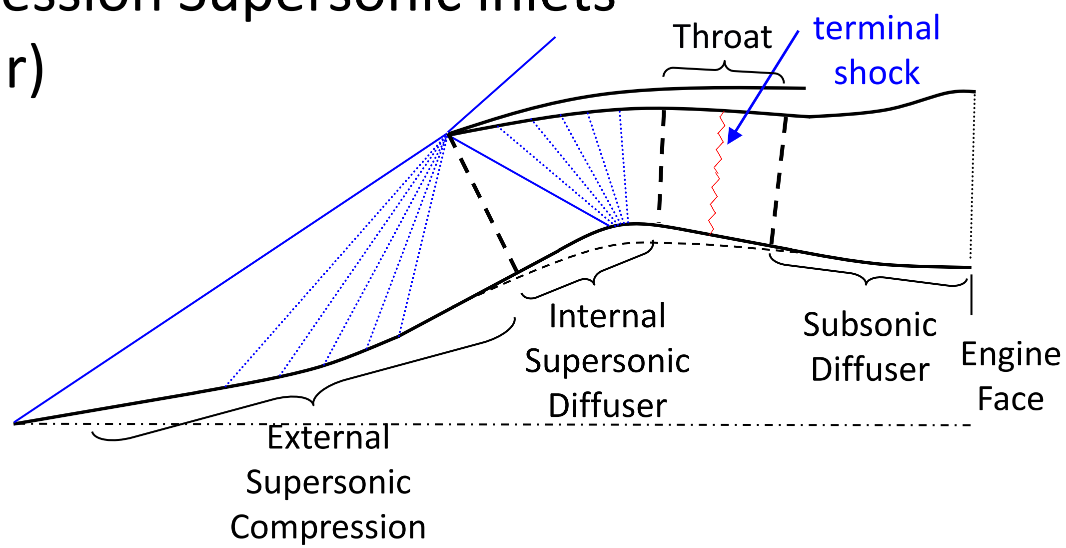
- Study shows potentially significant trust dynamics to warrant detailed APSE modeling and analysis



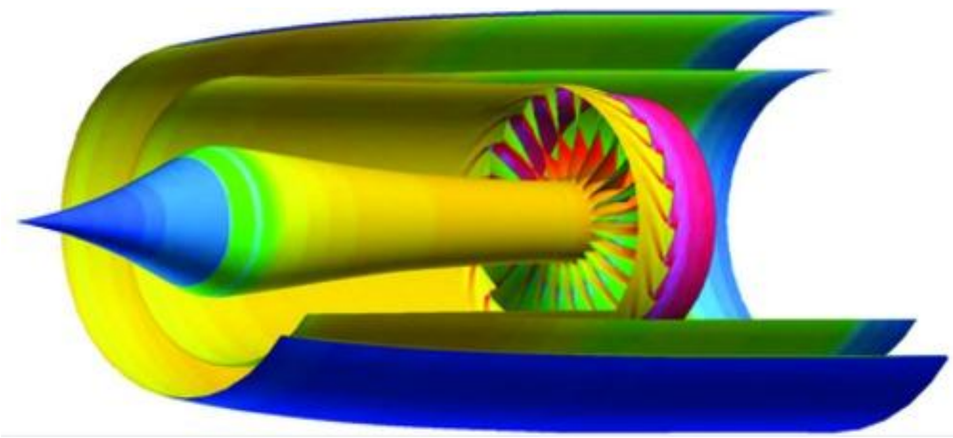
Supersonic Inlets Modeling

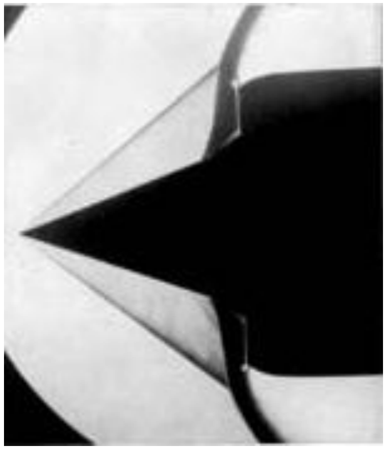
- Started with Mixed Compression Supersonic inlets (results presented last year)





- Now focusing on external compression axisymmetric Inlets
  -- Better overall performance for Mach 1.8 or less





External Compression Inlet Modeling - Approach

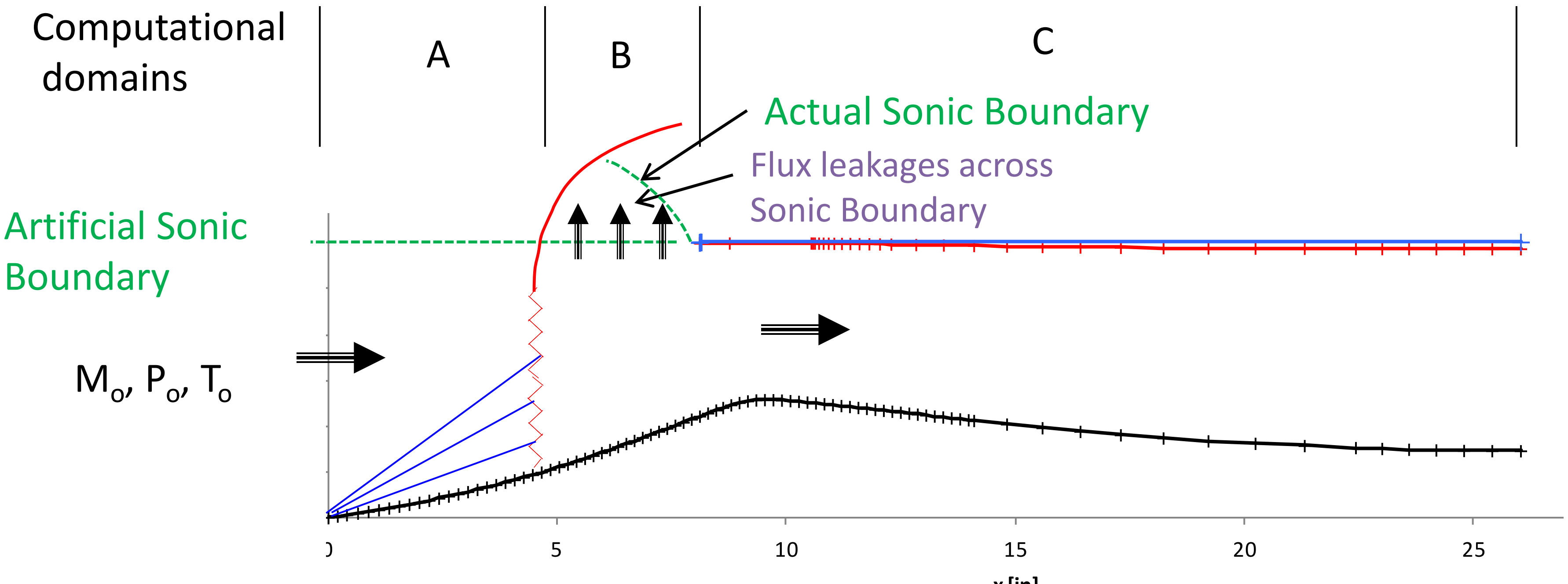
Computational Domain

A. **1-D compressible flow cells w/ flow propagation delay dynamics and averaging flows at shock boundary**

B. **Quasi 1-D CFD compressible flow cells w/ leakage fluxes estimation and artificial viscosity**

C. **Quasi 1-D CFD compressible flow cells w/ artificial viscosity**

A-B. Moving computational domains



Scaled Gulfstream Inlet Geometry - tested at GRC Dec. 2010

External Compression Inlet Modeling – Challenges

Challenges

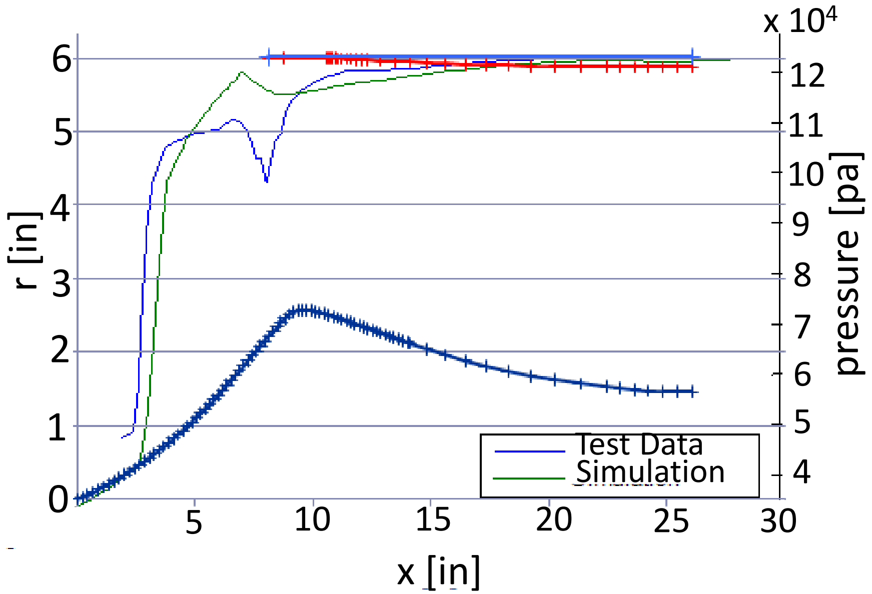
– Developing generalized formulations for conservation flux leakages across sonic boundary – Method hasn't worked yet

– Sensing the shock position to switch between compressible flow cells and quasi 1D CFD cells – Moving Domain

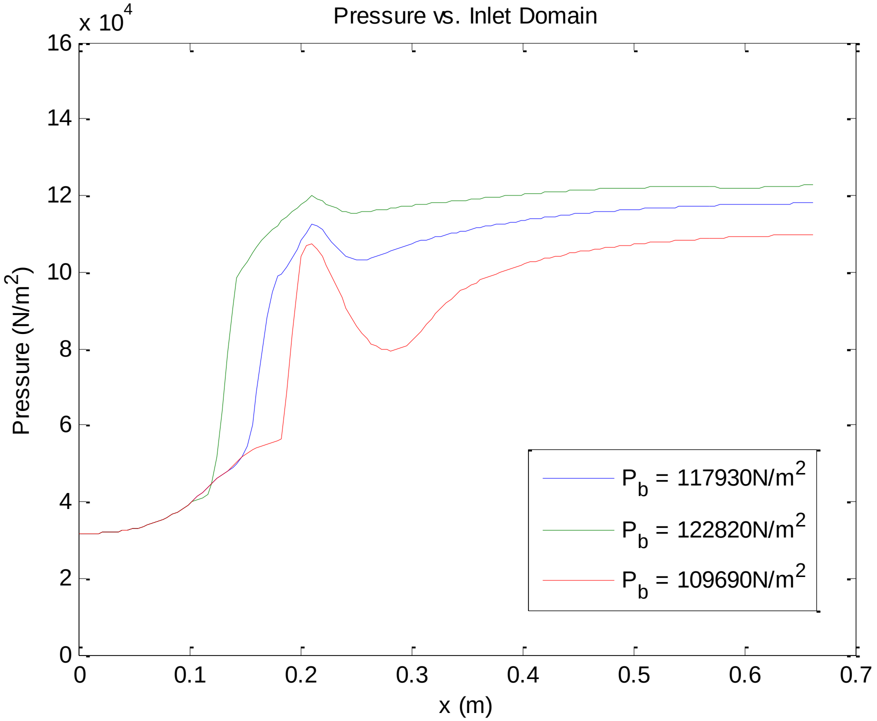
– Determined mass flow leakage based on test data for various engine face back pressures to calculate leakage fluxes – Approach worked but is not generalized

– Remaining issue for inlet dynamics Conical compressible flow field inherently 2D and 3D for pitch variations

External Compression Inlet Results



Comparing test and Simulation Results



Pressure profile by ramping back pressure

Difference In Shock Position

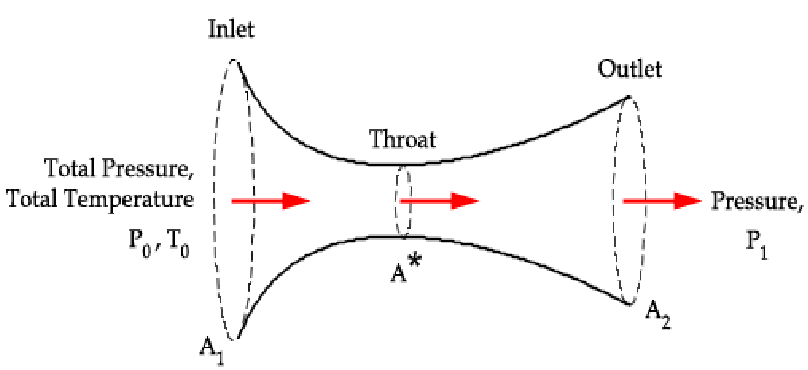
Back Pressure (N/m^2)	Test Data Shock Position (Cell)	Simulation Shock Position (Cell)
109690	41	42
117930	32	34-35
122820	26	28

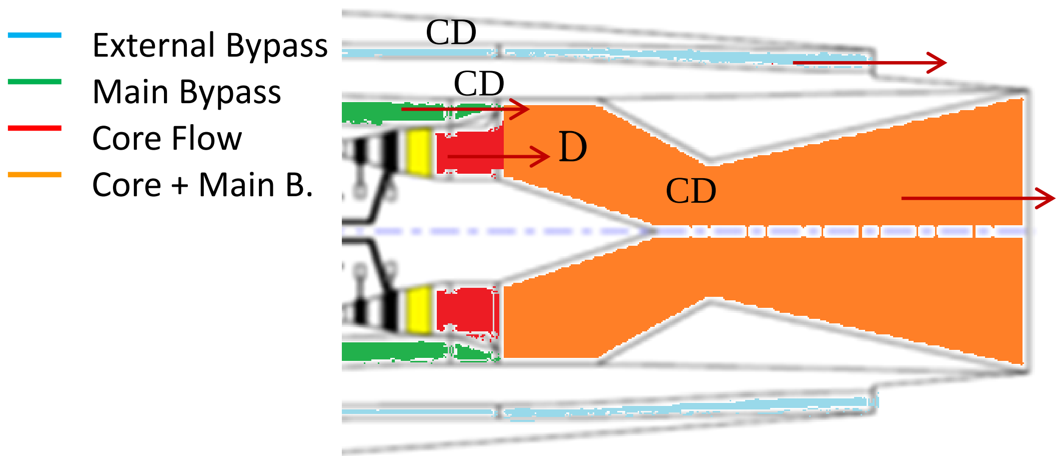
Objective/Approach

- Develop 1D CFD model for exit nozzles for thrust dynamics (before used nozzle lump volume and chocked compressible flow function)
  -- Chosen method: MacCormack's predictor-corrector technique assuming subsonic-supersonic isentropic nozzle flow

- **Step one** - develop model for generic Convergent-Divergent (CD) nozzle geometry – Simple shape profile w/ actual N+3 throat and areas

- **Step two** – develop model for more complex supersonic engine-nozzle concept geometry





CFD Method- Predictor Step

Predictor

$$\left(\frac{\partial \rho}{\partial t}\right)_i^t = -\frac{1}{A}\rho_i^t u_i^t\left(\frac{A_{i+1}-A_i}{\Delta x}\right) - u_i^t\left(\frac{\rho_{i+1}-\rho_i}{\Delta x}\right) - \rho_i^t\left(\frac{u_{i+1}-u_i}{\Delta x}\right)$$

$$\bar{\rho}_i^{t+\Delta t} = \rho_i^t + \left(\frac{\partial \rho}{\partial t}\right)_i^t \Delta t$$

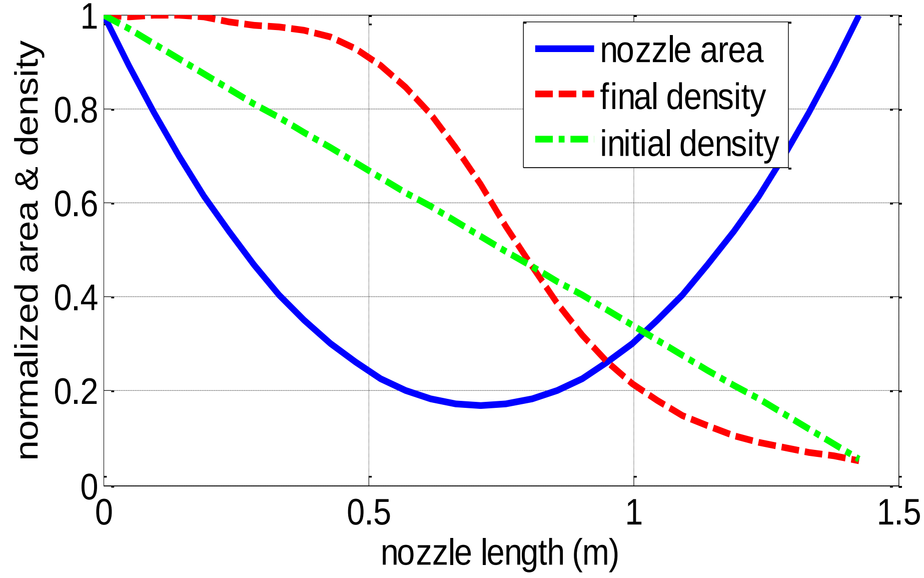
Corrector

$$\overline{\left(\frac{\partial \rho}{\partial t}\right)}_i^{t+\Delta t} = -\frac{1}{A}\rho_i^{t+\Delta t} u_i^{t+\Delta t}\left(\frac{A_i-A_{i-1}}{\Delta x}\right) - u_i^{t+\Delta t}\left(\frac{\rho_i^{t+\Delta t}-\rho_{i-1}^t}{\Delta x}\right) - \rho_i^t\left(\frac{u_i^{t+\Delta t}-u_{i-1}^t}{\Delta x}\right)$$

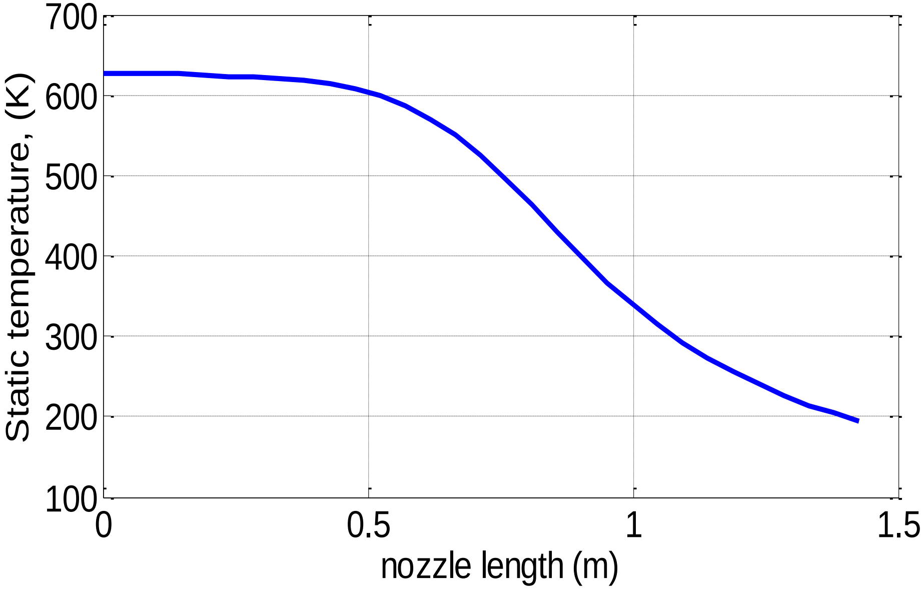
$$\rho_i^{t+\Delta t} = \rho_i^t + \frac{1}{2}\left[\left(\frac{\partial \rho}{\partial t}\right)_i^t + \overline{\left(\frac{\partial \rho}{\partial t}\right)}_i^{t+\Delta t}\right]\Delta t$$

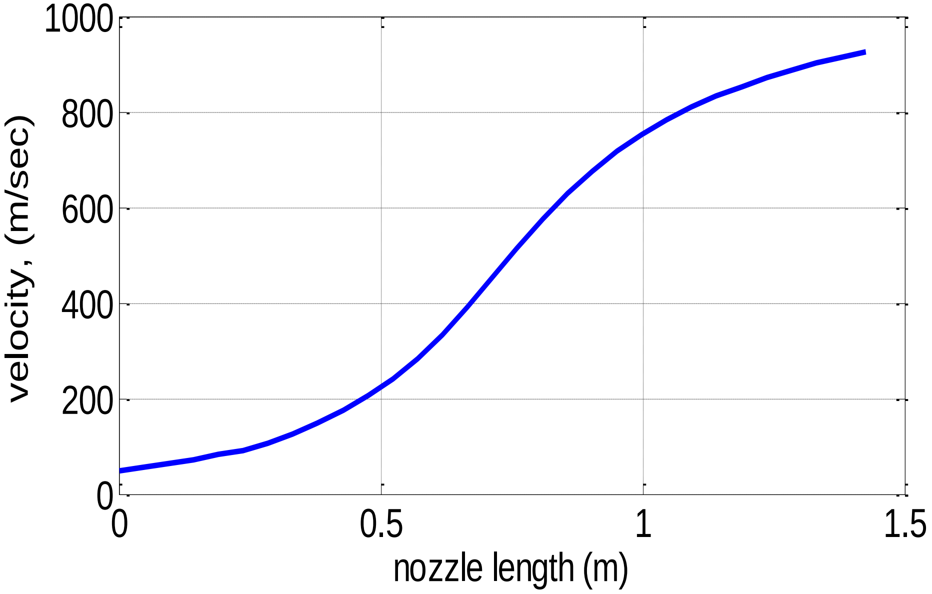
Results

(so far steady state – no freq responses)



- Generic model verified against results reported in literature



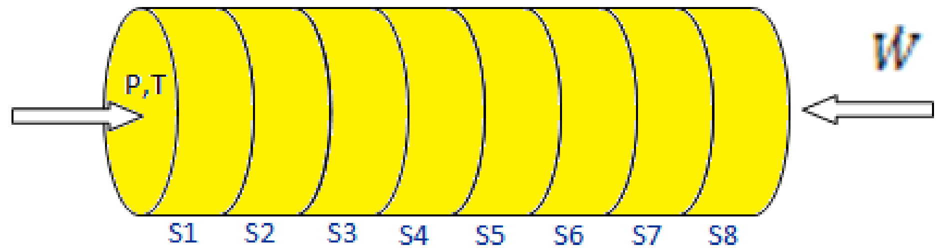


Parallel Compressor Modeling

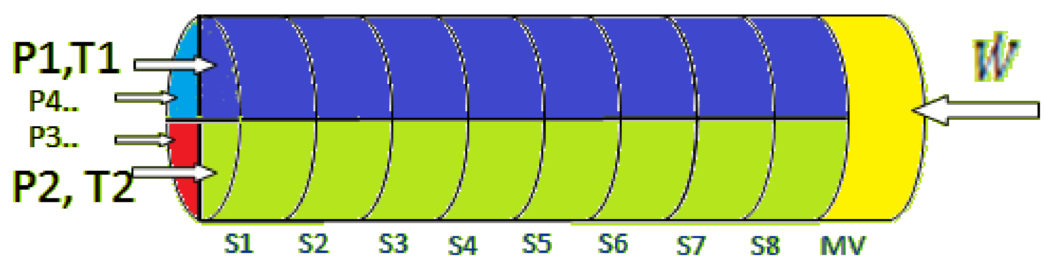
Objective

Develop parallel component flow path models to study effect of distortion on propulsion system dynamics and APSE

- New model derived in cylindrical coordinates - Euler
- Allows modeling of disturbance from changing flight conditions (pitch, yaw, roll, etc)
- Inlet conditions of Pressure, Temperature & outlet conditions of mass flow rate
- Path ratio of βi - scaling mass flow rate of stage maps by path ratio



Original model
Stage-by-stage, single flow path



New Model - Multiple Interacting Flow Paths

Parallel Compressor Modeling Approach

Conservation Dynamics in 2D Cylindrical Coordinates

- Equations were derived in cylindrical coordinates for compressible & inviscid flow, assuming flow properties do not vary in the radial direction

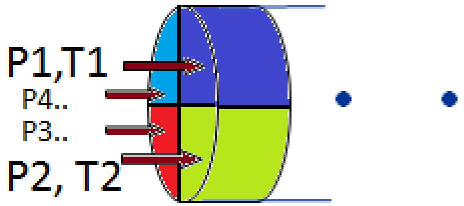
Conservation Equations $$\frac{\partial}{\partial t}(W_j) = -a_{xj}\frac{\partial}{\partial x}(F_{xj}) - a_{\varphi j}\frac{\partial}{\partial \varphi}(F_{\varphi j}) + S_j$$

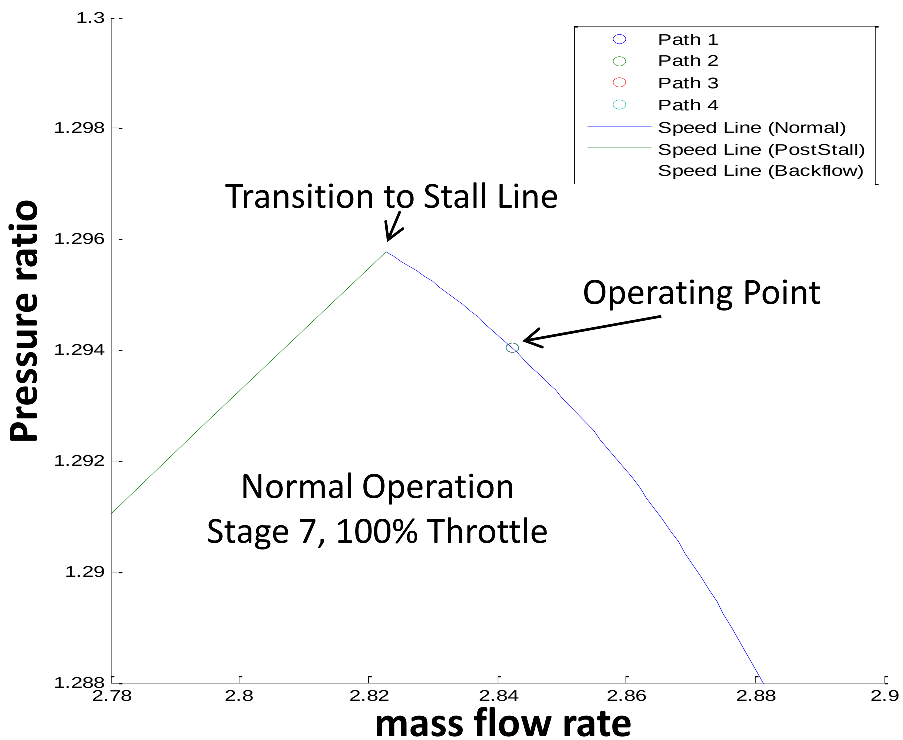
j	Wj	Fxj	Fϕj	Sj	a_{xj}	$a_{\phi j}$
1	ρ_s	$\rho_s u$	$\rho_s w$	0	1	$\frac{1}{r}$
2	$\rho_s u$	$\rho_s u$	$\rho_s u$	$-\frac{\partial P_s}{\partial x}$	u	$\frac{w}{r}$
3	$\rho_s w$	$\rho_s w$	$\rho_s w$	$-\frac{1}{r}\frac{\partial P_s}{\partial \varphi}$	u	$\frac{w}{r}$
4	$\frac{P_s}{\gamma-1}+\frac{\rho_s V^2}{2}$	$\frac{\gamma P_s u}{\gamma-1}+\frac{\rho_s u^3}{2}$	$\frac{\gamma P_s w}{\gamma-1}+\frac{\rho_s w^3}{2}$	0	1	$\frac{1}{r}$

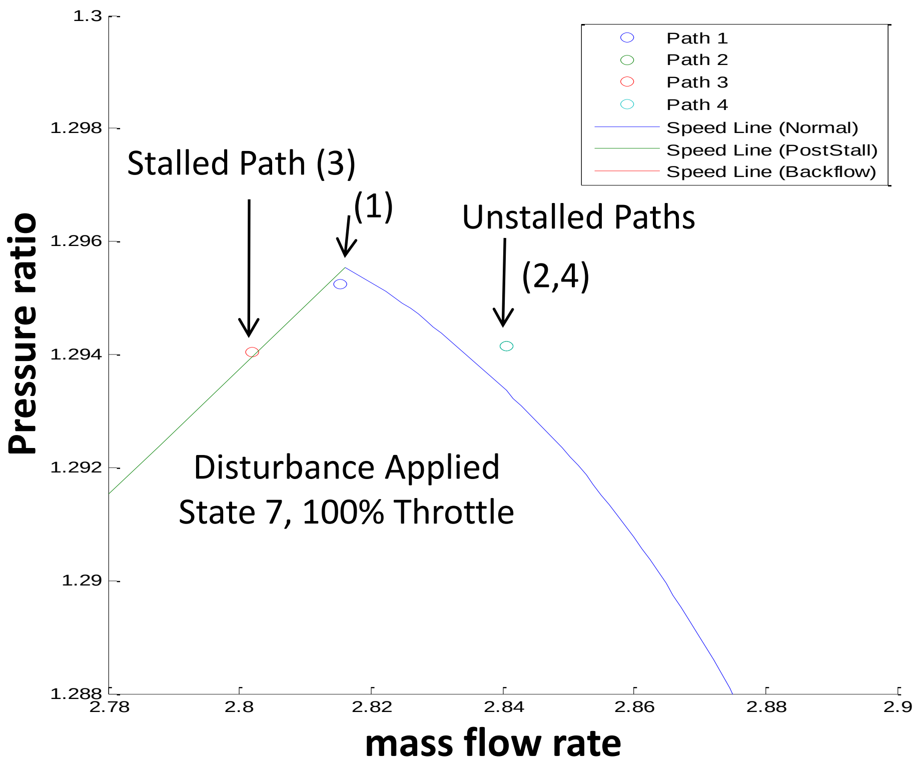
$$\frac{\partial}{\partial t}(W_{j,n,m}) = -a_{xj,n,m}\left(\frac{F_{xj,n+1,m} - F_{xj,n,m}}{\Delta x}\right) - a_{\varphi j,n,m}\left(\frac{F_{\varphi j,n,m+1} - F_{\varphi j,n,m-1}}{2\Delta\varphi}\right) + \frac{S_{j,n,m-1} - S_{j,n,m+1}}{2s}$$

Parallel Compressor Modeling Results

- Pressure distortion of approximately 0.1% applied to path 1



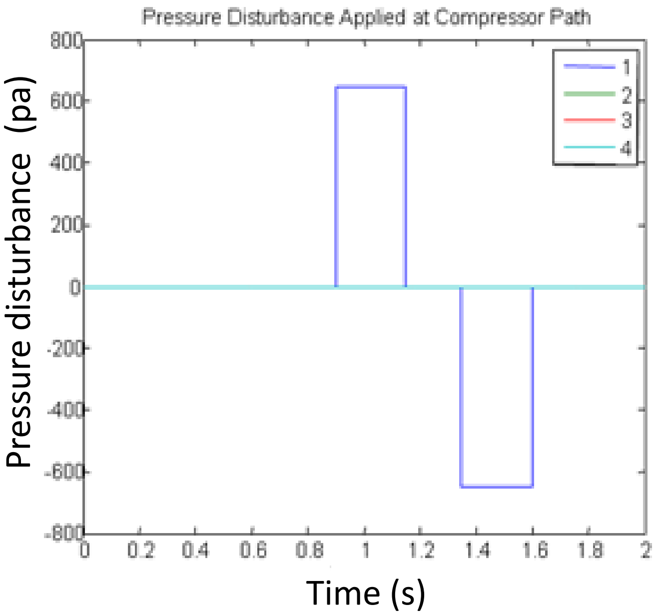


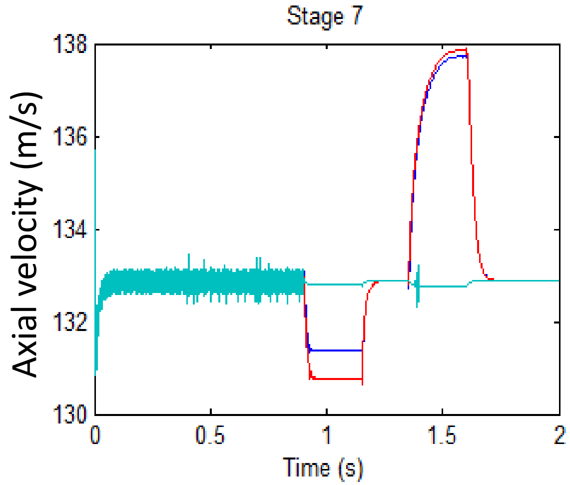


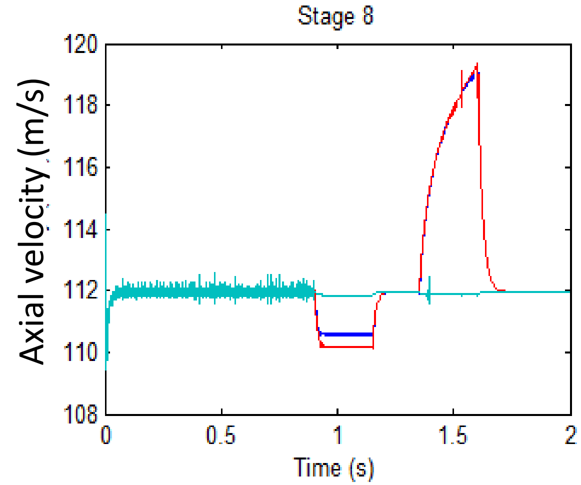
- Pressure disturbance moves Path 1, Path 3 operating points to surge line
- Would experience cascading stall if mass flow rate was not held constant (as with engine)

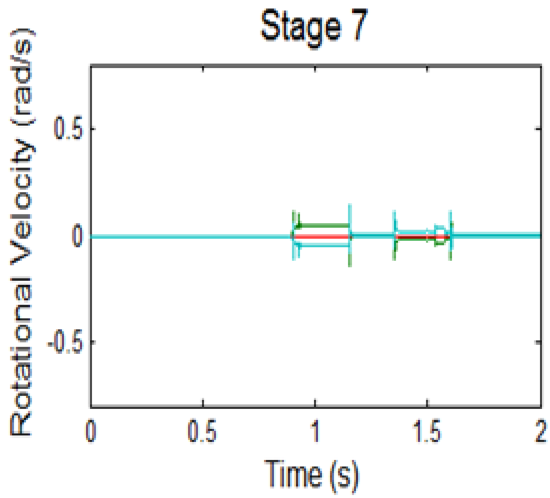
Parallel Compressor Modeling Results

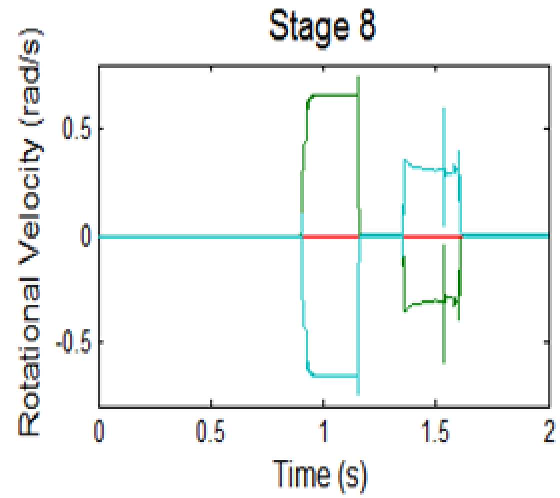
- Square wave distortion applied to compressor input, path 1







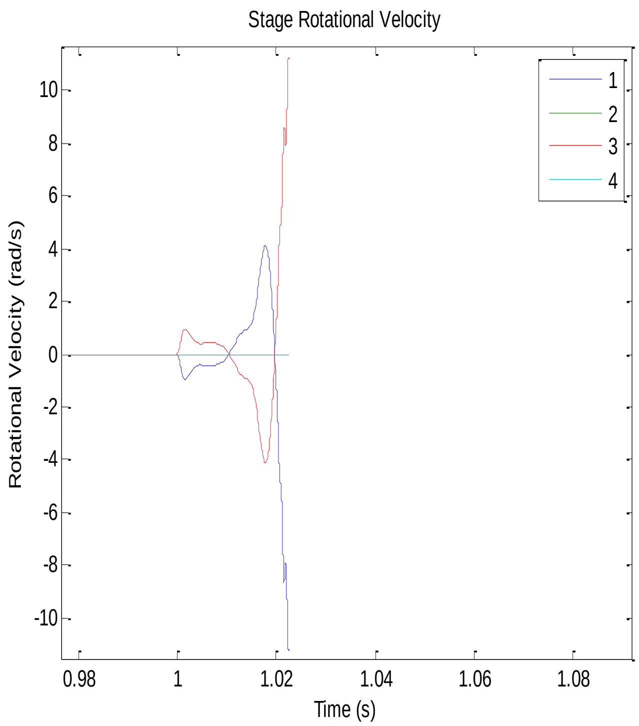


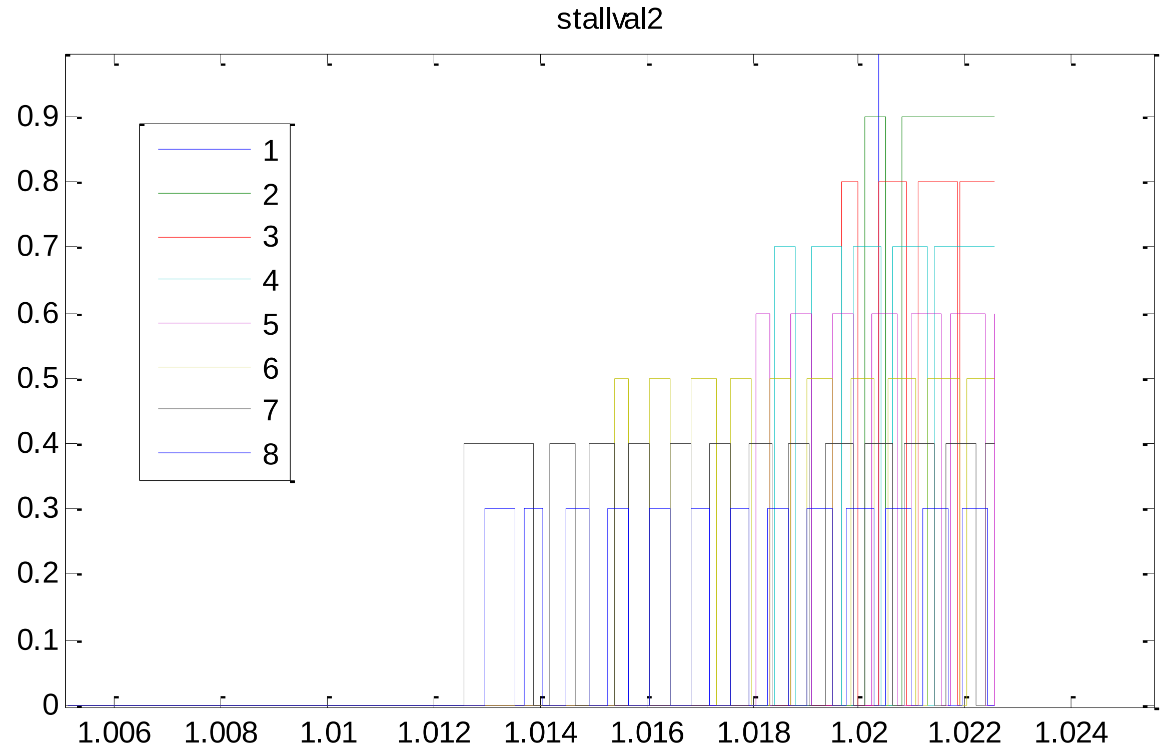


- Pulsating effect of rotational velocity from one stage to the next

Parallel Compressor Modeling Results

1st Stage at 100% Speed w/ 1300pa (0.16%) Distortion on Sector 2 & 4





Stall Pattern – From Back to Front of Compressor

(0 Normal, > 0 Stall)

Conclusion/Future Plans

- Developed first version of VCE model and preliminary analysis
- Develop complete dynamic VCE propulsion system models and control designs (feedback and operation schedules)
- Develop Integrated APSE system models, integrated vehicle controls, and conduct APSE studies
- Close integration between NPSS and APSE (already started)

Additional Possibilities of this Research

- Integrate w/ NPSS to develop a complete cycle deck design and verification package and controls development platform/Rig
- With gas dynamic model explore higher bandwidth controls to reduce stall margins and improve efficiency and design advanced controls to improve flight safety and operability

Publications

1. Kopasakis - Feedback Control Systems Loop Shaping Approach with Practical Considerations, NASA/TM-2007-215007
2. Kopasakis et al. - Volume Dynamics Propulsion System Modeling for Supersonic Vehicles, GT2008-50524, NASA/TM-2008-215172
3. Connolly et al. - Turbofan Volume Dynamics Model for Investigation of Aero-Propulso-Servo-Elastic Effects in a Supersonic Commercial Transport, AIAA-2009-4802
4. Kopasakis et al. - Shock Positioning Controls Design for a Supersonic Inlet, AIAA-2009-5117
5. Kopasakis et al. - Volume Dynamics Propulsion System Modeling for Supersonic Vehicles, *Journal of Turbomachinery* (Vol. 132, October 2010)
6. Kopasakis - Atmospheric Turbulence Modeling for Aero Vehicles- Fractional Order Fits, NASA/TM-2010-216961
7. Kopasakis - Modeling of Atmospheric Turbulence as Disturbance for Control Design and Evaluation of High Speed Propulsion, GT2010-22851
8. Connolly et al. – Loop Shaping Control Design for a Supersonic Propulsion System Model Using QFT Specifications and Bounds” AIAA-2010-7068
9. Connolly et al. - Nonlinear Dynamic Modeling and Controls Development for Supersonic Propulsion System Research, AIAA 2011-5635.
10. Kopasakis - Modeling of Atmospheric Turbulence as Disturbance for Control Design and Evaluation of High Speed Propulsion, *Journal of Dynamic Systems* (vol. 134, issue 2, 2012).
11. Kopasakis et al. - Quasi 1D Modeling of Mixed Compression Supersonic Inlets, AIAA 2012-0775.
12. Kopasakis et al. - Quasi One-Dimensional Unsteady Modeling of External Compression Supersonic Inlets, AIAA, JPC, 2012 (pending).

NASA