National Aeronautics and Space Administration

Fundamental Aeronautics Program

Supersonics Project

ASE/APSE Overview

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Cleveland, Ohio

What is the problem? Why is it hard? How is it solved today?

- These are the problems:
  - Supersonic flight offers the potential of short flight times across continents
  - BUT Supersonic flight demands highly optimized performance amongst all relevant disciplines (structures, aerodynamics, propulsion, controls, environment, noise)
  - If just one of the disciplines does not perform as required, supersonic flight becomes inefficient and irrelevant
  - Integration of aerodynamics, propulsion, controls, and structures (Aero-Propulso-Servo-Elasticity) is one of these primary integration challenges
- This is why it is hard:
  - Currently there are no supersonic transports in operation therefore there is no experience or database from which to draw on to analyze, design, and build new and efficient concepts
- How is it solved today?
  - Limited (if any) solutions for efficient supersonic flight including ASE
  - Current ASE models DO NOT include propulsion performance and vice versa

Enhanced Project Goals

- Phase I: Aero-Propulso-Servo-Elasticity (APSE)
  - Focus on use of SemiSpan SuperSonic Transport (S4T) for Experimental and Computational Tasks
  - Performed multiple aeroelastic/aeroservoelastic open- and closed-loop wind-tunnel tests (TDT)
  - Performed several linear and CFD-based aeroelastic analyses
  - NRA contractors performed ASE control law designs
  - FY2005 - FY2010
  - Primary focus of today's presentation

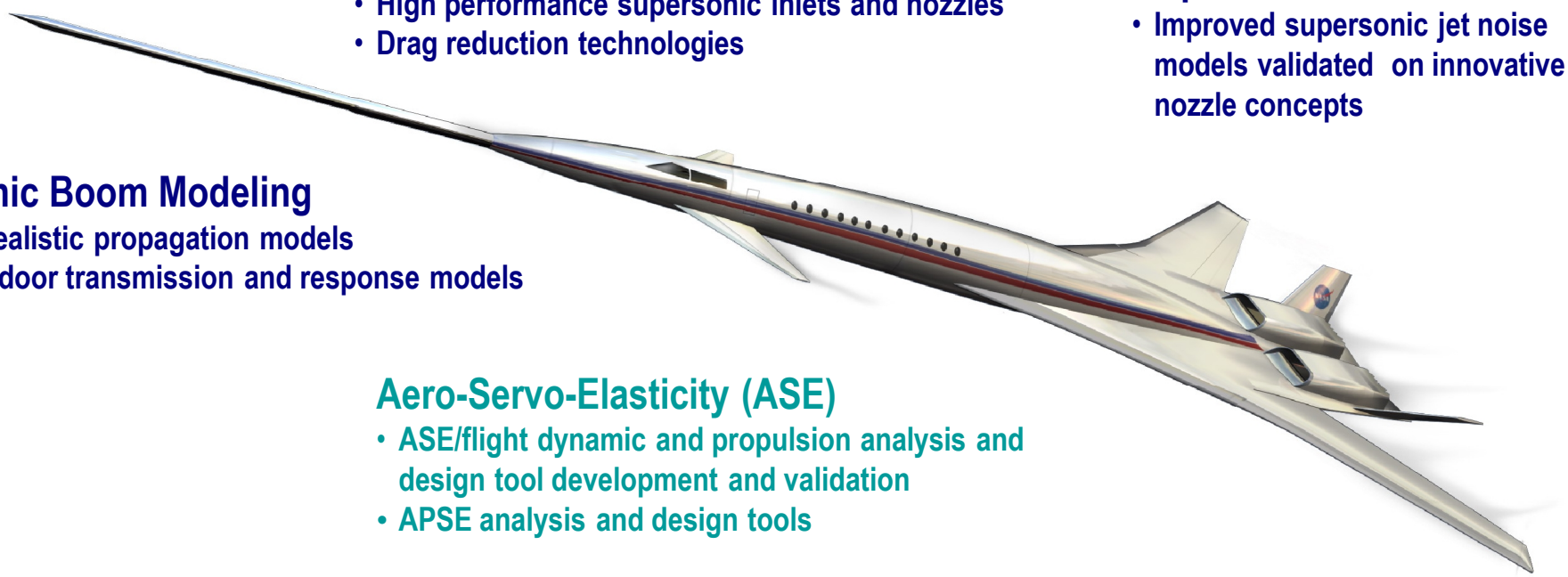
- Phase II: Aeroservoelasticity (ASE)
  - Shift focus to computational modeling of a full-span configuration (N+2, N+3)
  - Working to identify/define suitable FEM
  - Working with available CFD grids
  - Tasks now include: CFD Aeroelasticity, Reduced-Order Models (ROMs), APSE (GRC), Advanced Flight Simulator (AFS), and MDAO
  - FY2011 – FY2016

Supersonics Project Technical Elements

Deliver Knowledge, Capabilities, and Technologies Addressing Supersonics Challenges

Cruise Efficiency
- Improved prediction of cruise drag and sonic boom
- High performance supersonic inlets and nozzles
- Drag reduction technologies

Airport Noise
- Improved supersonic jet noise models validated on innovative nozzle concepts



Sonic Boom Modeling
- Realistic propagation models
- Indoor transmission and response models

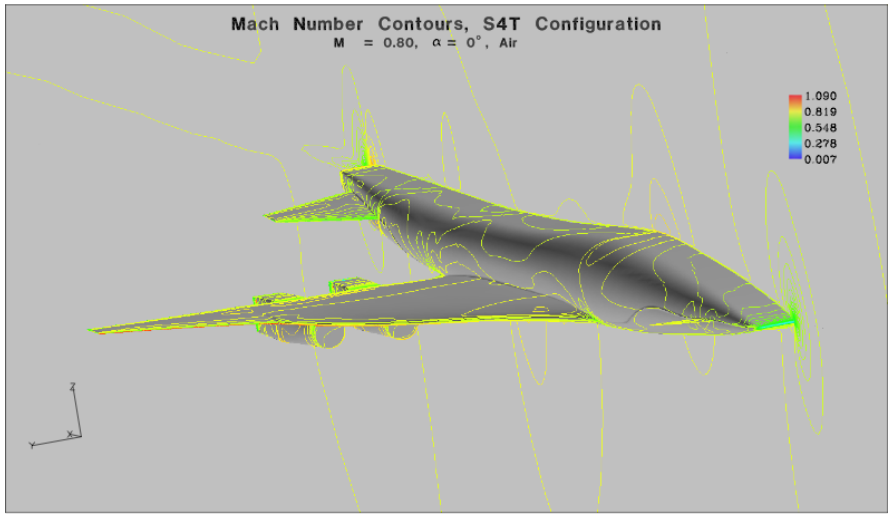
Aero-Servo-Elasticity (ASE)
- ASE/flight dynamic and propulsion analysis and design tool development and validation
- APSE analysis and design tools

Light Weight and Durability at High Temperature
- Materials, test and analysis methods for airframe and engine efficiency, durability and damage tolerance

High Altitude Emissions
- Improved prediction tools
- Low emissions combustors

Pervasive Technologies
- Multifidelity/Multidisciplinary analysis and design
- Experimental capabilities

APSE Tasks

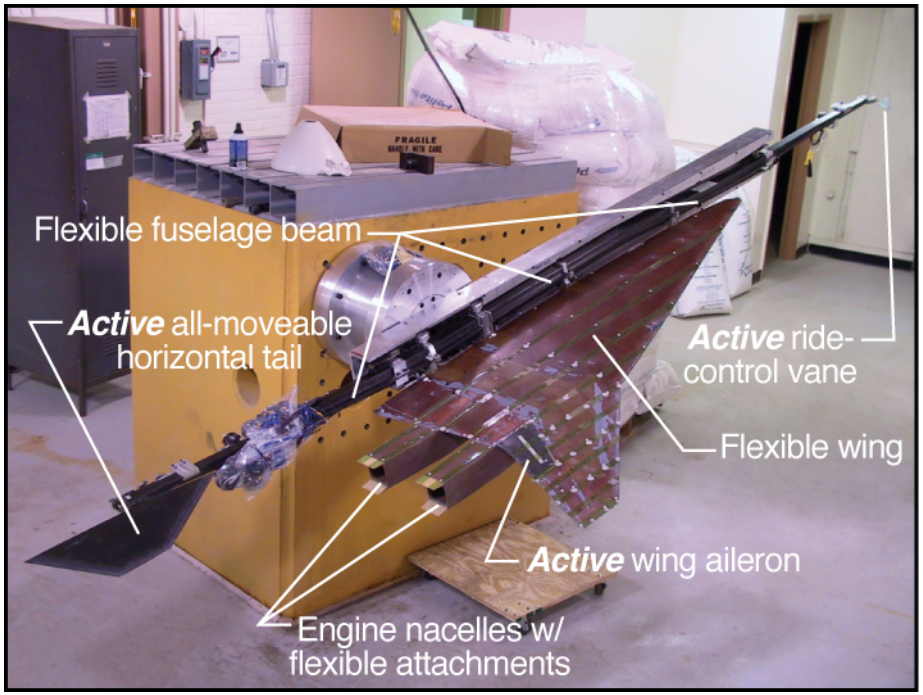




Computational Task
S⁴T configuration

Experimental Task
S⁴T wind-tunnel model

Wind-Tunnel Model
Semispan Supersonic Transport (S^4T)



Model designed and fabricated during NASA High Speed Research program

Model Component Features:
- Flexible fuselage beam
- Fiberglass-epoxy-over-honeycomb wing

Model Dimensions:
- 16.5-foot fuselage length
- 3.25-foot model span

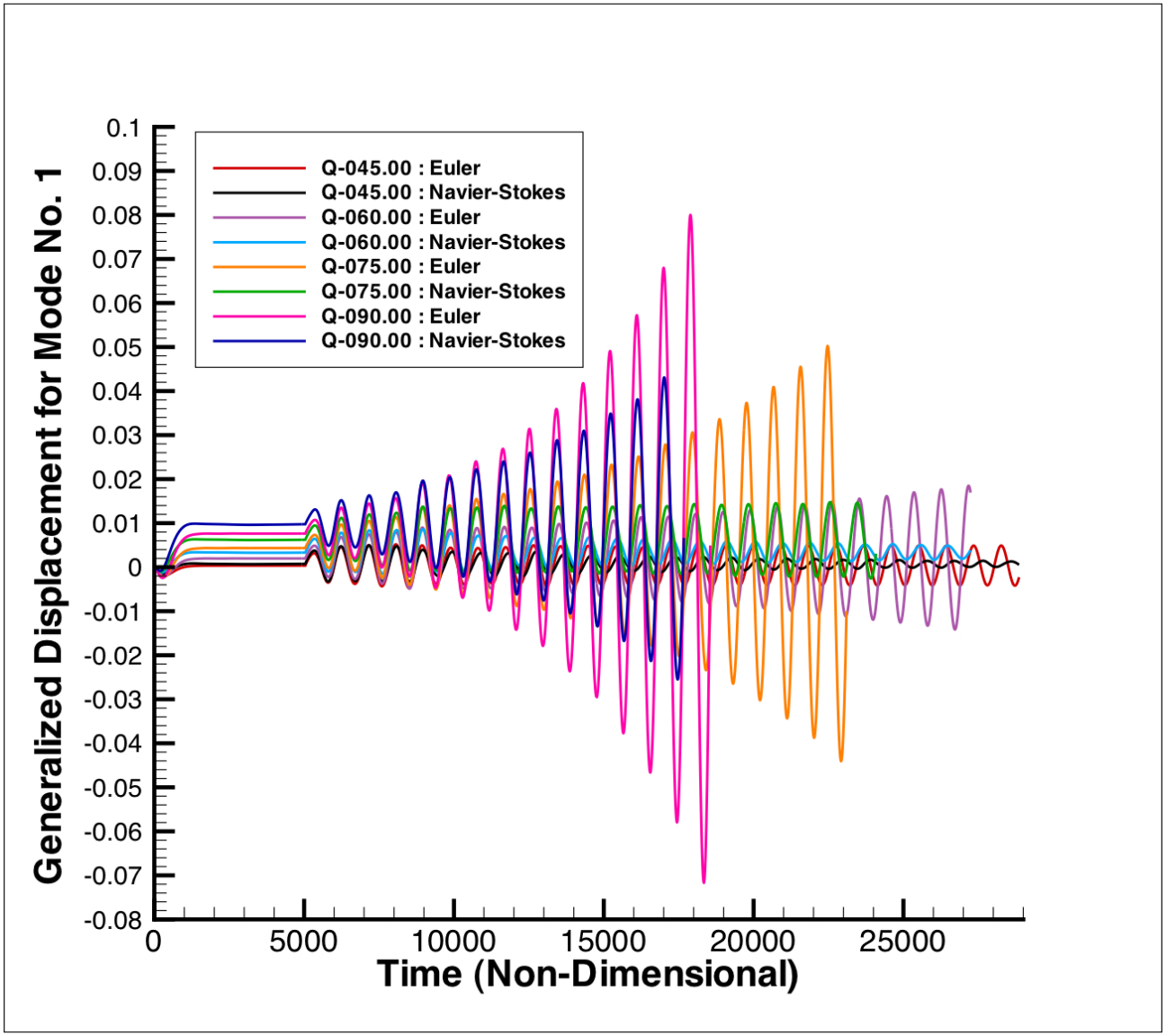
Engine Nacelles:
- Variable mass
- Variable attachment stiffness

Three active surfaces:
- Ride control vane
- Aileron
- Horizontal tail

Computational Task

- Inviscid CFL3D aeroelastic calculations for M = 0.80, 0.95, and 1.10 for several dynamic pressures
- Viscous CFL3D aeroelastic calculations for M = 0.80, 0.95, and 1.10 for several dynamic pressures
- All aeroelastic computations using 1% structural damping
- Actual structural damping ~ 2% - 3%
- Creation of aeroelastic ROMs for comparison with full CFD solutions and rapid parametric variations (damping, modal freqs, etc)
- Continued development of dynamic engine models (GRC) for integration with ASE math models

Dynamic Aeroelasticity (M=0.95)



Flutter Predictions

Linear

Mach No.	0.80	0.95	1.10
Q, psf	75.0	72.0	100.0

Inviscid CFL3D

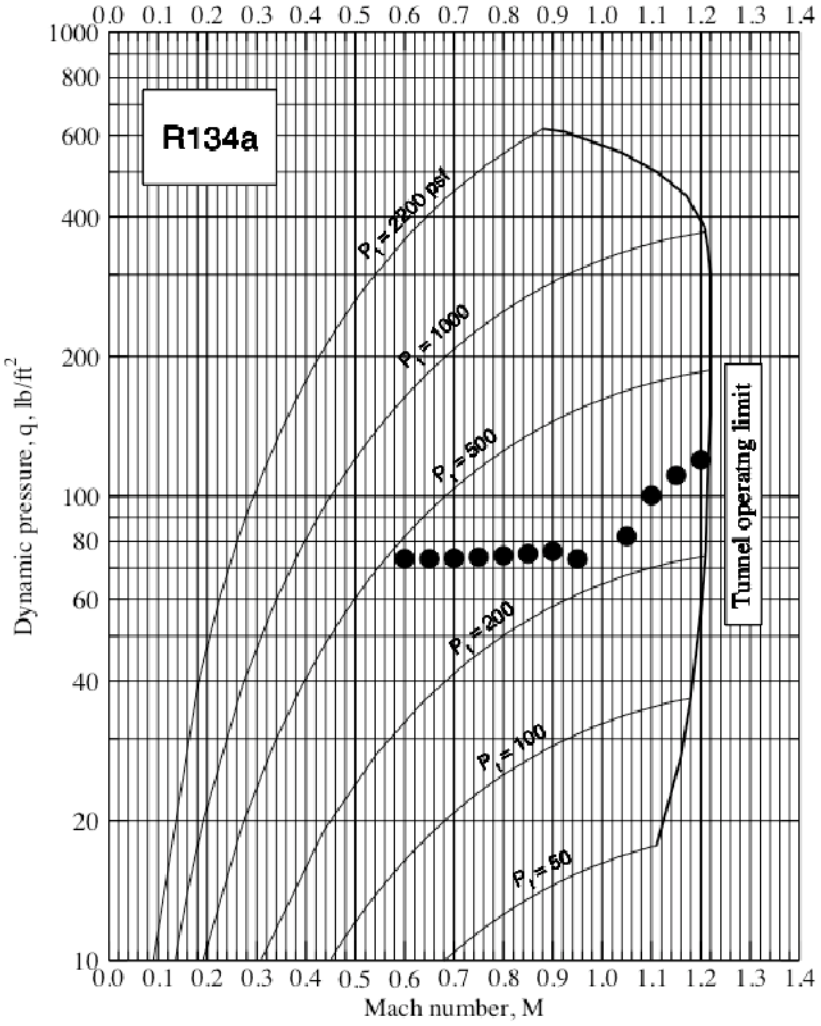
Mach No.	0.80	0.95	1.10
Q, psf	75.0	45.0	120.0

Viscous CFL3D

Mach No.	0.80	0.95	1.10
Q, psf	82.50	75.0	120.0

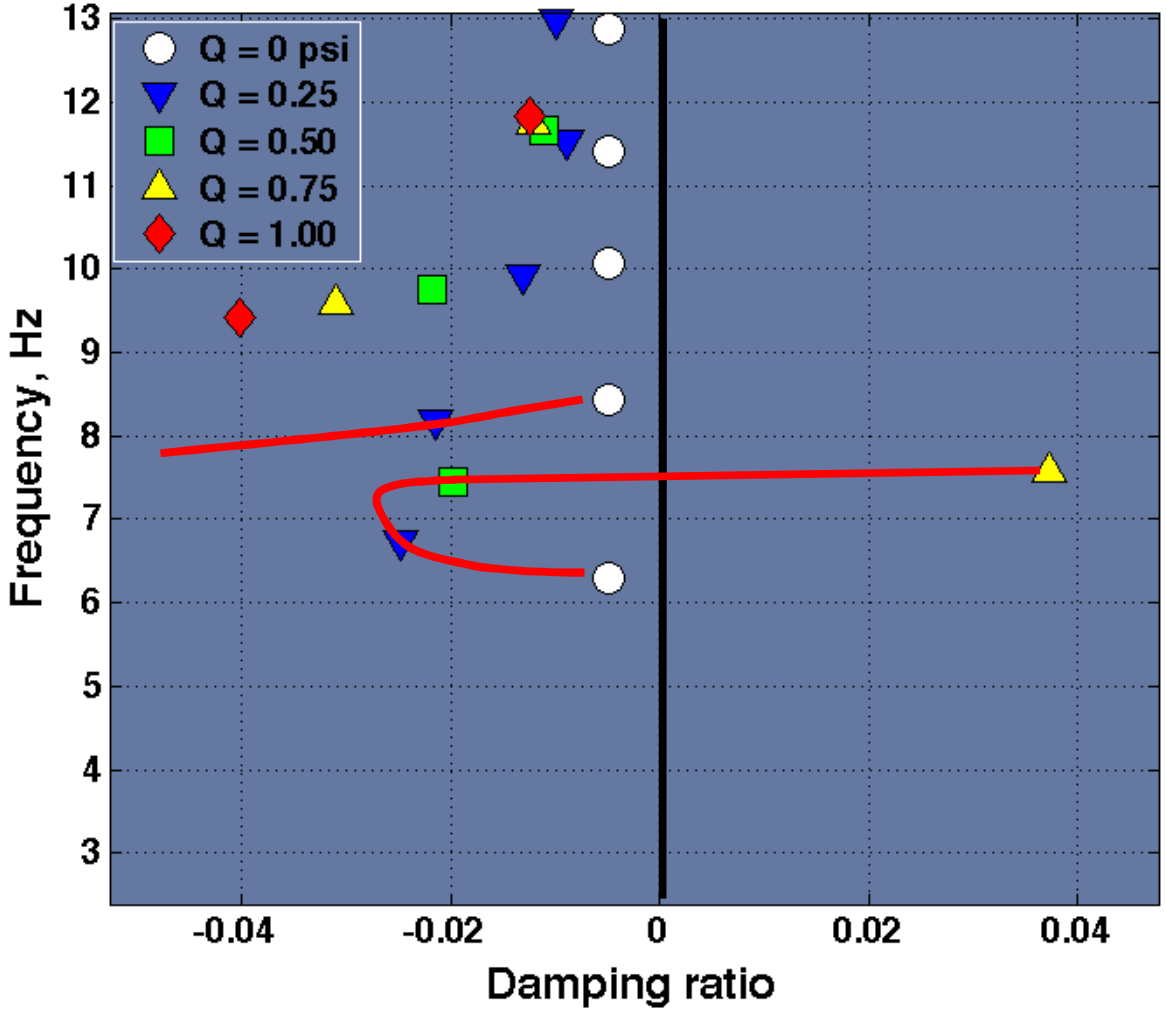
Experiment?

Linear Flutter Predictions



Reduced-Order Model Result for M=0.80

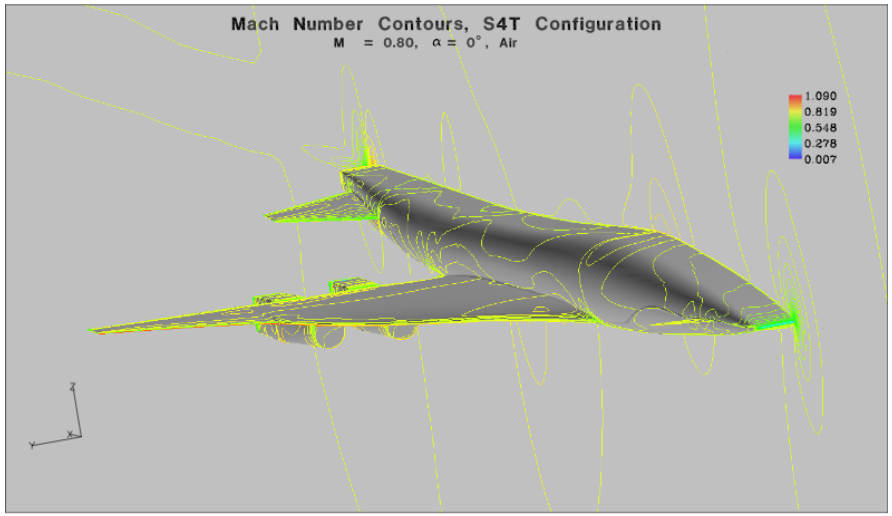
Root Locus - Zoomed



CFL3D-ROM:
Q=78 psf, 1% damp

CFL3D-viscous:
82.5 psf, 1% damp

APSE Tasks





Computational Task
S⁴T configuration

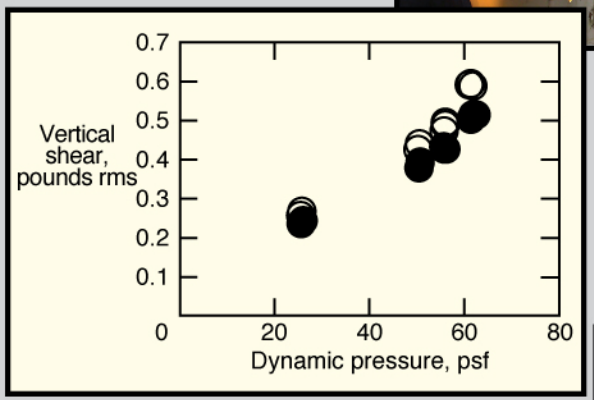
Experimental Task
S⁴T wind-tunnel model

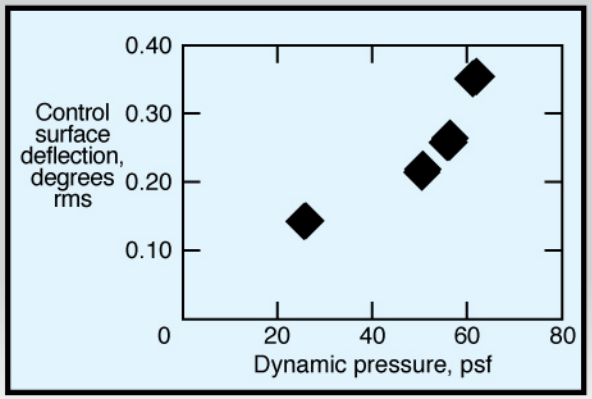
Gust-Load-Alleviation Systems Reduce Transonic Gust Loads on S⁴T Wind-Tunnel Model

Mach Number = 0.95

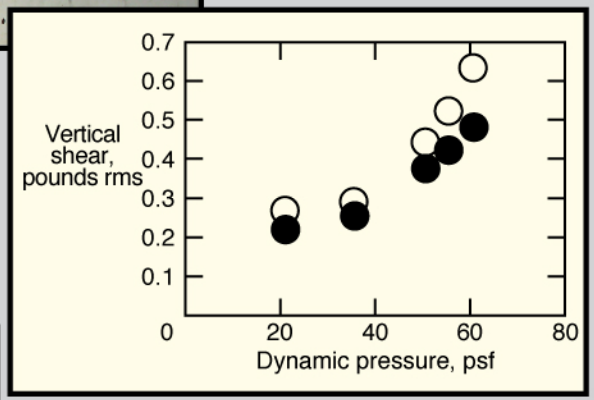


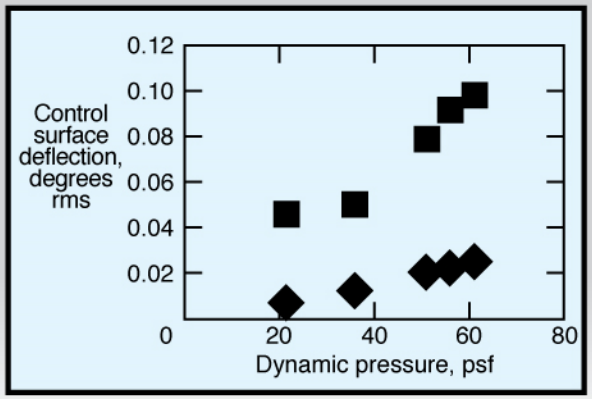
GLA Results for NRA Partner #1



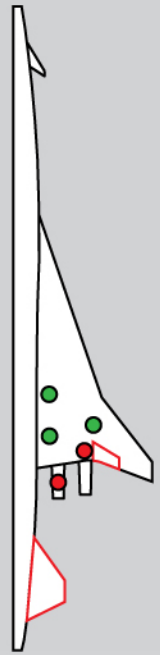


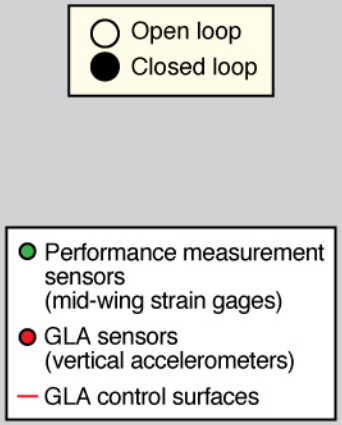
GLA Results for NRA Partner #2









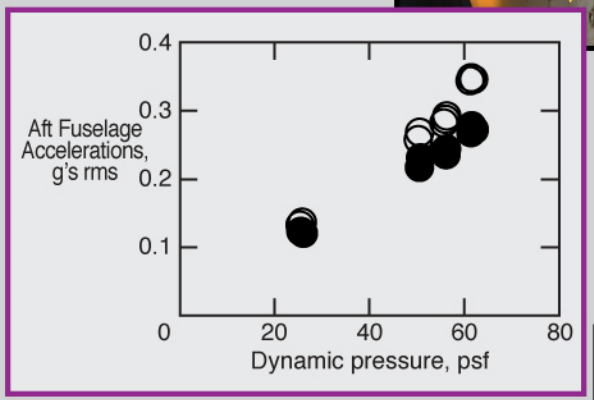


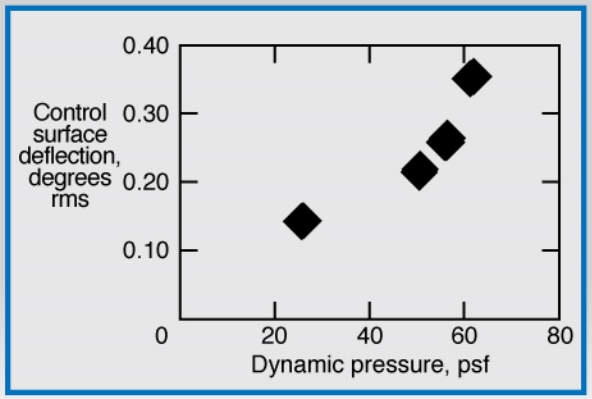
Ride Quality Enhancement Systems Reduce Fuselage Response on S⁴T Wind-Tunnel Model

Mach Number = 0.95



RQE Results for NRA Partner #1



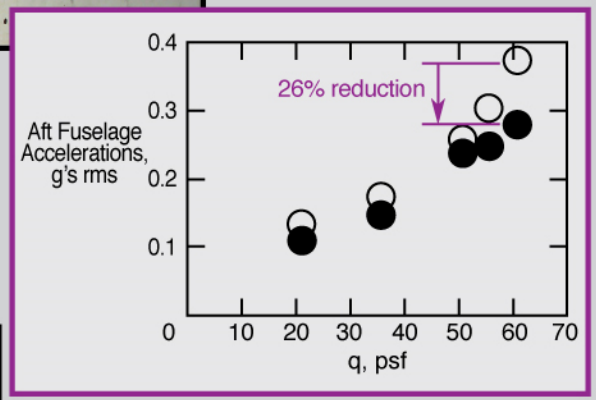


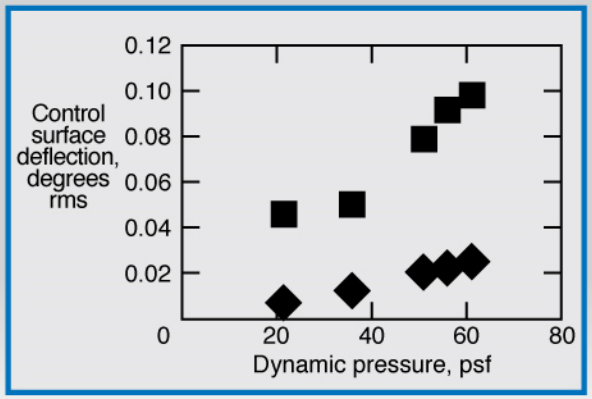
Open loop
Closed loop

Performance measurement sensors (fuselage accelerometers)
RQE sensors (vertical accelerometers)
RQE control surfaces

Aileron
Horizontal tail

RQE Results for NRA Partner #2









Successful Advancement Beyond Open-Loop Flutter

Objective

- Advance beyond open-loop flutter boundaries using flutter suppression control laws
- Identify the open-loop flutter boundary while operating in a safe, closed-loop mode

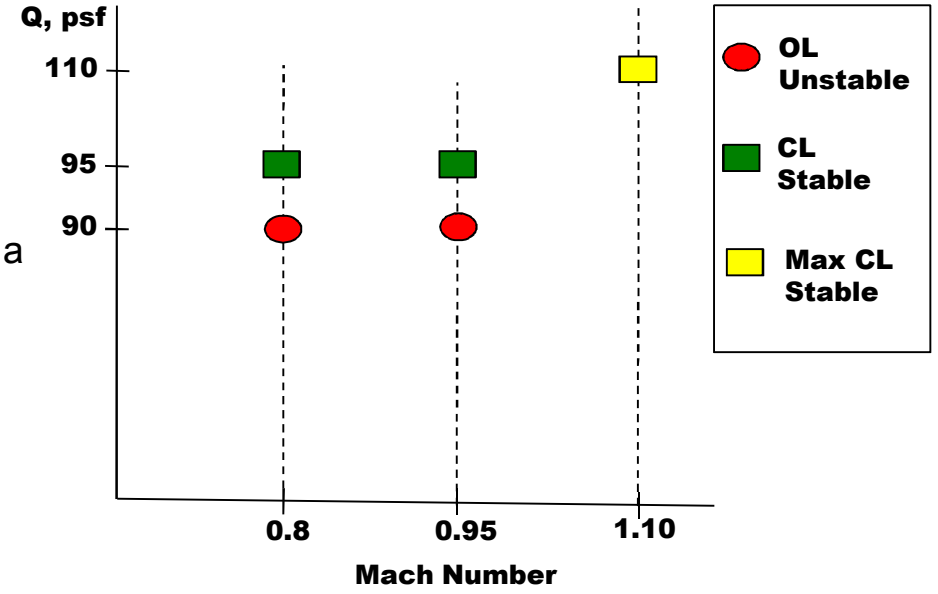
Approach

- Use the SemiSpan SuperSonic Transport (S4T) wind-tunnel model with active controls
- Perform the aeroservoelastic (ASE) test in the TDT
- Use flutter suppression control laws from the first closed-loop test
- While in closed-loop mode, carefully increase dynamic pressure until open-loop flutter point identified using Nyquist stability methods

Significance

- Improved understanding of the flutter boundary of a supersonic configuration
- Provided valuable experience in real-time closed-loop testing
- Will enable improved design of flutter suppression control laws for advanced supersonic configurations





Flutter Q Comparisons



Inviscid

Mach No.	0.80	0.95	1.10
Q, psf	75.0	45.0	120.0

Viscous

Mach No.	0.80	0.95	1.10
Q, psf	82.50	75.0	120.0

Experiment

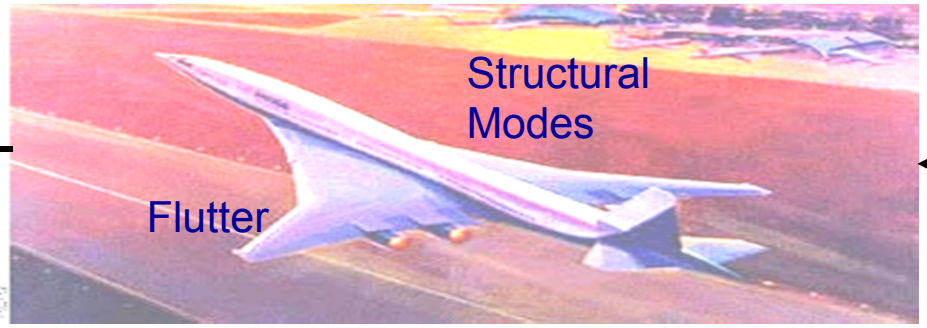
Mach No.	0.80	0.95	1.10
Q, psf	90.0	90.0	NA

Experimental Task

- **Important milestones completed**
- Successfully completed closed-loop tests of S^4T wind-tunnel model
- Successful tests involving a highly complex wind-tunnel model and a multi-organizational team
- Acquired open- and closed-loop data at M=0.80, 0.95, and 1.10 at multiple dynamic pressures
- Performance metrics identified and measured
- Most control laws provided improved ride quality, gust load alleviation, and flutter suppression
- Results were presented by M4 Engineering and Zona Technology at SDM conferences

Introduction: What is APSE?

Aero-Propulso-Servo-Elasticity



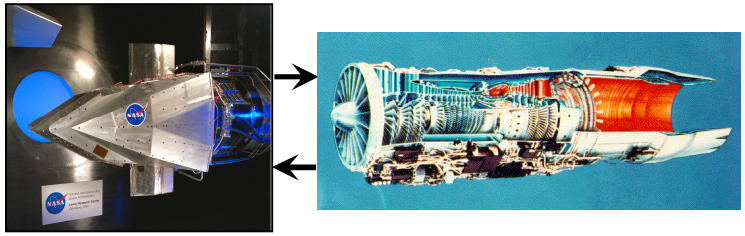
Aero-Servo-Elasticity

Thrust
Variations

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

APSE Flow
Disturbances

External Flow
Disturbances



Propulsion

- Cruise Efficiency

Design and Analysis

Integrated APSE Model
(collaboration with GRC)

APSE Propulsion Team

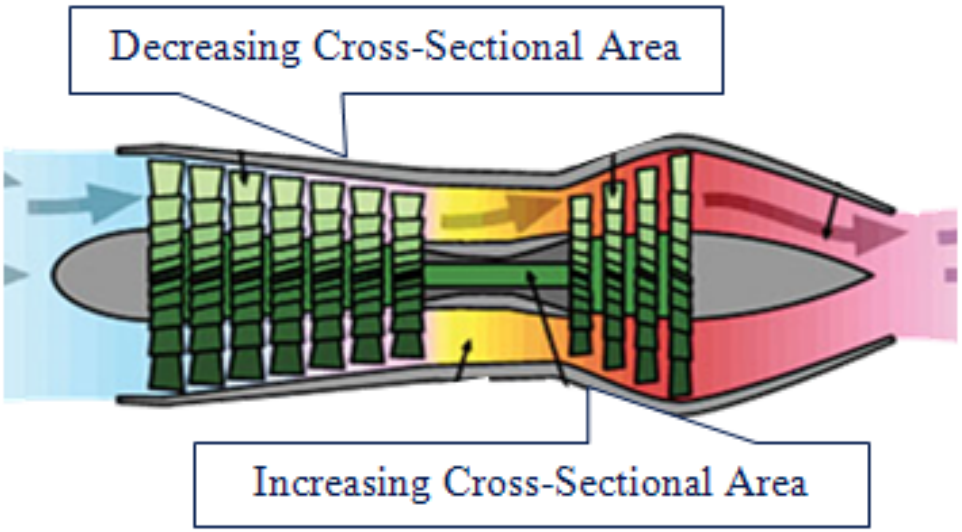
- Support at 2 FTE's & 0.3 WYEs
- Current Staffing at 1.6 FTE & 0.3 WYEs
- TEAM:

George Kopasakis

Joseph Connolly

Noulie Theofylaktos

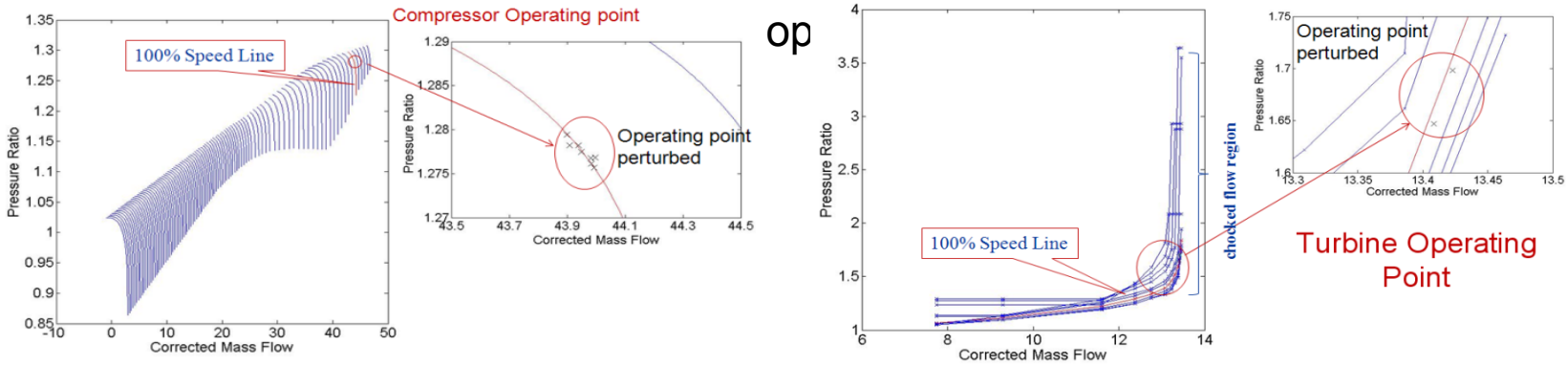
Richard Blech



Recent Progress – APSE Propulsion

- Developed stage-by-stage compressor and turbine models & methodology

a) Given a generic component map scale from ¾ size to ½ …to 1/n size, at each step substituting final flow conditions for initial conditions (until transient dies out)



c) Stack stages one at a time, each step disconnect Mach No. estimator and assuming stage (i) Mach no. run model and successively substitute final flow conditions for initial (until transient dies out)

d) Using final conditions, calculate effective stage area and reconnect Mach estimator

e) verify model runs stable at desire operating line, before connecting next stage

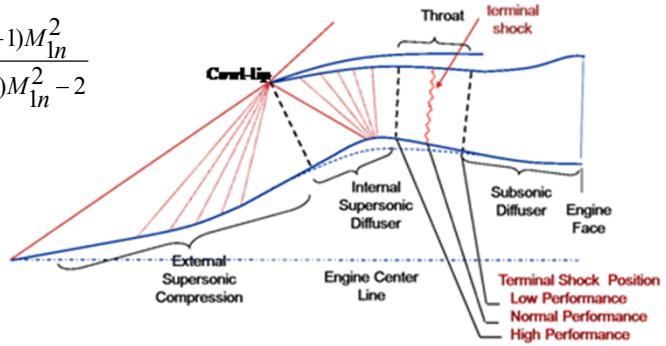
Current Progress – APSE Propulsion

- Quasi 1D CFD Modeling of Mixed Compression Supersonic Inlets

1) Modeling of external compression using compressible flow relations

$$\tan\vartheta = 2\cot\beta\frac{M_{1n}^2-1}{M_1^2(\gamma+\cos 2\beta)+2} \qquad M_{1n} = M_1\sin\beta \qquad \frac{P_2}{P_1} = 1+\frac{2\gamma}{\gamma+1}\left(M_{1n}^2-1\right)$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_{1n}^2}{(\gamma-1)M_{1n}^2-2} \qquad \frac{T_2}{T_1} = \frac{P_2}{P_1}\frac{\rho_1}{\rho_2} \qquad M_2 = \frac{1}{\sin(\beta-\vartheta)}\sqrt{\frac{1+\frac{\gamma-1}{2}M_{1n}^2}{\gamma M_{1n}^2-\frac{\gamma-1}{2}}}$$



2) Modeling internal compression using 1D CFD w/ central difference, w/ artificial viscosity & movable geometry

$$\frac{\partial}{\partial t}(W_{j,n}) = -\left(\frac{A_{n+1}F_{j,n+1}-A_{n-1}F_{j,n-1}}{2\Delta x A_n}\right)+\frac{S_{j,n}}{A_n}+$$

$$S_v\left[\frac{\left(|v_n|+a_n\right)\left(A_{n+1}W_{j,n+1}-A_nW_{j,n}\right)-\left(|v_{n-1}|+a_{n-1}\right)\left(A_nW_{j,n}-A_{n-1}W_{j,n-1}\right)}{\Delta x A_n}\right]$$

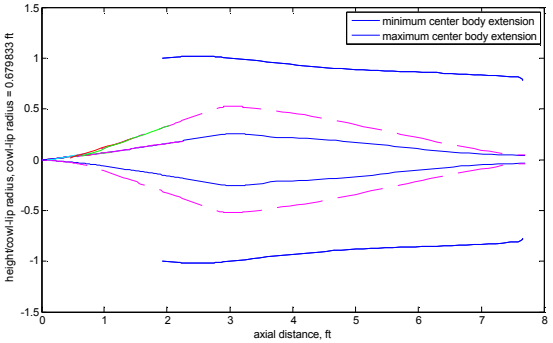
j	Wj	Fj	Sj
1	ρ	$\rho_s v$	$-\rho_s\frac{\partial A}{\partial t}$
2	$\rho_s v$	$P_s+\rho_s v^2$	$P_s\frac{\partial A}{\partial x}-\rho_s v\frac{\partial A}{\partial t}$
3	$\frac{P_s}{\gamma-1}+\frac{\rho_s v^2}{2}$	$\frac{\gamma P_s v}{\gamma-1}+\frac{\rho_s v^3}{2}$	$-\left(\frac{\gamma P_s}{\gamma-1}+\frac{\rho_s v^2}{2}\right)\frac{\partial A}{\partial t}$

21

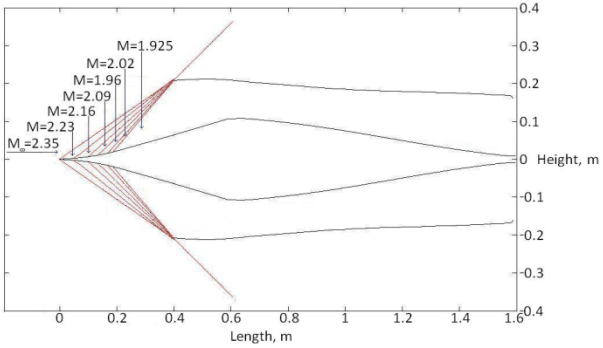
Current Progress – APSE Propulsion

- Quasi 1D CFD Modeling of Mixed Compression Supersonic Inlets

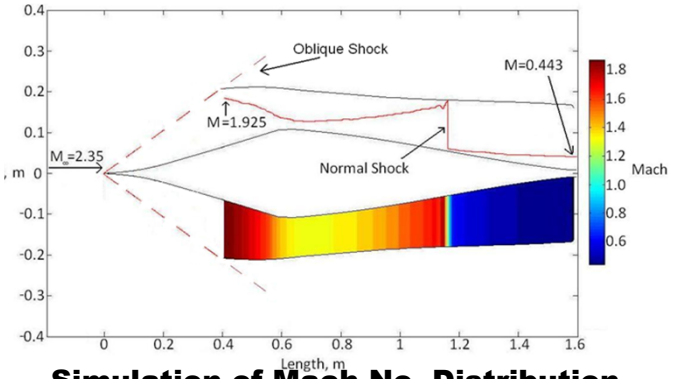
  -- Modeling of the 2 dimensional Bifurcated (2DB) inlet Geometry



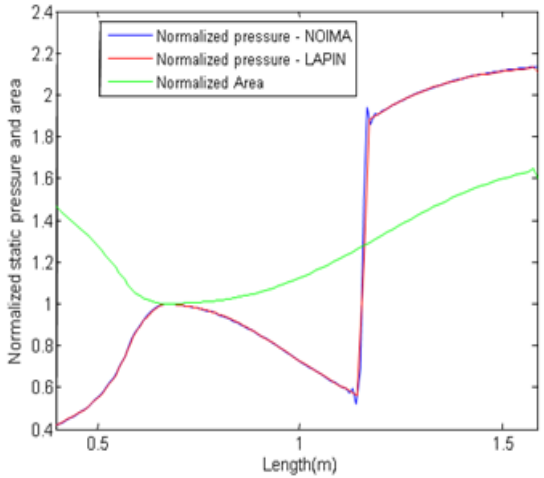
Inlet Geometry w/ Fully Extended and Fully collapsed Centerbody



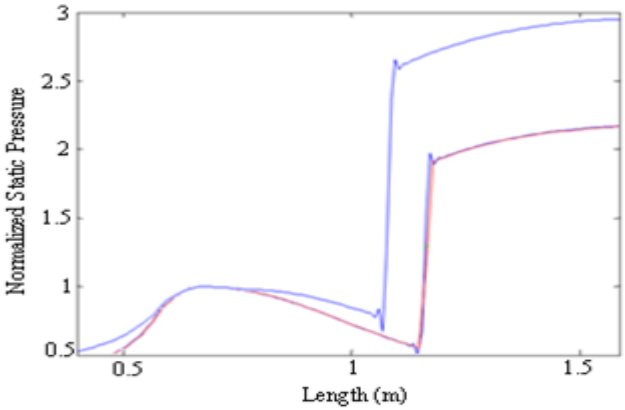
Simulation of External Compression w/ Multiple oblique shocks and mach No. Distribution



Simulation of Mach No. Distribution (Internal Compression) & Single Shock Model



Normalized Inlet Steady-State Pressure and area



Normalized Inlet Steady-State Pressure w/ Changing Centerbody Geometry

Current Progress – APSE Propulsion

- Quasi 1D CFD Modeling of Mixed Compression Supersonic Inlets

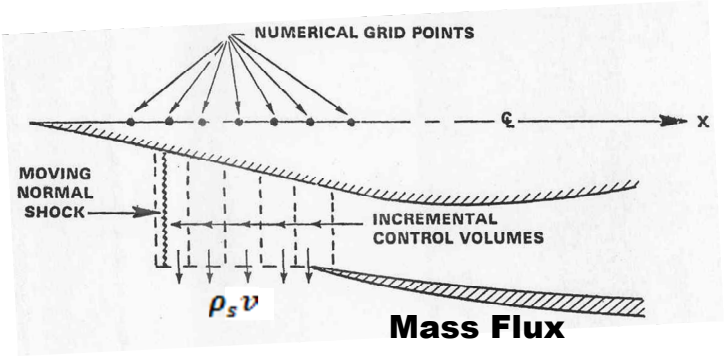
  3) Modeling of Start/Unstart problem of mixed compression inlets and similarly modeling of external compression inlets

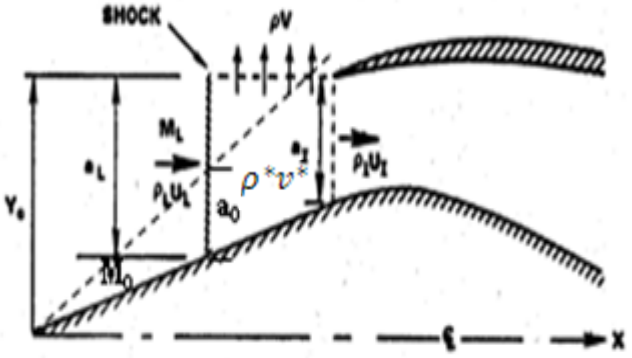
  -- Preliminary problem definition & approach established and distributed for review

  -- Challenges: a) Generating Non-physical CFD cell boundaries

  b) Bleed of mass, momentum and energy fluxes across the boundary as function of normal shock position

  c) Cells switching between compressible flow and CFD gas dynamics





$$M_L = \frac{a_O}{a_L} M_O + \frac{a_L - a_O}{a_L} M_\infty$$

$\rho_s v$ **Mass Flux**

$P_s + \rho_s v^2$ **Momentum Flux**

$\frac{\gamma P_s v}{\gamma - 1} + \frac{\rho_s v^3}{2}$ **Energy Flux**

$$F_C = F\left(\frac{2Y_C - a_L}{Y_C}\right)^j \left(\frac{a_L}{a_I}\right) \left[\frac{1 - \frac{\rho_I V_I}{\rho_L V_L}\left(\frac{2Y_C - a_I}{2Y_C - a_L}\right)^j \left(\frac{a_I}{a_L}\right)}{1 - \frac{\rho_I V_I}{\rho_L V_L}}\right]$$

Current Progress – APSE Propulsion

- Atmospheric Turbulence Modeling

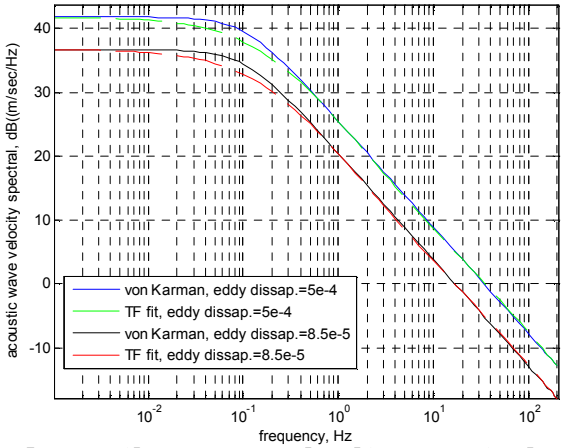
  -- Reason for this work – Atmospheric turbulence is fractional and past whole order models underestimate increasingly with frequency

  -- Developed Fractional order approximations for acoustic velocity gusts, temperature and pressure

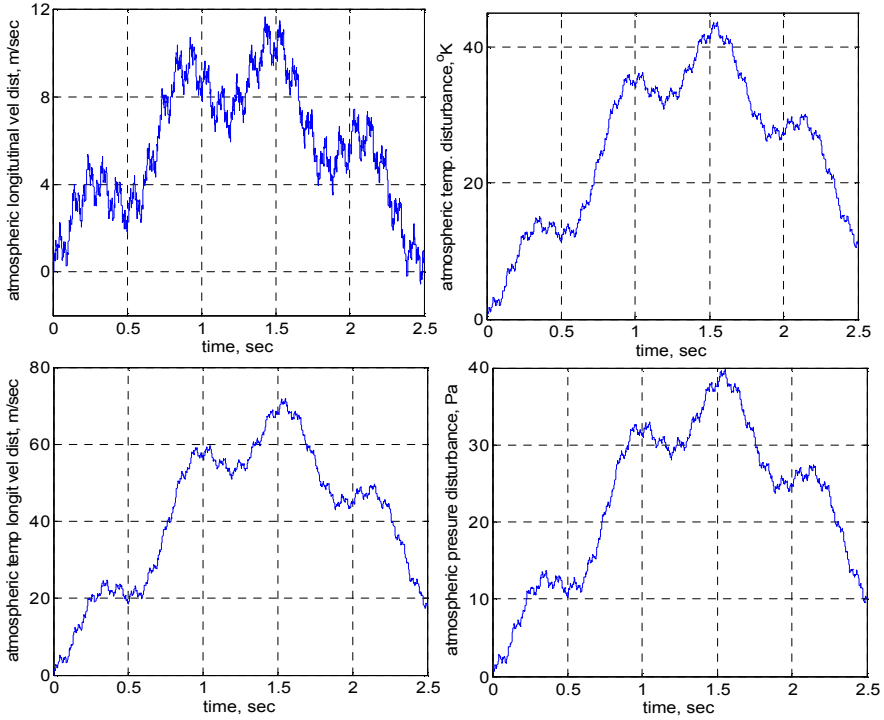
$$W_{t,o} \cong K_{t,fit} \frac{\prod_{l}^{m_z}(s/\omega_{zi}+1)}{\prod_{l}^{m_p}(s/\omega_{pi}+1)} W_t$$

$$\omega_{pi} = \frac{K_{\omega pi}\omega_{Hpi}\prod_{j=1}^{i-1}(\omega_{Hpi}/\omega_{pi-j}+1)}{10^{\eta(2i-1)q}\prod_{j=1}^{i-1}(\omega_{Hpi}/\omega_{zi-j}+1)-1}$$

$$\omega_{zi} = \frac{K_{\omega zi}\omega_{Hzi}\prod_{j=1}^{i-1}(\omega_{Hzi}/\omega_{zi-j}+1)}{10^{-2\eta iq}\prod_{j=1}^{i}(\omega_{Hzi}/\omega_{pi}+1)-1}$$



Acoustic wave velocity spectral and its TF fits due to temperature gust and its TF fits for different eddy dissipation rates



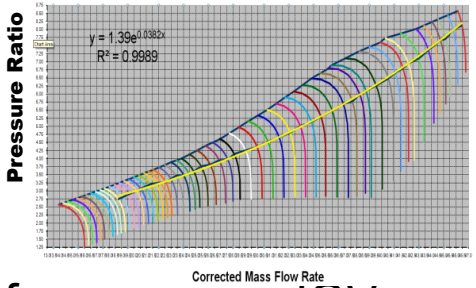
Time Domain Atmospheric Turbulence

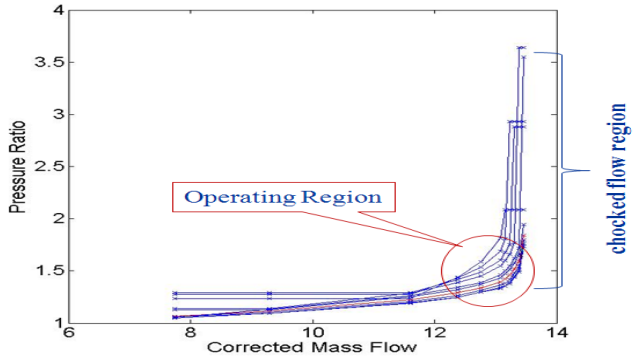
Current Progress – APSE Propulsion

- Engine Schedules

  -- Developed ways to scale maps if necessary to closer match turbine and compressor power and operate with choked flow

  -- Develop ways to manipulate & closer match geometries (i.e. component lengths and areas) to allow simulation to work properly, depicting more accurate engine geometries.





  -- Absent of compressor IGV maps, compressor operating schedule originally developed using bleed flow

Operating region

  -- Started developing exit nozzle area schedule approach to fully expend the flow

  -- Approach based on PR .vs Cd (discharge coefficient) schedule and area limit with .vs speed

Current Progress – APSE Propulsion

- Engine Schedules

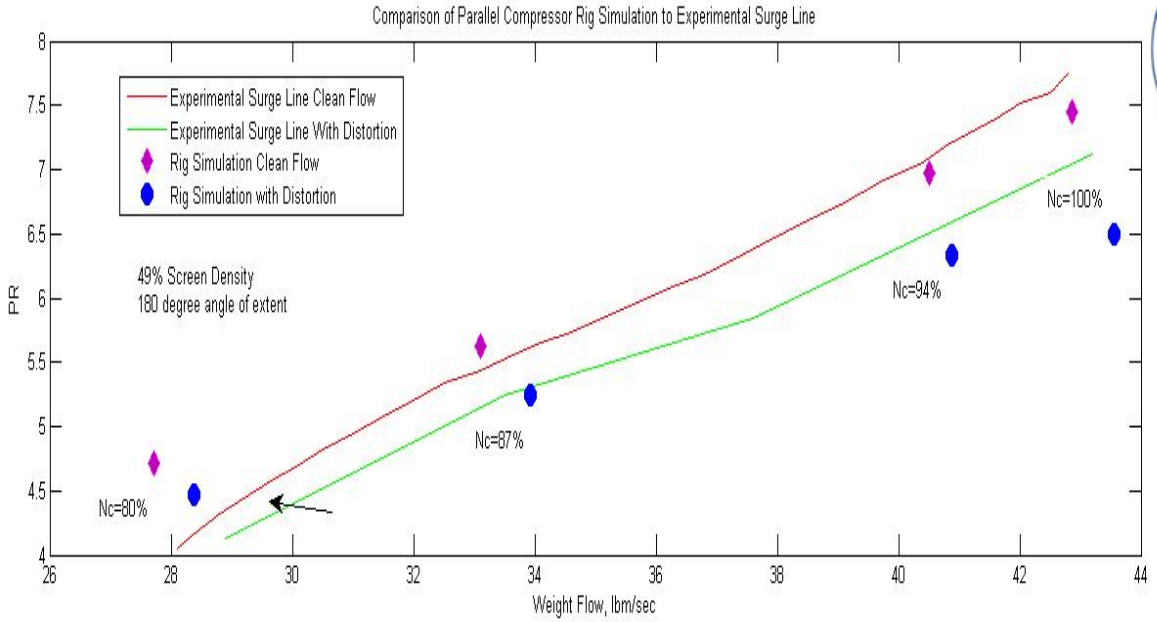
  -- This schedule creates complications - control feedback instabilities

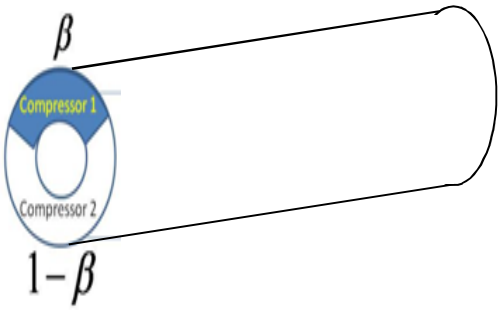
  (designed notch filters) and margin sensitivities that unchokes nozzle

Current Progress – APSE Propulsion

- Flow Distortion Modeling for surge/stall

  -- Multi-stage compressor model develop with parallel flow paths





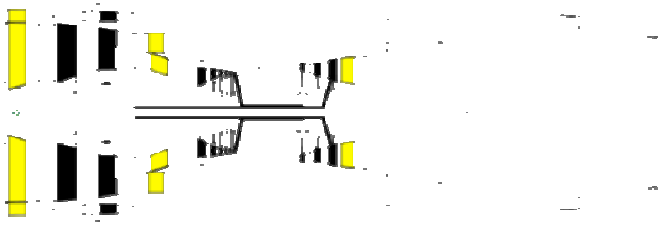
Comparison of Clean and Distorted Compressor Response to Experimental Data

Current Progress – APSE Propulsion

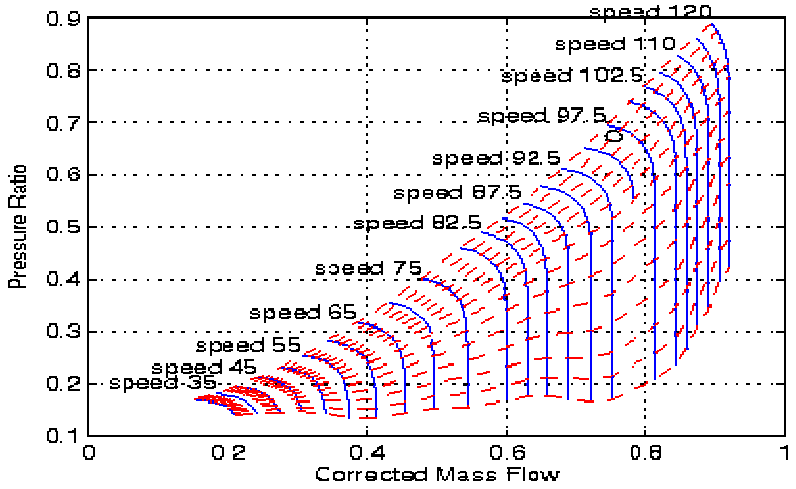
- N+3 Engine Modeling

  -- N+3 dynamic engine model is being developed & validated based on steady-state data provided by NPSS model developers

  -- Engine has multiple flow paths – So far 4 of major component models completed



Variable Cycle N+3 Engine Diagram



Normalized Compressor Map for Certain IGV angle

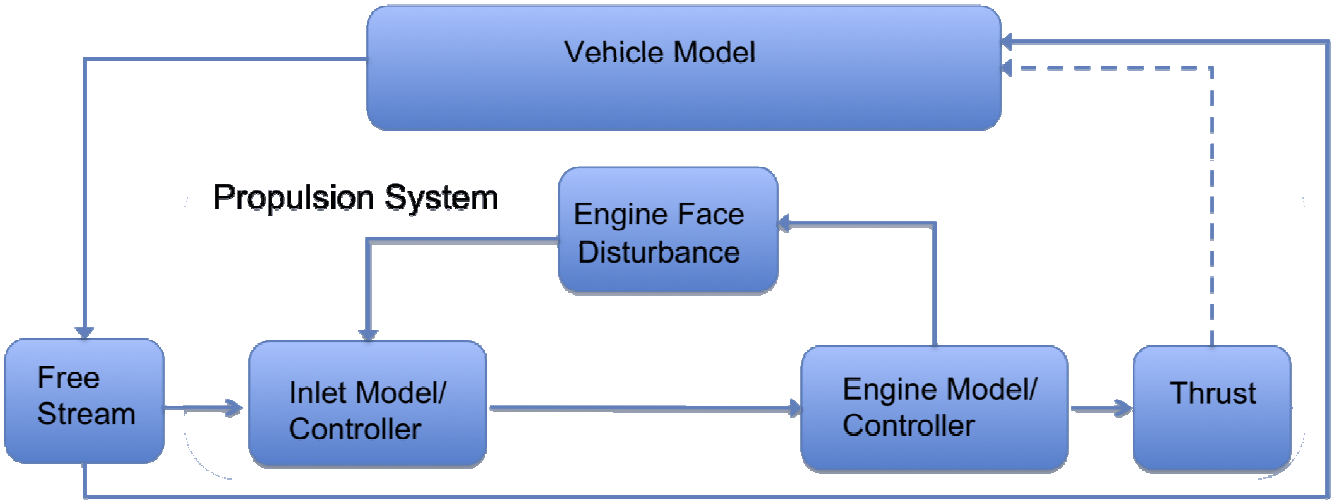
% error between dynamic model & NPSS

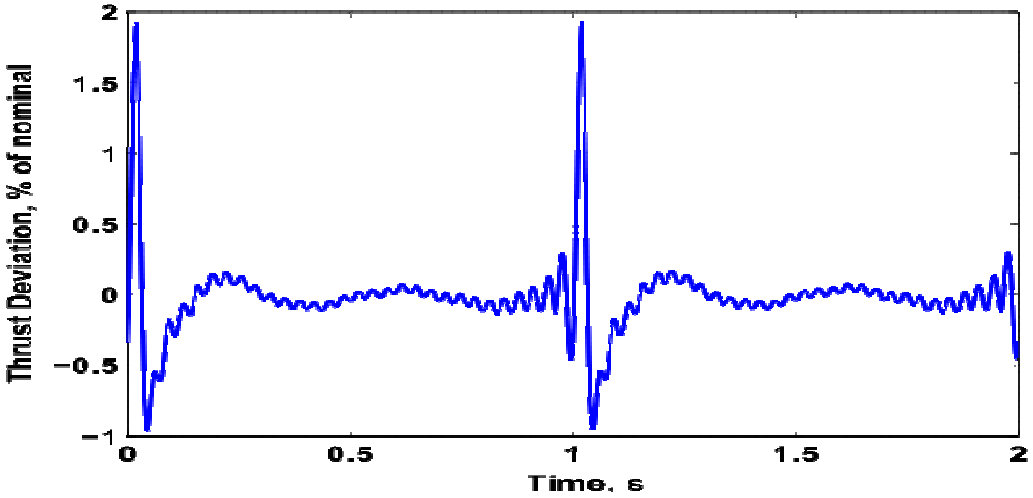
Design Point	P_T	T_T	W
Fan	0.1%	0.14%	0.2%
Fan VCE	0.2%	0.06%	3.7%
Compressor	4.8%	0.4%	0.07%
Combustor	2.01%	0.6%	2.97%

Current Progress – APSE Propulsion

- Flow Distortion Modeling for surge/stall

  -- Preliminary Linear Integrated APSE model developed





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APSE Propulsion

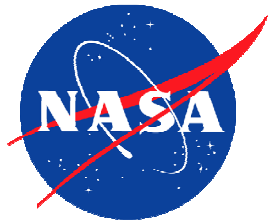


Future Plans:

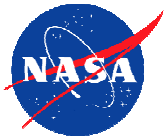
- Continue developing models (inlets, N+3 engine, parallel flow paths/distortion)
- Integrate Propulsion and AeroServoElastic models and controls
- Support Advanced Flight Simulator (AFS)

Concerns:

- Currently Under Staffed


NASA

Back-Up Charts

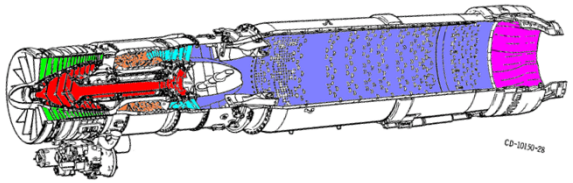


Prior Progress – APSE Propulsion

(prior to last FAP annual review – Nov. 2009)

- Developed turbojet & turbofan engine models (J85-13)

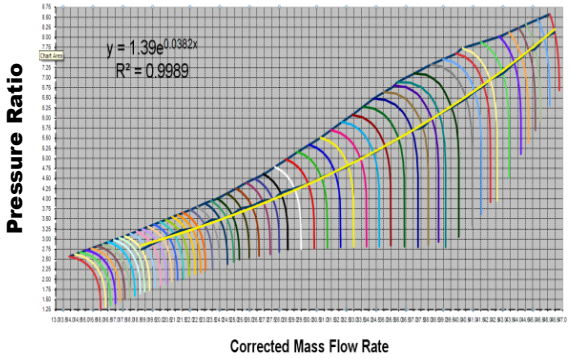
  -- Lump volume dynamics



$$\frac{\partial}{\partial t}(\rho_s A)+\frac{\partial}{\partial x}(\rho_s Av)=0$$

$$\frac{\partial}{\partial t}(\rho_s Av)+\frac{\partial}{\partial x}(\rho_s Av^2)=-Ag\frac{\partial P_s}{\partial x}$$

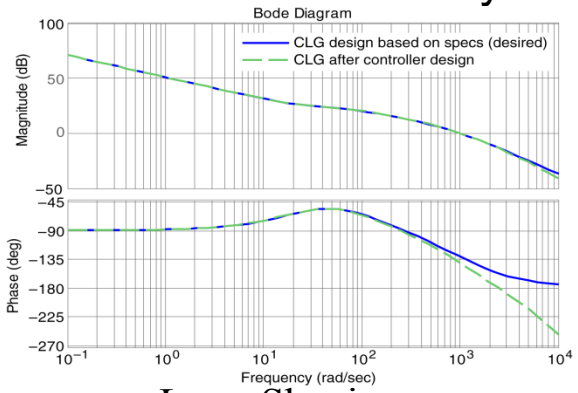
$$\frac{\partial}{\partial t}(\rho_s Au_t)+\frac{\partial}{\partial x}(\rho_s AvH)=0$$



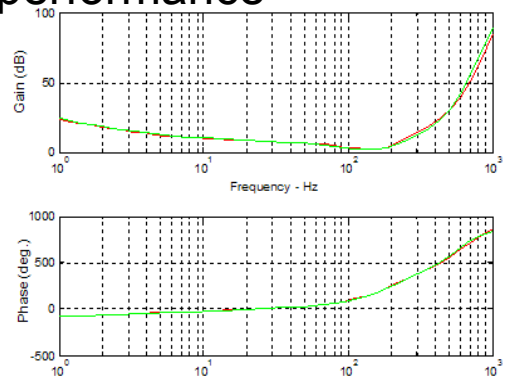
- Developed new loop shaping feedback controls design approach

  -- Relates hardware performance to control requirements

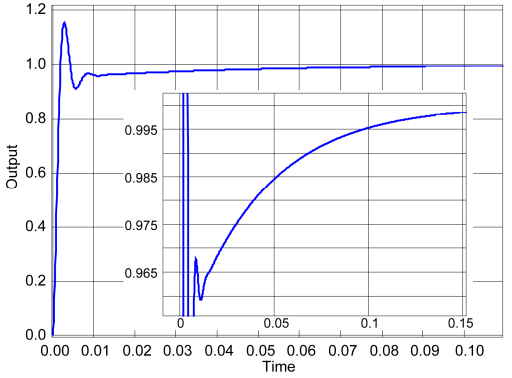
  -- Maximizes Control System performance



Loop Shaping



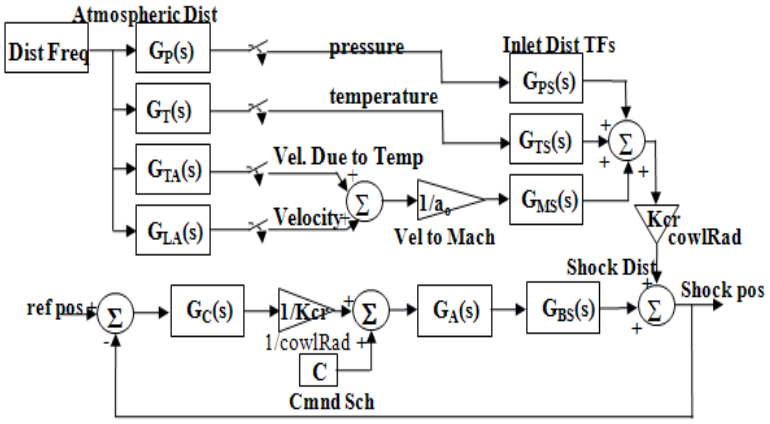
Control Law Fitting



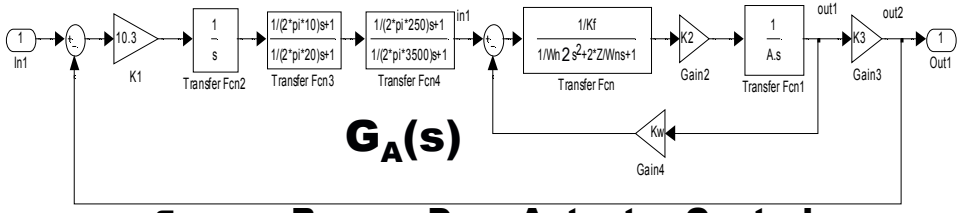
Time Response

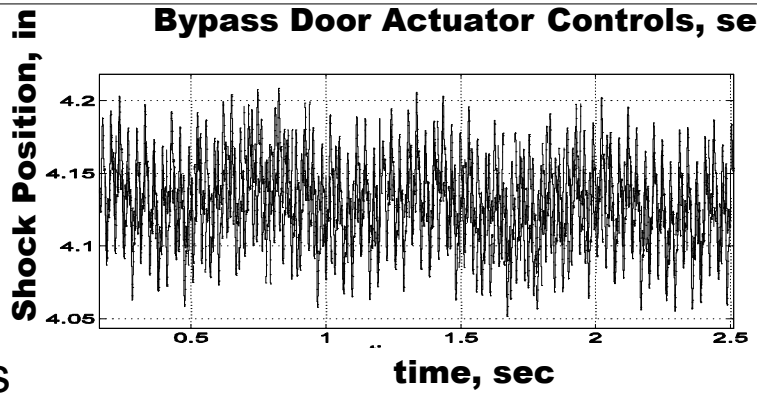
Prior Progress – APSE Propulsion (cont.)

- Designed shock position controls for internal compression inlets

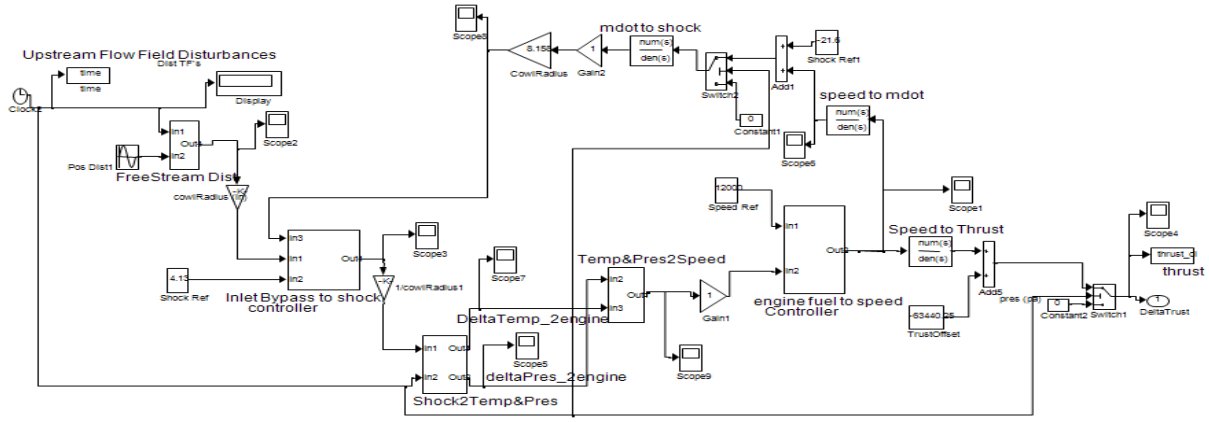


Shock Position Feedback Control Diagram





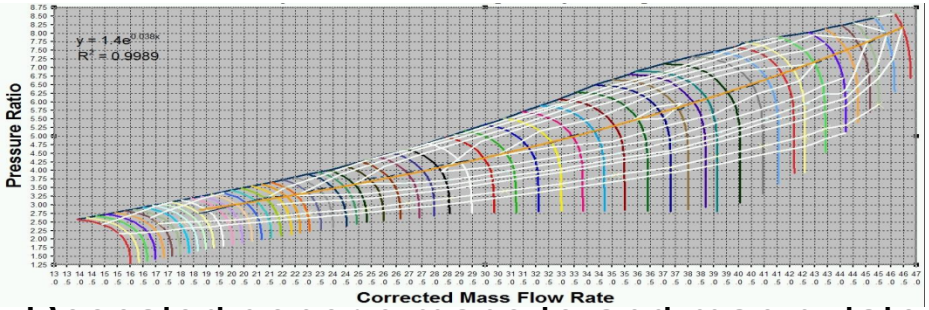
- Designed fuel engine speed controls
- Developed Linear Integrated Propulsion System Model

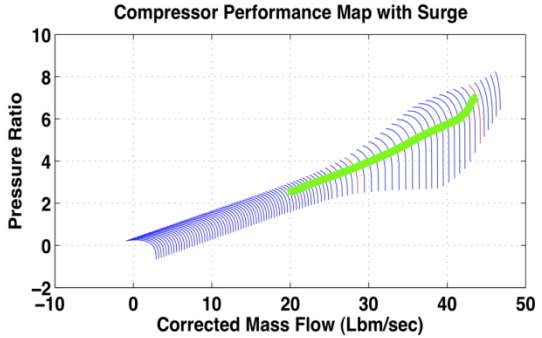


Linear Integrated Propulsion System Model

Prior Progress – APSE Propulsion (cont.)

- Derived compressor bleed schedules allowing compressor to operate over speed regime





- Rescaled generic maps to and manipulated geometries to match turbine to compressor

- Developed initial atmospheric turbulence models