Engine Component Characterization Based on Experimental Data and Modeling for Flow Distortion and Rotating Stall

Fundamental Aeronautics – Supersonics Project
AeroPropulsoServoElasticity Task

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Propulsion Controls and Diagnostics (PCD) Workshop
Cleveland OH, Dec. 8-10, 2009

Engine Modeling Based on Experimental Data

Outline

Background

Engine Model Test Case

-- Compressor
-- Turbine
-- Distortion response, surge, stall modeling

Status and plans

Engine Modeling Based on Experimental Data

Background

- A general purpose engine modeling technique has been developed to support controls development for the APSE project
- The approach allows models to be developed where the engine may be conceptual in nature
  - Engine component characteristic data is generated using preliminary design tools or best available data from similar engines
- Initial demonstration case was a J85-13 turbojet engine
  - Compressor, turbine, and other component performance data generated using data from in-house cycle codes, design tools
- An additional effort was initiated to utilize data from a 1D dynamic engine code developed for NASA
  - Component data was obtained from experimental data
  - Serves as a tool to compare compressor distortion/surge/stall model against prior experimental data
  - Provides validation of general purpose engine modeling approach

Engine Modeling Based on Experimental Data

Source of Data

- Aerodynamic Turbine Engine Code (ATEC) J85-13 simulation originally developed by AEDC for NASA
  - Component performance maps generated from engine manufacturer's cycle deck
  - Capability to run surge, stall, post stall and recovery transients
  - Maps were modified to account for modifications to baseline engine configuration to account for modifications made during test programs
- Test data available from prior NASA programs
  - Engine distortion response modeling and test data (GE contractor report NASA CR-134978)
  - Inlet-engine controls studies (NATO RTO-MP-8 report)

Compressor Maps

Procedure

ATEC Compressor Map Data File → ATEC to Excel → Excel to MATLAB → MATLAB S-Function

•Organized by speed, stage
• Speed lines defined by polynomial coefs./ breakpoints data

• Fortran utility to read map and generate file for import to Excel

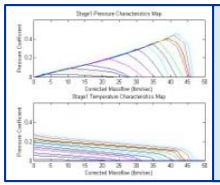
•Calculations of pressure/ temp. coefs at breakpoints

• MATLAB m-file
• Reads Excel file
•Generates MATLAB input file

• MATLAB m-file to generate pressure, temperature coef. speed lines from polynomials
• Interpolation between speed lines
•Extrapolation for speeds beyond 102%

Resulting Pressure, Temperature Coefficient Maps Combined with Volume Dynamics

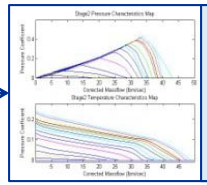
Stage 1 Characteristics



Volume Dynamics

Stage 1

Stage 2 Characteristics

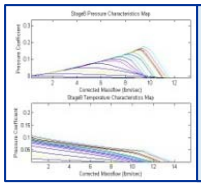


Volume Dynamics

Stage 2

• • •

Stage N Characteristics



Volume Dynamics

Stage N

Compressor Model

- Stage-by-stage compressor model developed
  - Compressor element calculates pressure and temperature characteristics
  - Volume dynamics elements between compressor elements through conservation equations.
  - Efficiency is computed for reference purposes

$$\eta_{cp} = \frac{\left(\frac{\gamma - 1}{\gamma}\right)}{\ln(TR)/\ln(PR)}$$

TR = Stage Temperature ratio
PR= Stage Pressure Ratio

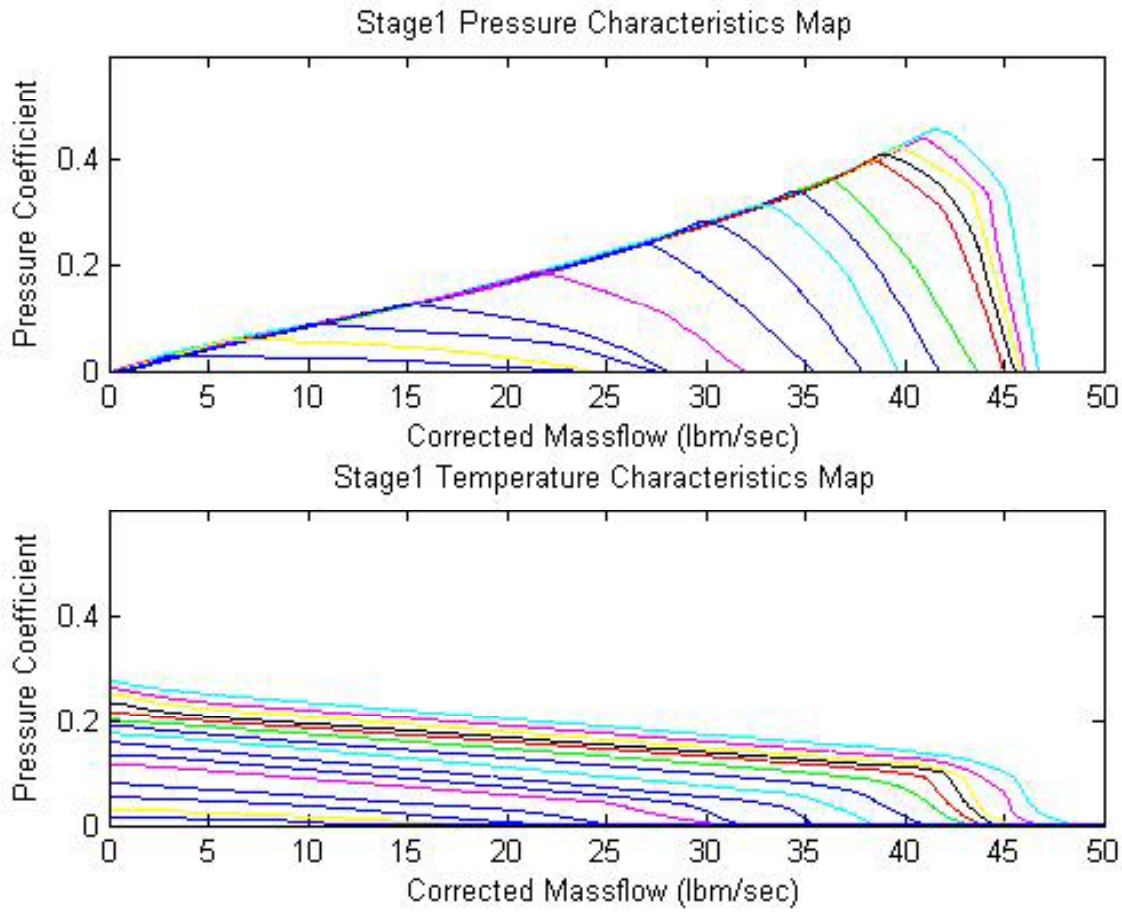
- Bleed is implemented as a percentage of engine mass flow only for stages 3-5 as in the actual engine. Bleed schedules taken from GE report
- Inlet Guide Vanes not modeled, but vanes are full open at ~ 90% design corrected speed and beyond

Compressor Results

The new compressor model was integrated with the Tecdyn7 engine model, replacing the original single-lump compressor. The steady state results are shown below.

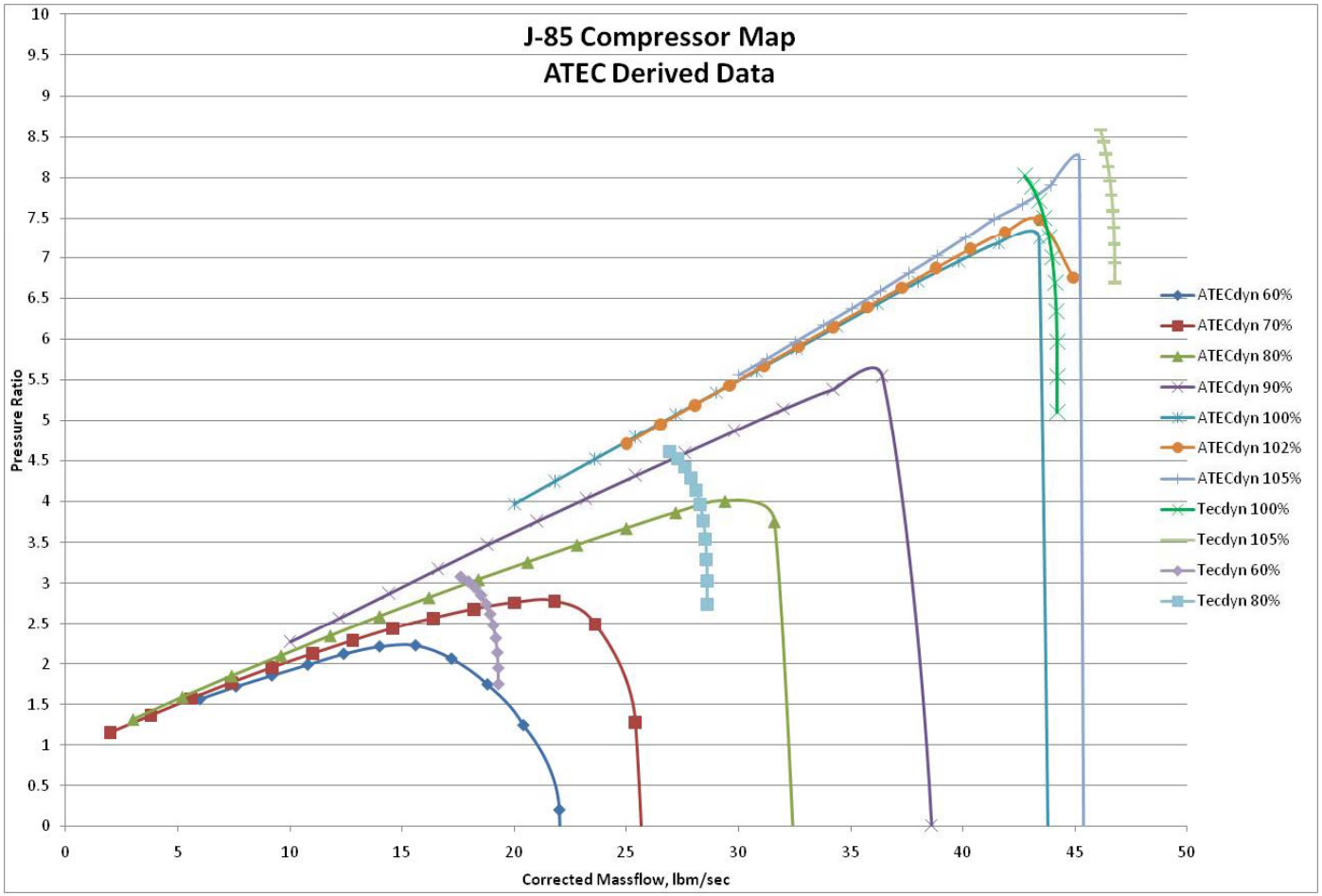
Source	N % design corr. speed	Pt3 kN/m2	Tt3 ºK	Air flow Kg/sec
Experiment	100	703.8	544	19.9
Seldner	100	709.6	550	20.0
ATECdyn	100	659	539	19.8

Stage 1 Pressure and Temperature Coefficient Maps



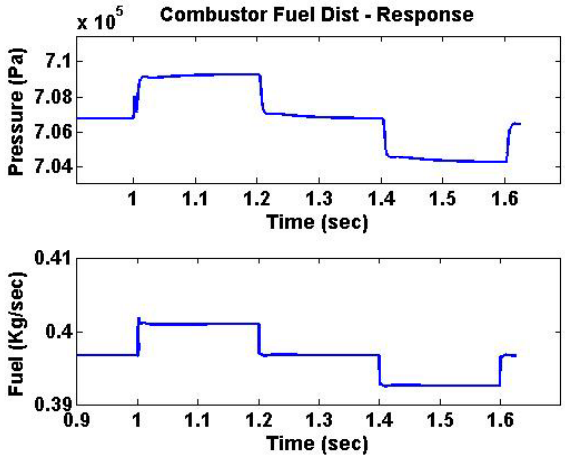
Overall Compressor Map

ATECdyn : Tecdyn7 with stage-by-stage compressor model based on ATEC data
Tecdyn7 : Original code with single lump compressor model

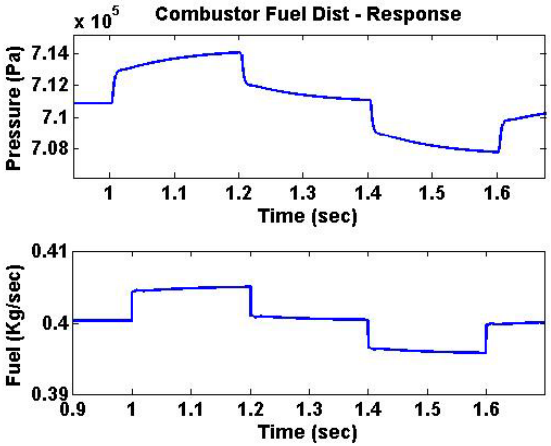


Compressor Model Results

Transient Response



ATECdyn



Tecdyn7

Turbine Model

- ATEC turbine model based on the following parameters

$$Turbine\ Corrected\ Speed = XNFFT = \frac{N}{\sqrt{T_{t4}}}$$

$$Turbine\ Flow\ Function = TFF = \frac{\dot{W}_5\sqrt{T_{t4}}}{P_{t4}}$$

$$Turbine\ Work\ Done = DHQ = \frac{h4 - h5}{T_{t4}} = f\left(TFF, XNFFT\right)$$

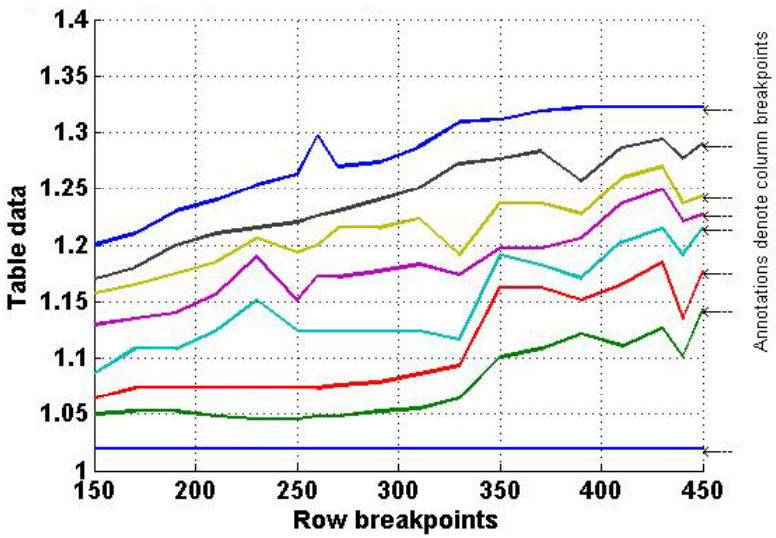
$$Turbine\ Temperature\ Ratio = TR_5 = \frac{T_{t4}}{T_{t5}}$$

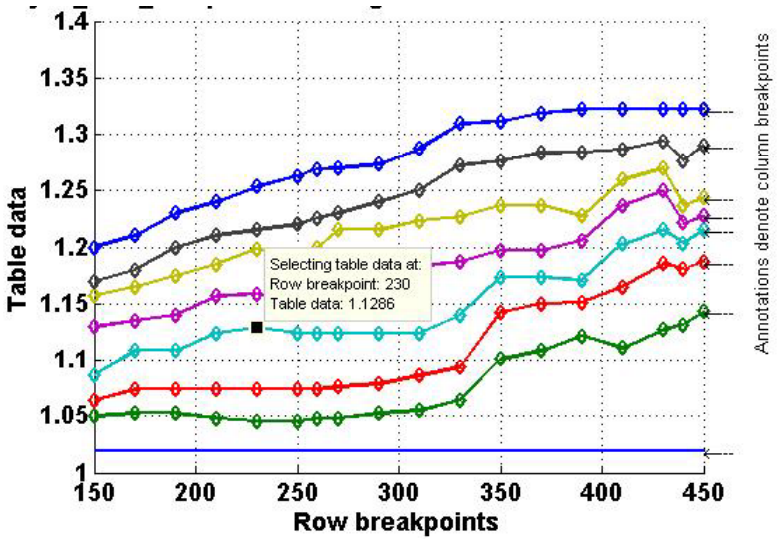
$$Turbine\ \mathrm{Pr}essure\ Ratio = PR_5 = \frac{P_{t4}}{P_{t5}} = f\left(TR_5, XNFFT\right)$$

- Corrected speed and TFF are computed and used to determine DHQ
- Enthalpy drop is computed and used to determine temperature
- Turbine temperature is computed and used to determine PR
- Volume dynamics based on conservation equations

Turbine Model

- ATEC code contains turbine maps using data from engine company cycle deck (based on experimental data)
- Maps contained abrupt changes, requiring smoothing





Turbine Model

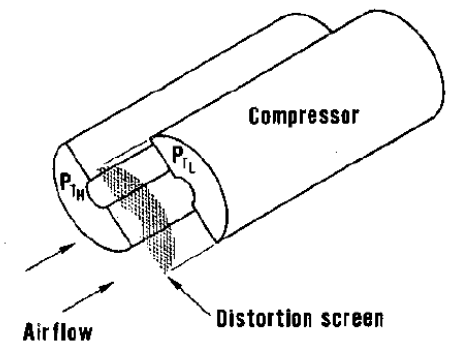
- A turbine model has been developed using the maps from the ATEC code
- Steady state solutions have been obtained, but at speeds greater than design speed
- Map scaling is currently being investigated.

Compressor Distortion Response and Surge/Stall Models

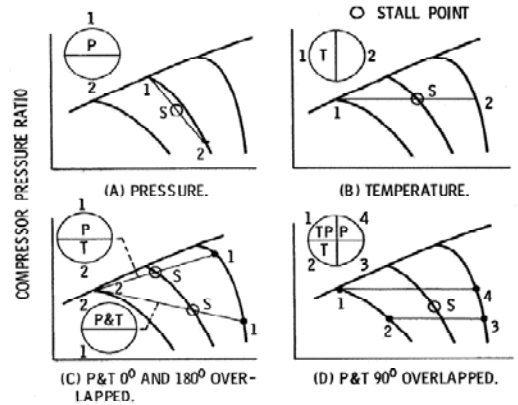
- Response to distortion is a key element of APSE controls development
  - Distortion can result in engine surge and stall
  - Engine model must at least predict reduction in surge margin for inlet distortion conditions
  - A full surge/stall initiation, in-stall operation, and stall recovery capability is a long term objective

- Modeling Techniques (increasing order of complexity)
  - Braithwaite algebraic stall pressure ratio loss model
  - Parallel Compressor Model
    - No circumferential interaction
    - Inclusion of circumferential terms
  - 2D and 3D models
    - Expensive and impractical due to computer time requirements

Parallel Compressor Model



A 2-segment parallel compressor model

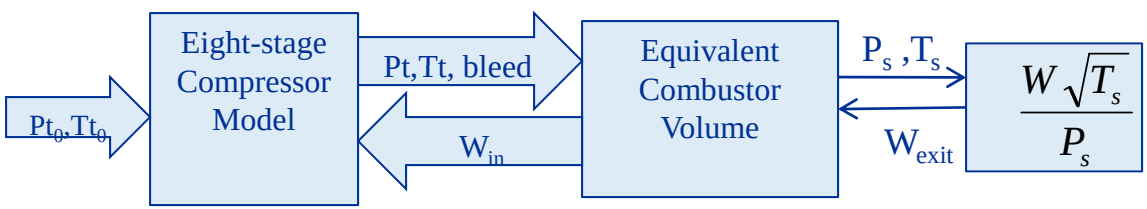


Averaging procedure for combined and overlapped distortion

- The compressor is divided into several separate flow regions or sub-compressors, each with the same performance characteristics as the original clean compressor.
- Each sub-compressor has its own uniform flow inlet boundary condition that can include distortion. The mass flow in each sub-compressor is multiplied by a factor that accounts for the fraction of the inlet flow area that is represented by that sub-compressor.
- Each sub-compressor ends at a common, uniform, static pressure region. There is no cross-flow between sub-compressors
- The overall compressor is considered to reach its stall point when any one of the distorted sub-compressors reaches the stall point on its clean compressor map
- The overall compressor pressure ratios are computed as the common exit total pressure divided by an area-weighted average of the individual sub-compressor inlet pressures. The overall mass flow is the sum of those for the individual sub-compressors.

Initial Compressor Model for Stability, Surge Line Development

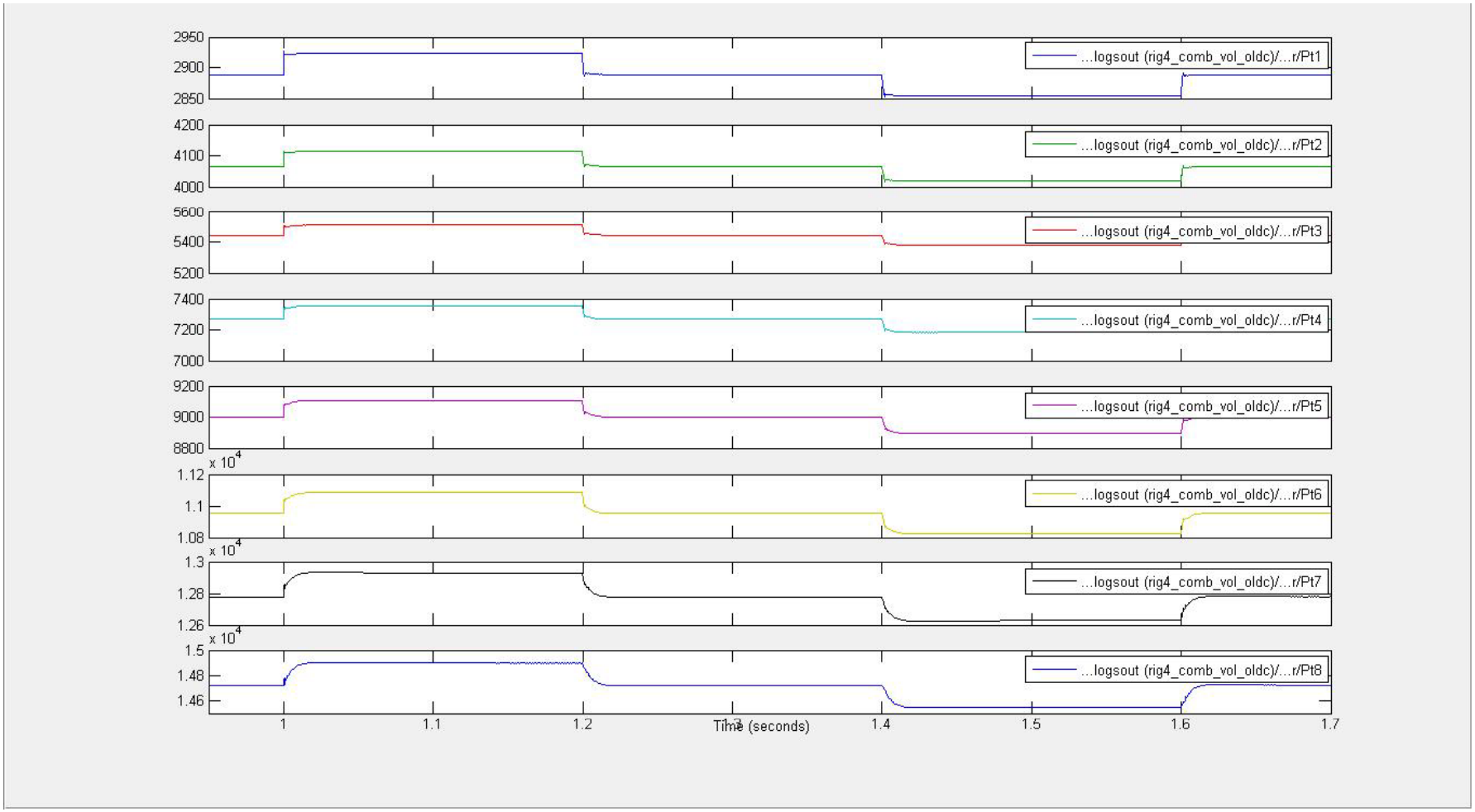
- A compressor 'rig' model was developed that models the engine system as a compressor subsystem coupled to a plenum and valve.
  - Avoids complexity of dealing with combustion, turbine, rotor dynamics and possible instabilities
  - A constant mass flow function at the combustor exit volume boundary provides a stable BC (turbine is choked during normal engine operation
  - The mass flow can be easily throttled by increasing/decreasing this value to determine the surge line
- The rig model will be used for clean flow surge line determination and testing of the parallel compressor model



Compressor Rig Simulation

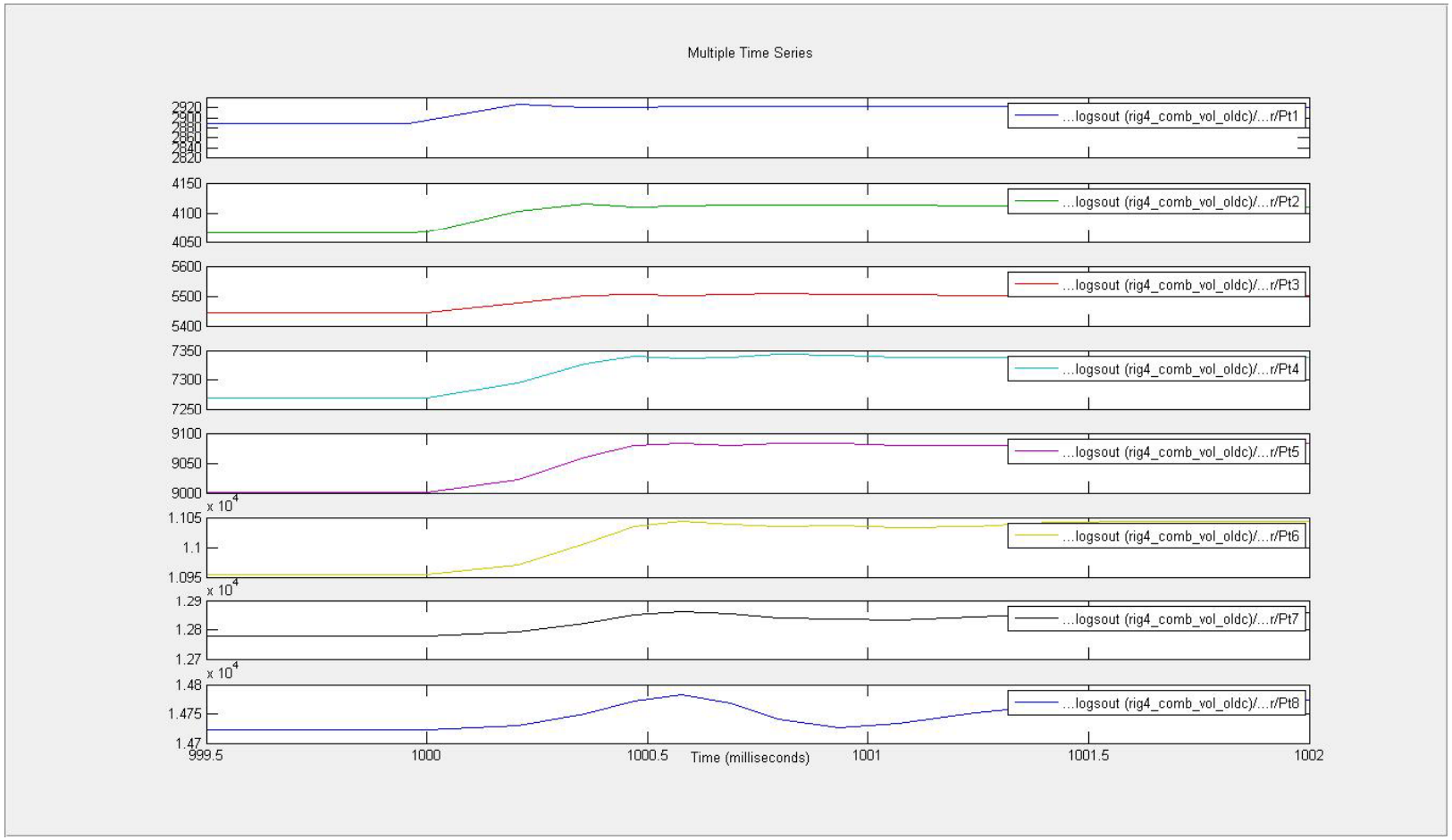
Propagation of a 25 psf Pressure Pulse Through the Compressor

100% Design Corrected Speed



Compressor Rig Simulation

Propagation of a 25 psf Pressure Pulse Through the Compressor
Rising edge detail



Conclusions and Future Plans

• Results from models based on experimental data from the ATEC code verify the generic modeling approach used is accurate
• Current stage-by-stage compressor modeling tools provide a necessary and solid foundation for future distortion response/surge/stall model development.
• Data from ATEC code will continue to be useful for extending distortion, surge, stall models

Future plans:
•Complete incorporation of algebraic and static compressor distortion response models
    •Calculate reduced compressor surge line
• Determine and implement interfaces to atmospheric models and NASA LaRC aeroelastic codes to provide flowfield perturbation boundary conditions.
• Add capability to model turbofan engines
•Revisit compressor distortion response model to account for circumferential interactions