NASA/CP—2018-219891

Sixth NASA Glenn Research Center Propulsion Control and Diagnostics (PCD) Workshop

Jonathan S. Litt, Compiler
Glenn Research Center, Cleveland, Ohio

April 2018

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Sixth NASA Glenn Research Center Propulsion Control and Diagnostics (PCD) Workshop

Jonathan S. Litt, Compiler
Glenn Research Center, Cleveland, Ohio

Proceedings of a conference held at the Ohio Aerospace Institute
sponsored by NASA Glenn Research Center
Cleveland, Ohio
August 22–24, 2017

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

April 2018

Level of Review: This material has been technically reviewed by technical management.

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Contents

Sixth NASA Glenn Research Center Propulsion Control and Diagnostics (PCD) Workshop

Abstract

The Intelligent Control and Autonomy Branch at NASA Glenn Research Center hosted the Sixth Propulsion Control and Diagnostics Workshop on August 22–24, 2017. The objectives of this workshop were to disseminate information about research being performed in support of NASA Aeronautics programs; get feedback from peers on the research; and identify opportunities for collaboration. There were presentations and posters by NASA researchers, Department of Defense representatives, and engine manufacturers on aspects of turbine engine modeling, control, and diagnostics.

Introduction

The Intelligent Control and Autonomy Branch at NASA Glenn Research Center, Cleveland, OH, hosted the Sixth Propulsion Control and Diagnostics (PCD) Workshop on August 22–24, 2017. Previous workshops were held approximately every 2 years, in November 2007, December 2009, February 2012, September 2013, and September 2015, with overwhelmingly positive response. The attendees had consistently expressed interest in keeping up with the latest developments in PCD technologies, and thus the workshops have become a highly anticipated recurring event. The objectives of the 2017 PCD workshop were to

- Disseminate information to the research community about the propulsion control and diagnostics research being done by the Intelligent Control and Autonomy Branch at NASA Glenn in support of various projects under the NASA Aeronautics Research Mission Directorate (ARMD) programs.
- Get feedback from peers on the value of the research and the validity of the technical approach.
- Identify opportunities for potential collaboration and sharing of tools and methods.

The workshop consisted of

- Overview presentations of ongoing research in aircraft engine control and diagnostics at NASA, the Department of Defense, and engine manufacturers.
- Detailed presentations on the NASA Glenn PCD research efforts—progress to date and future plans, and tools and simulations available for public use.
- A poster session that provided the opportunity for more in-depth discussion about ongoing research projects, and for work that was related to but not explicitly part of the workshop agenda to be represented.
- A session to discuss ideas for future PCD research that supports the goals of ARMD strategic research thrusts.
- One-on-one discussions between NASA researchers and attendees to answer any questions and identify potential collaboration opportunities.

This report contains the presentations and posters that were allowed to be reproduced, which covers the vast majority, including all of those from NASA. The NASA presentations described work being performed in the Intelligent Control and Autonomy Branch, often in collaboration with other branches or outside entities. They were grouped into sessions of generally related topics. Overviews of each of the NASA sessions follow:

Propulsion System Modeling and Autonomy
These presentations cover the work on an Intelligent Propulsion Control Architecture to enable more autonomous operation of air vehicles; modeling of engine performance at high angles of attack to help improve flight simulator fidelity for pilot training on stall recognition and recovery; and development of the Toolbox for the Modeling and Analysis of Thermodynamic Systems, an open source graphical simulation language.

Control Techniques and Tools for Future Propulsion Systems
This set of charts describes work in the following areas: Dynamic Systems Analysis tool development with application to N+3 concepts; Modeling and analysis of hybrid electric propulsion systems with application to testing in the NEAT—NASA Electrified Aircraft Testing facility; Development of advanced control logic for a small turbofan engine with a view towards validation in engine test; and Development of tools and methods for verification of advanced control logic.

Active Component Control and Engine Icing Session
The presentations cover work being done under active combustion control, active turbine tip clearance control, and engine icing detection and mitigation.

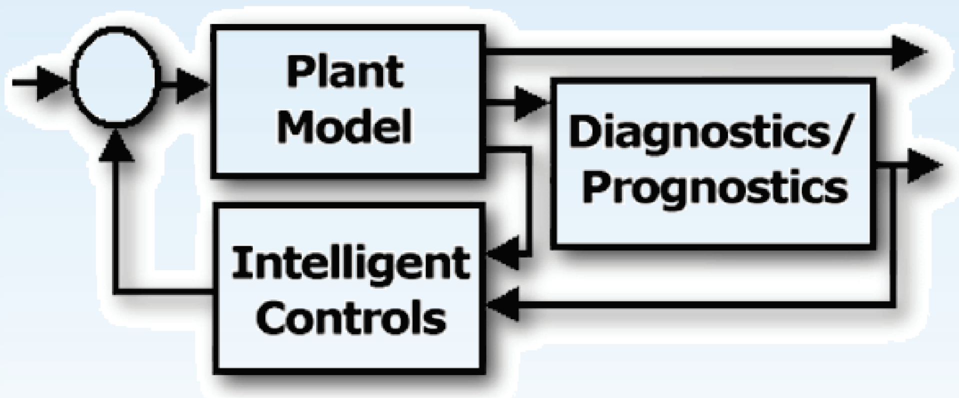
Distributed Engine Control Technologies
These presentations describe the current status of distributed engine control technology development at NASA Glenn Research Center. Topics include an overview, capabilities in modeling, simulation, and hardware in the loop testing, dynamic thermal modeling and optimization, high temperature smart node development, and high temperature silicon carbide electronics.

The following sections contain the NASA presentations as well as some of the industry presentations, and the posters. They mostly represent snapshots in time of ongoing work, and many contain a list of references in case the reader wants additional information.

Session Overview

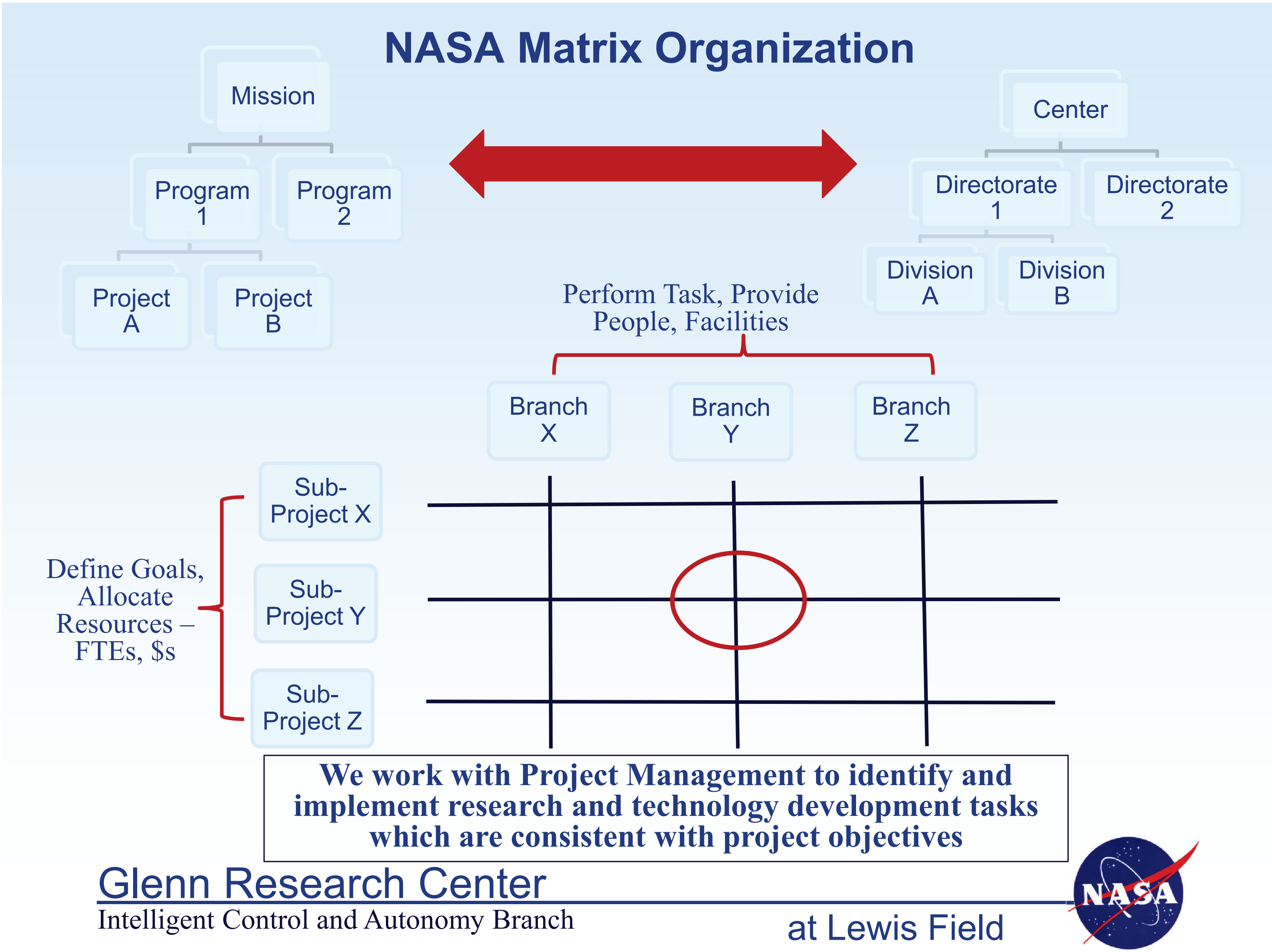
NASA GRC Aero-Propulsion Controls Research

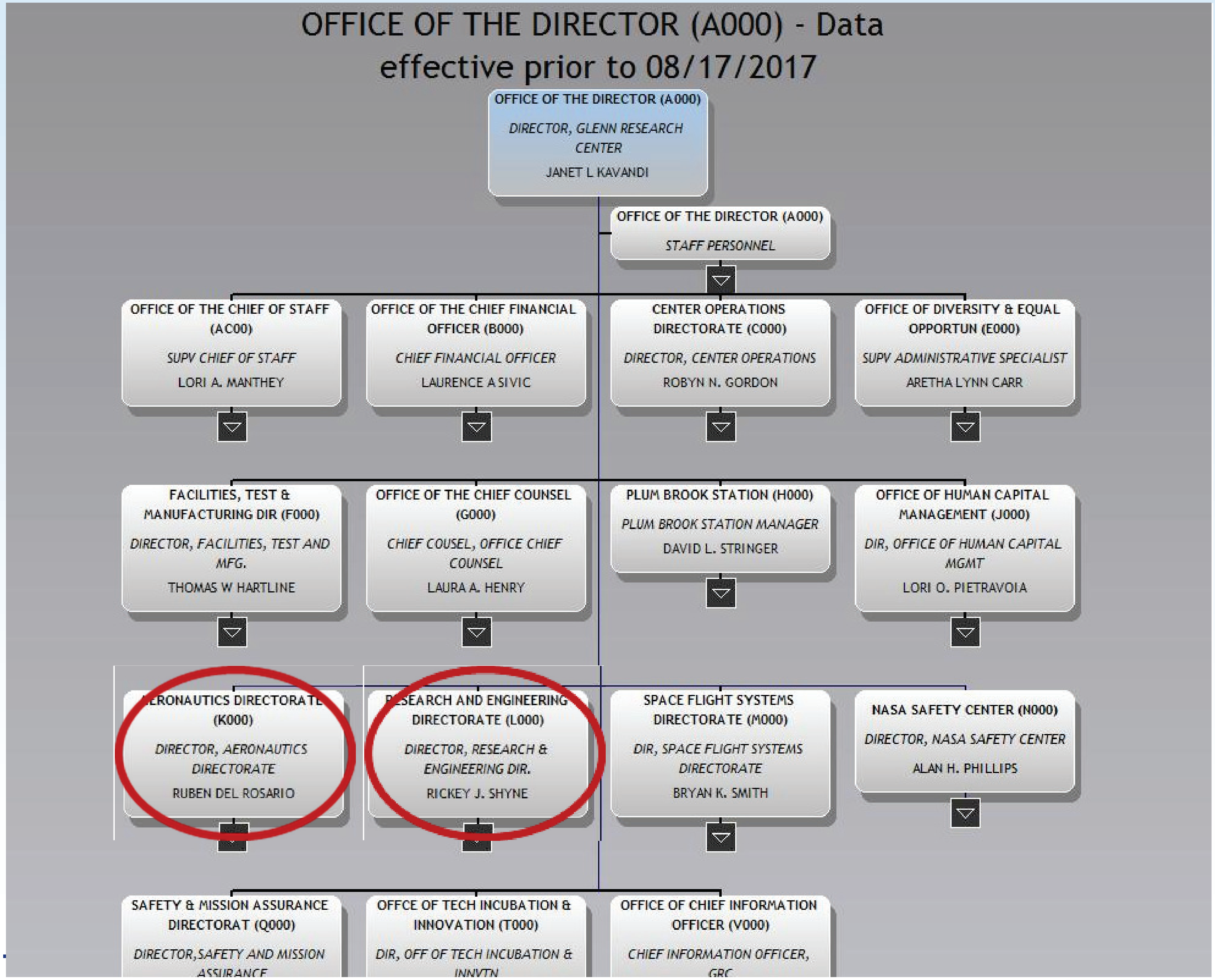
NASA GRC Aero-Propulsion Control Research - Overview



6th NASA GRC PCD Research Workshop
Aug. 22-24, 2017, Cleveland, OH

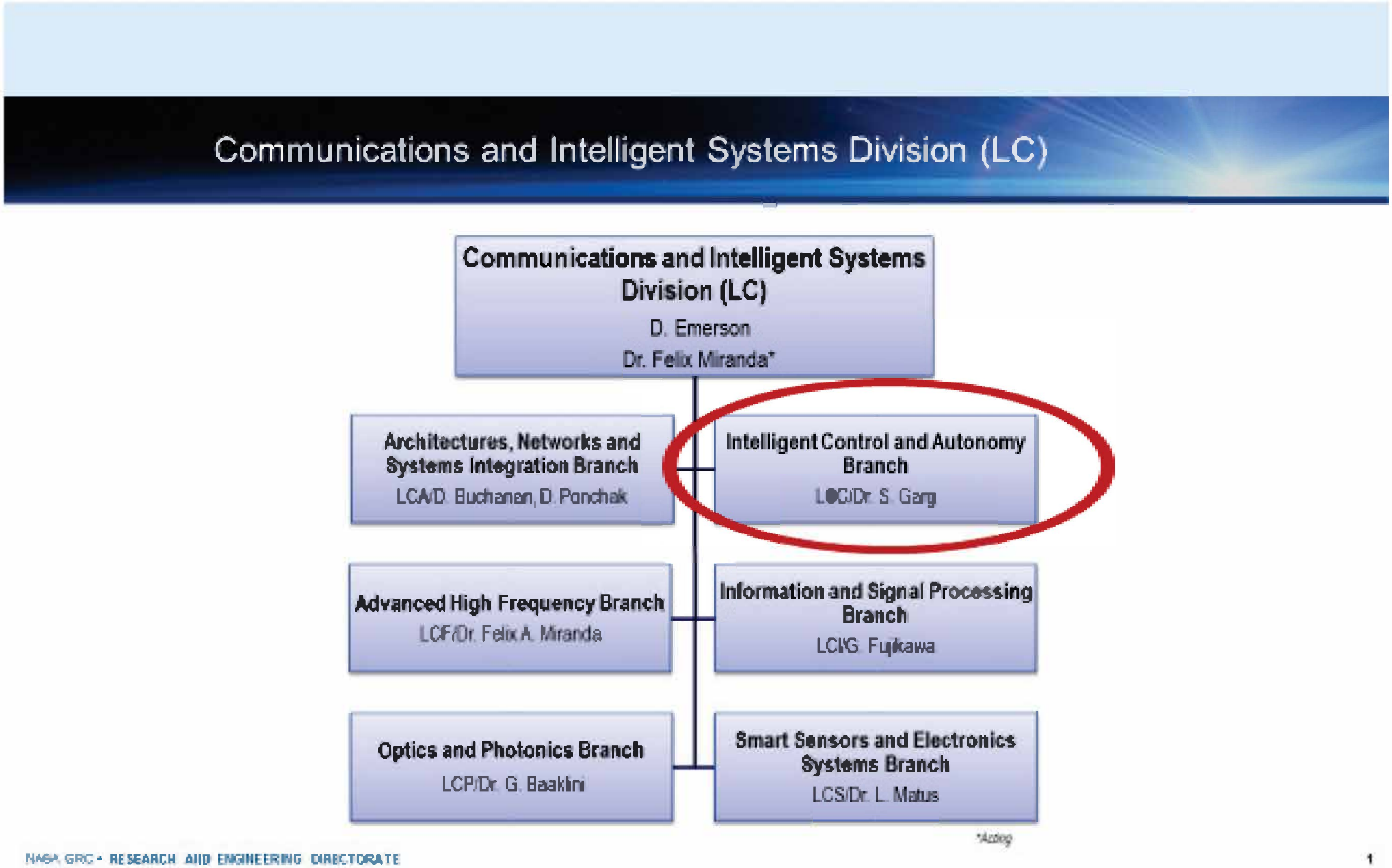
Dr. Sanjay Garg
Branch Chief
Ph: (216) 433-2685
email: sanjay.garg@nasa.gov
http://www.grc.nasa.gov/WWW/cdtb/


NASA Matrix Organization
Mission
Program 1
Program 2
Project A
Project B
Center
Directorate 1
Directorate 2
Division A
Division B
Perform Task, Provide People, Facilities
Branch X
Branch Y
Branch Z
Define Goals, Allocate Resources – FTEs, $s
Sub-Project X
Sub-Project Y
Sub-Project Z
We work with Project Management to identify and implement research and technology development tasks which are consistent with project objectives
Glenn Research Center
Intelligent Control and Autonomy Branch
at Lewis Field
NASA



Glenn Research Center
Controls and Dynamics Branch

at Lewis Field


Communications and Intelligent Systems Division (LC)
Communications and Intelligent Systems Division (LC)
D. Emerson
Dr. Felix Miranda*
Architectures, Networks and Systems Integration Branch
LCA/D. Buchanan, D. Ponchak
Intelligent Control and Autonomy Branch
LCC/Dr. S. Garg
Advanced High Frequency Branch
LCF/Dr. Felix A. Miranda
Information and Signal Processing Branch
LCI/G. Fujikawa
Optics and Photonics Branch
LCP/Dr. G. Baaklini
Smart Sensors and Electronics Systems Branch
LCS/Dr. L. Matus
*Acting
NASA GRC • RESEARCH AND ENGINEERING DIRECTORATE
1

ICAB Overview

- **Mission**
  - Research, develop and verify aerospace propulsion dynamic modeling, health management, control design and implementation technologies that provide advancements in performance, safety, environmental compatibility, reliability and durability
  - Facilitate technology insertion into the mainstream aeropropulsion community
- **Capabilities**
  - 25 engineers and scientists (16 CS, 9 Contractors) - most with advanced degrees and extensive experience in aeropropulsion controls related fields
  - Extensive computer-aided control design and evaluation facilities including real-time and man-in-the-loop simulation facility
  - Strong working relationship with controls technology groups in the aerospace propulsion industry, academia and other agencies
  - Strong collaborative activities with other groups at GRC - Various Branches in the Propulsion Division and with controls groups at NASA ARC, AFRC and LaRC

NASA ARMD Management Structure

PM – Project Manager

PS – Project Scientist

- **Each Center: AFRC, ARC, GRC, LaRC; has a center Point of Contact (PoC) who coordinates with Program Directors and Project Managers**
- **Line Management coordinates with Technical Leads**

Aeronautics Strategic Research Thrusts

Safe, Efficient Growth in Global Operations
- Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

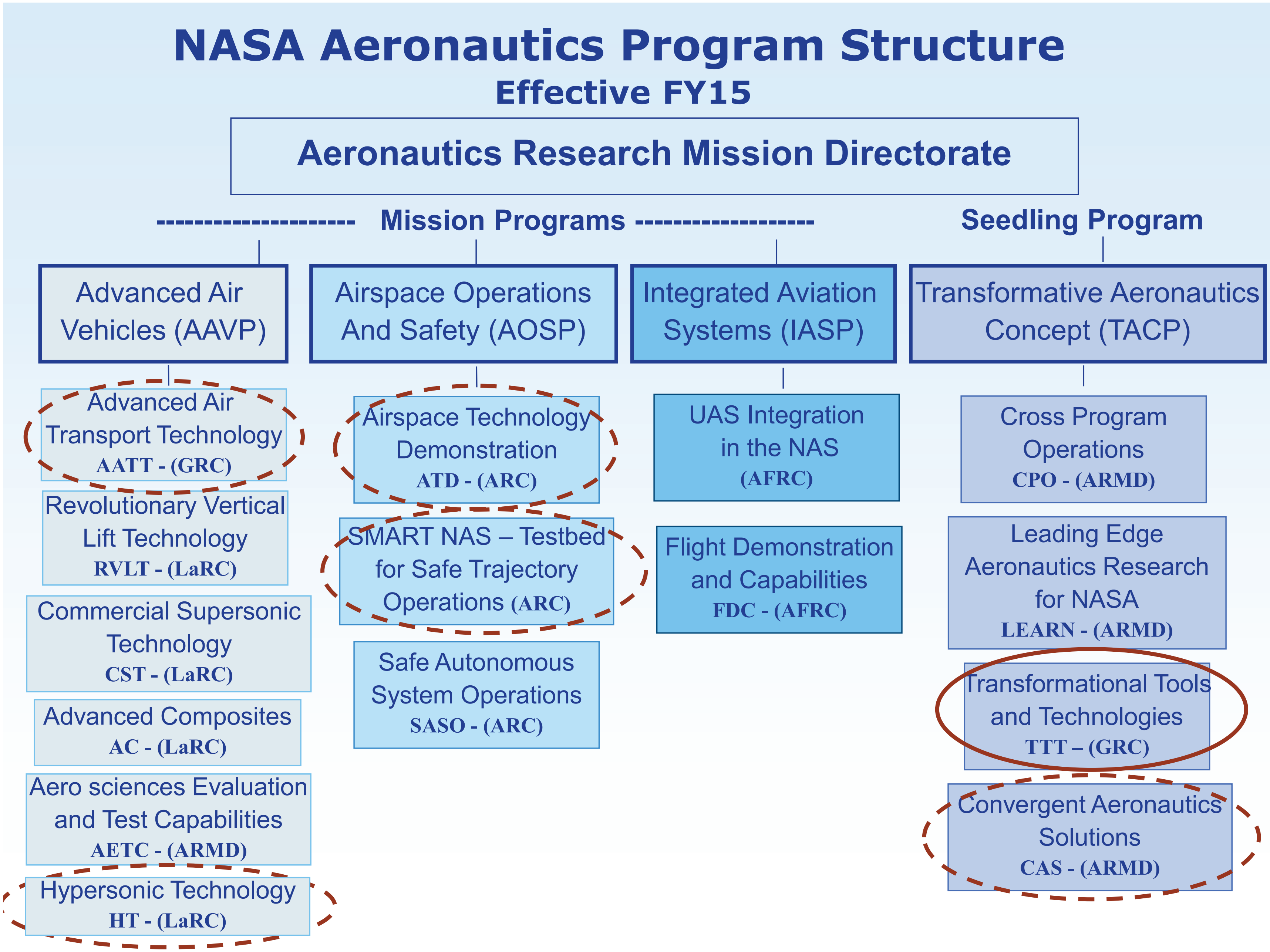
Innovation in Commercial Supersonic Aircraft
- Achieve a low-boom standard

Ultra-Efficient Commercial Vehicles
- Pioneer technologies for big leaps in efficiency and environmental performance

Transition to Alternative Propulsion and Energy
- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Real-Time System-Wide Safety Assurance
- Develop an integrated prototype of a real-time safety monitoring and assurance system

Assured Autonomy for Aviation Transformation
- Develop high impact aviation autonomy applications


NASA Aeronautics Program Structure
Effective FY15
Aeronautics Research Mission Directorate
-------------------- Mission Programs ------------------
Seedling Program
Advanced Air Vehicles (AAVP)
Airspace Operations And Safety (AOSP)
Integrated Aviation Systems (IASP)
Transformative Aeronautics Concept (TACP)
Advanced Air Transport Technology AATT - (GRC)
Revolutionary Vertical Lift Technology RVLT - (LaRC)
Commercial Supersonic Technology CST - (LaRC)
Advanced Composites AC - (LaRC)
Aero sciences Evaluation and Test Capabilities AETC - (ARMD)
Hypersonic Technology HT - (LaRC)
Airspace Technology Demonstration ATD - (ARC)
SMART NAS – Testbed for Safe Trajectory Operations (ARC)
Safe Autonomous System Operations SASO - (ARC)
UAS Integration in the NAS (AFRC)
Flight Demonstration and Capabilities FDC - (AFRC)
Cross Program Operations CPO - (ARMD)
Leading Edge Aeronautics Research for NASA LEARN - (ARMD)
Transformational Tools and Technologies TTT – (GRC)
Convergent Aeronautics Solutions CAS - (ARMD)

GRC "Aero Controls" Tasks

Advanced Air Vehicles Program

- AAVP – Intelligent Propulsion System Architecture
- AATT – Dynamic Systems Analysis Tools and Methods
- AATT – Engine Icing Detection and Mitigation*
- AATT – Active Turbine Tip Clearance Control*
- AATT – Dynamic Modeling and Control of HEP system
- *HTP – CCE-LIMX Modeling and Control*
- *HTP – Propulsion System Model Uncertainty Quantification*

Airspace Operations and Safety Program

- ATD – Propulsion Simulation for Enhanced Simulator Fidelity
- SMART NAS – Runtime Assurance of Complex Systems*

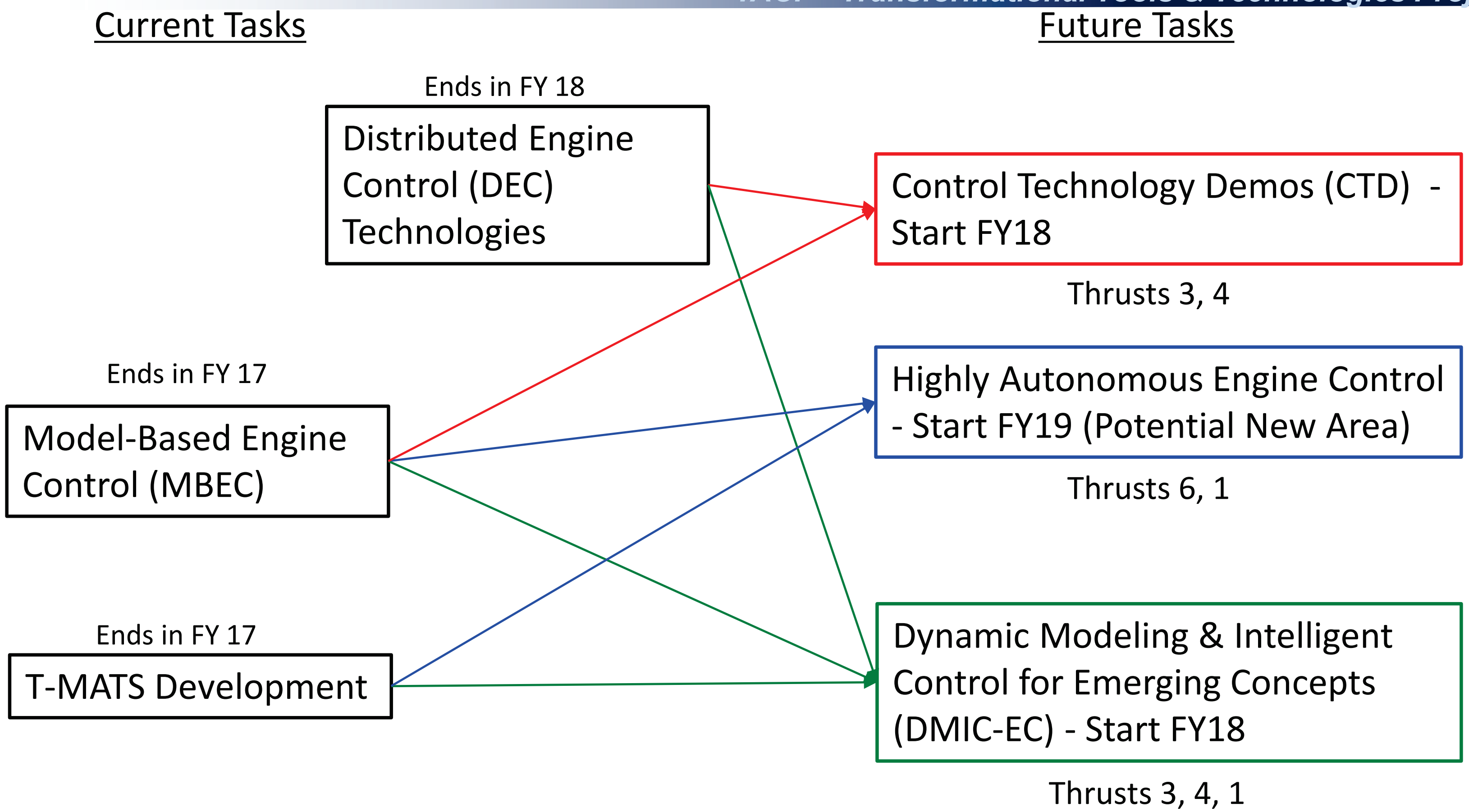
Transformative Aeronautics Concept

- TTT – Distributed Engine Control Tools and Technologies
- TTT – Model Based Engine Control*
- TTT – T-MATS Tool Development*
- TTT – Active Combustion Control
- *TTT – Pressure Gain Combustion*

** Tasks ending at end of FY17*

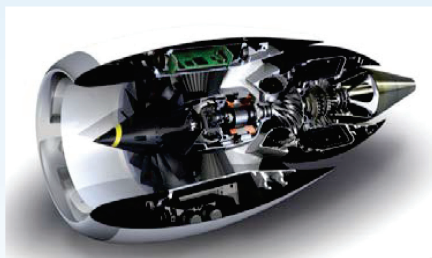
TTT – Propulsion Controls Notional Roadmap

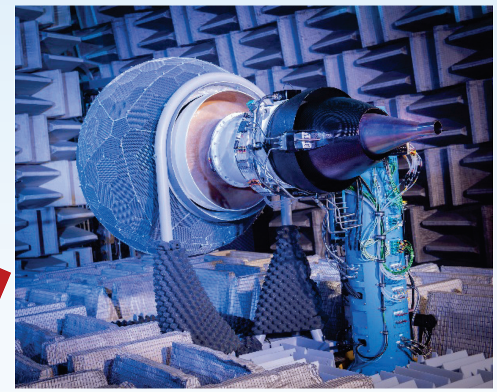
TACP - Transformational Tools & Technologies Project



DART – DGEN Aero-Propulsion Research Turbofan

- Facility based on the DGEN 380 Turbofan Engine developed by Price Induction
  - Dual spool, high bypass geared turbofan rated for 500 lb thrust with FADEC
- Provides an excellent low cost platform to validate advanced control logic schemes through engine test





Glenn Research Center

Intelligent Control and Autonomy Branch

at Lewis Field

Future Opportunities

Significant Realignment of work as programs/projects get reformulated and Center priorities evolve:

- **Hybrid-Electric Propulsion** – Dynamic modeling and control of power generation system, integrated modeling of propulsion+power system for all class of vehicles including the emerging Urban Air Mobility market
- **Autonomy** – Intelligent Propulsion Control and Health Monitoring for Turbomachinery Based propulsion systems as well as Electrified Aircraft

"Controls" Technologies Available for Licensing

NASA GRC Technology Transfer Office provides information on partnering with NASA including technologies available for licensing:
http://technology.grc.nasa.gov/

Following are some GRC developed "controls" technologies listed as available for licensing:

- **Optimized tuner selection for engine performance estimation –** Patent Issued
  http://technology.grc.nasa.gov/patent/GRC-QL-0022
- **High speed idle engine control mode**
  http://technology.grc.nasa.gov/patent/LEW-TOPS-55
- **Atmospheric Turbulence Modeling for Aero Vehicles**
  http://technology.grc.nasa.gov/search/patent/turbulence
- **Conditionally Active Min-Max Limit Regulators** – Patent Issued
  http://technology.grc.nasa.gov/patent/LEW-TOPS-56
- **A Tool to Evaluate the Dynamic Capability of Turbine Engines**– Patent Pending
  https://technology.grc.nasa.gov/patent/LEW-TOPS-96
- **Model-Predictive Automatic Recovery System**
  https://technology.grc.nasa.gov/patent/LEW-TOPS-89

Collaboration Opportunities

- NRA (NASA Research Announcements)
  - Open to industry and universities
  - Very focused on specific topics
  - Announced by Projects on a periodic basis

  http://www.aeronautics.nasa.gov/nra.htm

- SBIR (Small Business Innovative Research)
  - Open to small businesses
  - Very broad areas of call. Topics determined by Programs/Projects

  http://sbir.gsfc.nasa.gov/

- Space Act Agreement – no direct NASA funding
  - Open to industry/universities/govt. agencies
  - Ideal for collaboration on mutual areas of interest without exchange of funds or with inflow of funds to NASA efforts
  - Opportunity for industry to leverage NASA investment in projects

- Student and Faculty Programs

  http://www.nasa.gov/centers/glenn/education/index.html

Session 1

Propulsion System Modeling and Autonomy

NASA/CP—2018-219891

20

National Aeronautics and Space Administration

6th Propulsion Control and Diagnostics Workshop

Session 1: Propulsion System Modeling and Autonomy

Jonathan S. Litt

NASA Glenn Research Center

T. Shane Sowers, Scott B. Norin, and
Jeffryes W. Chapman

Vantage Partners, LLC

NASA/CP—2018-219891

National Aeronautics and Space Administration

6th Propulsion Control and Diagnostics Workshop

Ohio Aerospace Institute

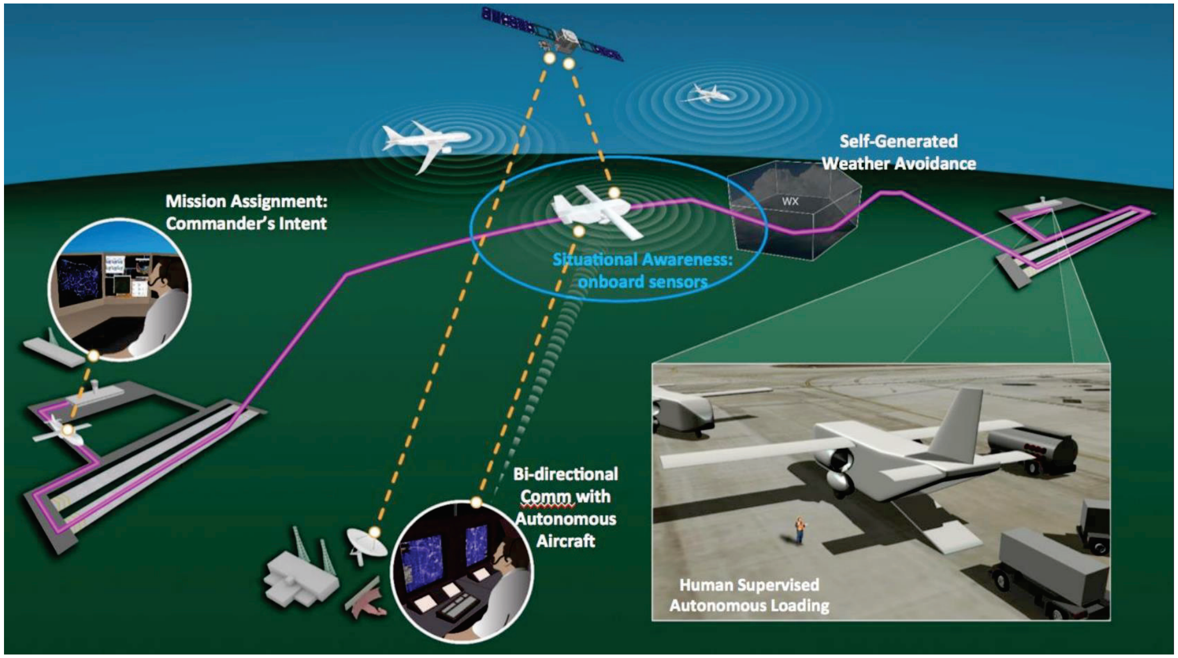
August 22-24, 2017

Agenda

10:00-12:00	Session 1: Propulsion System Modeling and Autonomy - Jonathan Litt
10:00	Session Overview - Jonathan Litt
10:10	Intelligent Propulsion System Architecture to Enable Vehicle Autonomy - Shane Sowers
10:40	Propulsion System Modeling for High Angle of Attack Simulation - Scott Norin
11:20	T-MATS: Overview and Recent Capability Enhancements - Jeff Chapman

The Path to Fully Autonomous Aircraft

- NASA Aeronautics continues to plan their role in the development of technology to enable autonomously operated aircraft
- NASA Glenn performed preliminary proof of concept work to demonstrate how the propulsion system contributes to this goal



https://www.nasa.gov/sites/default/files/atoms/files/armd-sip-thrust-6-508.pdf

National Aeronautics and Space Administration

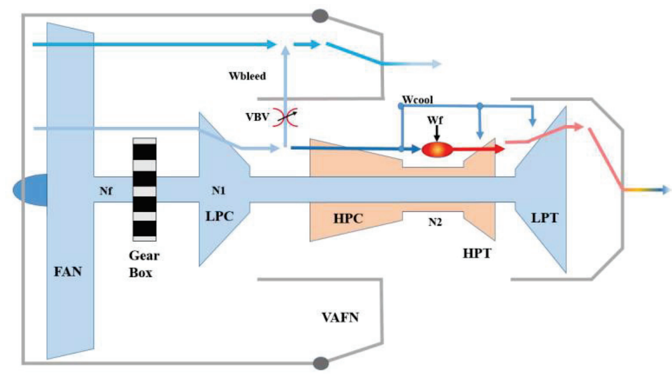
Safety Enhancement 209: Simulator Fidelity

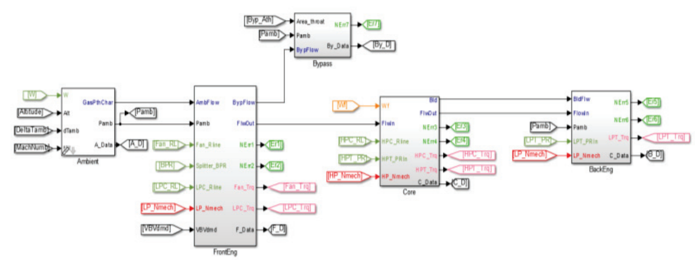
- As a result of the 2009 Colgan Air crash, the FAA has mandated stall recognition and recovery training for commercial pilots beginning in 2019
- One of NASA's roles is to define aerodynamic model parameters, along with their availability and associated uncertainties, that are necessary for replicating full stall flight characteristics of various aircraft models, including wing-mounted twins, high-wing turboprops, and T-tail/aft engine configurations
- NASA Glenn and Langley are collaborating on research into stall and post-stall behavior of a T-tail regional jet

https://www.youtube.com/watch?v=33NUAy3eomg

Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)

- T-MATS is an open-source, graphical simulation package developed at NASA GRC
- It is primarily used to model gas turbines, but has been used to model other thermodynamic systems as well
- It is built using MATLAB/Simulink and C code, and is a plug-in to Simulink
- Over 4,500 downloads worldwide and increasing steadily
- Used by NASA, industry, and academia





NASA/CP—2018-219891

Intelligent Propulsion System Control Architecture to Enable Vehicle Autonomy

Shane Sowers
Vantage Partners, LLC
Jonathan S. Litt
NASA Glenn Research Center

August 22, 2017

Outline

- Introduction
- Background
- Quickstart Project
- Summary

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Introduction

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Objectives

To develop an engine control architecture that works harmoniously with the flight control, with reduced pilot intervention over time. It will:

- Automatically recognize the vehicle operating mode
- Configure the engine control to optimize performance with knowledge of the engine condition and capability
- Coordinate with the flight control to optimize vehicle performance
- Recognize and respond to “off-nominal” propulsion situations

2017 PCD Workshop
NASA Glenn Research Center

Perspectives on Increasing Autonomy

- There will be a natural progression from the current state to fully autonomous operation.

- The Intelligent Propulsion Control architecture must be flexible enough to accommodate evolving requirements.

- The approach must maintain safety.

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Background

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Role of the pilot

- Integrate the flight and propulsion control
- Recognize and respond to off-nominal situations

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Current situation in commercial aircraft

- The pilot actually flies the aircraft less than eight minutes per flight on average (takeoff and landing), the rest is automated
- Today's modern aircraft engine control computers incorporate a significant amount of automated detection and accommodation logic to address the common faults that an engine may experience, in many cases the pilot is not even notified

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

What if something goes wrong?

- First responsibility is to fly the aircraft!
  - There is no failure in modern turbofan engines that requires immediate shutdown
  - Commercial aircraft are certified to fly with an engine failed
  - First, apply basic stick and rudder commands to maintain aerodynamic control of the aircraft, then diagnose engine malfunction when time permits
- Appropriate pilot response to engine malfunctions is defined in aircraft flight manual
  - Checklist procedures define the sequence of steps pilots are to follow in the event of a malfunction

Engine Failure After V1 Procedure

If engine failure occurs at or after V_1, follow this procedure:

PILOT FLYING (PF)	PILOT MONITORING (PM)
Maintain directional control, rotate to takeoff attitude at V_R.	Call "ROTATE" at V_R.
When a positive rate of climb is indicated, call "GEAR UP."	Call "POSITIVE RATE" when positive rate of climb indicated. Position the landing gear lever UP on command.
* Climb at V_2, limit bank angle to 15 degrees.	Monitor engine and flight instruments.
400 feet AGL, call "HEADING SELECT."	Select HDG SEL.
** At flap retraction altitude "SET TOP BUG," retract flaps (as required on the flap/speed schedule). Maintain pitch attitude indicated by F/D. (See Note below.)	Set airspeed cursor to V_M Flaps 0. Retract the flaps on command. Monitor flap indications and leading edge lights.
At flap retraction (as required), call for "MAXIMUM CONTINUOUS THRUST," climb at V_M for existing flap setting. Call for the "**ENGINE FAILURE / FIRE / SHUTDOWN / SEVERE DAMAGE / SEPARATION CHECKLIST**."	Set Maximum Continuous Thrust after flaps are retracted. Complete the **ENGINE FAILURE / FIRE / SHUTDOWN / SEVERE DAMAGE / SEPARATION** checklist on command.
Determine the next course of action.	Advise ATC of the Captain's intentions.

Note: If a fire is indicated, the **ENGINE FAILURE / FIRE** checklist should be called for by the PF and executed by the PM immediately upon reaching flap retraction altitude: "SET TOP BUG, ENGINE FAILURE / FIRE / SHUTDOWN / SEVERE DAMAGE / SEPARATION CHECKLIST."

* If an engine failure occurs prior to V_2, maintain V_2 up to the altitude required for obstacle clearance. If an engine failure occurs after V_2, but less than $V_2 + 20$ knots, maintain the speed reached at the time of the engine failure.

If an engine failure occurs at a speed higher than $V_2 + 20$ knots with the flaps at takeoff setting, increase pitch attitude to reduce speed to and maintain $V_2 + 20$ knots until clear of obstacles.

F/D pitch commands maintain the above engine failure speeds.

Example engine failure checklist[1]

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Propulsion Malfunctions & Observed Symptoms[2]

	Engine Separation	Severe Damage	Surge	Bird Ingestion/FOD	Seizure	Flameout	Fuel control problems	Fire	Tailpipe fires	Hot Start	Icing	Reverser Inadvertent Deploy	Fuel Leak
Bang	O	X	X	O	O						O		
Fire warning	O	O		O				X					
Visible flame	O	O	O	O				O	X	O			
Vibration		X	O	X	O						X	X	
Yaw	O	O	O	O	O	O	O					X	
High EGT		X	X	O	O		X		O	X	O		
N1 change	X	X	O	O	X	X	X						X
N2 change	X	X	O	O	X	X	X						X
Fuel flow change	X	O	O		O	X	O	O					X
Oil indication change	X	O	O		O	X		O					
Visible cowl damage	X	X						O				X	
Smoke/odor in cabin bleed air		O		O	O								
EPR change	X	X	X	O	X	X	X						X

X = Symptom very likely
O = Symptom possible
Note: blank fields mean that that symptom is unlikely

However, Propulsion System Malfunction plus Inappropriate Crew Response is the leading cause of propulsion system related accidents for commercial aircraft[3].

Propulsion System Malfunction plus Inappropriate Crew Response

Kegworth Air Disaster, 1989[4]

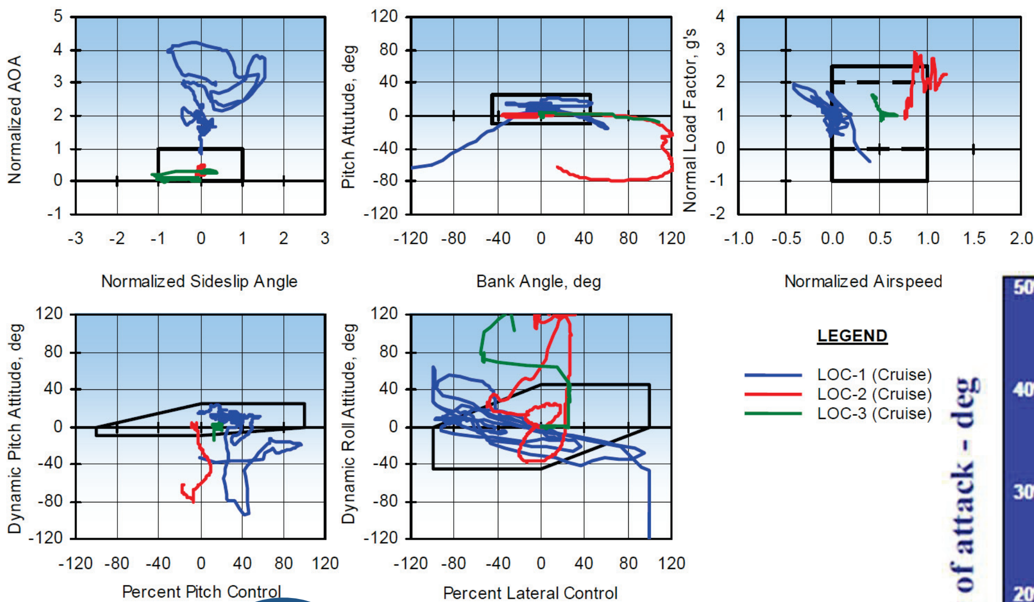
- British Midland-operated Boeing 737-400
- Fan blade detached, resulting in
  - Heavy vibration
  - Smell of smoke in cabin
- The pilots misdiagnosed the problem engine and shut down wrong one, unknowingly continuing to fly on the bad engine
- Eventually the damaged engine ceased operating and burst into flames
- 47 fatalities out of 118 passengers (all 8 of the crew survived)

Source: Report on the accident to Boeing 737-400 G-OBME near Kegworth, Leicestershire on 8 January 1989

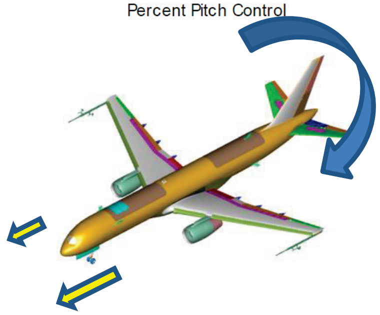
https://www.gov.uk/aaib-reports/4-1990-boeing-737-400-g-obme-8-january-1989

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Performance and safety enhancement through integration with the flight control

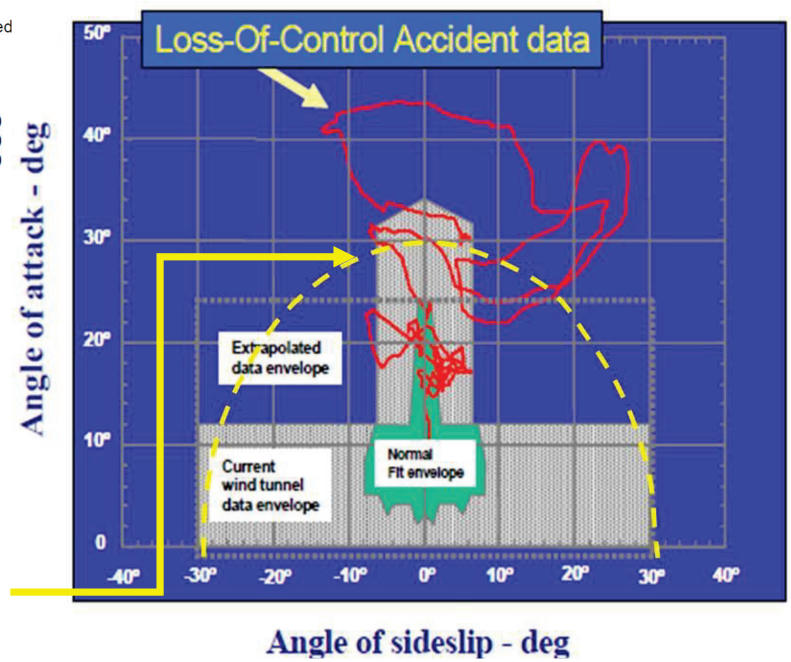


Wilborn and Foster's Quantitative Loss-of-Control Criteria[5] showing example Loss-of-Control data.



The engine is a very powerful actuator with a large region of effectiveness

Region of engine effectiveness



Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Vehicle-Centric Autonomy Quickstart Project

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Overview

- Small demonstration effort with the goal of supporting the increase in vehicle autonomy – from current state to fully autonomous
- Assumed the "intelligence" is located outside of the engine thereby preserving original controller functionality and certification
- A join endeavor with NASA Glenn and Langley that leveraged the competencies of each
- Demonstrated the operation of a basic intelligent propulsion control that was part of a larger architecture

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Team Members

- Jonathan Litt, GRC
- Don Simon, GRC
- Shane Sowers, GRC/VPL
- Amy Chicatelli, GRC/VPL
- Aidan Rinehart, GRC/VPL
- Karl Owen, GRC DRA
- Chris Spiers, GRC Intern
- Mike Acheson, LaRC
- Dick Hueschen, LaRC Affiliate

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Technical Capabilities

- GRC Leadership
  - Engine performance estimation algorithm development
  - Engine fault detection, isolation, and accommodation algorithm development
  - Model-Based Engine Control ("Personalized" engine control)
- LaRC Leadership
  - Flight control
  - Propulsion control requirements

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Resource Capabilities

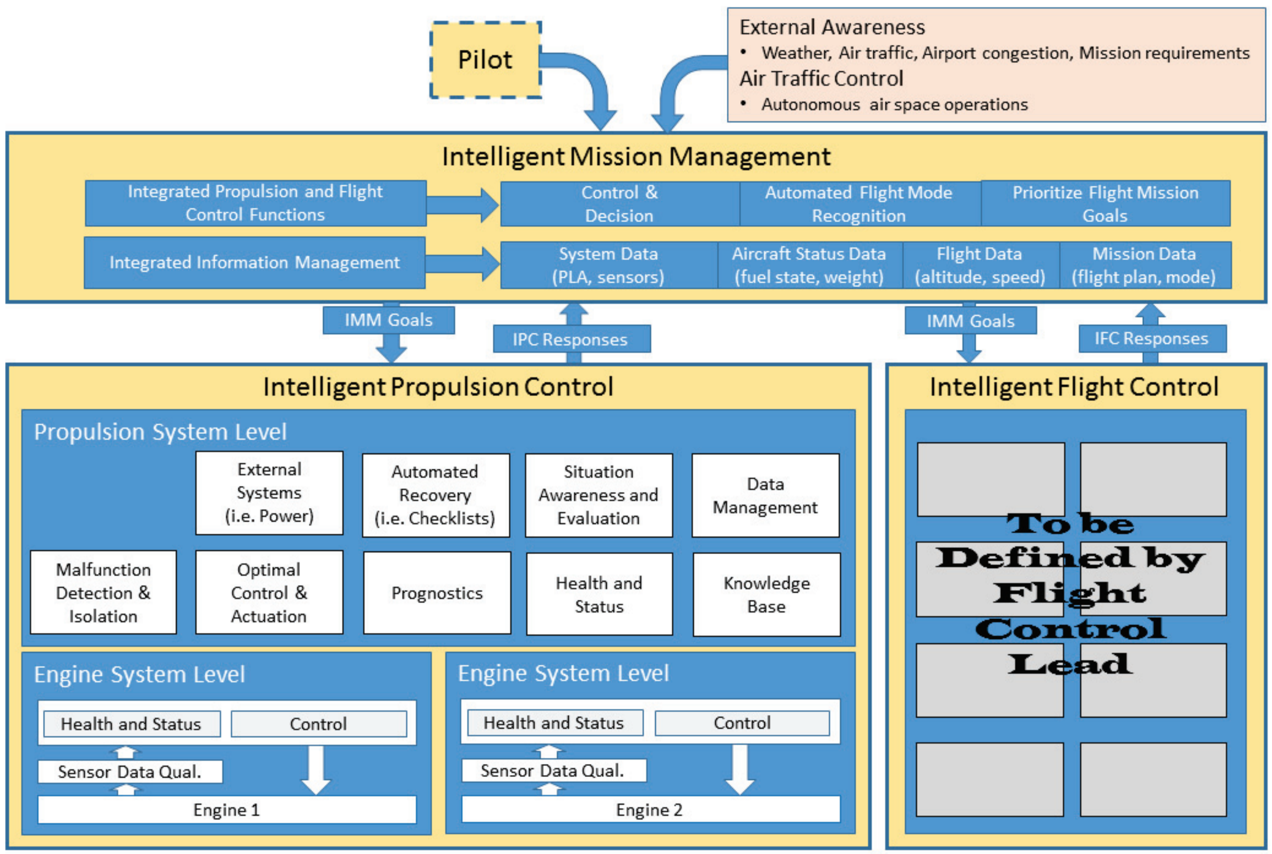
- Distinguished Research Associate (former Air Force pilot) as a consultant
- NASA Langley provided flight control consultants
- Fully configurable flight simulator cockpit for architecture evaluation

NASA/CP—2018-219891

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Milestone

Developed a preliminary Intelligent Propulsion Control System architecture that supports increasing vehicle autonomy.



Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Milestone

Demonstrated several representative applications of Intelligent Propulsion Control in flight simulator that enable reduced pilot workload, enhanced vehicle performance, and improved engine diagnostic capability.

- Minimum control airspeed protection against loss of control for an one engine out situation
- Estimation of unmeasured engine variables
- Asymmetric thrust detection and confirmation
- Automation of pilot checklist for engine in-flight shutdown
- Inhibition of incorrect engine shutdown

Demonstrated integrated flight/propulsion control for improved performance.

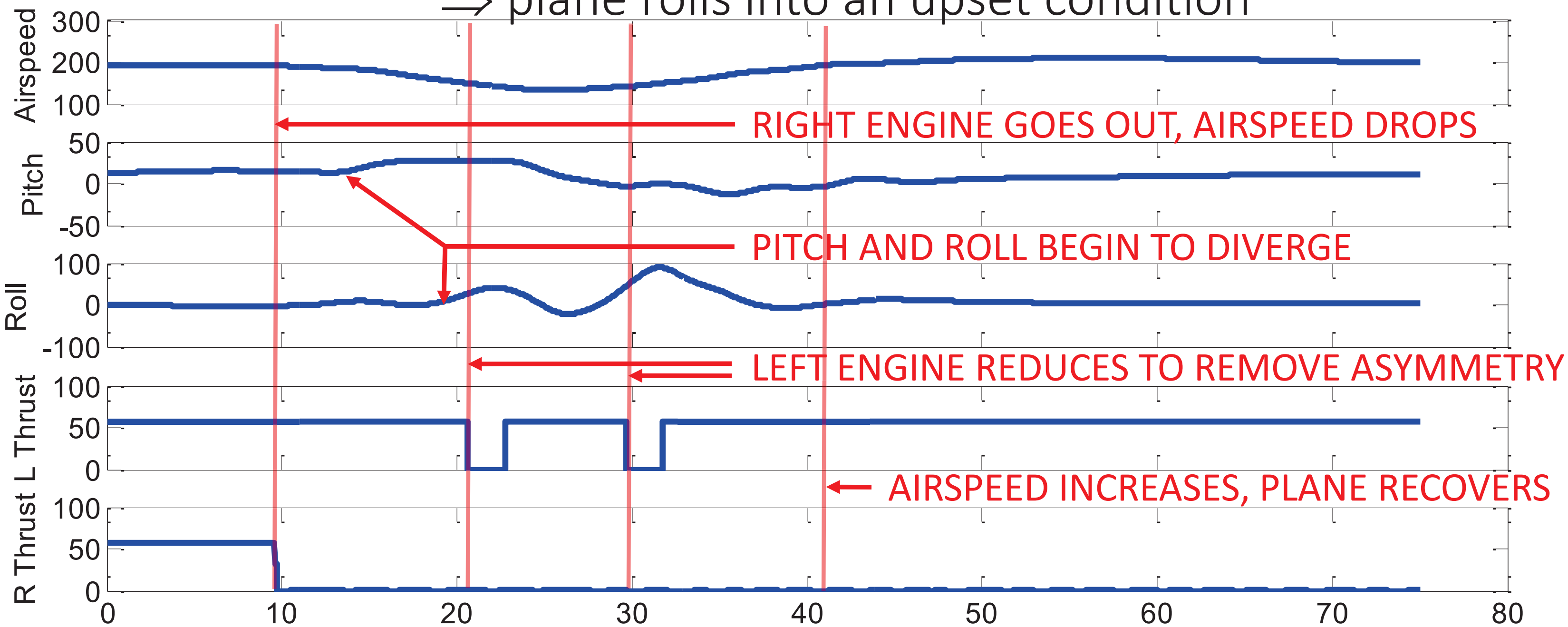
- High crosswind landings

Demonstrated requested augmentation of flight control with propulsion to compensate for stuck, limited, and ineffective flight control surfaces.

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Example: Minimum control airspeed protection against loss of control for an engine out situation

One engine is inoperative on a twin engine aircraft
- ⇒ speed drops
  - ⇒ rudder becomes ineffective
    - ⇒ rudder cannot counteract thrust asymmetry
      - ⇒ plane rolls into an upset condition



Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Lessons Learned

- Although current flight management systems are effective, more can be done.
- When using the propulsion system to augment flight control, an effective strategy it to use the engines for coarse and slow control input while the control surfaces are best for fine and rapid adjustments.
- While Intelligent Propulsion Control reduces the workload of the pilot flying, it is beneficial for the pilot monitoring since it parallels many of those roles.
- Intelligent Propulsion Control provides significant advantages during off-nominal situations by improving situational awareness of the pilot and by inhibiting inappropriate crew responses (i.e., reduce the “startle” factor, help assess conflicting information).
- Because the sub-elements may generate opposing engine control commands, high-level command logic is important.
- An awareness of the flight phase is needed to configure the operation of the sub-elements and to properly set logic priorities.

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Summary

- Intelligent Propulsion Control supports increasing vehicle autonomy and reduces pilot workload.
- Addressing inappropriate crew response to propulsion system malfunctions and utilizing the large region of effectiveness of the propulsion system for flight control are examples of the need for Intelligent Propulsion Control.
- A quick-start project was enacted to develop a preliminary demonstration architecture and to help guide future work.

Intelligent Propulsion System Architecture to Enable Vehicle Autonomy

Acknowledgment

Thank you to the Program Directors of the NASA Advanced Air Vehicles Program (AAVP) and the Transformative Aeronautics Concepts Program (TACP) who jointly sponsored this research.

The authors gratefully acknowledge the funding support of AAVP.

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2. ATA and FAA, “Turbofan Engine Malfunction Recognition and Response Final Report,” 2009.
3. AIA/AECMA: Project Report, “Propulsion System Malfunction Plus Inappropriate Crew Response (PSM + ICR), Volume 1,” 1998.
4. Air Accidents Investigation Branch (AAIB) - United Kingdom, Report on the Accident to Boeing 737-400 G-OBME Near Kegworth, Leicestershire on 8 January 1989 (AAIB AAR 4/1990).
5. Wilborn, J., Foster, J., “Defining Commercial Transport Loss-of-Control: A Quantitative Approach”, AIAA Atmospheric Flight Mechanics Conference and Exhibit, August 16-19, 2004, Providence, Rhode Island.

Thank You

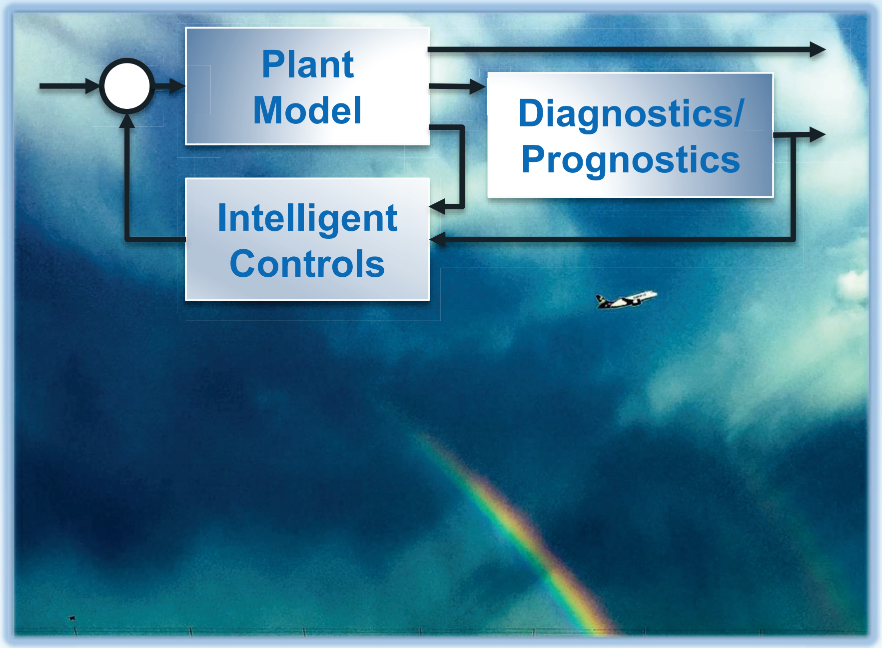

Photo by Scott Norin

SE209 Overview

Propulsion System Modeling for High Angle of Attack Simulation

Scott B. Norin
Aerospace Engineer, Vantage Partners LLC
Intelligent Control and Autonomy Branch (LCC), NASA Glenn Research Center

2017 Propulsion Controls and Diagnostics Workshop
22-24 August 2017

Outline

- Summary
- Overview
- Baseline T-MATS Model
  - Turbofan Engine Model
  - Engine Controller
  - Engine Simulation Output
  - Inlet / Streamtube
- Volume Dynamics Models
- Integrated Turbofan Engine Model
- Requirements
- Future Work
- Conclusions
- Questions

Photo by Scott Norin

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at Lewis Field

Scope

Key Questions Addressed:

- What is the objective of the SE209 project?
- What tools and methodologies have been used?
- How are the engine and controller modeled?
- How are the effects of high angle of attack modeled?
- What approach is used to validate the model?

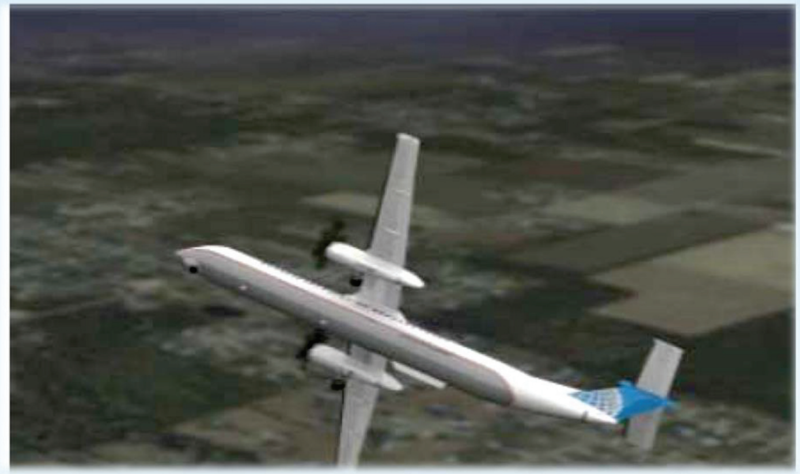
Photo by Scott Norin

Overview

Colgan Air 3407

Bombardier DHC-8-400 Turboprop
Buffalo, NY - February 12th, 2009
Inappropriate Crew Response

- Icing Conditions
- Decreased Throttle
- Pulled Yoke Back/Override Stall Warnings
- Upset Flight Condition
- Ineffective Aero Surfaces to Recover



Reference: Crider, 2014

NTSB Recommendations

Recommendation A-10-22
Require 14 *Code of Federal Regulations* Part 121, 135, and 91K operators and 14 *Code of Federal Regulations* Part 142 training centers to develop and conduct training that incorporates stalls that are fully developed; are unexpected; involve autopilot disengagement; and include airplane-specific features, such as a reference speeds switch.

Recommendation A-10-23 (Supersedes Safety Recommendation A-07-4)
Require all 14 *Code of Federal Regulations* Part 121, 135, and 91K operators of stick pusher-equipped aircraft to provide their pilots with pusher familiarization simulator training.

Recommendation A-10-24
Define and codify minimum simulator model fidelity requirements to support an expanded set of stall recovery training requirements, including recovery from stalls that are fully developed. These simulator fidelity requirements should address areas such as required angle-of-attack and sideslip angle ranges, motion cueing, proof-of-match with post-stall flight test data, and warnings to indicate when the simulator flight envelope has been exceeded.

Reference: Crider, 2014

Overview

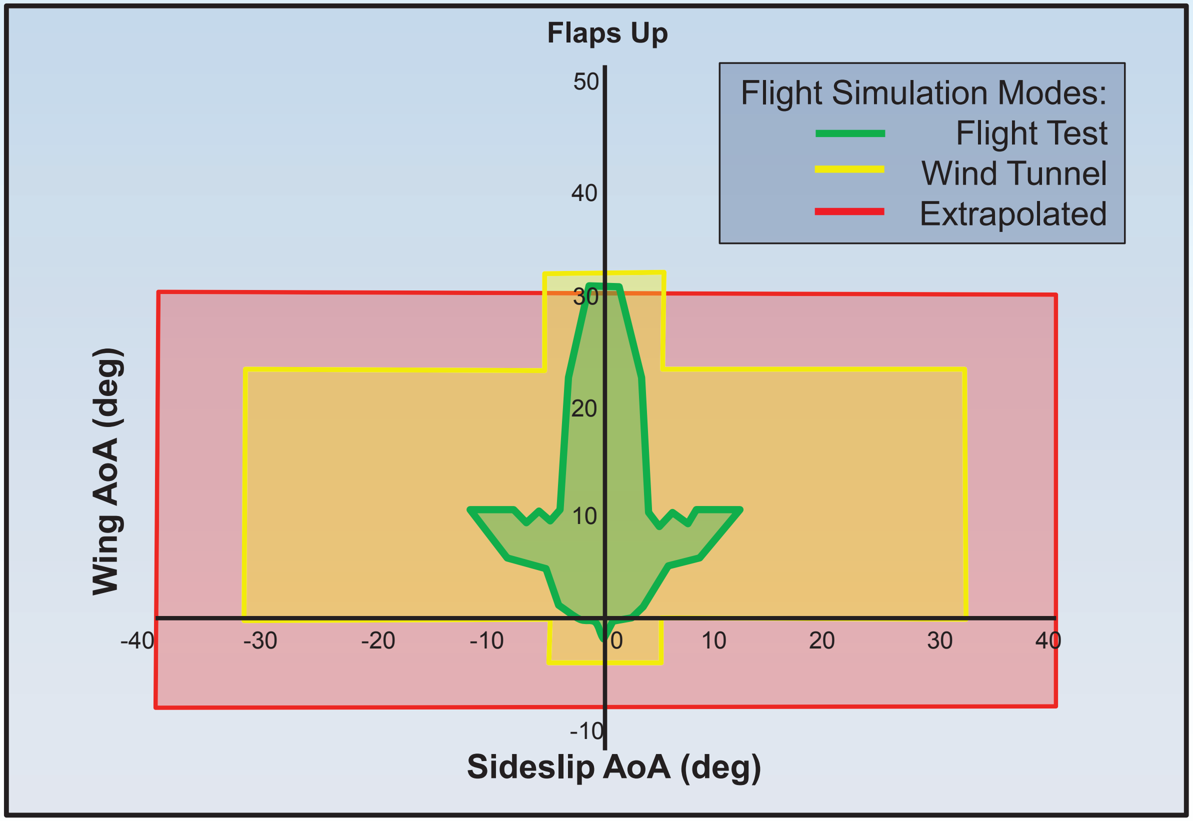
CAST Safety Enhancement (SE-209) Project Objectives

- Learning Metrics for Pilot Training
- Full Stall Modeling
- Improve Fidelity in Full Stall
- Simulator Realism
- Validate Pilot Training thru Flight Testing

Reference: The Commercial Aviation Safety Team (CAST), 2016.

Overview

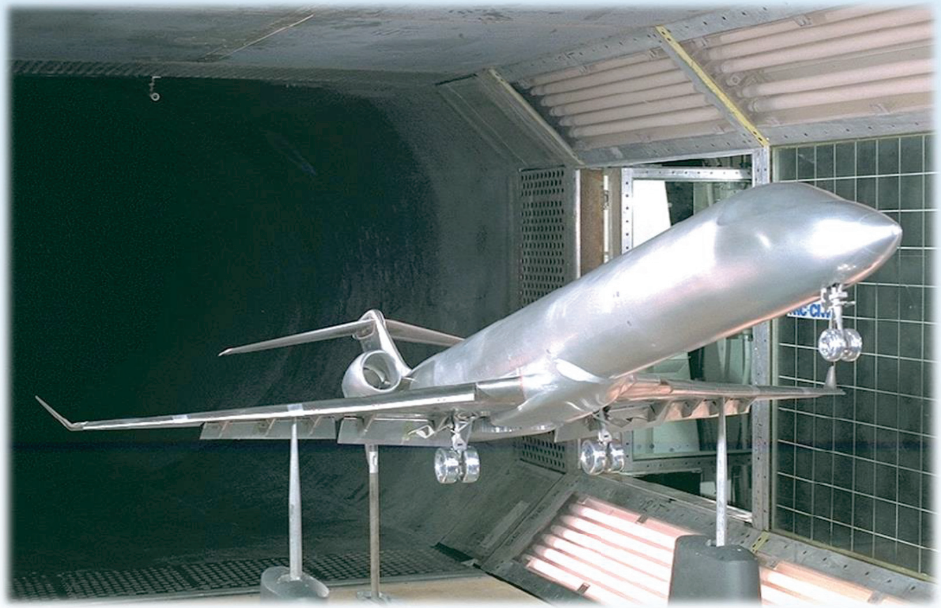
Upset Prevention and Recovery Training



Reference: FAA NSP GB 11-05, 2016

Overview

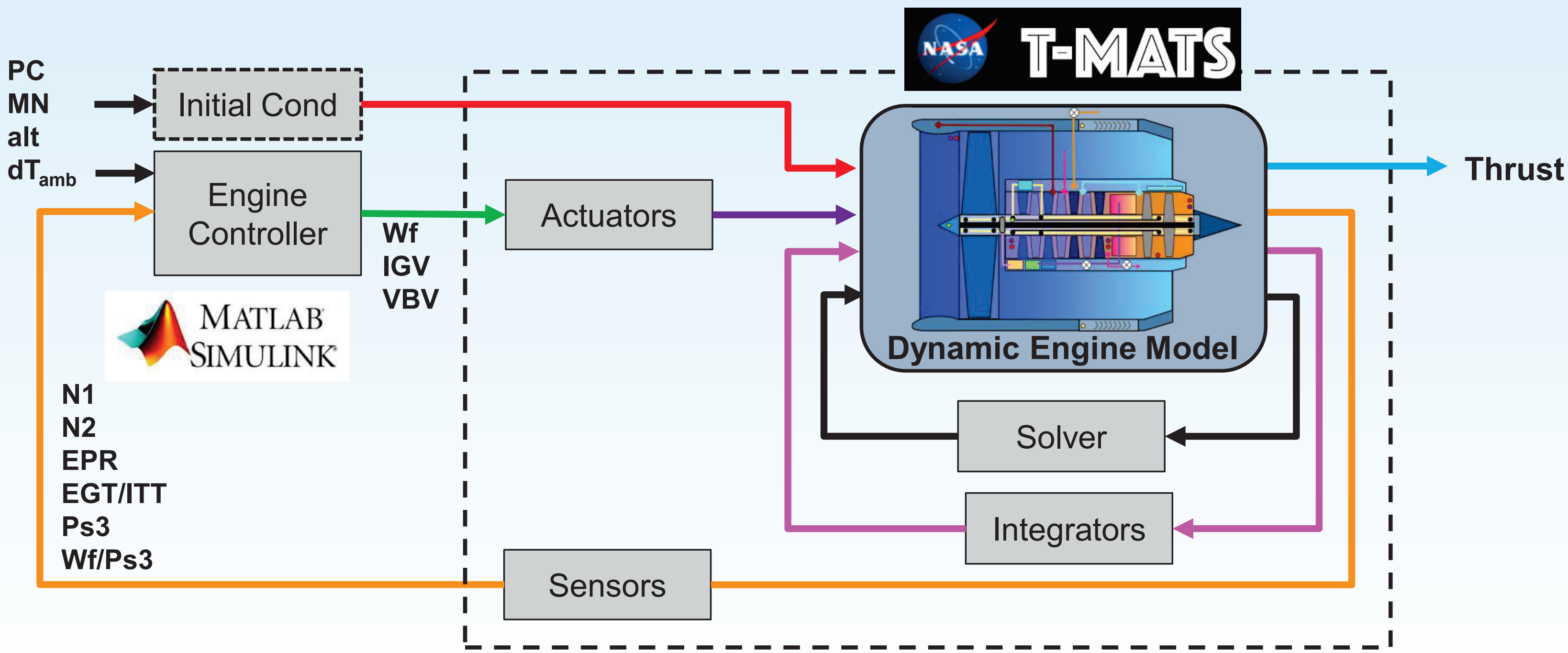
CRJ 700 Bombardier Wind Tunnel Testing



Reference: Kafyeke, 2002

AoA Testing:
Non-Slat: -6˚ to 25˚
Slats Deployed: -6˚ to 30˚(some tests up to 33.5˚)

Baseline Turbofan Engine Model



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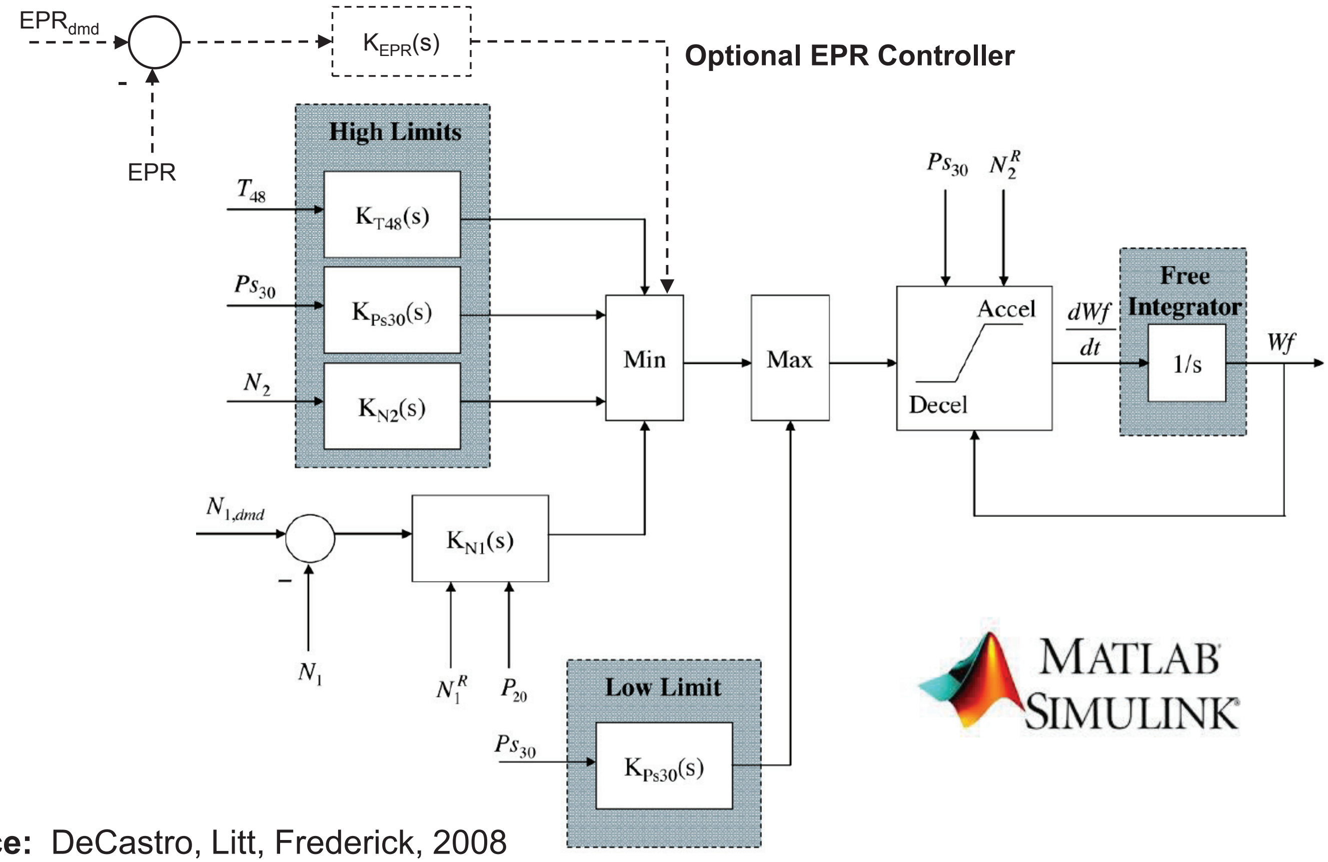
Baseline Turbofan Engine Controller

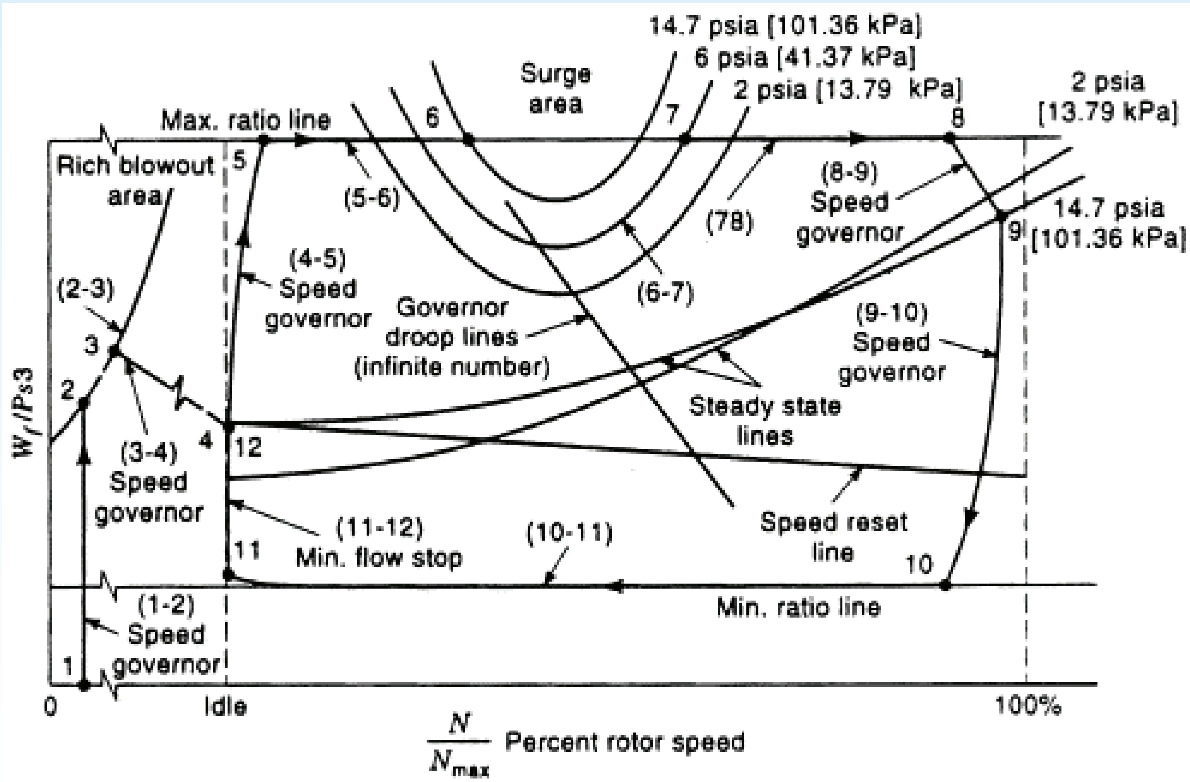
Modification to Implement N1 or EPR Control



Reference: DeCastro, Litt, Frederick, 2008

Baseline Turbofan Engine Controller

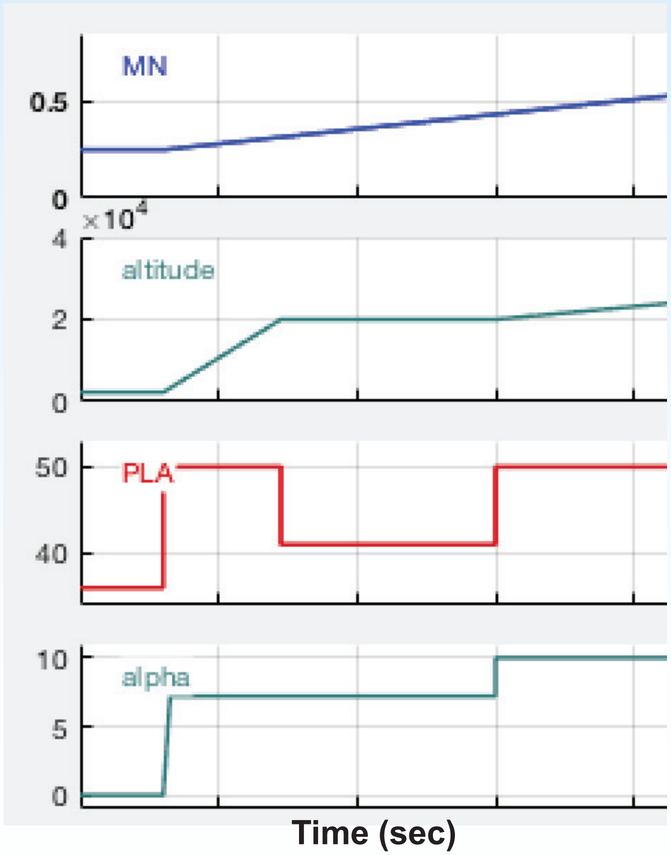
Control Limiters

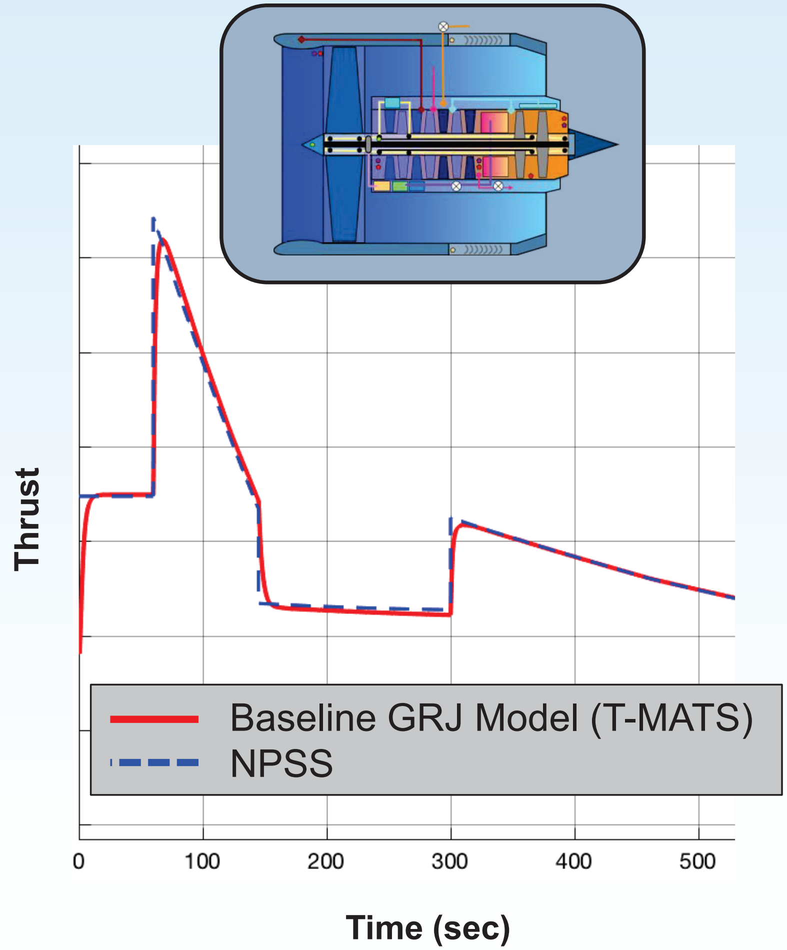


Reference: Spang III, Brown, 1999.

Baseline Turbofan Engine Simulation Output

Ascent Flight Profile





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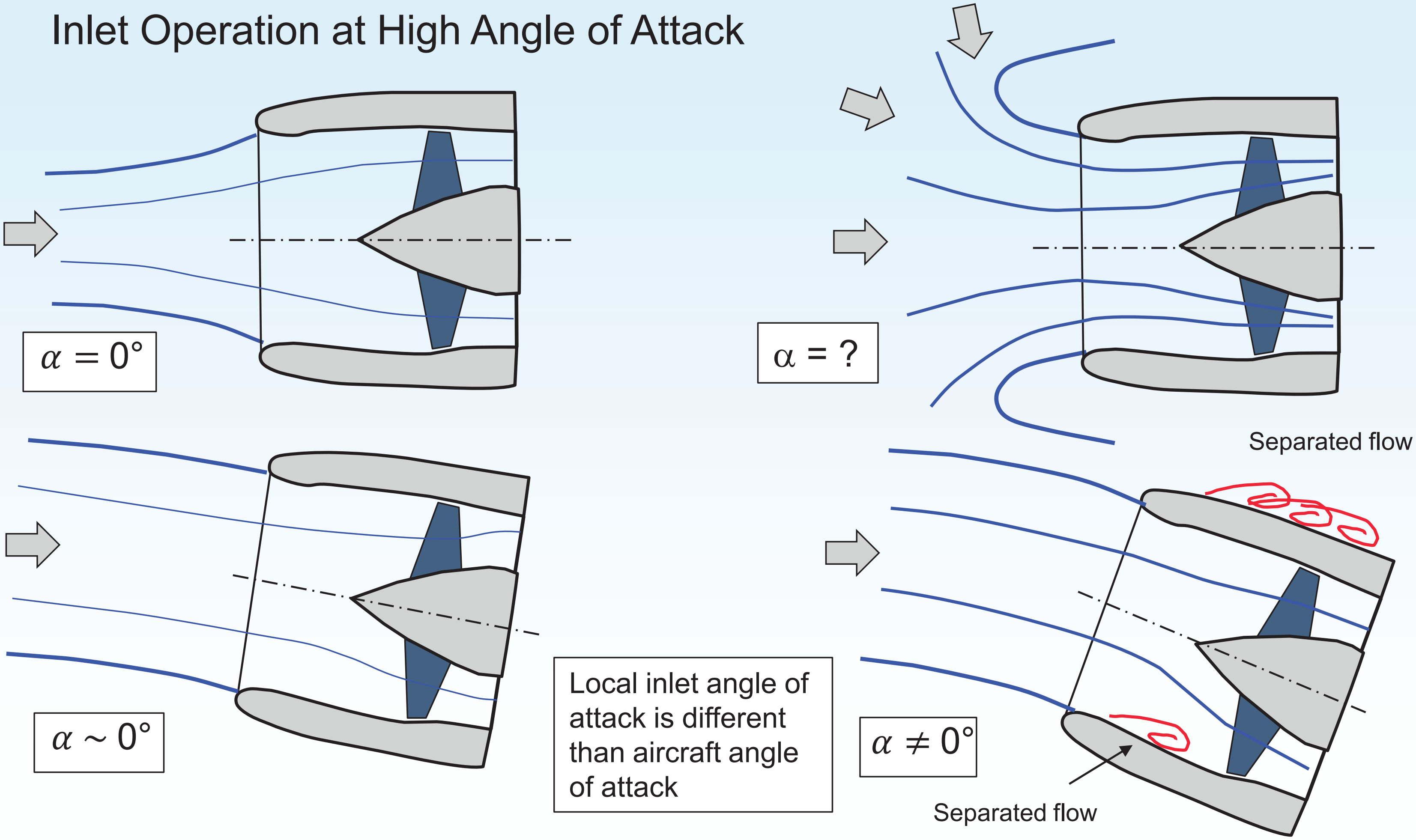
Dynamic Inlet Modeling

Inlet Operation at High Angle of Attack



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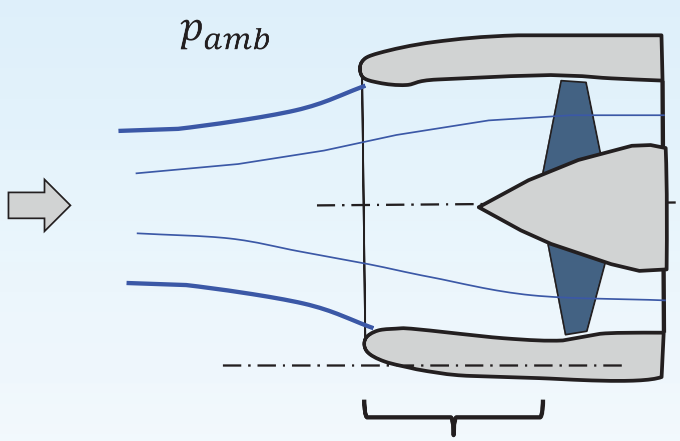
Dynamic Inlet Modeling

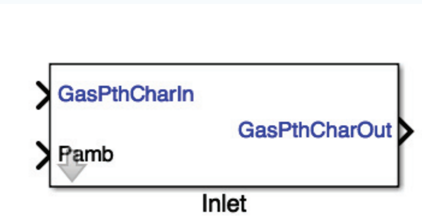
0D Model in T-MATS



$$\Delta p_t = \eta_e \, p_{t_{in}} \, f\left[\frac{p_t}{p_{amb}}\right]$$

Assumptions:

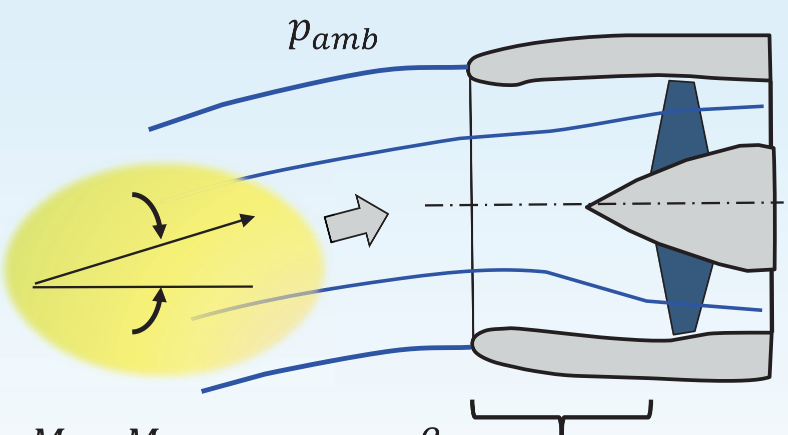
- Isentropic, Adiabatic, Frictionless
- Geometry / Profiles are Not Defined
- Inlet pressure drop is a function of ambient pressure (lookup table) and efficiency η_e = 0.999



Reference: Chapman, Lavelle, May, Litt, Guo, 2014.

Dynamic Inlet Modeling

0D Model in T-MATS with Angle of Attack Terms



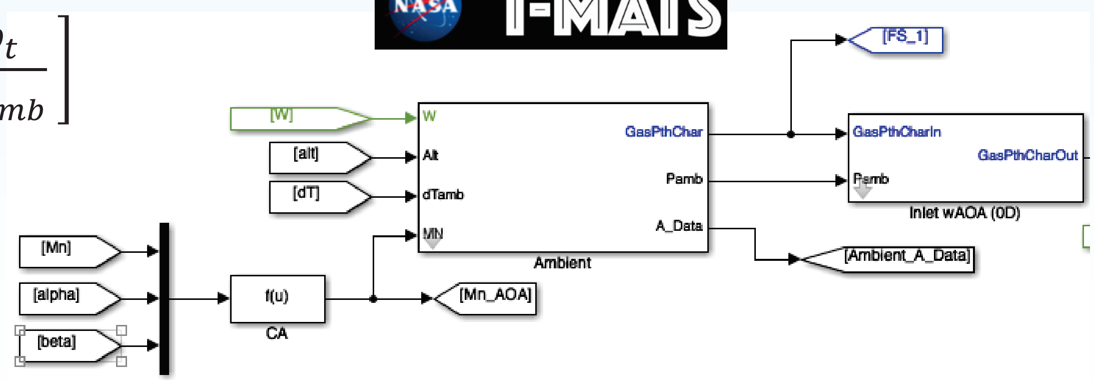
$$M = M_{amb} \cos\alpha \ \cos\beta$$

$$\Delta p_t = \eta_e \, p_{t\,in} \, f\left[\frac{p_t}{p_{amb}}\right]$$

Assumptions:

- Isentropic, Adiabatic, Frictionless
- Geometry / Profiles are Not Defined
- Inlet pressure drop is a function of ambient pressure (lookup table) and efficiency η_e = 0.999

T-MATS



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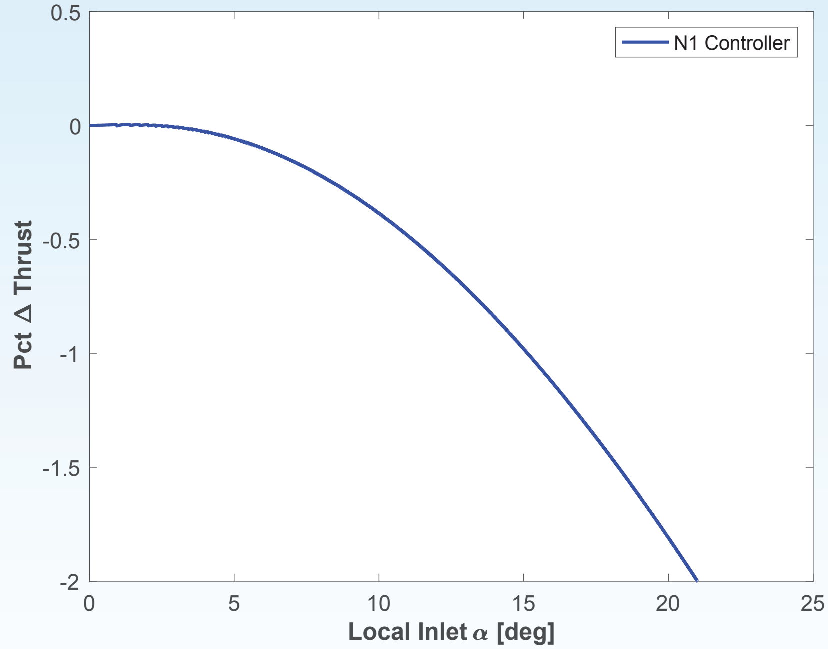
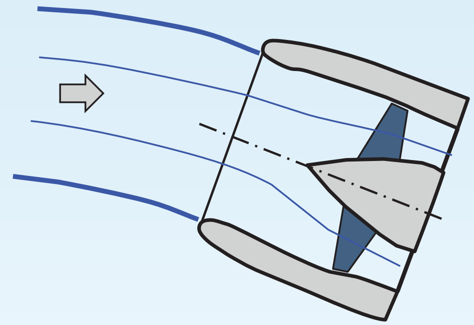
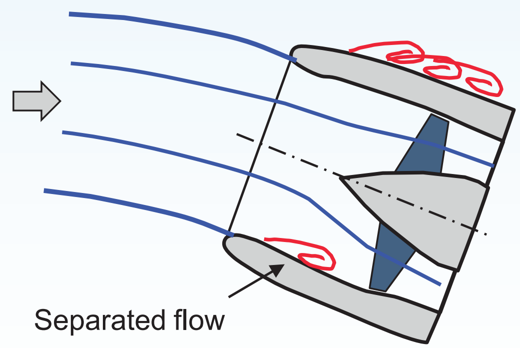
Baseline Turbofan Engine Simulation Output

Thrust Variation versus Angle of Attack





- At low angles of attack, variation in local inlet angle of attack only contributes to a small variation in thrust.

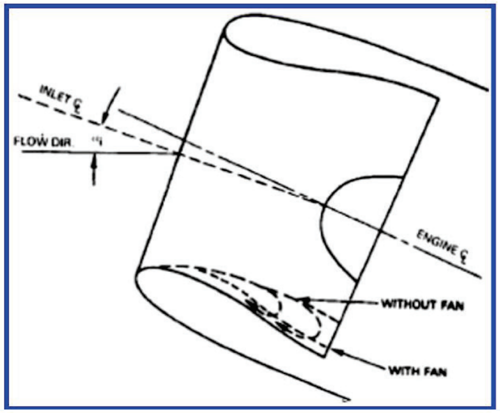


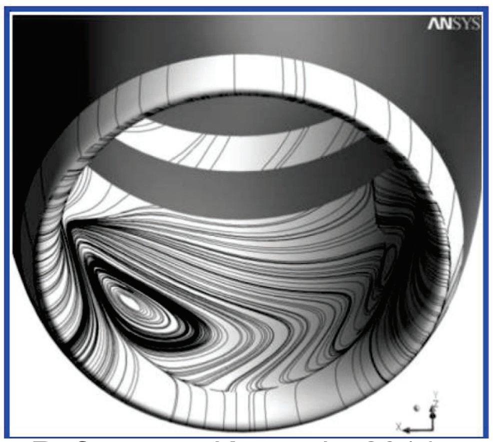
Baseline T-MATS engine with dynamic inlet model is shown but does not capture separated flow effects.

- Separation inside the inlet occurs at higher angles of attack with a larger reduction in thrust. Need a high fidelity model.

Dynamic Inlet Modeling

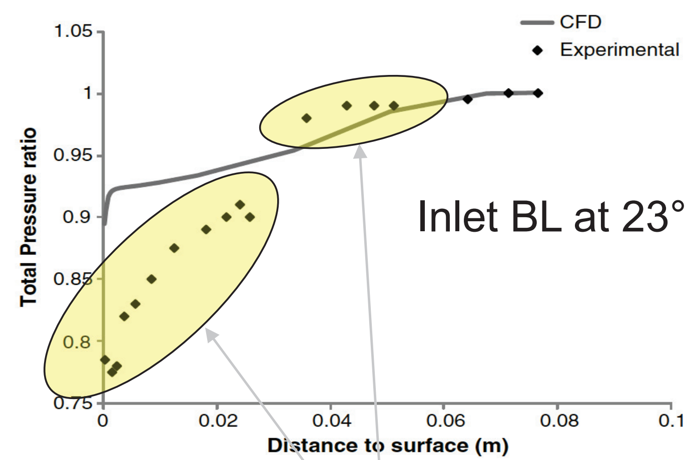
High Fidelity 3D CFD Modeling (Bombardier)





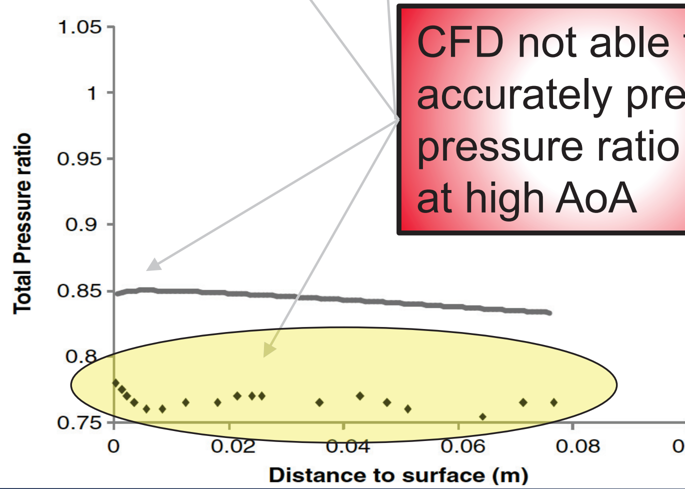
Reference: Kennedy, 2014.

Without Fan Influence



Inlet BL at 23° AoA

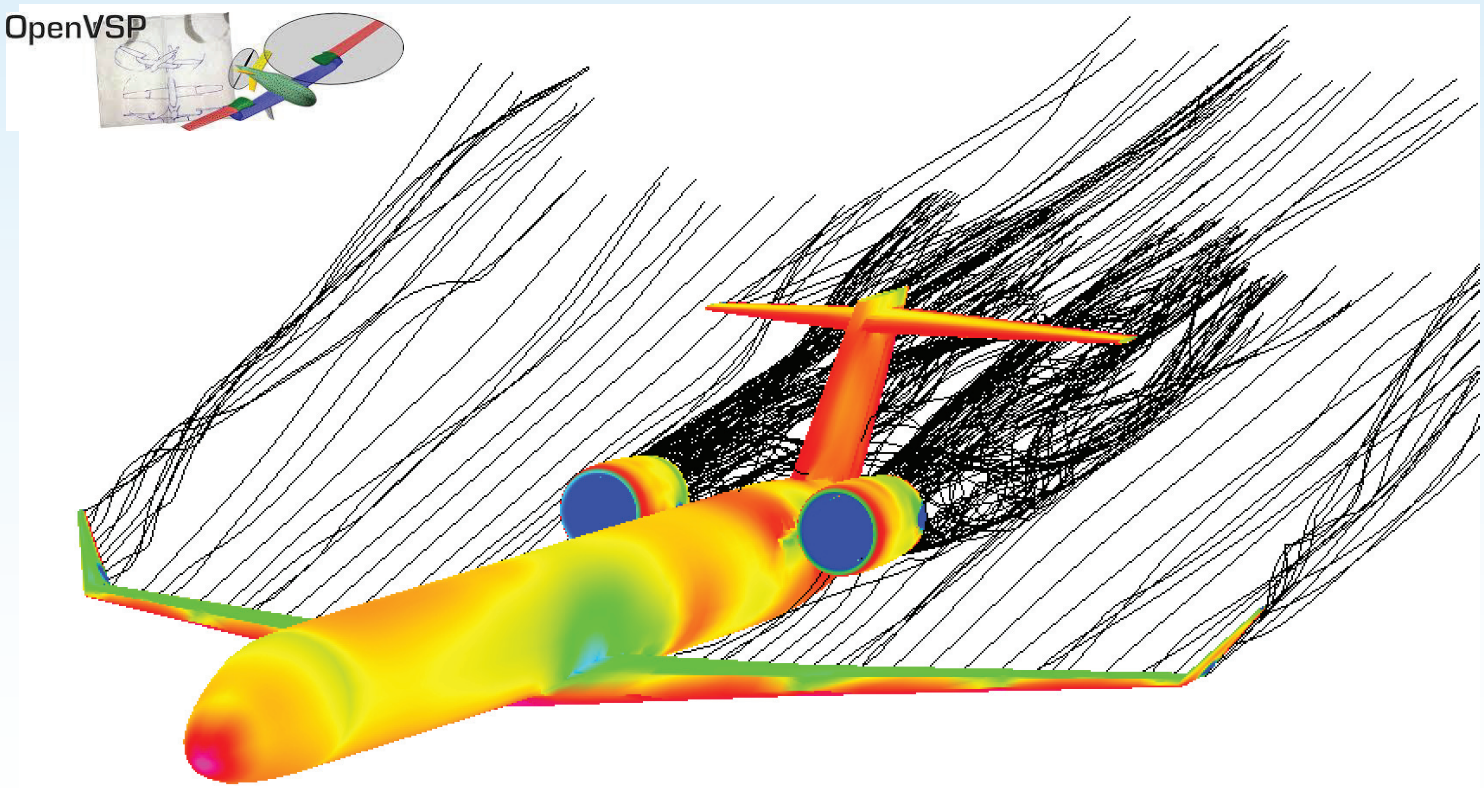
With Fan Influence



CFD not able to accurately predict pressure ratio at high AoA

Dynamic Streamtube Model

OpenVSP Wake Effect and Inlet Interactions



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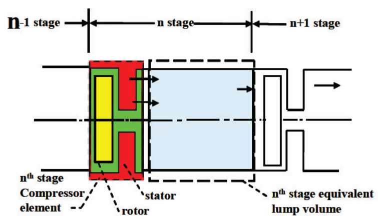
Volume Dynamics

High Fidelity Modeling for Analytic Region of Flight Envelope

1. Lump volume: Component treated as single volume for axial gas dynamics and performance characteristics



Compressor stage

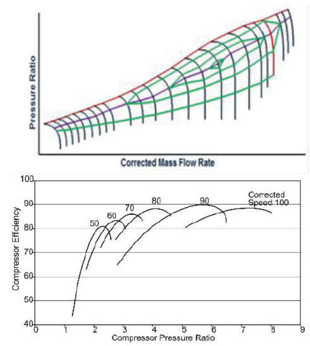
$$\frac{d}{dt}\rho_{sv,n} = \frac{1}{V_n}(\dot{W}_{c,n} + \dot{W}_{c,n+1} - \dot{W}_{b,n})$$

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

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

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

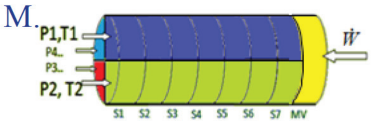
Volume dynamics



Performance maps

2. Stage-by-stage: Component treated as multiple volumes for axial gas dynamics and performance characteristics – new methodology

3. Parallel Flow: Component treated as multiple volumes and multiple flow paths for axial and rotational gas dynamics and performance characteristics – new M.



Parallel flow path compressor model

$$\frac{\partial\rho_s}{\partial t} = -\frac{\partial(\rho_s u)}{\partial x} - \frac{1}{r}\frac{\partial(\rho_s w)}{\partial\varphi}$$

$$\frac{\partial(\rho_s u)}{\partial t} = -u\frac{\partial(\rho_s u)}{\partial x} - \frac{w}{r}\frac{\partial(\rho_s u)}{\partial\varphi} - \frac{\partial P_s}{\partial x}$$

$$\frac{\partial(\rho_s w)}{\partial t} = -u\frac{\partial(\rho_s w)}{\partial x} - \frac{w}{r}\frac{\partial(\rho_s w)}{\partial\varphi} - \frac{1}{r}\frac{\partial P_s}{\partial\varphi}$$

$$\frac{\partial}{\partial t}\left(\frac{P_s}{\gamma - 1} + \frac{\rho V^2}{2}\right) = -\frac{\partial}{\partial x}\left[\left(\frac{\gamma P_s u}{\gamma - 1} + \frac{\rho u^3}{2}\right)\right] - \frac{1}{r}\frac{\partial}{\partial\varphi}\left[\left(\frac{\gamma P_s w}{\gamma - 1} + \frac{\rho w^3}{2}\right)\right]$$

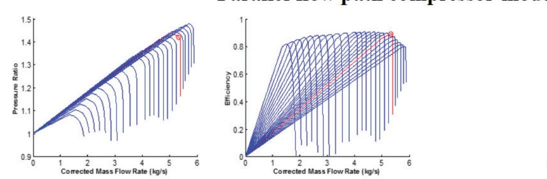
Volume dynamics of stage sector

$$\frac{d}{dt}\rho_{s,mv} = \frac{1}{V_{mv}}(\dot{W}_{mv} - \dot{W}_{cb})$$

$$\frac{d}{dt}\dot{W}_{mv} = \frac{A_{mv}g}{l_{mv}}\left[\sum_{m=1}^{q}(\beta_m P_{tm,n=k}) - P_{t,mv}\right]\left(1 + \frac{\gamma_{cp} - 1}{2}M_{mv}^2\right)^{\frac{-\gamma_{cp}}{\gamma_{cp} - 1}}$$

$$\frac{d}{dt}(\rho_{s,mv}T_{t,mv}) = \frac{\gamma_{mv}}{V_{mv}}\left[\dot{W}_{mv}\sum_{m=1}^{q}(\beta_m^2 T_{tm,n=k}) - \dot{W}_{cb}T_{t,mv}\right]$$

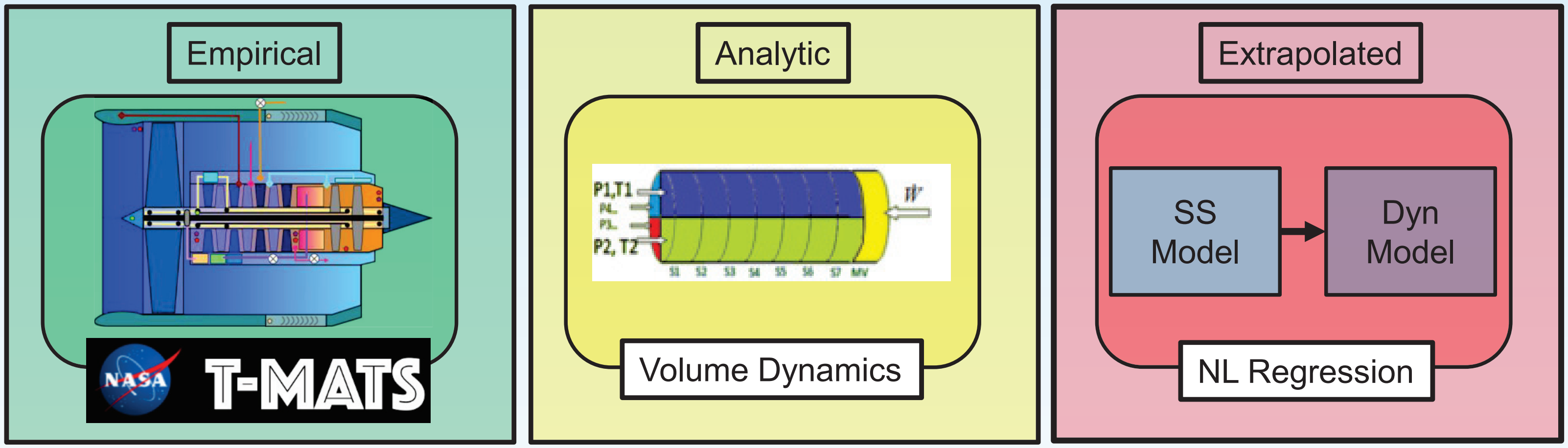
Mixing volume dynamics



Reference: Kopasakis, 2014.

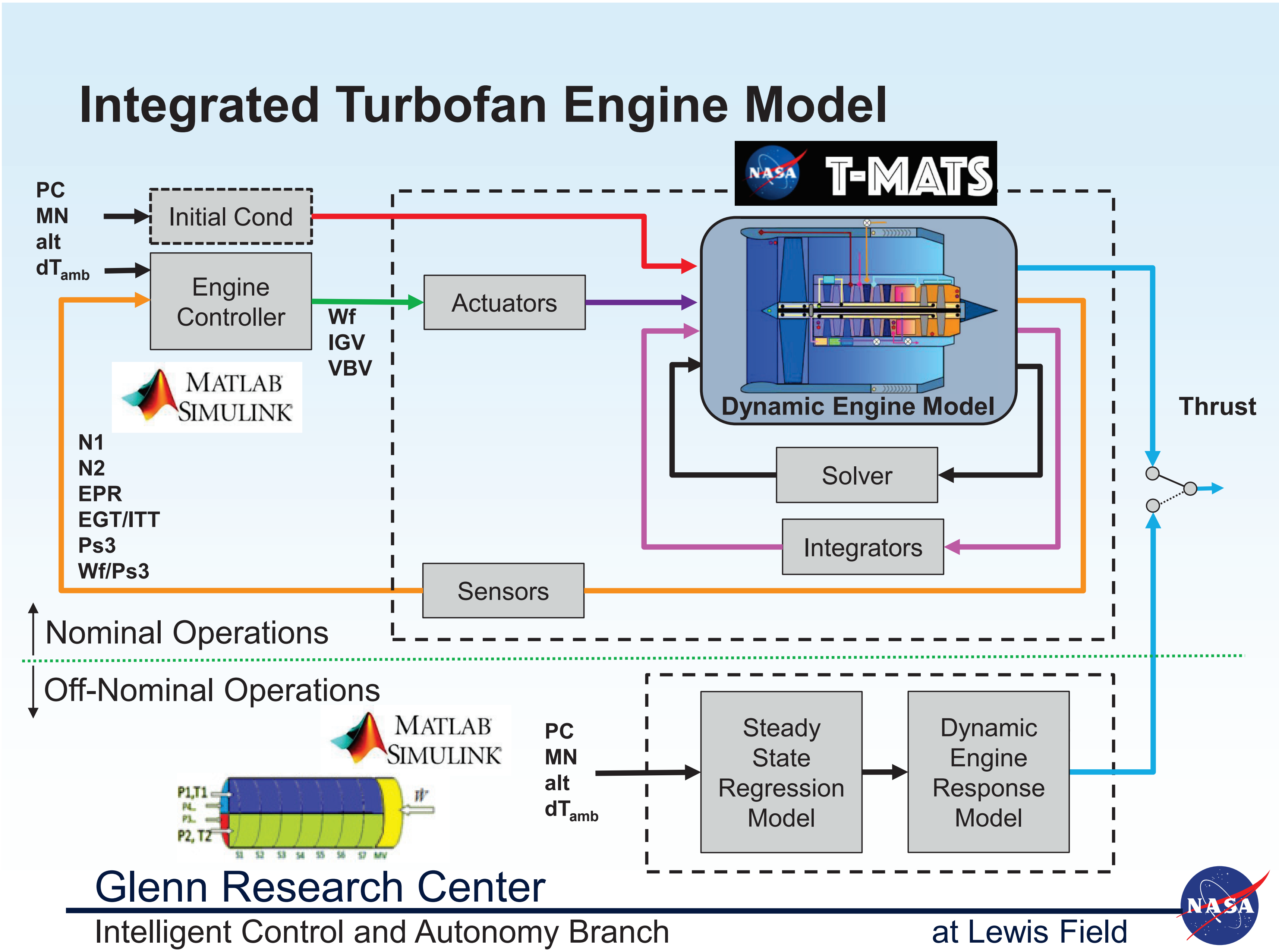
Requirements

Simulation for Highly Varying Flight Regimes



MATLAB SIMULINK

	Empirical	Analytic	Extrapolated
Real Time	●	Non-Real Time	●
Physics Based	●	●	NL Regression Model
Accurate in Full Stall Conditions	Normal Flight Ops Only	●	●
Start in Simulated Trimmed Flight Conditions	●	Stable Initial Conditions	●
T-Tail Aircraft Which Engines are on Fuselage or Wings	●	●	●
Dynamic Behavior in Abnormal/Emergency Operations ››› High Angle of Attack/Aircraft Stall ››› Engine Stall ››› Flameout	Normal Flight Ops Only	●	●
Defined Envelopes	●	●	●


Integrated Turbofan Engine Model
T-MATS
PC
MN
alt
dT$_{amb}$
Initial Cond
Engine Controller
Wf
IGV
VBV
Actuators
Dynamic Engine Model
Solver
Integrators
Sensors
MATLAB SIMULINK
N1
N2
EPR
EGT/ITT
Ps3
Wf/Ps3
Thrust
Nominal Operations
Off-Nominal Operations
MATLAB SIMULINK
PC
MN
alt
dT$_{amb}$
Steady State Regression Model
Dynamic Engine Response Model
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Intelligent Control and Autonomy Branch
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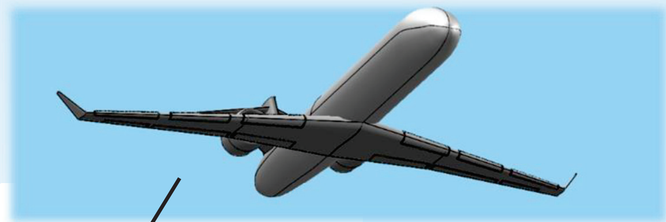
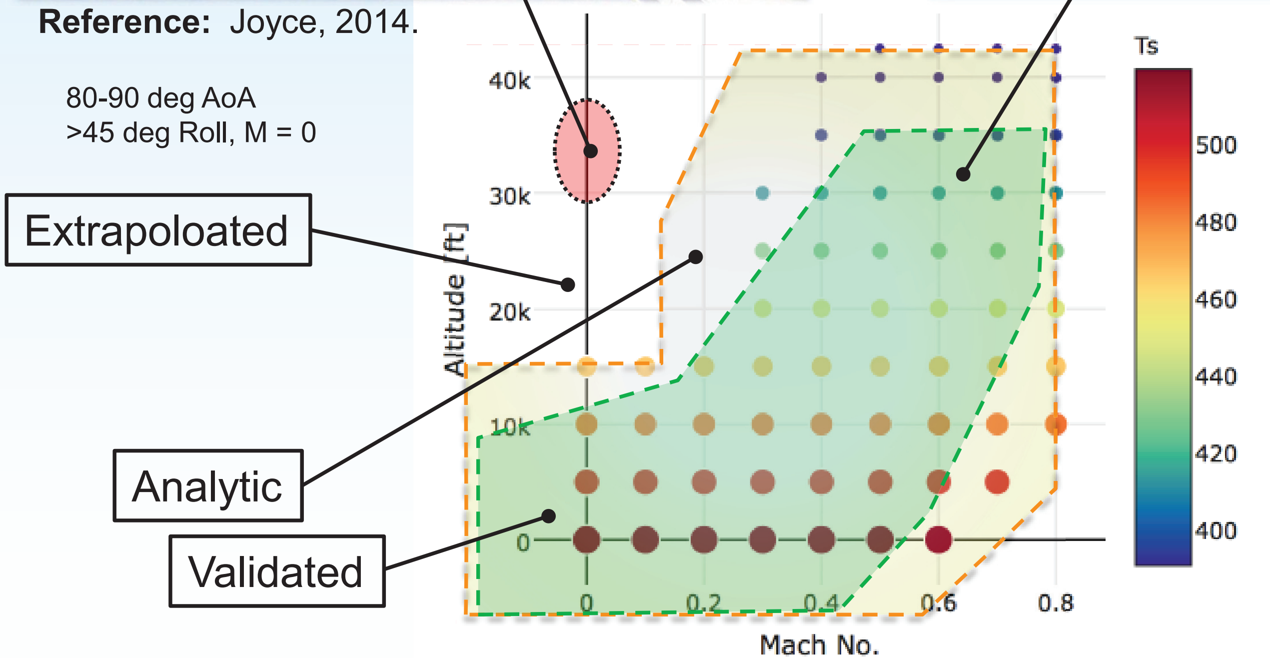
Future Work

Use Engine Controller Modes to Define Flight Envelope



Reference: Joyce, 2014.

80-90 deg AoA
>45 deg Roll, M = 0



Conclusions

- T-MATS is essential to start a working dynamic engine model.
- A baseline T-MATS turbofan engine is modeling nominal behavior.
- Preliminary results indicate the local inlet angle of attack contributes to a small change in thrust.
- High angles of attack will generate flow separation and inlet distortion. Wing wake effects will influence engine performance with side/fuselage mounted engines.
- A high fidelity engine simulation is required to capture these effects.

Acknowledgments

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Vantage Partners LLC

- Shane Sowers, Jeff Chapman, Aiden Reinhart, Amy Chicatelli.

NASA LaRC

- Brent Pickering, Kevin Cunningham, Melissa Hill, Gautam Shah.

Questions?

Photo by Scott Norin

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National Aeronautics and Space Administration

Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)

6th Propulsion Control and Diagnostics Workshop
Ohio Aerospace Institute (OAI)
Cleveland, OH
August 22, 2017

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  Vantage Partners, LLC. Cleveland, OH 44142

Outline

- T-MATS Overview
  - High level description
  - Role of T-MATS within NASA
- Features
  - General use
  - Types of blocks
  - Advanced capabilities
- New features and updates
- AGTF30
- Summary

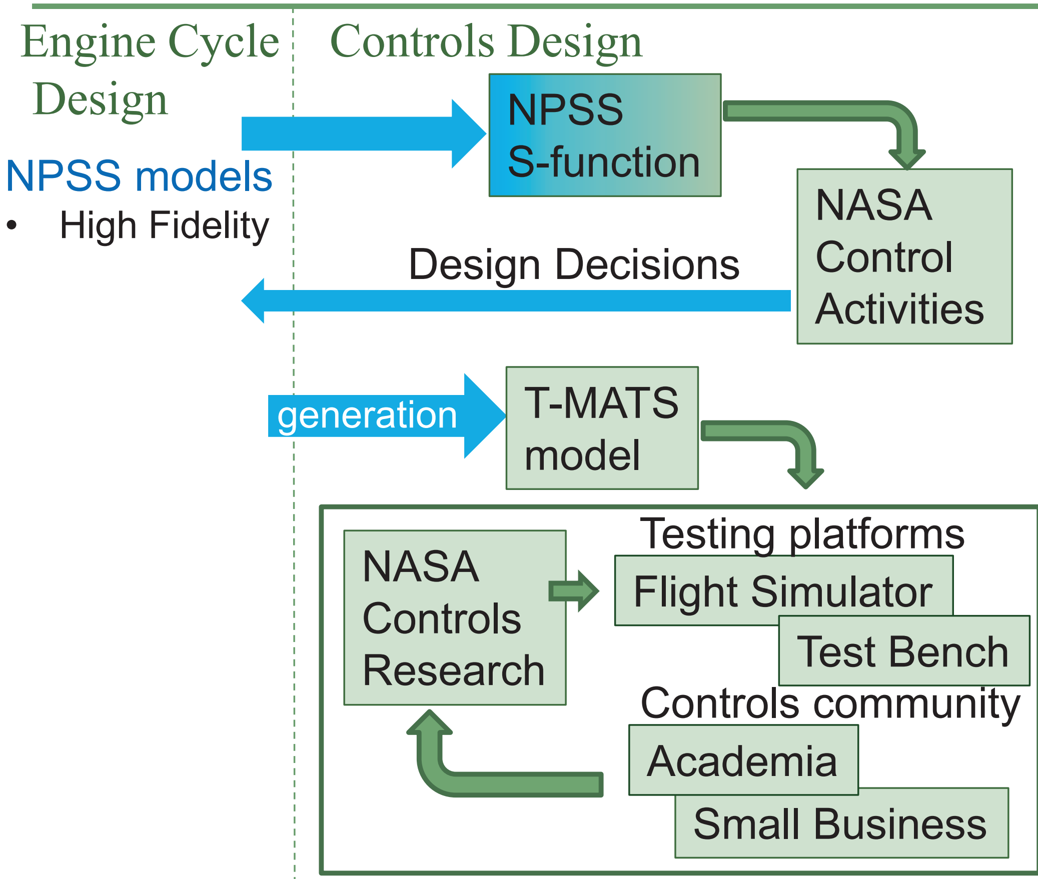
T-MATS Description

- Toolbox for the Modeling and Analysis of Thermodynamic systems, T-MATS
  - Modular thermodynamic modeling framework
  - Designed for easy creation of custom Component Level Models (CLM)
  - Built in MATLAB®/Simulink®
- Package highlights
  - General thermodynamic simulation design framework
  - Variable input system solvers
  - Advanced turbo-machinery block sets
  - Control system block sets
- Development being led by NASA Glenn Research Center
  - Non-proprietary, free of export restrictions, and open source
    - Open collaboration environment

National Aeronautics and Space Administration

NPSS and T-MATS Relationship

- T-MATS works in harmony with and in parallel to industry standard engine modeling software, the Numerical Propulsion System Simulation (NPSS)
  - NPSS: Cycle design, truth models, high fidelity modeling
  - T-MATS: Controls design, fast development, fast hardware in the loop capability

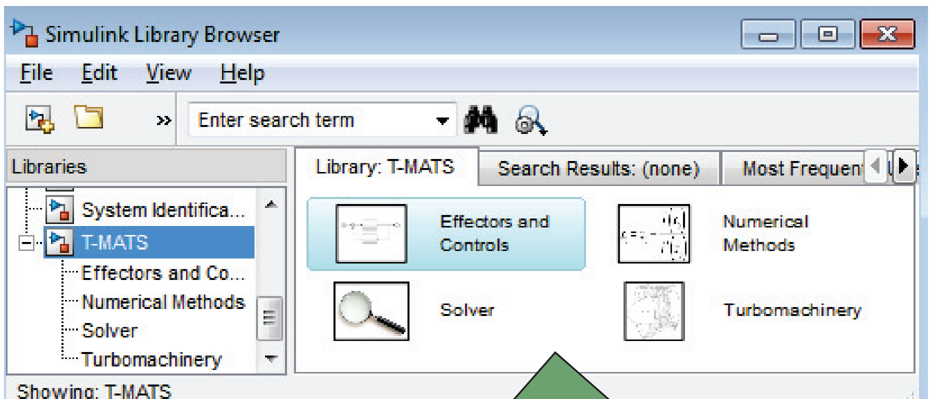


S-function based design
- Ideal for projects where multidisciplinary teams can collaborate
- Exact model match with truth model
- Promotes rapid prototyping between engine cycle design and controls

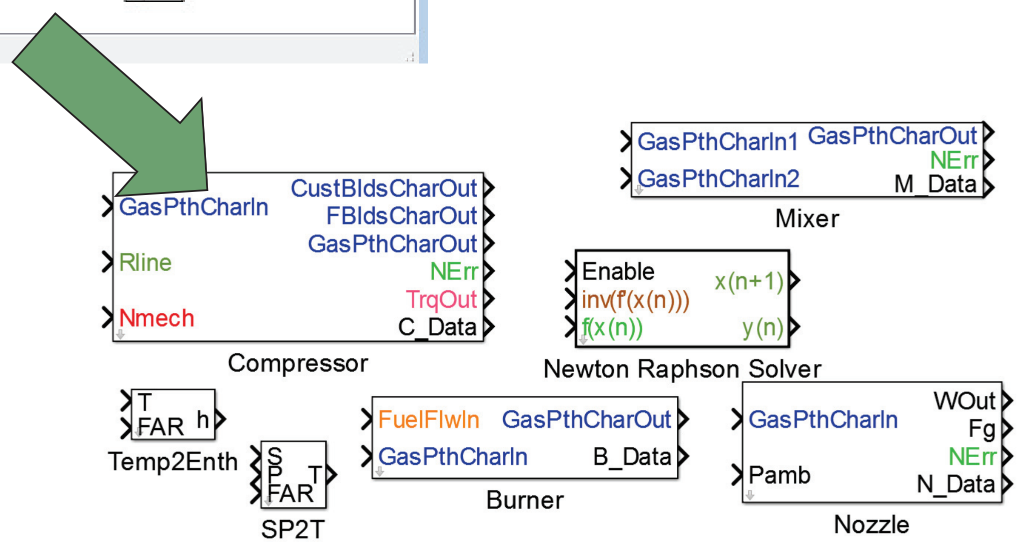
T-MATS based research
- Allows conceptual designs to be quickly brought to testing platforms
- Needs based model fidelity
- Enables controls research using a single tool
- Promotes aero propulsion to engineers without NPSS experience
- Allows independent research activities with the controls community

T-MATS Framework

- Plug-in for the industry-standard MATLAB/Simulink platform
  - additional blocks in the Simulink Library Browser:



Added Simulink Thermodynamic modeling and numerical solving functionality

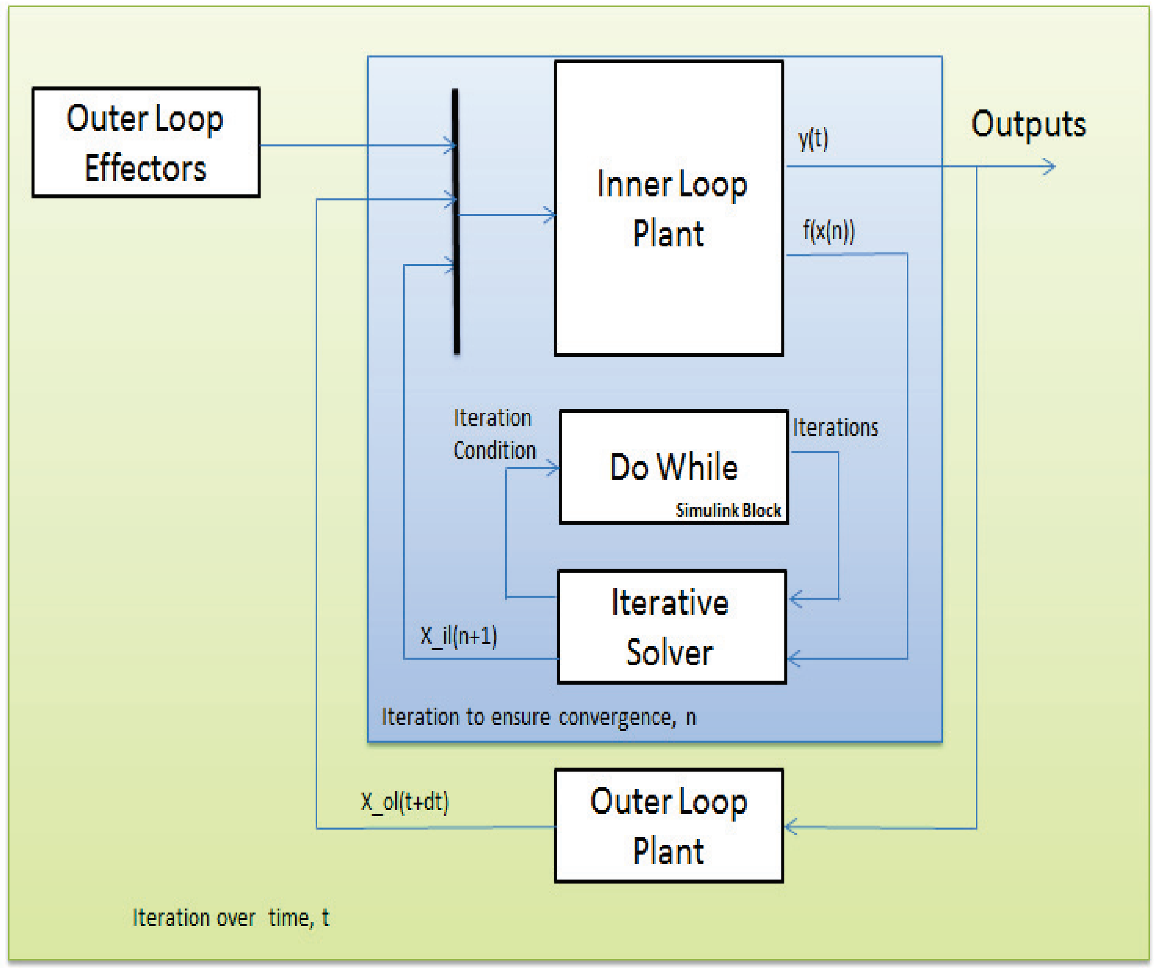


Faster and easier model creation

T-MATS Framework

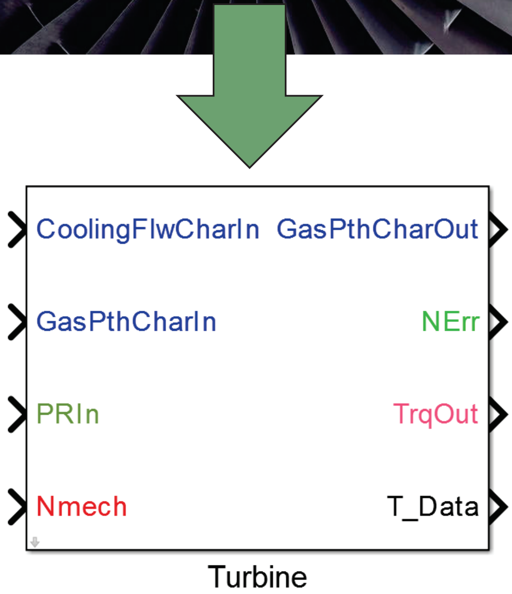
Dynamic Simulation Example:

- Multi-loop structure
  - The "outer" loop (green) iterates in the time domain
    - Not required for steady-state models
  - The "inner" loop (blue) solves for plant convergence during each time step



Blocks: Turbo-machinery

- T-MATS contains component blocks necessary for creation of turbo-machinery systems
  - Modeling theory based on common industry practices
    - 0-D flow components, $W_{in} = W_{out}$
    - Energy balance modeling approach
    - Compressor models utilize R-line compressor maps
    - Turbine models utilize Pressure Ratio turbine maps
  - Blocks types; compressor, turbine, nozzle, flow splitter, and valves among others.
    - Color Coding for easy setup
  - Built with S-functions, utilizing compiled C code/ MEX functions



Blocks: Controls

- T-MATS contains component blocks designed for fast control system creation
  - General Design

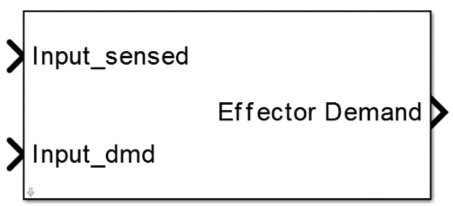
– Sensors:

1st order Sensor

– Actuators:

1st order Actuator

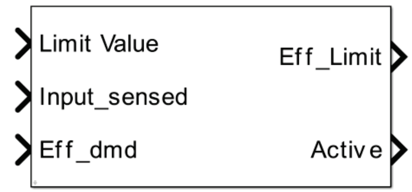
– PI controllers:



Simple PI controller

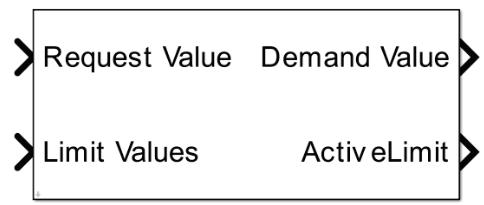
  - Engine Design

– PI Regulator Controller:



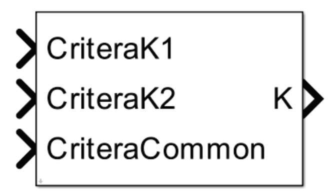
Limit Controller (PI)

– Limit selection logic:



Limit Selection

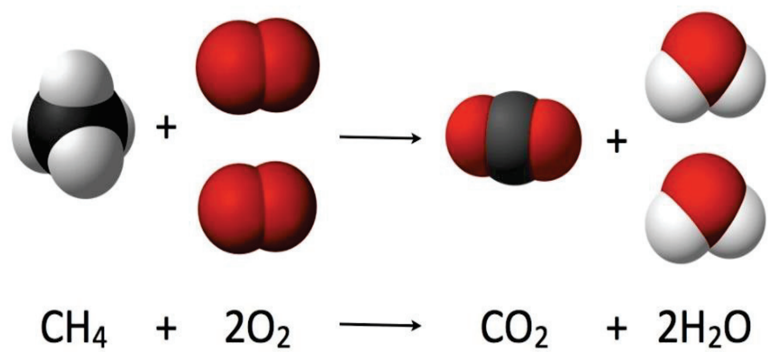
– Standardized table lookups:



GainSchedulerD2D

Advanced Capabilities

- Integration with Cantera
  - Cantera models chemical kinetics, thermodynamics, and/or transport properties.
    - It is C++ based code with interfaces for python, MATLAB, C, and Fortran 90 (Code-based and open source)
    - Integration enables T-MATS to model fuel cells, engines using alternative fuels, etc.
      - Integration with T-MATS enables Cantera's capabilities to be utilized in a graphical plug and play modeling environment



https://en.wikipedia.org/wiki/File:Combustion_reaction_of_methane.jpg

Combustion reaction of methane

Simplification

T-MATS custom class based scripts and blocks simplify Cantera and allow easy creation of complex systems.

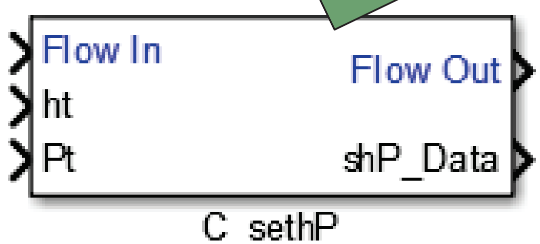
```
while  abs (lasterr)>.000000001 && count < 50
 set(fs,'Y',obj.CompVal_Can);
 set(fs, 'T', Ttg*5./9.,'P',Ptg*6894.75729 );
 equilibrate(fs, 'TP');
 htg = enthalpy_mass( fs )*.0004302099943161011;
 root = htg-htOut;
 sec_out = TMATSC.FlowDef.iterSecant( root, Ttg, last,
   lasterr, .1 );
 next = sec_out(1);
 last = sec_out(2);
 lasterr = sec_out(3);
 Ttg = next;
end
```

Cantera Code

```
TMATSC.set_hP(FlowObj,ht,Pt)
```

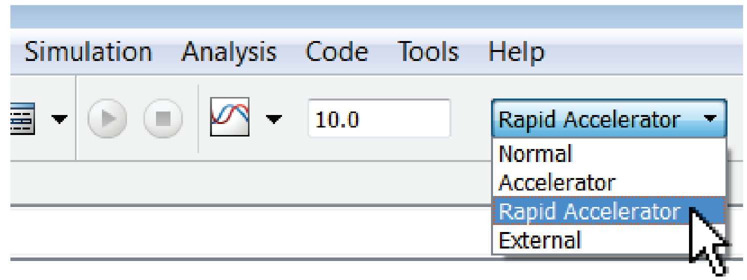
T-MATS Script

T-MATS Blocks

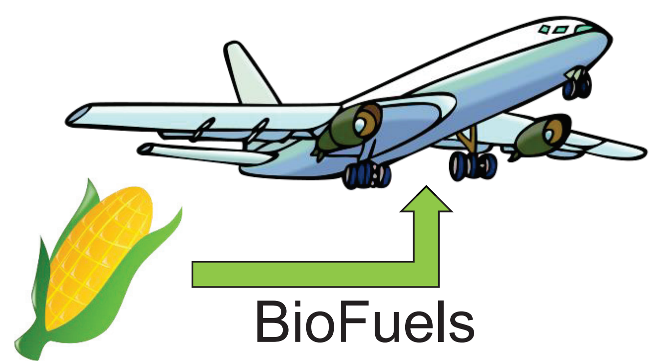


New Features: Enhancing capability

- Code generation
  - Generation of executables for operation outside of MATLAB environment or MATLAB accelerator modes



- Off Nominal Gas Property Tables
  - Create property tables to explore alternative fuels or air compositions with faster run times.



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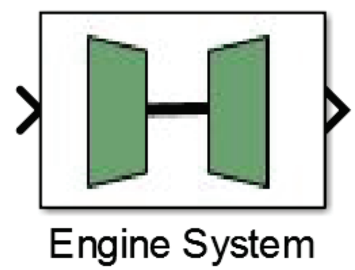
New Features: Model Auto-Generation

- NPSS to T-MATS auto coder
  - Utilizes a like-for-like building process to generate a T-MATS model directly from an NPSS model.

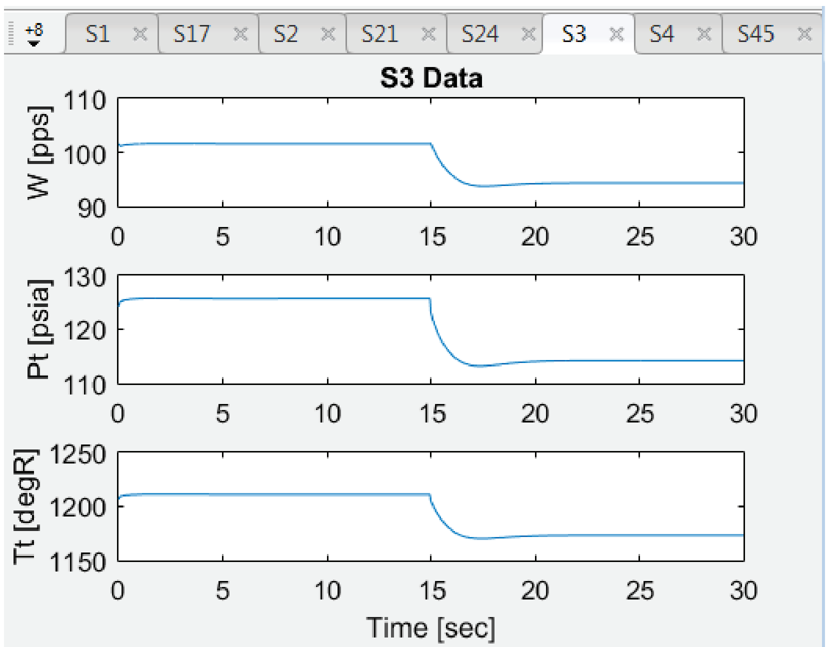
NPSS Model	Data Gathering NPSS Scripts	Model Setup MATLAB Script	T-MATS Model

`Npss.run`
`Npss.mdl`
…
	Component Linking Data and block Setup Data
	`BlockTransMTLB_TMATS.fnc`
	Map Data
	`mapplot_matlab.fnc`
		Utilize gathered data to automatically generate T-MATS model
		`AutoLinker_TMATS.m`
			

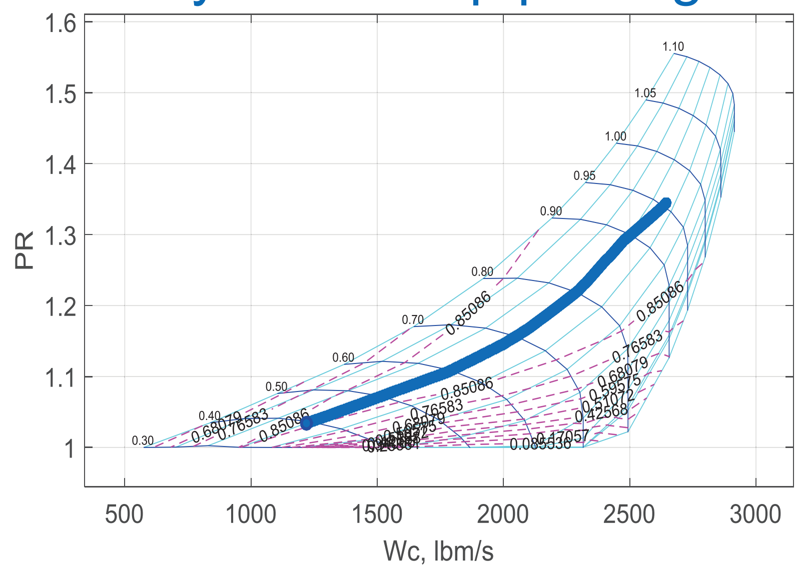
New Features: Visualization

- T-MATS plotting tools
  - Makes use of timeseries “To Workspace” blocks along with known output bus format to auto generate sets of plots to helping to visualize engine performance.

Station Performance traces:



Dynamic map plotting:



Simple Syntax, after running the model use:

```
TMATS.TDplot('JT9D_Model_Dyn');
```

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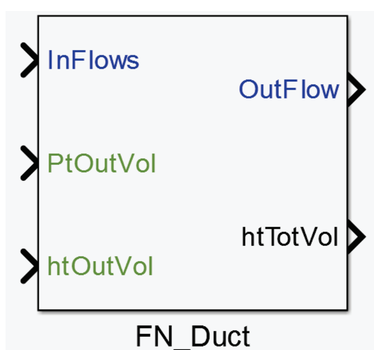
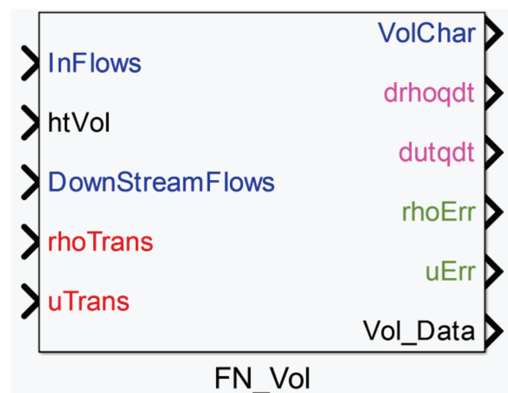
Additional Major Updates

- Health parameter handles for turbomachinery
  - Degradation for turbomachinery components
- Piecewise linear model creation
- Engine heat soak dynamics

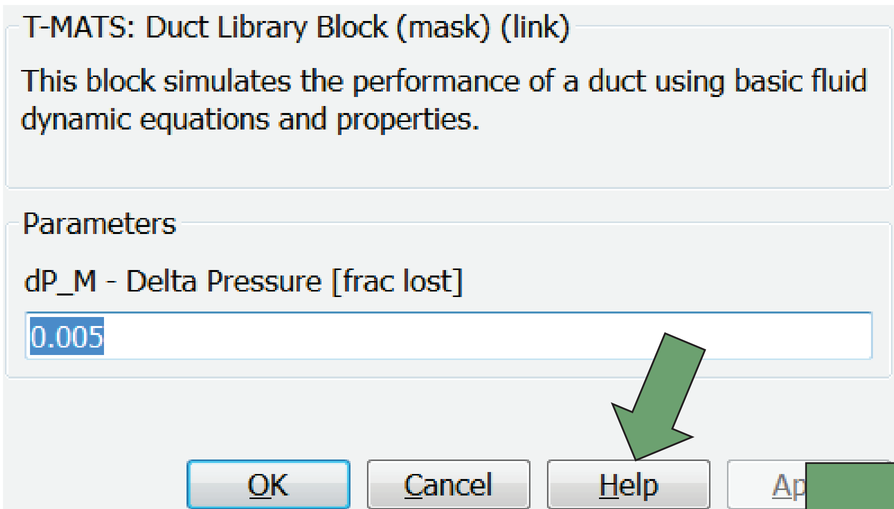
- Volume dynamics components.

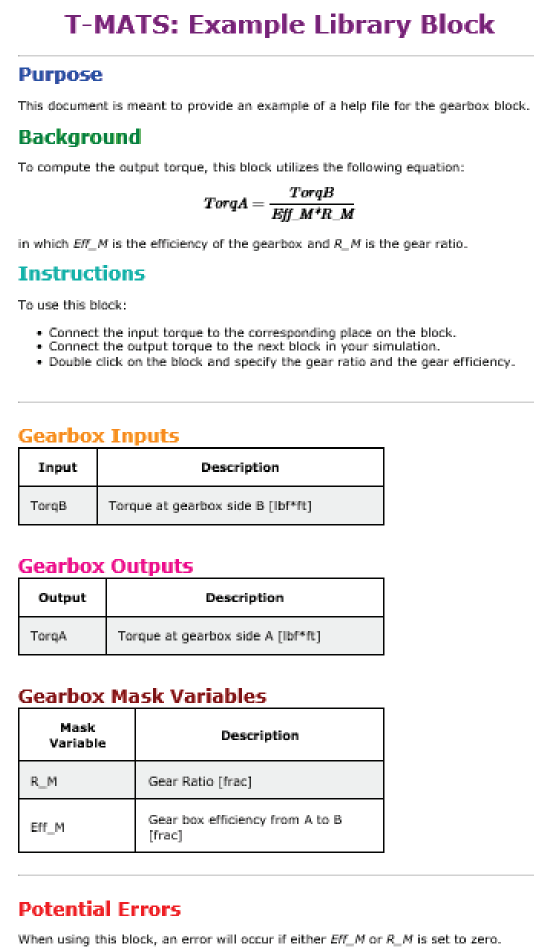




Help Files

Help files have been updated to be more…. Helpful.





T-MATS: Example Library Block

Purpose

This document is meant to provide an example of a help file for the gearbox block.

Background

To compute the output torque, this block utilizes the following equation:

$$TorqA = \frac{TorqB}{Eff\_M * R\_M}$$

in which *Eff_M* is the efficiency of the gearbox and *R_M* is the gear ratio.

Instructions

To use this block:

- Connect the input torque to the corresponding place on the block.
- Connect the output torque to the next block in your simulation.
- Double click on the block and specify the gear ratio and the gear efficiency.

Gearbox Inputs

Input	Description
TorqB	Torque at gearbox side B [lbf*ft]

Gearbox Outputs

Output	Description
TorqA	Torque at gearbox side A [lbf*ft]

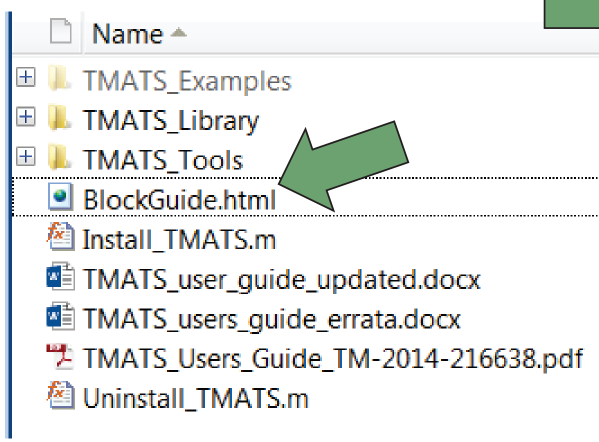
Gearbox Mask Variables

Mask Variable	Description
R_M	Gear Ratio [frac]
Eff_M	Gear box efficiency from A to B [frac]

Potential Errors

When using this block, an error will occur if either *Eff_M* or *R_M* is set to zero.

Access through the Block Guide or by clicking on Help for any T-MATS or block



Research Platform Development (AGTF30)

- In preparation for the next generation of aircraft. T-MATS has been used to model advanced high-efficiency engine concepts.

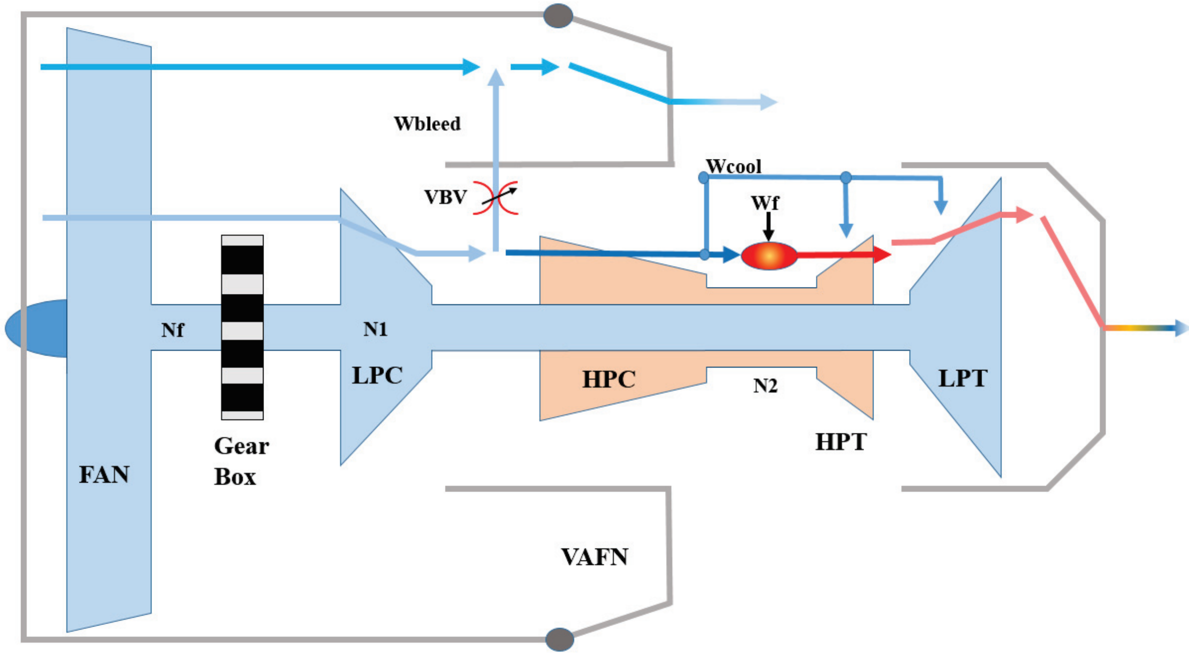
The Advanced Geared Turbofan, 30,000 lbf (AGTF30) engine simulation was developed to investigate possible next generation engine system designs including:

1. Dual spool Geared Turbofan engine design
2. Ultra-high bypass configuration
3. Small engine core
4. Variable area fan nozzle (VAFN)
5. Fully operational dynamic control system

- Mission
  – Provide a dynamic platform for next generation engine system research.

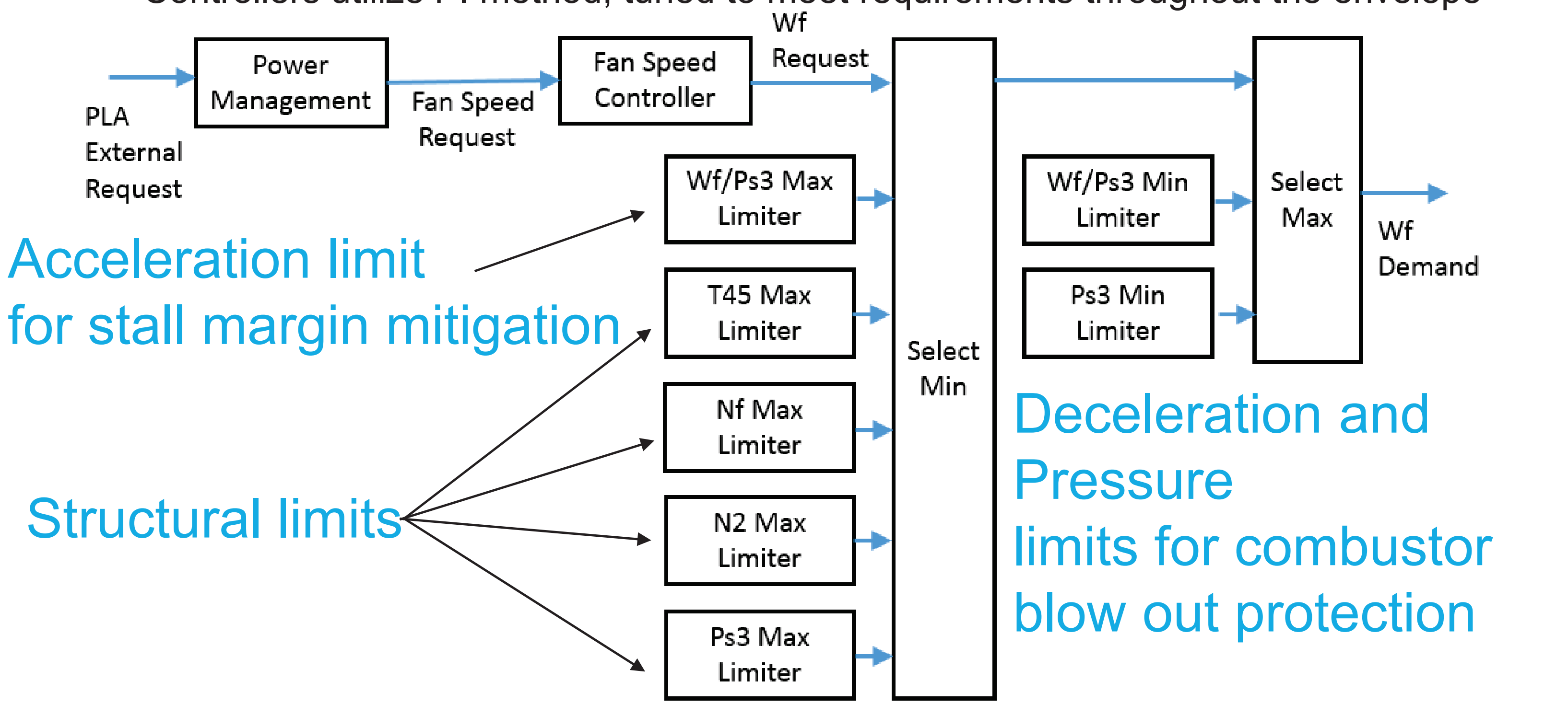
Advanced Geared Turbofan 30,000 (AGTF30)

- Advanced Geared Turbofan features
  - Variable area fan nozzle (VAFN)
  - Dual spool with low pressure shaft connected to fan via a gear box
- Performance
  - BPR = 24, OPR = 50, TIT = 3000, TSFC = 0.46 at cruise
  - 30,000 lbf takeoff thrust
- Control Effectors: VAFN, fuel flow (Wf), and variable bleed valve (VBV)



Fuel Control Architecture

- Fuel Control methodology based on literature
  - Power Management generates fan speed request based on power lever angle (PLA)
  - Fan speed controller generates a fuel flow request
  - Sets of limiters adjust the fuel flow request to operate the engine safely, avoiding engine stall, exceeding structural limits, combustor blowout, etc.
  - Controllers utilize PI method, tuned to meet requirements throughout the envelope



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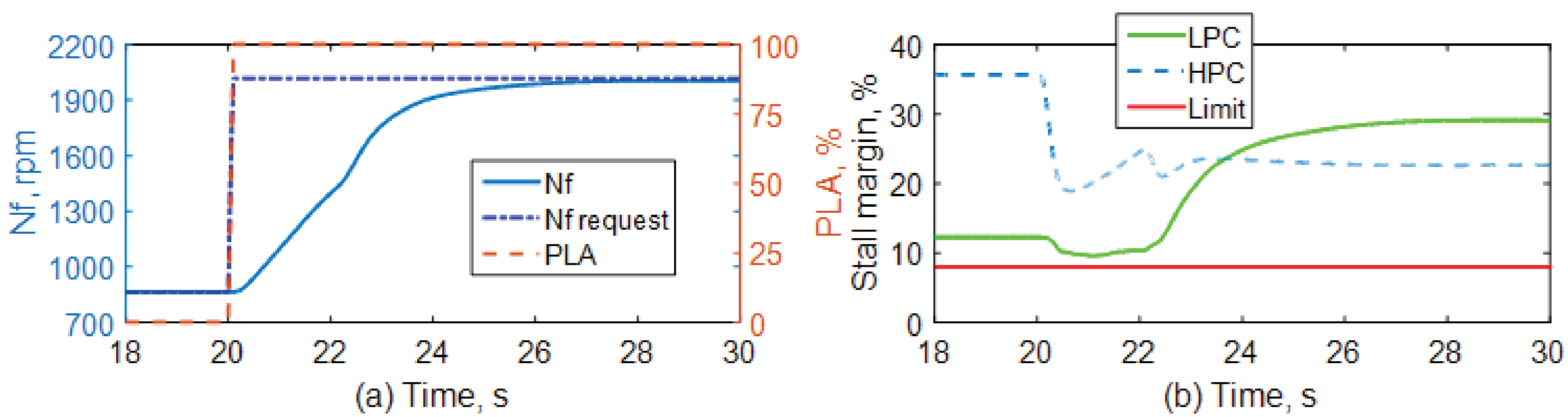
Setting Fuel Limiters

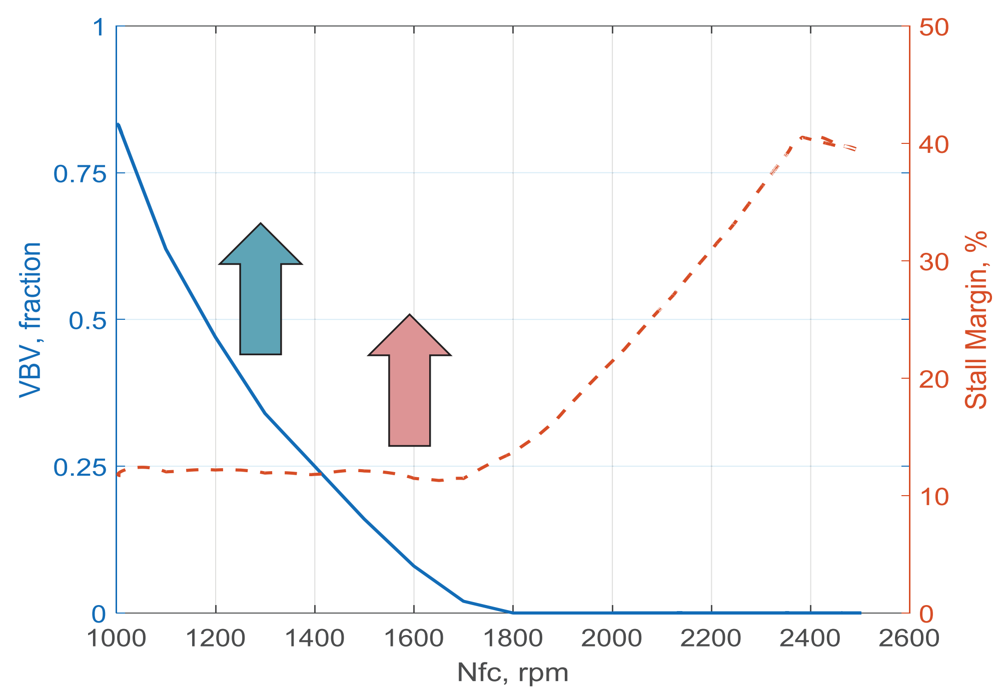
- Limiters designed to maintain safe engine operation
  - Set to avoid engine stall, structural limits, and engine blow out.
    - Structural limits based on anticipated next generation requirements.
    - Stall mitigated by limiting acceleration with a maximum Wf/Ps3 limit
    - Hypothetical engine blow out mitigated with minimum Wf/Ps3 and Ps3 limits
  - Limiters tuned to allow acceleration from idle to 95% takeoff power within 5 seconds
  - Minimum stall margin requirement set to 8%.



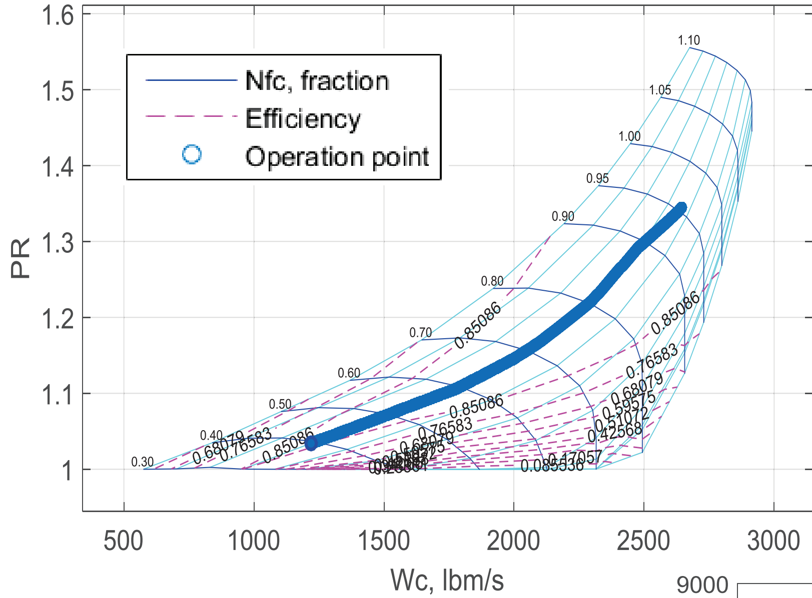
VBV Control Architecture

- Variable bleed valve opens to reduce low pressure compressor (LPC) pressure ratio (PR), increasing stall margin.
  - Schedules constructed to maintain 10% stall margin during steady-state operation.

Opening VBV to increase LPC stall margin



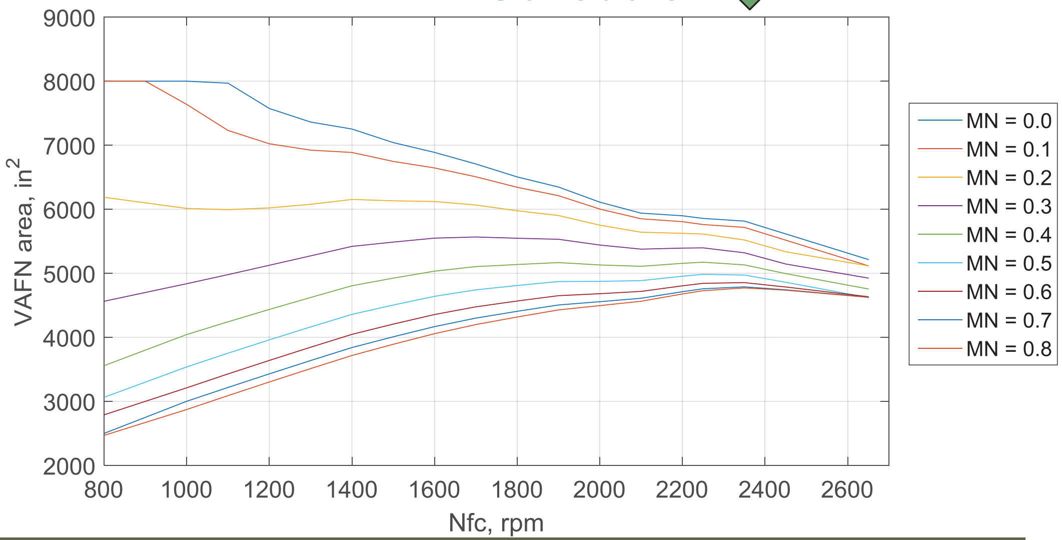
VAFN Control Architecture



Fan Performance

Optimal efficiency

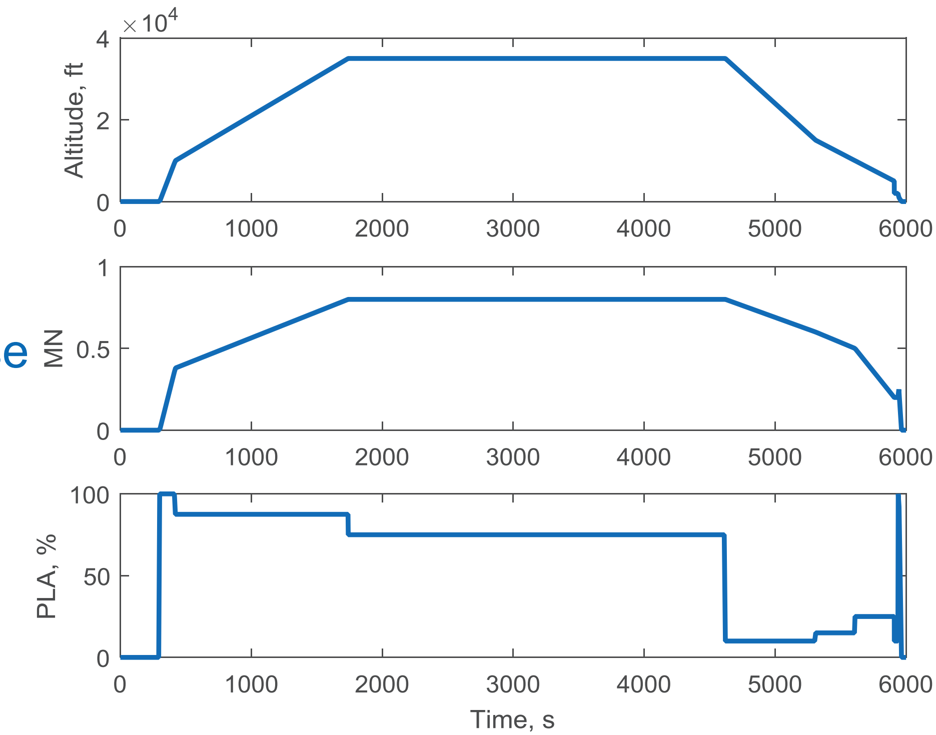
VAFN Schedule



- Variable area fan nozzle area scheduled to maintain optimal fan efficiency.
  - Nozzle area increased to reduce fan PR
  - Nozzle area decreased to increase fan PR

Model Validation

- Engine Model validation
  - Simulation of an abbreviated mission profile
    - Engine idling
    - Acceleration from idle to full power followed by a take off at sea level static conditions
    - Engine climbs to cruise at 35,000 ft
    - Deceleration and descent
    - Aircraft lands then returns to idle



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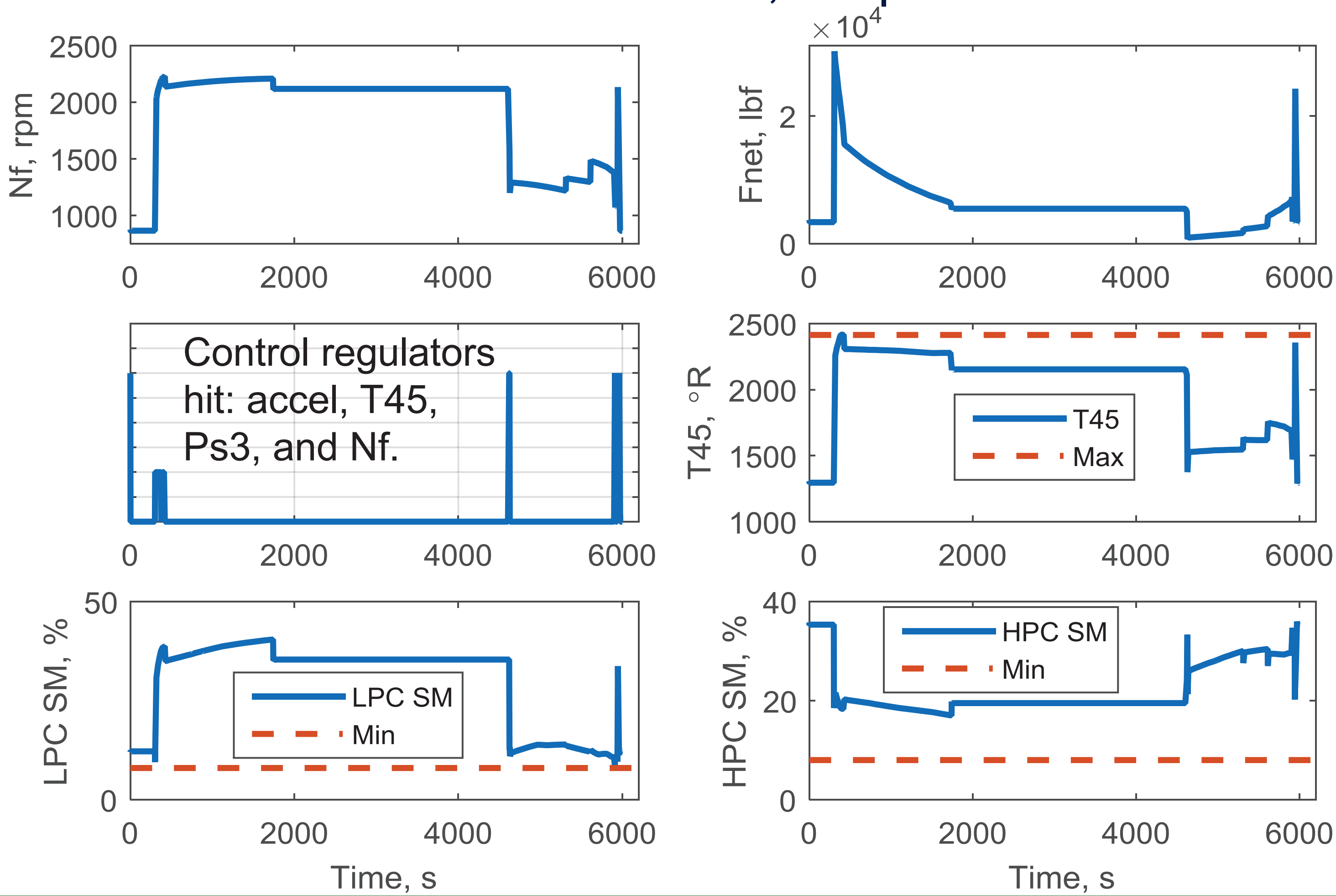
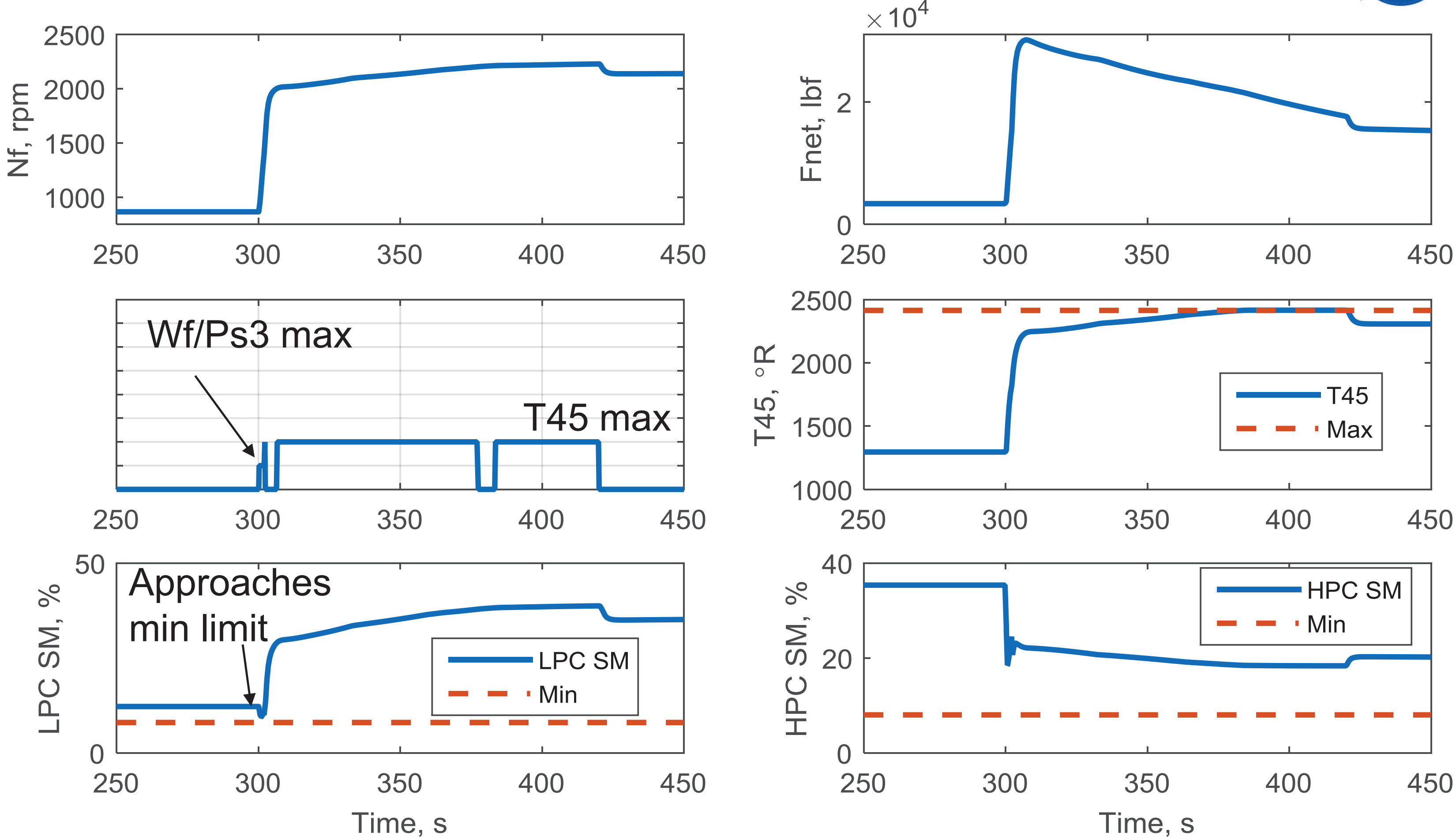
Model Validation, full profile



For the validation profile, all parameters remain within acceptable parameters and the engine performs as expected

Model Validation, takeoff and climb



During acceleration and climb to altitude the control regulators act to maintain stall margin and maximum T45 limit

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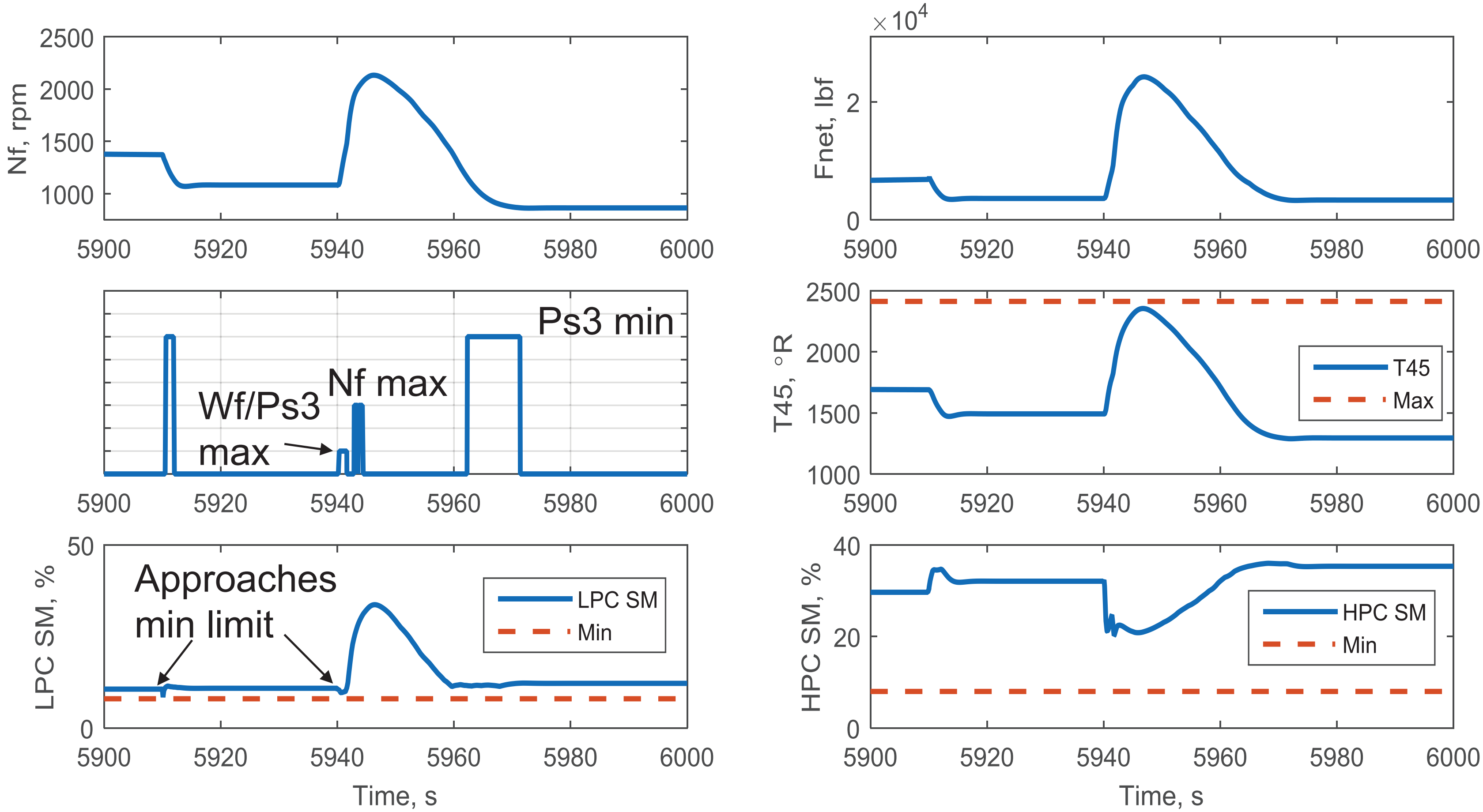
Model Validation, approach and landing



During approach and landing the control regulators act to maintain stall margin, maximum Nf limit and minimum Ps3 limit

Input File

- Enter inputs manually

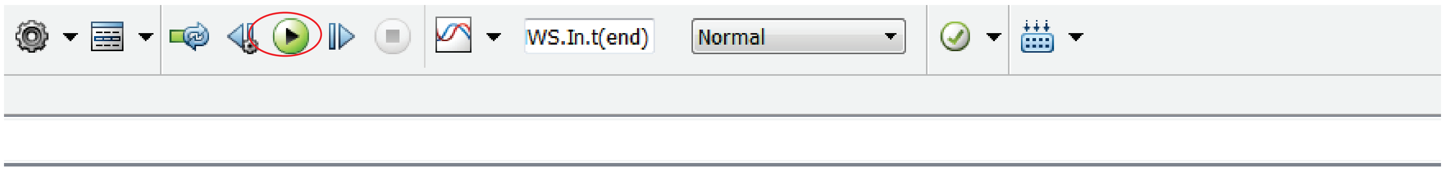
```
%% Set default time vector name
DefTVNm = 't';
% Set default time vector values
MWS = SetInput(MWS,DefTVNm, [0 10 20 20.1 50],inputs);
```

```
% PLA or Power Code (40 to 80.5)
MWS = SetTVec(...
    MWS, 'PLA',...
    [40 40 40 80 80],...
    DefTVNm,inputs);
```

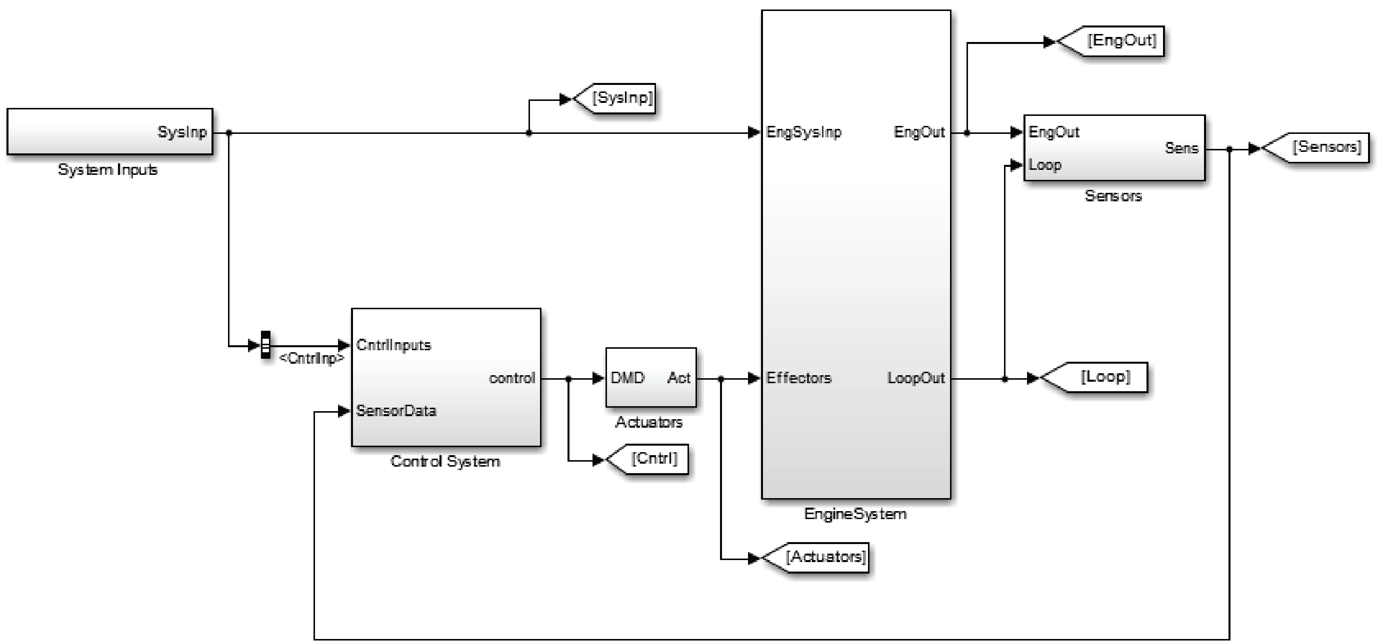
- Or use an excel spread sheet

	A	B	C	D	E	F	G	H
1	Description	Input Variable	Associated Time Vector	Data:				
2	time (s)	t	NA	0	10	20	20.1	50
3	Altitude (ft)	Alt	t	0				
4	Mach Number	MN	t	0				
5	Delta Temperature (degF)	dT	t	0				
6	PLA (deg)	PLA	t	40	40	40	80	80

Running the Model



Dynamic AGTF30
Advanced Geared Turbofan Engine System

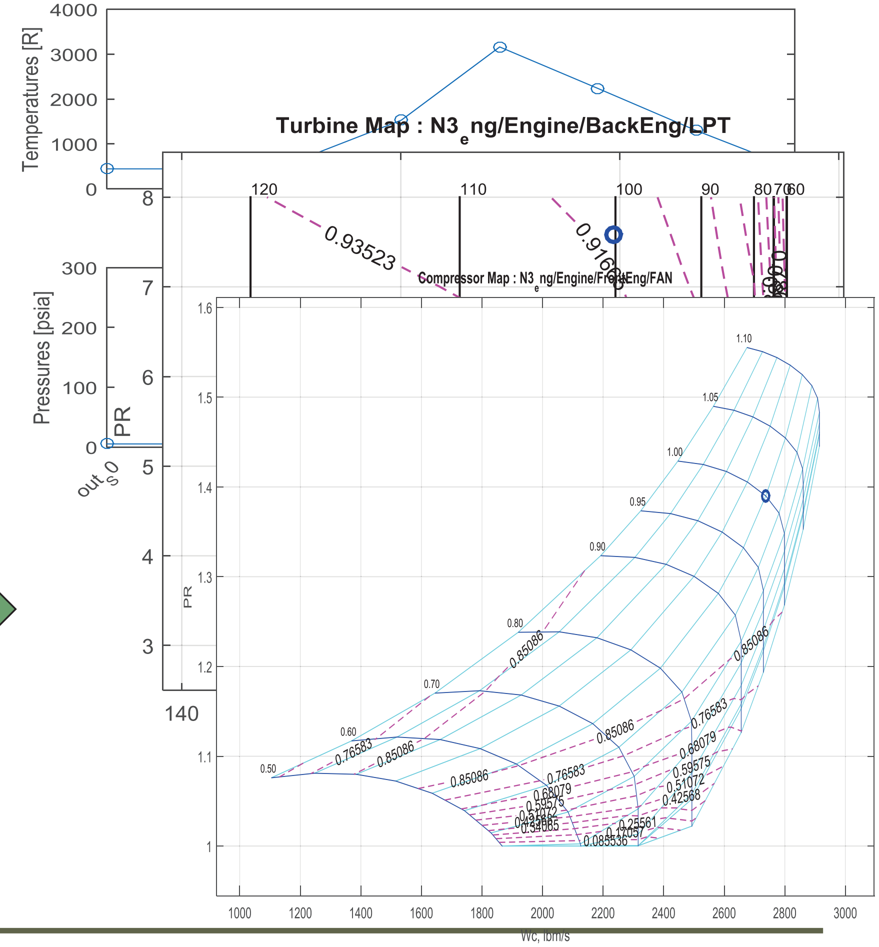


Data Presentation

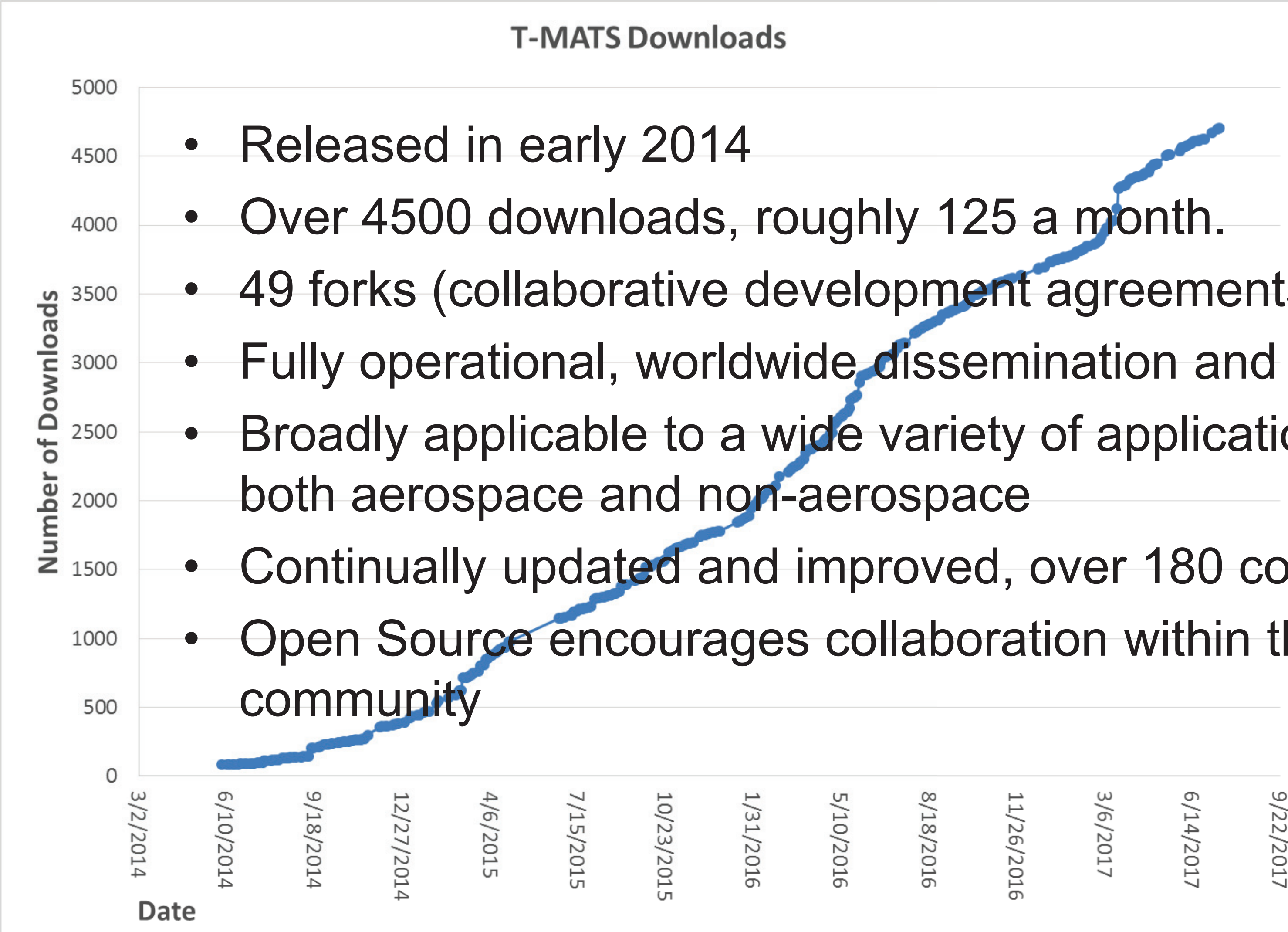
```
>> out_Dyn

out_Dyn =

     act: [1x1 struct]
   cntrl: [1x1 struct]
     eng: [1x1 struct]
    loop: [1x1 struct]
     sen: [1x1 struct]
      in: [1x1 struct]
```

Data gathered in an output structure.

Formatted to make use of T-MATS auto plotting tools



Status



- Released in early 2014
- Over 4500 downloads, roughly 125 a month.
- 49 forks (collaborative development agreements)
- Fully operational, worldwide dissemination and use
- Broadly applicable to a wide variety of applications, both aerospace and non-aerospace
- Continually updated and improved, over 180 commits
- Open Source encourages collaboration within the community

Summary

- T-MATS offers a comprehensive thermodynamic simulation system
  - Major updates in NPSS model translation, data visualization, and platform compatibility.
  - Increased engine modeling functionality ranging from health parameters to heat soak
  - AGTF30, advanced geared turbofan simulation, offers an advanced engine platform to be used for research purposes.
    - Planned public release
  - T-MATS can be downloaded at the address: https://github.com/nasa/T-MATS/releases

Acknowledgments

Funding for this work was provided by the Transformative Aeronautics Concepts Program (TACP)/Transformational Tools and Technologies (TTT) project and the Advanced Air Vehicles Program (AAVP)/Advanced Air Transport Technology (AATT) project.

Session 2

Control Techniques and Tools for Future Propulsion Systems

NASA/CP—2018-219891

Control Techniques and Tools for Future Propulsion Systems Session

Joseph Connolly & Edmond Wong
NASA Glenn Research Center

George Thomas
N&R Engineering via Vantage Partners, LLC

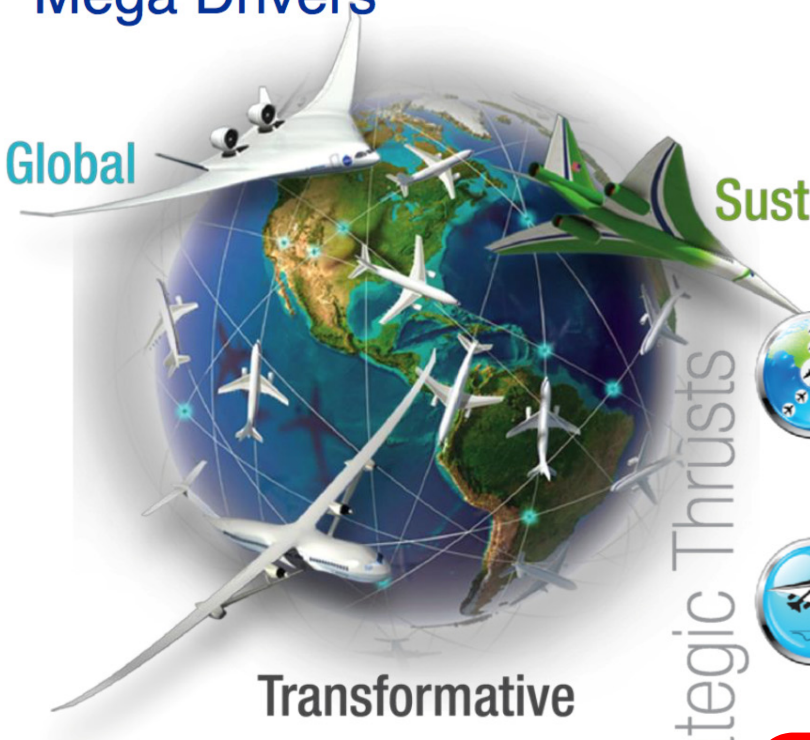
NASA Glenn Research Center – Intelligent Control and Autonomy Branch
6th Propulsion Control and Diagnostics (PCD) Workshop
Ohio Aerospace Institute (OAI), Cleveland, OH
August 22, 2017

www.nasa.gov

Advanced Propulsion Systems: Motivating Controls Research

NASA Aeronautics Research Mission Directorate

Mega Drivers



Strategic Thrusts

Safe, Efficient Growth in Global Operations
Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

Transition to Low-Carbon Propulsion
Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Innovation in Commercial Supersonic Aircraft
Achieve a low-boom standard

Real-Time System-Wide Safety Assurance
Develop an integrated prototype of a real-time safety monitoring and assurance system

Ultra-Efficient Commercial Vehicles
Pioneer technologies for big leaps in efficiency and environmental performance

Assured Autonomy for Aviation Transformation
Develop high impact aviation autonomy applications

Strategic Thrust 3: Ultra-Efficient Commercial Vehicles – Subsonic Transport

	2015	2025	2035
Outcomes	New Transport-class Aircraft that Achieve N+1 Levels of Efficiency	Technology and Potentially New Configuration Concepts that Achieve N+2 and N+3 Levels of Efficiency and Environmental Performance	Technology and Configuration Concepts, Including Low-carbon Propulsion, that Stretch Beyond N+3 Levels of Efficiency and Environmental Performance

Research Themes

Advanced Ultra-efficient Airframes

Research and development of tools and technologies to enable new airframe configurations with high levels of aerodynamic performance, lower structural weight, and innovative approaches to noise reduction

Transformative Aeronautics Concepts

Advanced Ultra-efficient Propulsion

Research and development of tools and technologies to reduce turbofan-thrust-specific fuel consumption, propulsion noise, and emissions

Advanced Airframe-engine Integration

Research and development of innovative approaches and the supporting tools and technologies to reduce perceived noise and aircraft fuel burn through integrated airframe-engine concepts

STRATEGIC THRUST 4: TRANSITION TO ALTERNATIVE PROPULSION AND ENERGY

	2015	2025	2035
Outcomes	Introduction of Low-carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems	Initial Introduction of Alternative Propulsion Systems	Introduction of Alternative Propulsion Systems to Aircraft of All Sizes

Research Themes

Alternative Power, Propulsion, and Vehicle Architectures **Advanced Air Vehicles**
Research and development of clean, quiet, and efficient transformative alternative integrated energy, power, and propulsive systems with synergistic vehicle-level integration

Alternative Fuel Combustors and Environmental Impact
Research and development of engine/fuel system integration, optimization, and performance including characterization of emissions and environmental impact

Electrified Aircraft Propulsion Components and Technology
Research and development of electrical components (e.g., electric machines, converters) and enabling technologies (e.g., materials, controls) that address weight, efficiency, and altitude challenges unique to flight

Modeling, Simulation, and Test Capability **Transformative Aeronautics Concepts**
Research and development of innovative tools and methods (computational, experimental, analytical) to transform power and propulsion system capability in less time with reduced uncertainty and cost

References

- Key Documents Located at: http://www.aeronautics.nasa.gov/strategic-plan.htm

  - Shin, J. & et. al. “NASA Aeronautics: Strategic Implementation Plan 2017 Update”, 2017
  - Esker, B. Wahls, R. and et. Al., “ARMD Strategic Thrust 4: Transition to Low-Carbon Propulsion” May, 2016.
  - Collier, F. Wahls, R. and et. Al., “ARMD Strategic Thrust 3: Ultra-efficient Commercial Vehicles Subsonic Transport” May, 2016.
  - Thole, K., Whitlow, W. & et al., “Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carob Emissions,” The National Academies Press, 2016

NASA/CP—2018-219891

Dynamic Analysis for Futuristic (N+3) Engine Concepts

George Thomas
N&R Engineering via Vantage Partners, LLC

Dennis Culley & Jeffrey Csank
NASA Glenn Research Center

NASA Glenn Research Center – Intelligent Control and Autonomy Branch
6th Propulsion Control and Diagnostics (PCD) Workshop
Session 2: Control Techniques and Tools for Future Propulsion Systems
Ohio Aerospace Institute (OAI), Cleveland, OH
August 22, 2017

www.nasa.gov

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      - Kenneth Fisher
  - Communication and Intelligent Systems Division (LC)
    - Intelligent Control and Autonomy Branch (LCC)
      - Dennis Culley
      - George Thomas (N&R Engineering)
      - Jeffrey Csank (moved to LEM branch)

Outline

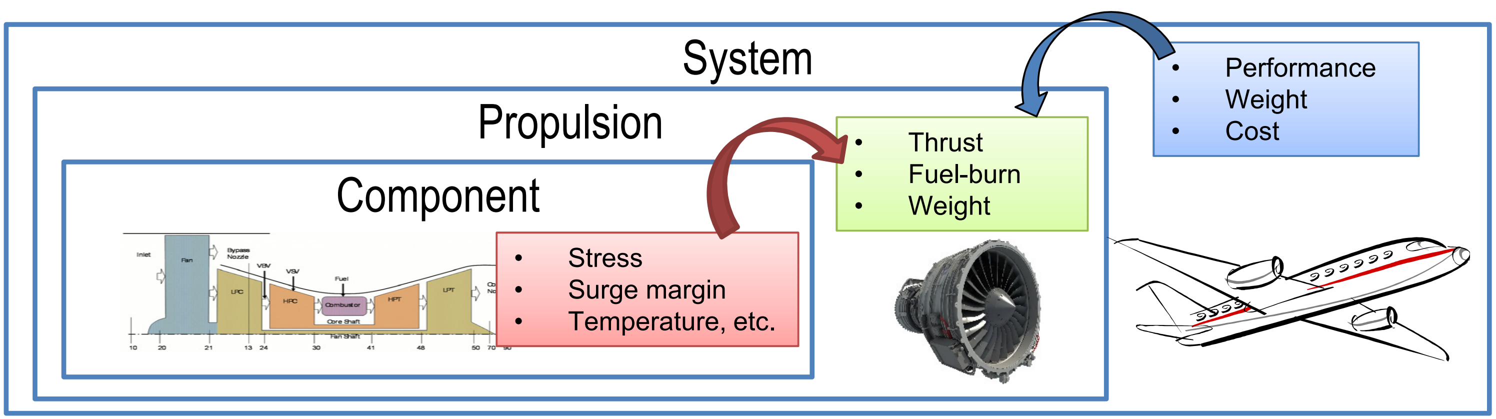
- Introduction
  - Motivation
  - Engine Design Process (Systems Analysis)
  - Dynamic Systems Analysis
- NASA N+3 Geared Turbofan
  - Engine
  - Closed-loop system
  - Low-speed analysis
- Simulation Results
  - Baseline Controller
  - Dynamic Systems Analysis
- Conclusions

Introduction – Motivation

- NASA N+3 commercial aviation goals[1]
  (3 generations ahead, ~2030-2035)
  - Noise, emissions, fuel burn reductions
- NASA Advanced Air Transport Technologies (AATT)
  - Systems analysis and integration (SA&I) subproject
  - Look at NRA and NASA in-house concepts
    - **Advanced geared turbofan (GTF)**
    - hFan
    - *Next in FY 18: STARC-ABL (HPX)*
- Goal of work: Dynamic analysis of N+3 concepts
  - Determine if designs meet transient requirements
  - Make recommendations for redesign, if any

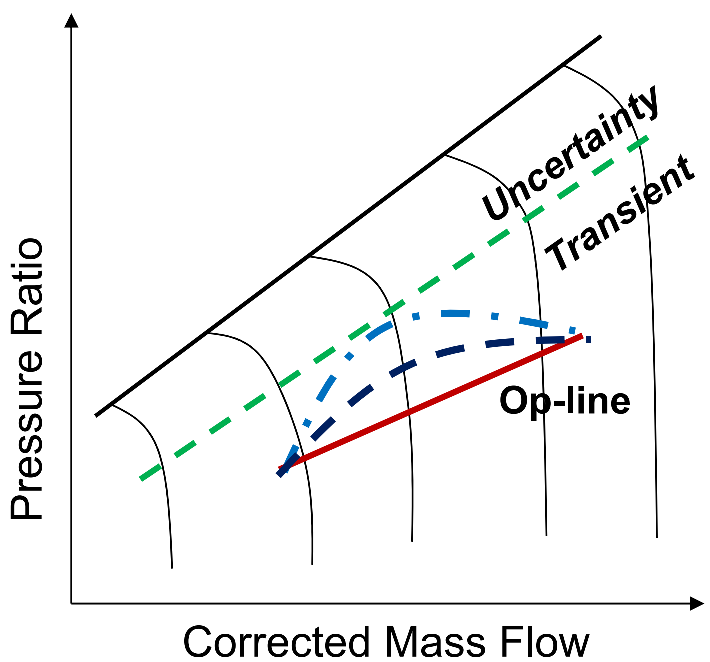
Introduction – Engine Design Process

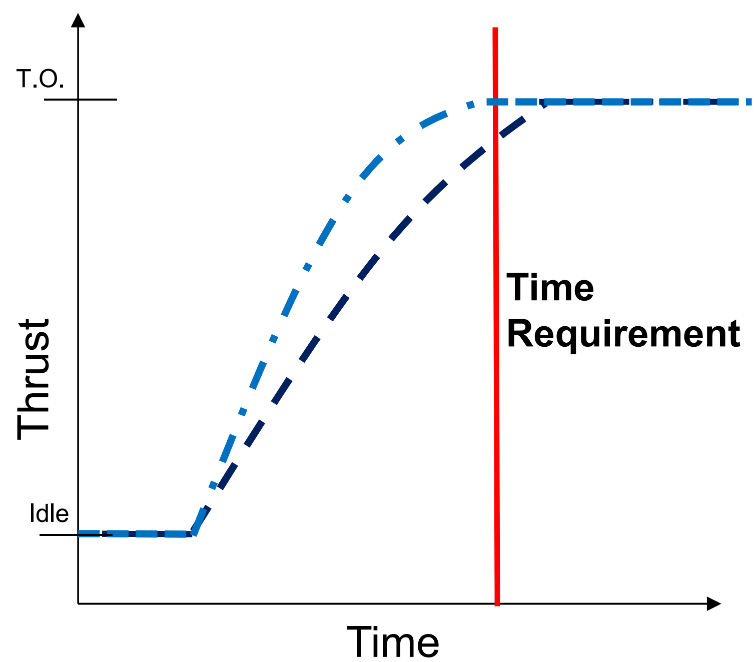
- Engines are designed using systems analysis
  – Steady-state system-level simulations
  – Evaluate system tradeoffs to find optimal designs
- Propulsion systems designed given objectives and constraints
  – Objectives: fuel burn, emissions, noise, cost, performance
  – Constraints: component min/max operating conditions (e.g. surge margins)
  – **Transients** (dynamic) cause engine to run **closer to constraints**
  – Solution is to add **additional margin** to steady-state (design) constraint



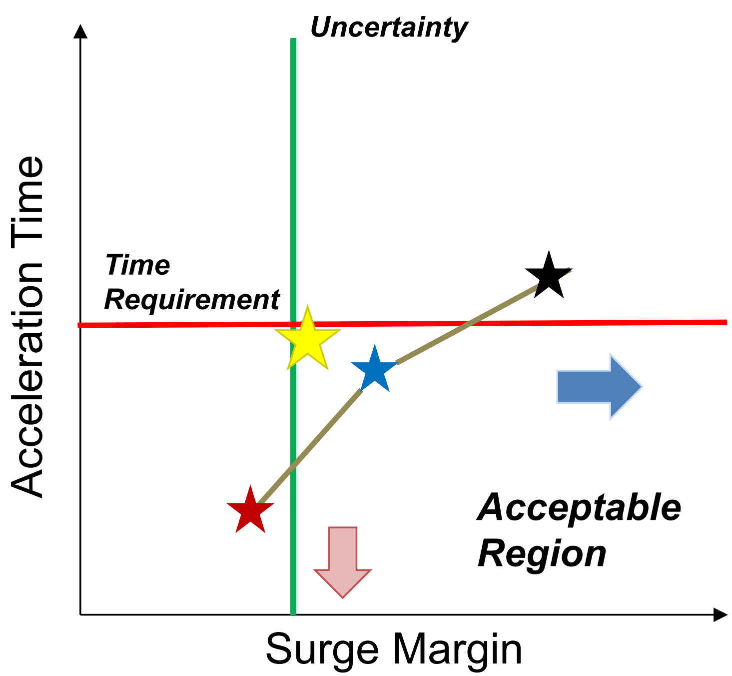
Introduction – Dynamic Operation

- Less margin when controller transitioning between operating points
- Steady-state engine design **operability** constraints include
  - **Uncertainty stack** (how much needed for off-nominal margin debits)
  - **Transient stack** (how much is needed for controller to transition)
- **Performance** requirement for closed-loop system (Accelerate within 5 seconds)
- Controls affects performance (response time) vs operability (SM) tradeoff





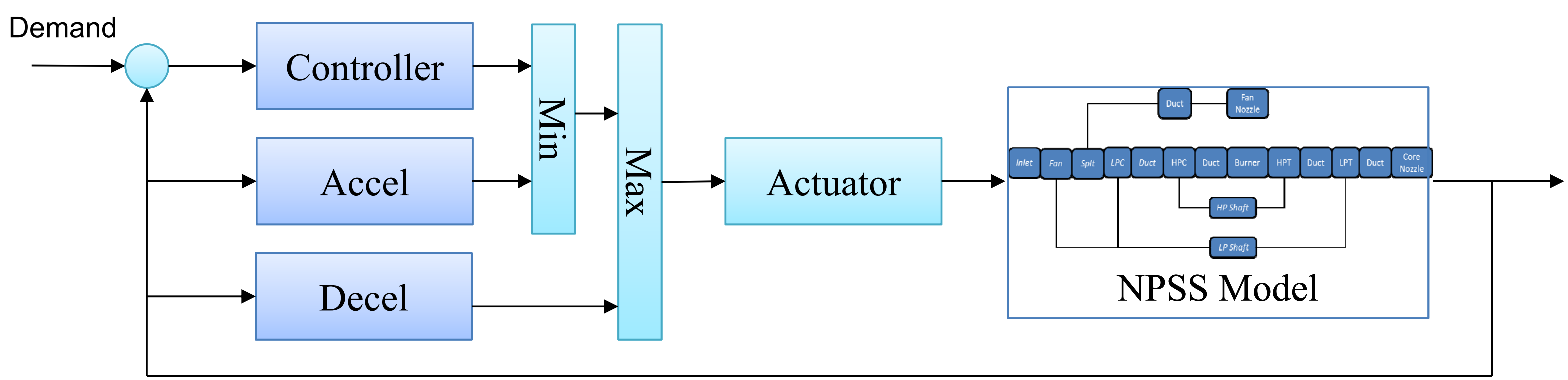
Introduction – Dynamic Systems Analysis



- Performance-operability trend for one engine design assessed with three control designs
  - TTECTrA (MATLAB/Simulink) controllers
  - Controls cannot improve efficiency for a given engine, but can reduce need for design margin
- Ideal closed-loop design… (★)
  - Meets 5 second acceleration requirement (takeoff/go-around)
  - Has minimal excess margin
- Engine designs with extra margin tend to be less efficient
  - Characterizing dynamic performance can help guide the system studies (analysis)

Introduction – Dynamic Analysis Tools

- Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)[2]
  - Open source: https://github.com/nasa/TTECTrA/releases
  - Defines general Wf controller architecture **(engine agnostic)**
  - Designs Wf controller to protect transient operability (SMs, FAR, T40)
  - Design family of controllers to estimate transient performance tradeoff
- Integrate TTECTrA with NPSS engine models via S-function interface[3]
- Version discussed in this work is currently closed-source, NASA only
  - Augmented with design tools for other actuators for **specific engines**
  - VBV, VAFN
  - Electric machine (motor/generator)



Introduction – Dynamic Analysis Tools

- Dynamic systems analysis workflow using TTECTrA control design code
- Characterize system by way of…
  - Designing controllers to meet transient operability requirements
  - Run dynamic simulations with controllers to obtain performance and operability metrics
- Observing the trends in these metrics and using that information to guide system design

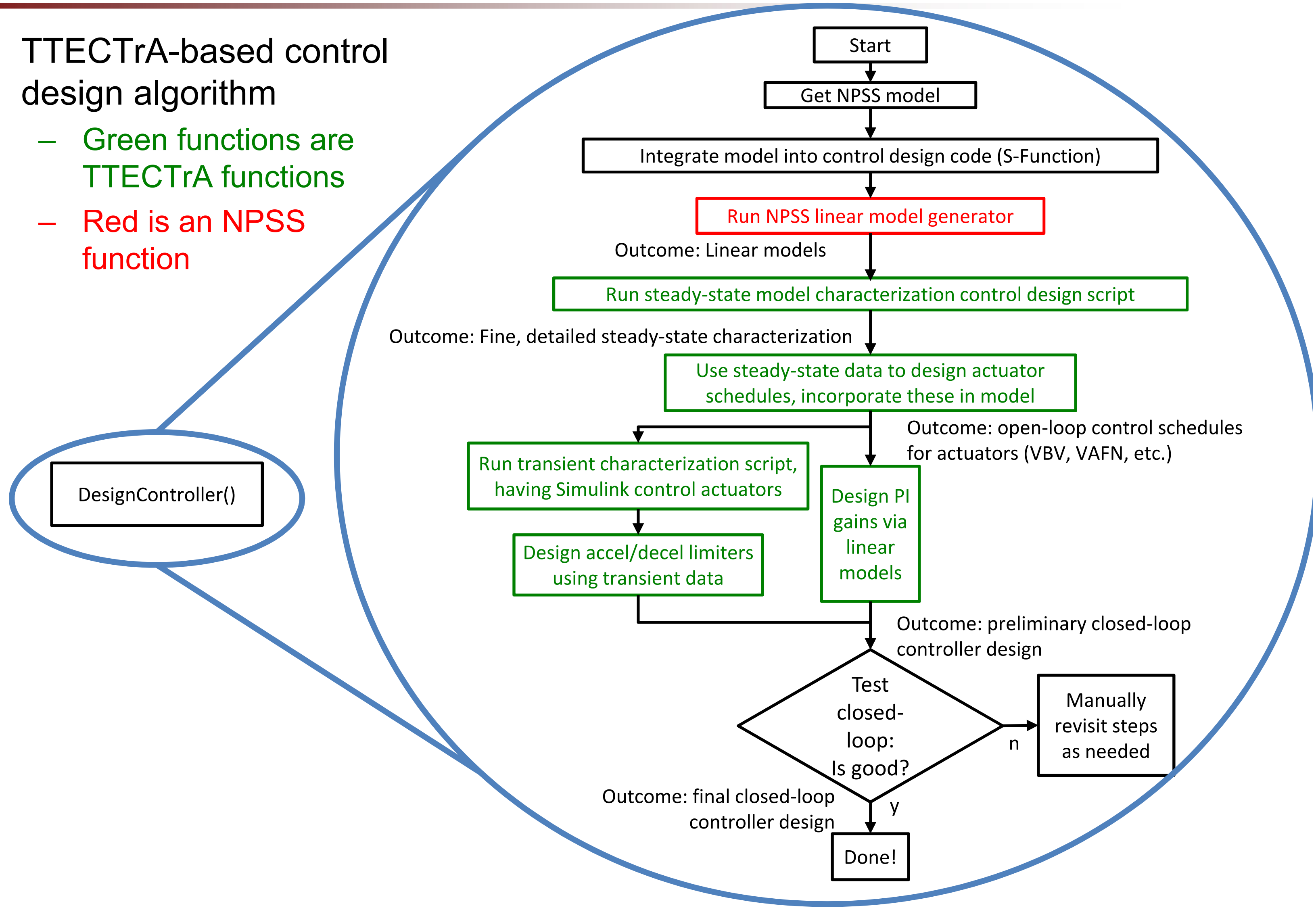
```
// Design a baseline controller for system design constraints on
// variables x, y, and z
baselineController = DesignController(x_design, y_design, z_design)

// Ensure controller meets requirements, perform DSA if it is valid
controllerValidFlag = TestControllerValidity(controller(i))

If controllerValidFlag
  // Pick a control design (operability) variable of interest, x
  // (e.g.: min HPC SM)
  // Explore trade space by designing controllers to protect n different
  // constraint values for x.
  // i.e.: x = x_min(1) ... x = x_min(i) ... x = x_min(n)
  // (e.g.: min HPC SM = 10%, 12%, 14%)
  for i = 1 : n
    // Design controller for x_min(i)
    controller(i) = DesignController(x_min(i) , y_design, z_design)
    // Obtain the response of the closed-loop system with controller(i)
    [x_act(i), y_act(i), z_act(i), perf_act (i)] = ...
      evaluateController(controller(i))
  end
  // Analyze the results
  plot(x_act, perf_act)
```

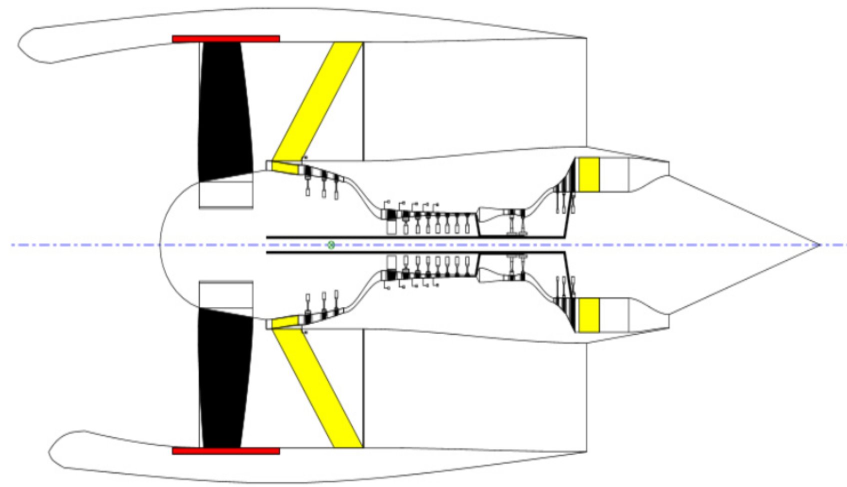
Introduction – Dynamic Analysis Tools

- TTECTrA-based control design algorithm
  - Green functions are TTECTrA functions
  - Red is an NPSS function



N+3 Geared Turbofan – Engine

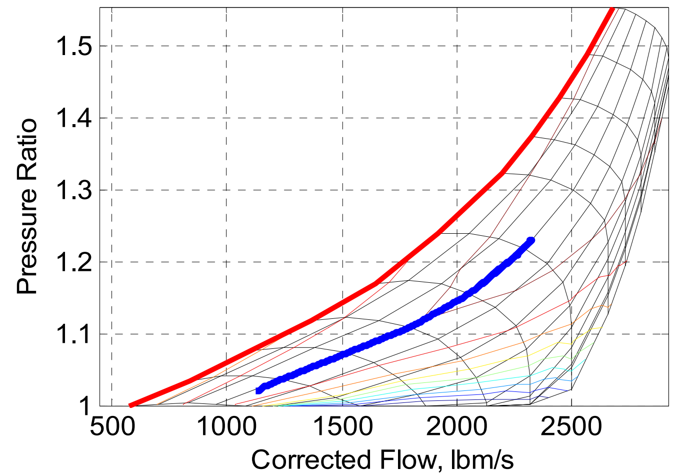
- NASA "Advanced" NPSS (N+3) Geared Turbofan (GTF)
  - Single-aisle thrust class (29,000 lbf)
  - Fan drive gearbox (ratio 1 : 3.1)
  - Variable area fan nozzle (VAFN)
  - Foundation for many AATT advanced vehicle concept studies

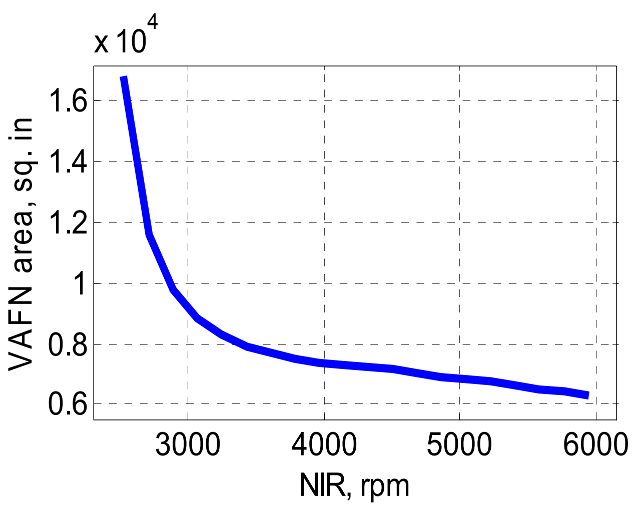


- Small core to get high BPR
  - Needs robust materials (High temperature, increased loading capability)
  - Model makes N+3 materials/technology assumptions

N+3 Geared Turbofan – Closed-Loop System

- Variable area fan nozzle (VAFN)
- Controls fan pressure ratio
  - Open at idle to reduce Fan backpressure (protect against stall)
  - Closed at cruise for efficiency
  - Scheduled to corrected low spool speed, for optimal fan operating line





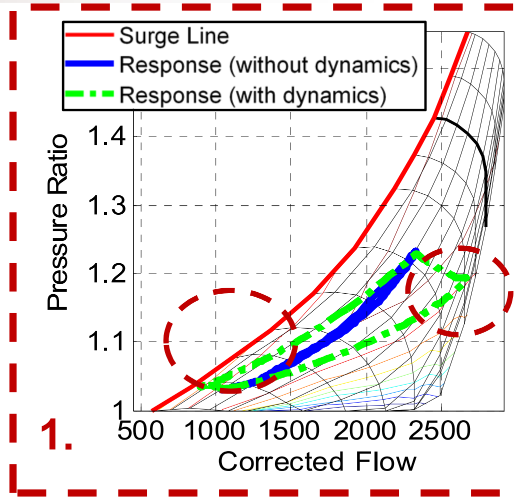
- SA studies show hydraulic, electric, etc. actuators too heavy for VAFN
  - Weight fuel burn penalty offsets benefit
- Therefore VAFN assumed to use shape memory alloy (SMA) actuators
  - Solid state, high force-to-weight
  - Actuation rate may be slow
    - 15 s for full stroke demonstrated[5]
  - **1st order linear**, 45 s Tr used in model
    - Very slow to make up for **low fidelity**

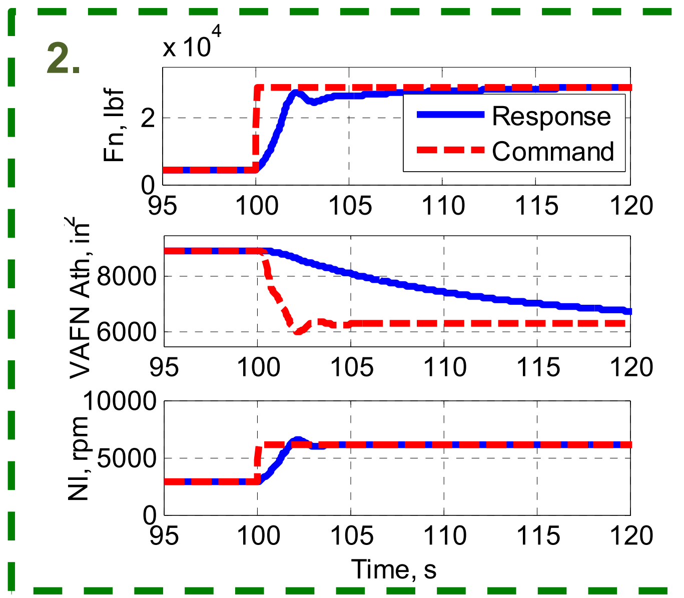
N+3 Geared Turbofan – Closed-Loop System

Slow VAFN causes off-nominal transient operation!

1. Accel and decel data shown on fan map
   - Decel: VAFN area smaller than scheduled
     - Fan surge margin suffers
   - Accel: VAFN smaller larger than scheduled
     - Fan in danger of operating choked
     - Controlling to thrust results in running higher than nominal fan speed
     - Care must be taken not to violate fan max speed and min SM constraints

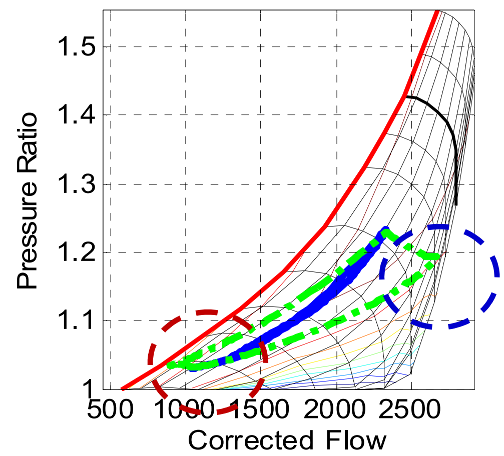
2. Accel transient simulation, controlling engine to fan speed with a slow VAFN
   - Shows that less thrust obtained per fan speed if VAFN too open
   - Complicates reaching 95% thrust in 5 s with traditional fan speed controller architecture

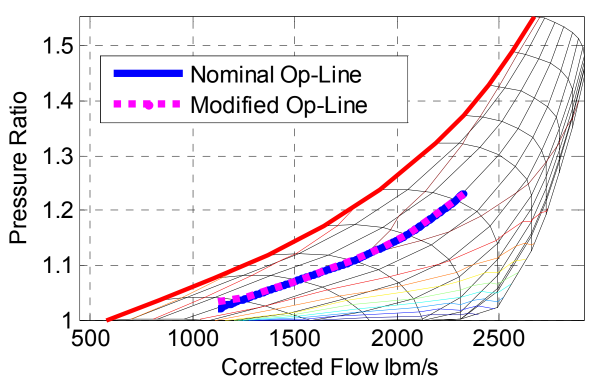


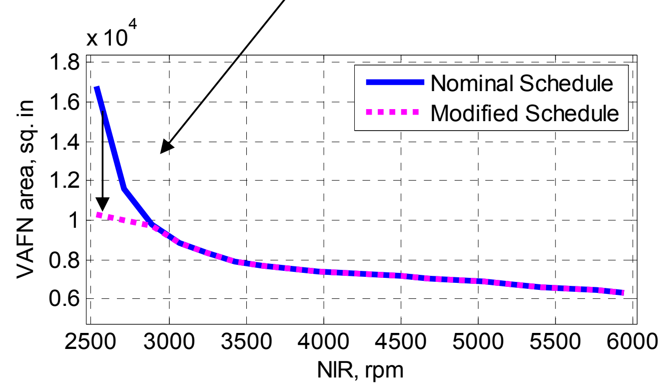


N+3 Geared Turbofan – Low Speed Analysis

- Transients to or from low idle (below 12% Fn) cause either very low fan surge margin or very high fan speed overshoot (going off map)
- This is due to the scheduled nozzle area at low idle being very large, thus transient nozzle area being very far off nominal
- Therefore, redesigned schedule
  - Reduced actuator requirement (dynamic range reduced from 62% to 40%)
  - Stopped fan from going off map in all test cases

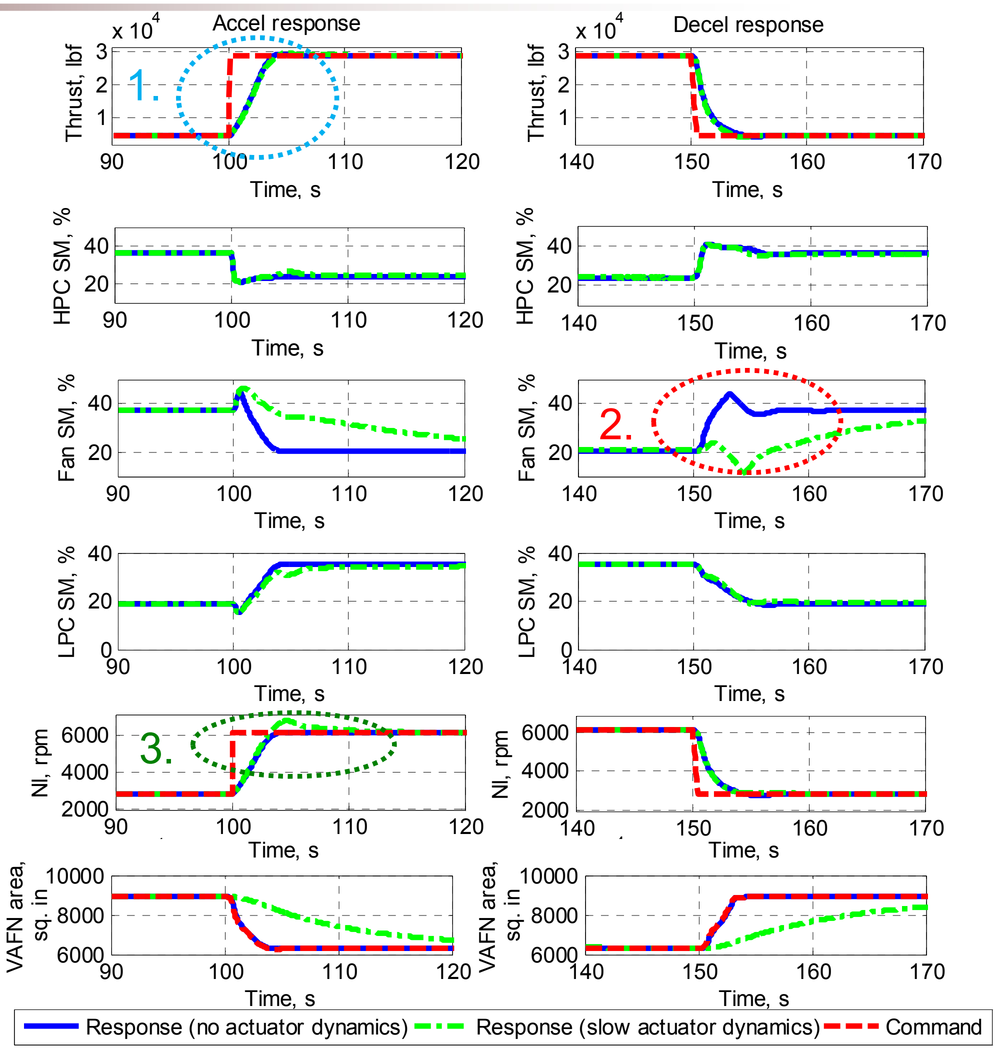






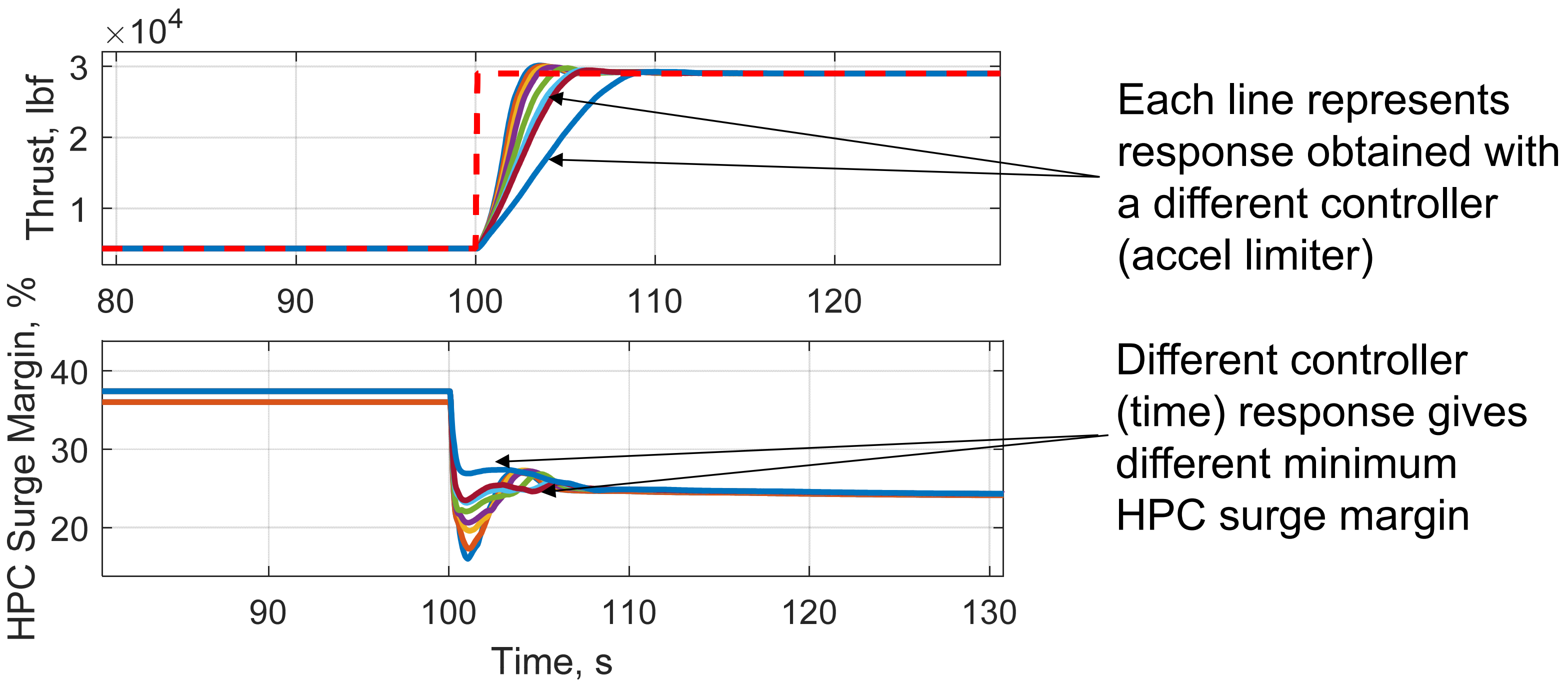
Simulation Results – Baseline Controller

- Baseline controller
- 15-100% thrust response (accel and decel)
- Nominal closed-loop system with and without VAFN actuator dynamics
  1. Approximately same thrust response regardless of VAFN dynamics
  2. Fan surge margin is the only surge margin affected
  3. Thrust controller drives Nl above steady-state value until VAFN transient dies out
- Shows that advanced control logic can ensure performance while maintaining operability with slow VAFN as long as higher fan speed and lower fan surge margin are acceptable



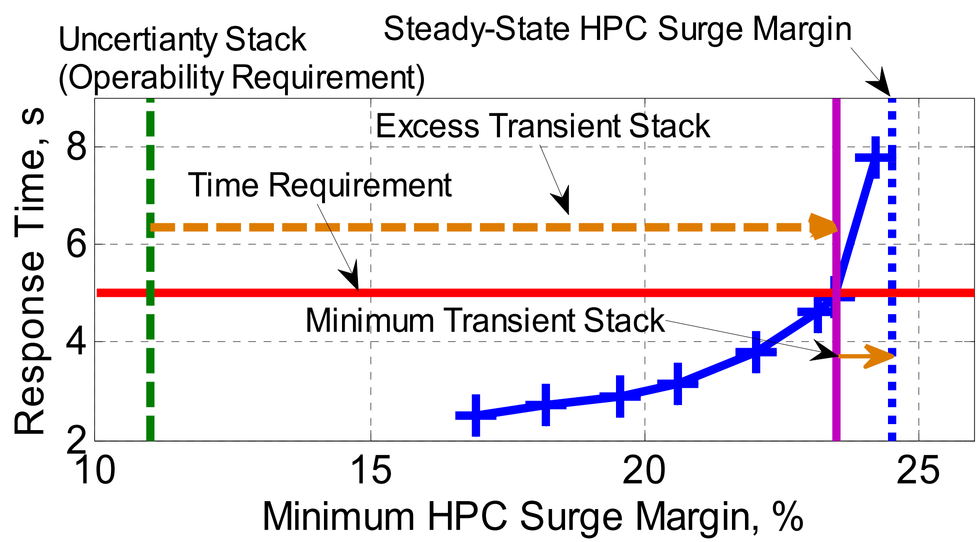
Simulation Results – DSA

- TTECTrA used to tune accel limiters for different HPC surge margin constraints
  - Controllers designed for 12, 14, 16, 18, 20, 22, 23, 24% minimum HPC surge margin
  - 15-100% snap accel transients ran at sea-level static for each controller
  - Thrust, surge margin responses shown
  - Response time (15% – 95% thrust) and minimum HPC surge margin metrics obtained



Simulation Results – DSA

- Response time and minimum HPC surge margin metrics shown (blue crosses)
  - Connecting the dots: Performance-Operability trend (blue line)
  - Hypothetical controller that just meets 5 s requirement exists at the intersection of (red line) and (purple line) gives maximum possible operability margin (lots of excess)
  - Excess transient stack built into engine (dashed orange arrow) may be reduced if redesigned



- Study represents nominal engine running at sea-level static
  - Analysis should be done at more conditions for more accuracy

- Takeaway: Min HPC surge margin design constraint can be reduced to include only the minimum necessary transient stack to meet 5 s requirement

Conclusions

- Closed-loop N+3 Advanced Geared Turbofan demonstrated
  – NPSS model integrated into Simulink-based TTECTrA controller via S-Function

- Issues associated with slow variable area fan nozzle (VAFN) identified
  – Reduced thrust per fan speed during accel (complicates 5 s requirement)
  – Minimum fan surge margin suffers during decel
  – Model-based engine control (MBEC) a good candidate for solving issues

- VAFN control schedule designed
  – Puts fan in efficient operating region
  – Maximum nozzle area constrained to solve issues transitioning to/from low idle

- Dynamic systems analysis conducted
  – TTECTrA controllers designed to assess performance vs operability
  – Suggests steady-state HPC surge margin can be reduced, and engine redesigned
  – Conduct DSA at more flight and uncertainty conditions to obtain better estimate

Acknowledgments

- This work was funded by the NASA Advanced Air Transport Technologies (AATT) project

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5. Song, G., Ma, N., Lee, H.-J., and Arnold, S., "Design and Control of a Proof-of-Concept Variable Area Exhaust Nozzle Using Shape-Memory Alloy Actuators," IOP Publishing, Smart Materials and Structures, Vol 16, pp 1342-1347, June 2007.

Thank You!!

Questions?

NASA/CP—2018-219891

Modeling and Control for Hybrid Gas-Turbine Electric Propulsion

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NASA Glenn Research Center – Intelligent Control and Autonomy Branch
6th Propulsion Control and Diagnostics (PCD) Workshop
Ohio Aerospace Institute (OAI), Cleveland, OH
August 22, 2017

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Outline

- Introduction and Motivation
- hFan Concept
- STARC-ABL Concept
- NEAT Facility
- Single String Test
- Turbine Integration and Control Research Plans
- Conclusions

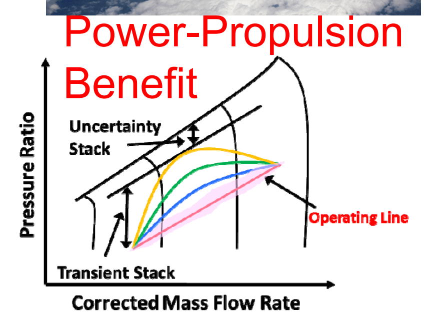
Major System Level Challenge

Electrified Aircraft have the potential to provide significant benefits for efficiency and emissions reductions, to assess these potential benefits modeling tools are needed to provide rapid evaluation of diverse concepts and ensure safe operability and peak performance over the mission

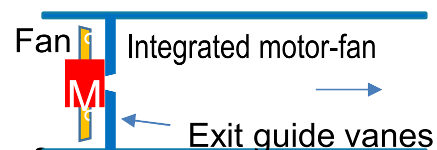
- For large scale vehicles (>90 PAX) it is expected that initial vehicles introduced to the market will require turbomachinery

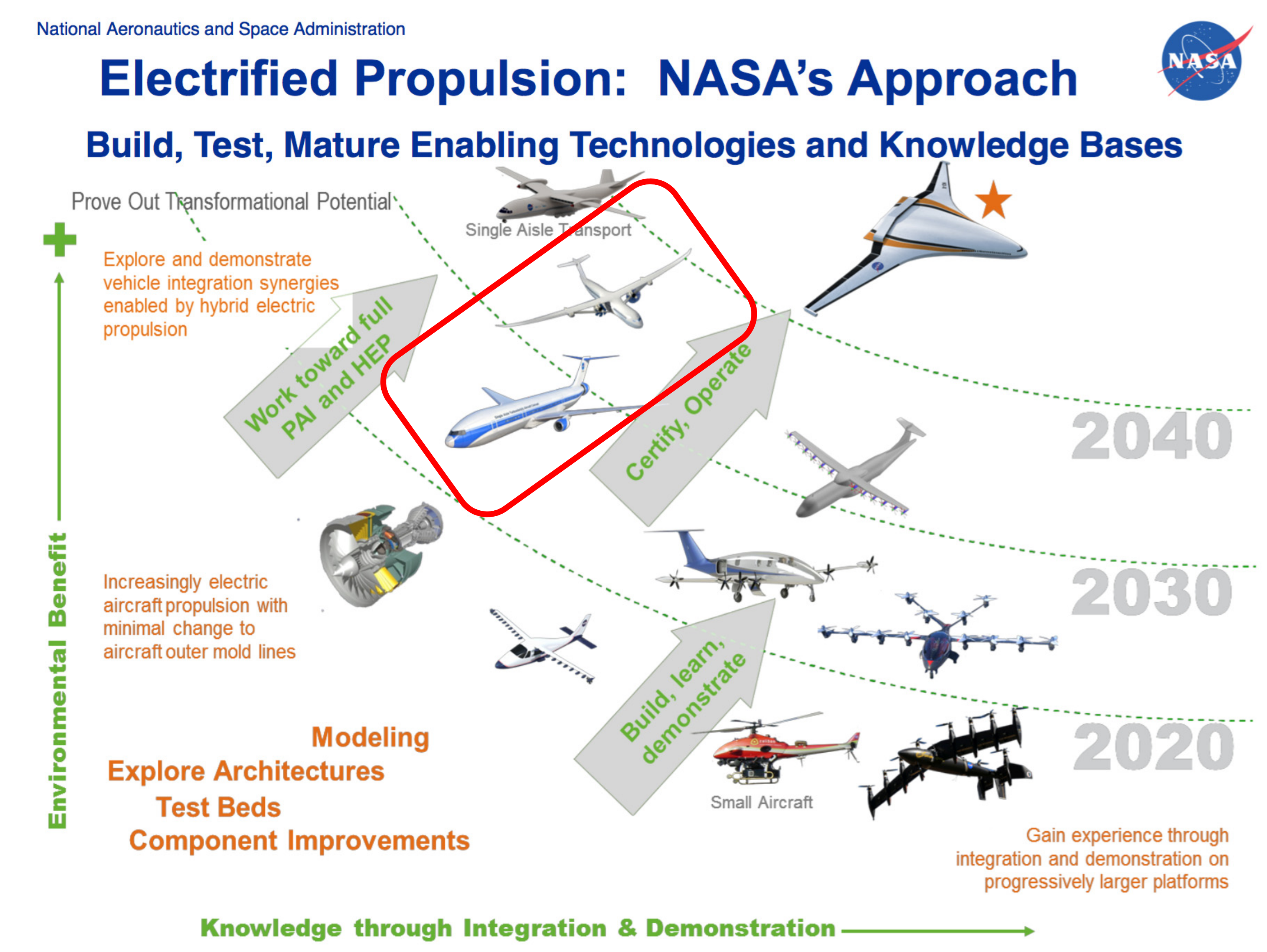
The Modeling challenge for these vehicles is the ability to show significant benefits over the current highly refined aircraft systems*. To illustrate benefits:*

- Modeling and controls tools need to be more detailed early in the design phase.
- Integration of the subsystems are required to take advantage of potential performance enhancements of the coupled system.
- Need to enable subsystem experts the ability to work simultaneously



Thermal System Benefit




National Aeronautics and Space Administration
Electrified Propulsion: NASA's Approach
Build, Test, Mature Enabling Technologies and Knowledge Bases
Prove Out Transformational Potential
Single Aisle Transport
Explore and demonstrate vehicle integration synergies enabled by hybrid electric propulsion
Work toward full PAI and HEP
Certify, Operate
2040
2030
2020
Increasingly electric aircraft propulsion with minimal change to aircraft outer mold lines
Build, learn, demonstrate
Small Aircraft
Modeling
Explore Architectures
Test Beds
Component Improvements
Gain experience through integration and demonstration on progressively larger platforms
Environmental Benefit
Knowledge through Integration & Demonstration

Hybrid Gas-Turbine Electric Propulsion Research: Current Technical Challenges

- **Aircraft Systems Complexity and Integration**
  - Disciplined system integration is required to introduce new technologies so that the improvement of one system does not adversely impact the performance of the aircraft as a whole.
  - **Small Engine Cores.** Activities being pursue to improve overall propulsion efficiency result in smaller core sizes. Could present challenges when extracting power.
- **Research Infrastructure for Electrical Technology**
  - The research and development of megawatt-class turboelectric aircraft propulsion systems is hampered by the lack of development testing facilities.
- **Electrical Technologies**
  - Electrical machines need to be developed to attain specific power, weight, and reliability for commercial aircraft application.

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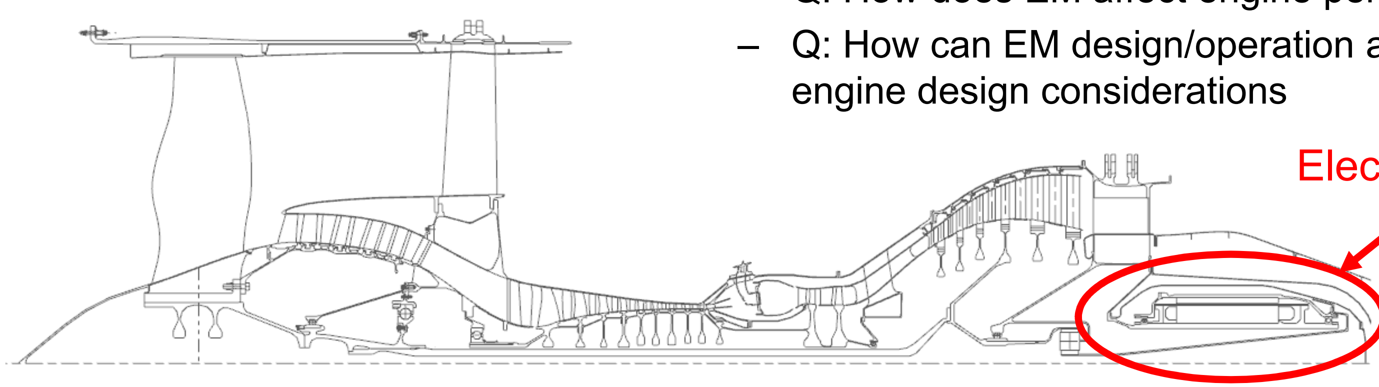
N+3 hFan – Engine

- NASA hFan (Parallel Hybrid Electric Turbofan, for SUGAR Volt-like aircraft)

SUGAR Volt

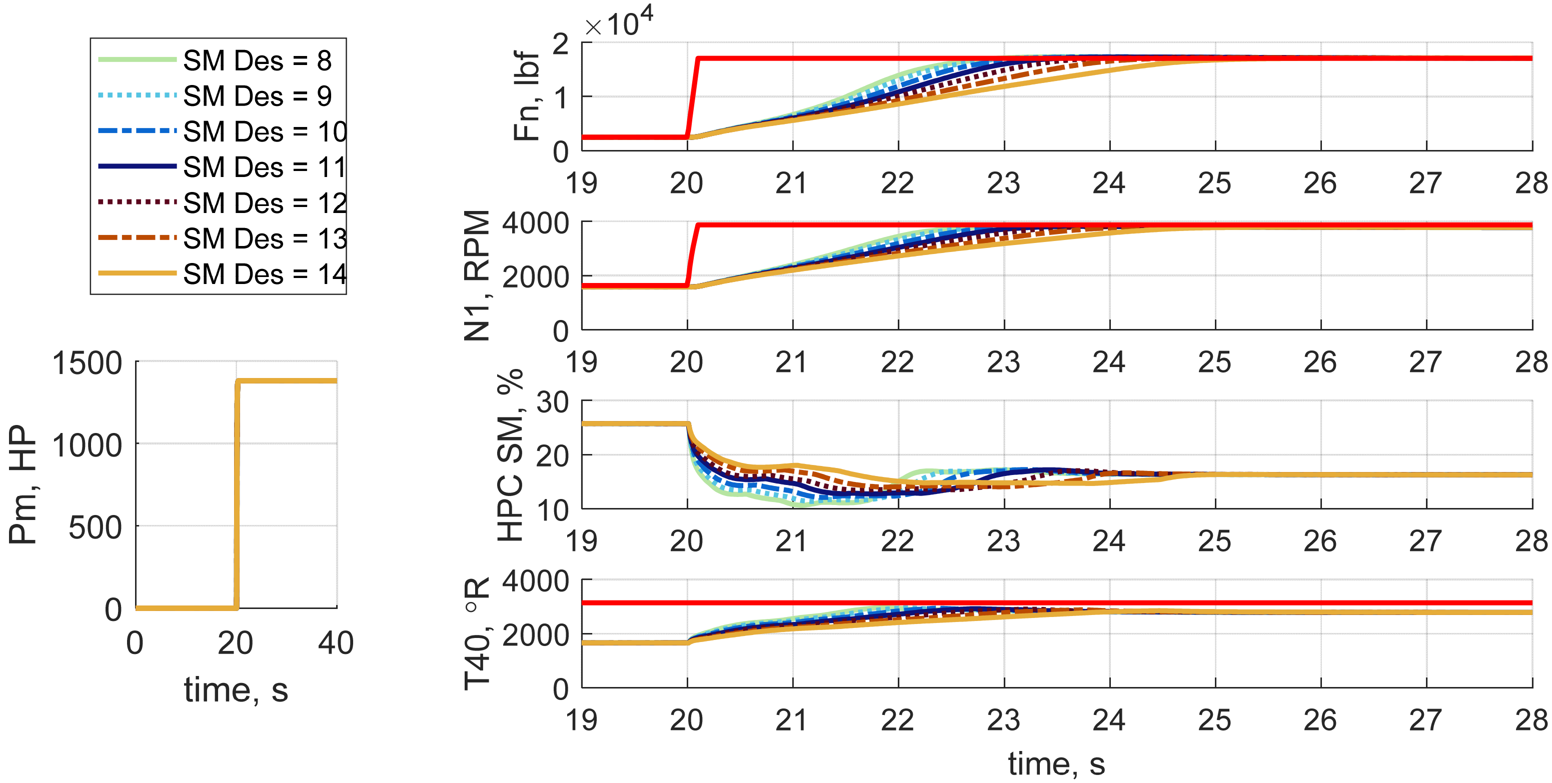
TOGW:	170,000 lbf
Top of Climb Thrust per engine:	3,500 lbf
Takeoff BET required per engine:	17,500 lbf
Takeoff SLST:	20,100 lbf

- Long, truss-based wings, high L/D, 150 PAX
  - 3500 mi max mission
  - 900 mi avg or eff target mission
- Direct drive twin spool turbofans
- Similar N+3 technology assumptions as GTF
- 1380 HP electric machine (EM) on LP spool
  - Assists driving fan for most of flight
  - Driven by batteries in underwing pods
- Initial analysis only at steady-state
- Q: How does EM affect engine performance?
- Q: How can EM design/operation affect engine design considerations



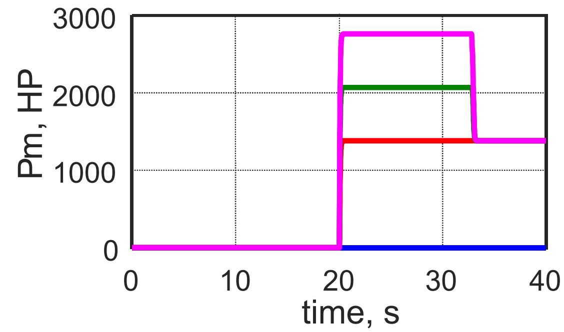
N+3 hFan – Dynamic Analysis

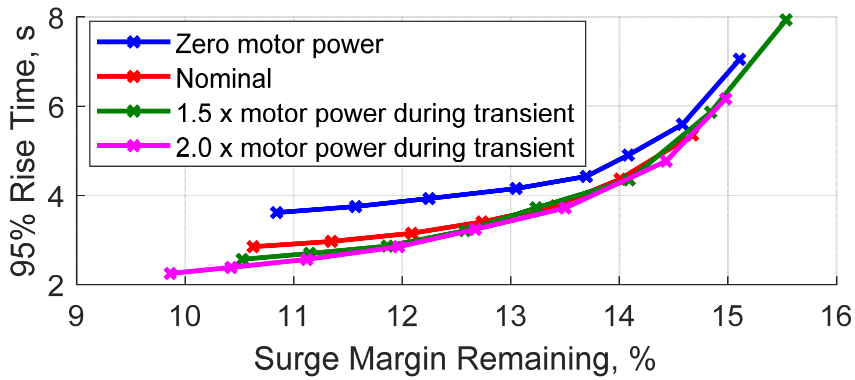
- Acceleration transients varying design value for min HPC SM
  - Fuel flow controller accel limiter varied
- Controller commands same motor power for all runs (step to full power)
- Typical acceleration response (faster accel = lower min HPC SM)

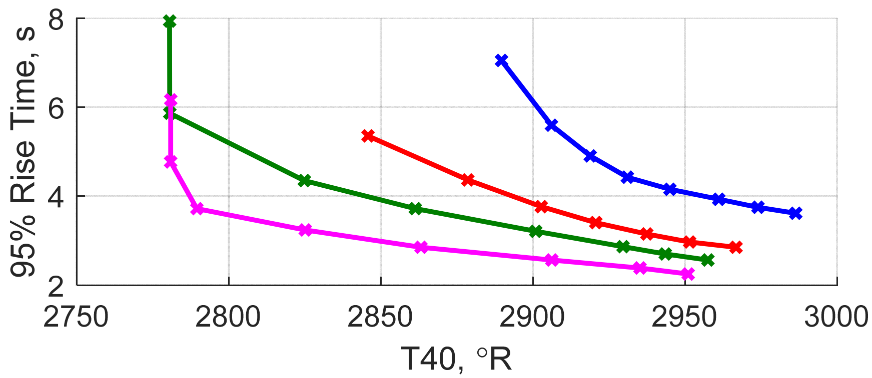


N+3 hFan – Dynamic Analysis

- Preliminary dynamic analysis on different motor designs shows different performance-operability trends



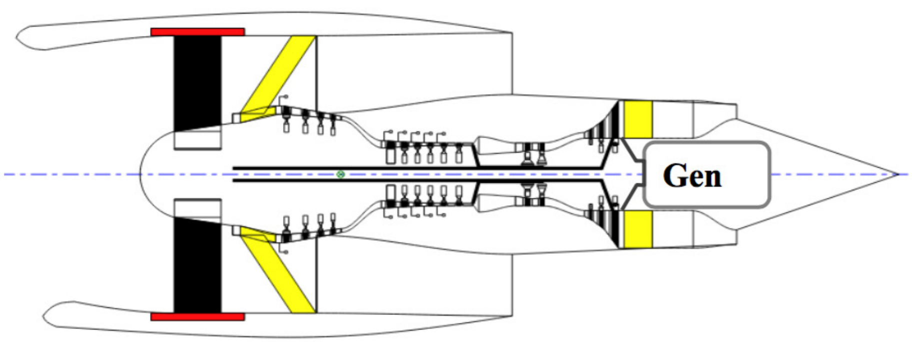


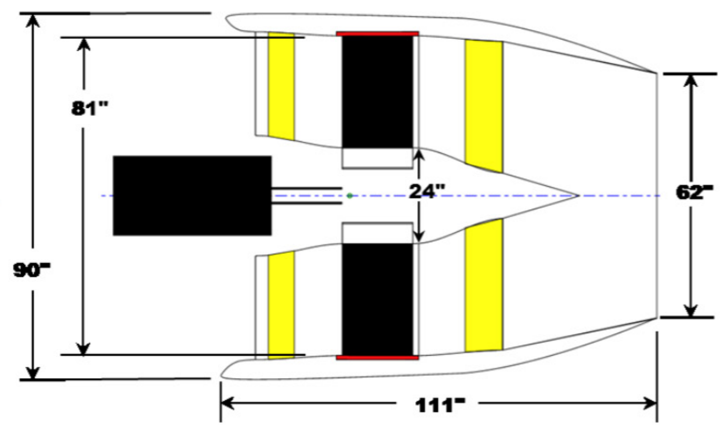


- Preliminary results with naïve, on/off control scheme suggest
  - More motor power during accel significantly lowers T40
  - Does not significantly affect HPC surge margin
- Higher max motor power during accel may prolong engine life
- Different control schemes may show more dramatic affect on HPC surge margin

STARC-ABL* (Partial Turboelectric/Fuselage BLI Fan)

Passengers	**150**
Range	3500 nm
Cruise Speed	Mach 0.7
Tailcone Thruster Motor	2.6 MW (3500 hp)
Turbofan Generator	1.44 MW (1940 hp)
Turbofan Fan	1.95 MW (2615 hp)
Fuel Burn Reduction (vs same tech turbofan)	~10%



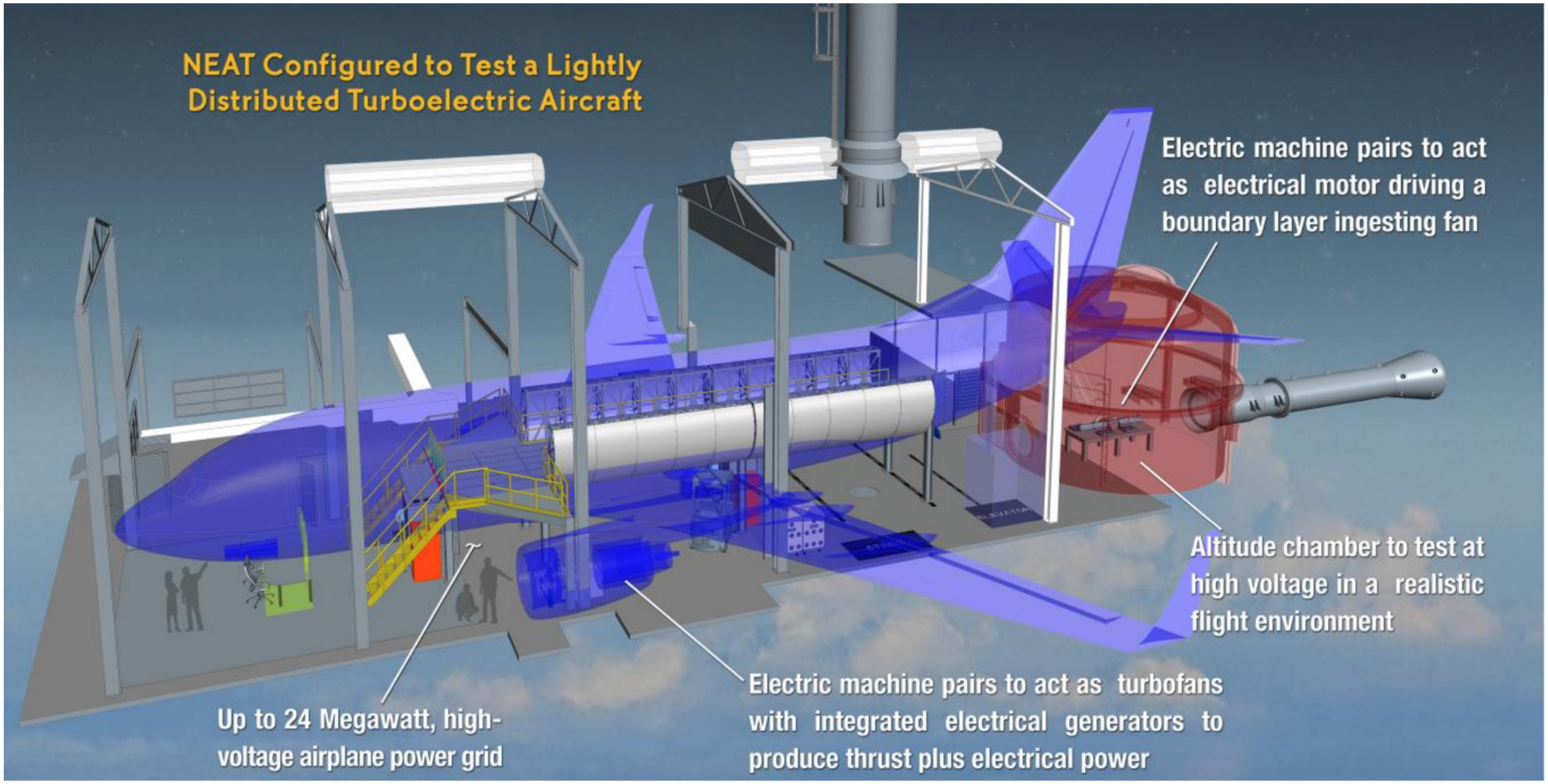


*STARC-ABL: Single-aisle Turboelectric AirCRaft – Aft Boundary Layer

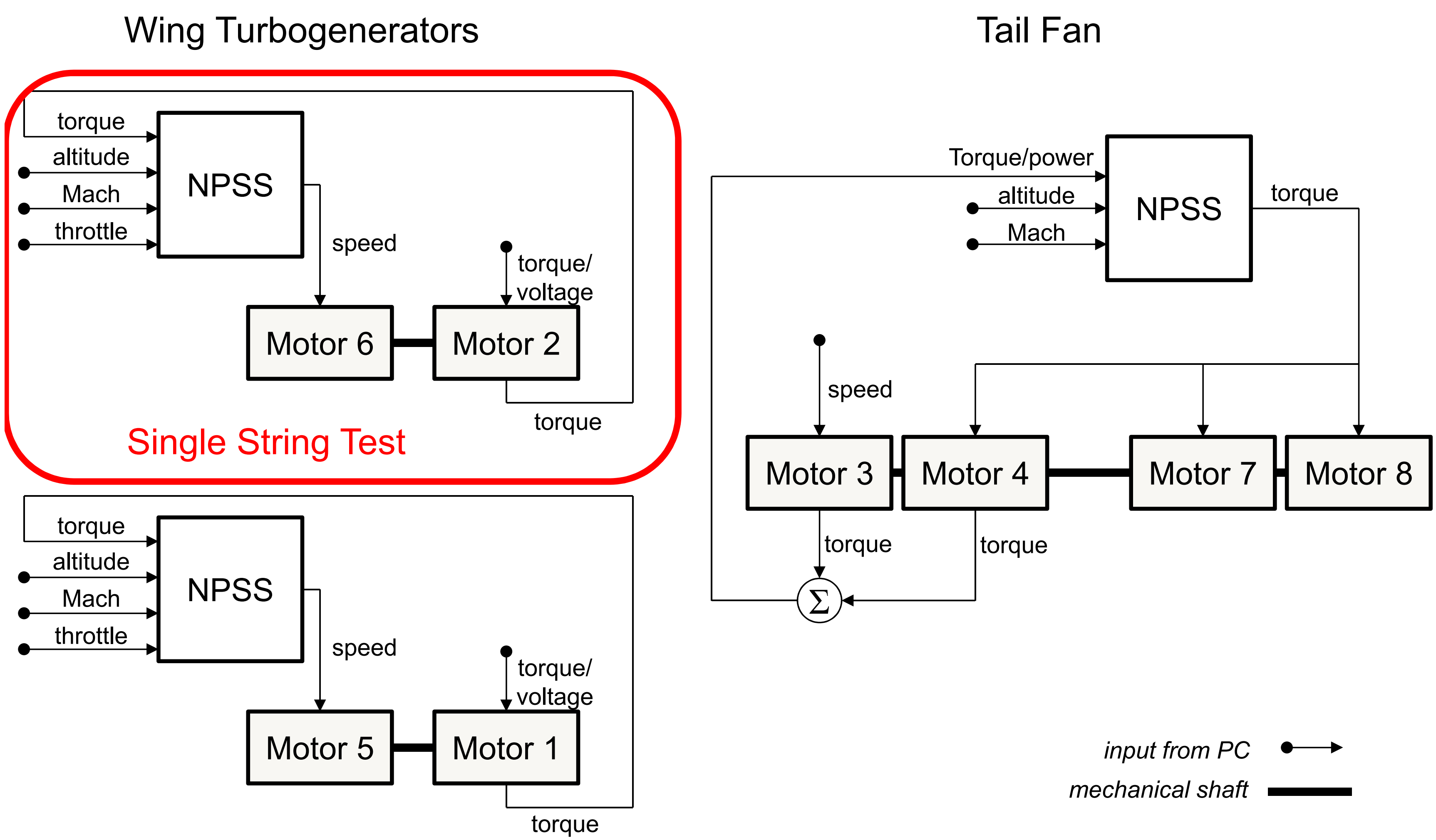
NASA Electric Aircraft Testbed (NEAT)

- Primary purpose of the testbed is to enable the high power ambient and cryogenic flight-weight power system testing that is required for the development of the following components to Technology Readiness Level 6
  - **Bus Architecture**
  - **MW Inverters & Rectifiers**
  - **MW Motors & Generators**
  - **System Communication**
  - **EMI Mitigation**
  - **System Fault Protection**

NASA Electric Aircraft Testbed (NEAT)



NEAT STARC-ABL Control Diagram



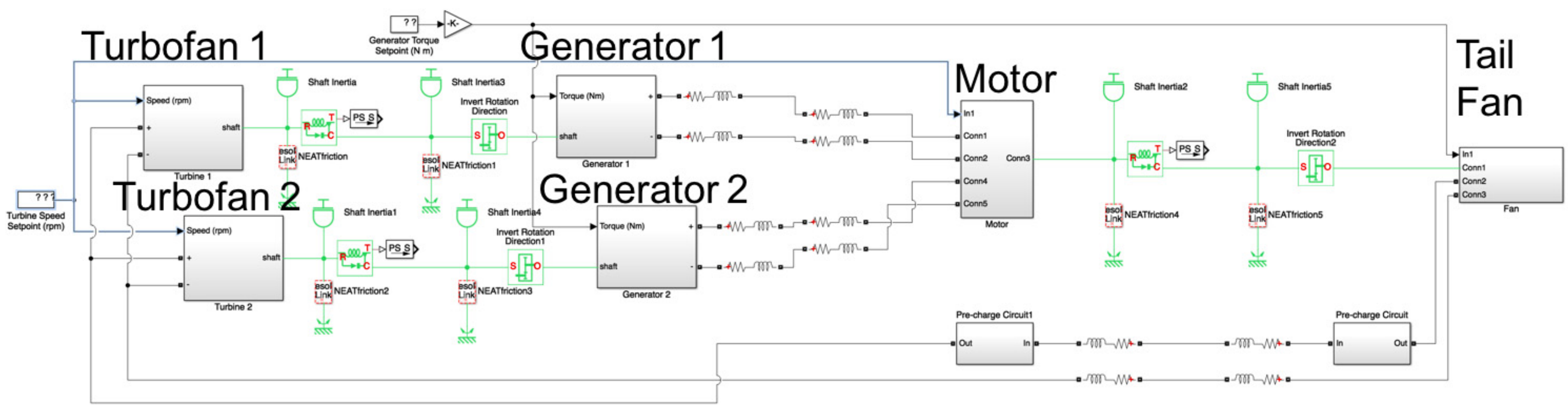
Modeling Conducted in MATLAB/Simulink

Assumptions for Electrical Systems:

- Average-model based Voltage Source Converters as inverter (100% efficient, no switching harmonics)
- Power supplies replaced with ideal DC source
- Simscape Mechanical shaft replaced with Simulink signals
- Inverter control algorithms bypass Pulse Width Modulation generation

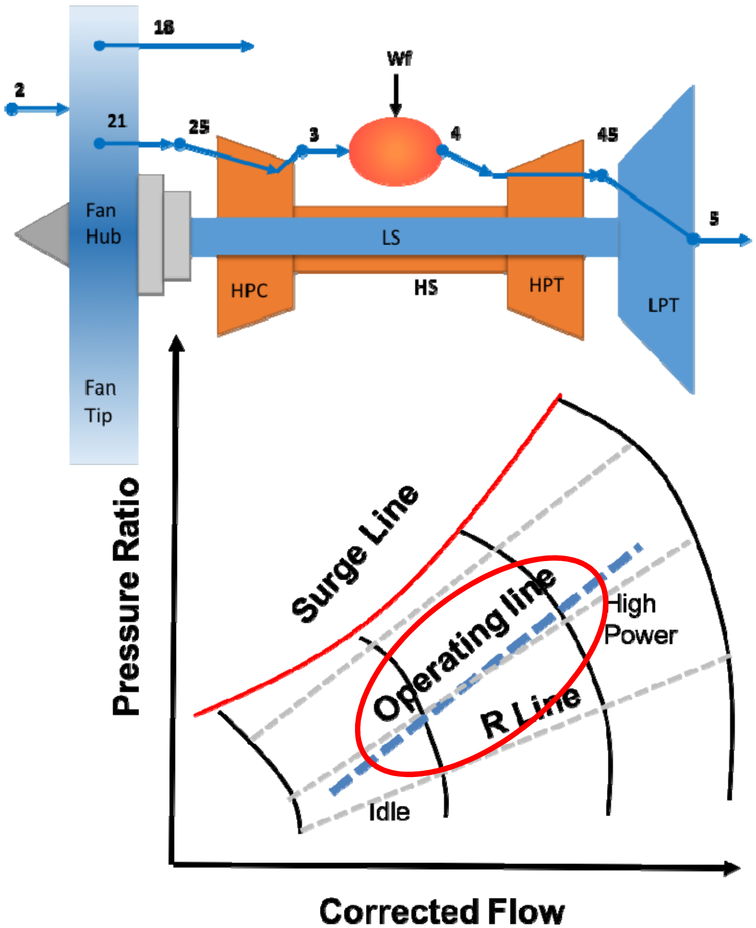
Assumptions for Propulsion System

- Model is running on open-loop fuel flow command
- Simple turbofan model not designed for power extraction



Turbofan Simulation NEAT Integration

- **Objective:**
  - Enable a more realistic dynamic response for the NEAT facility that accounts for the turbofan shaft inertias impact on power generation.
- **Approach:**
  - Numeric Propulsion System Simulation
    - Industry standard engine cycle modeling tool, able to model shaft dynamics.
    - Integrating NPSS into the Matlab/Simulink environment via the S-function for a common platform with other NEAT simulation tools
  - Engine Model Integration for NEAT
    - A Simulink UDP library block in the NPSS Simulink Simulation is used to send and receive data from the NEAT GUI that includes

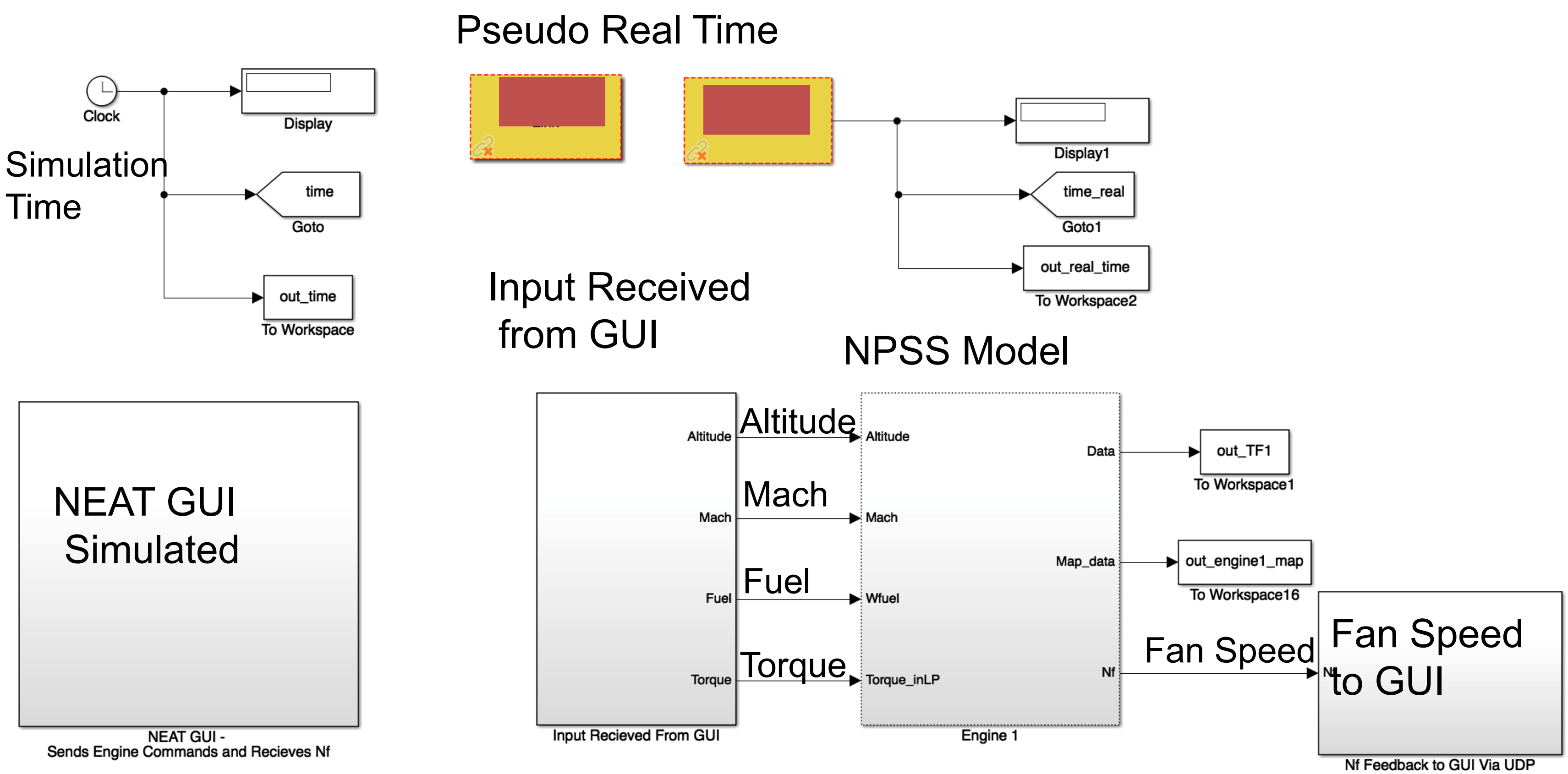


Risks:

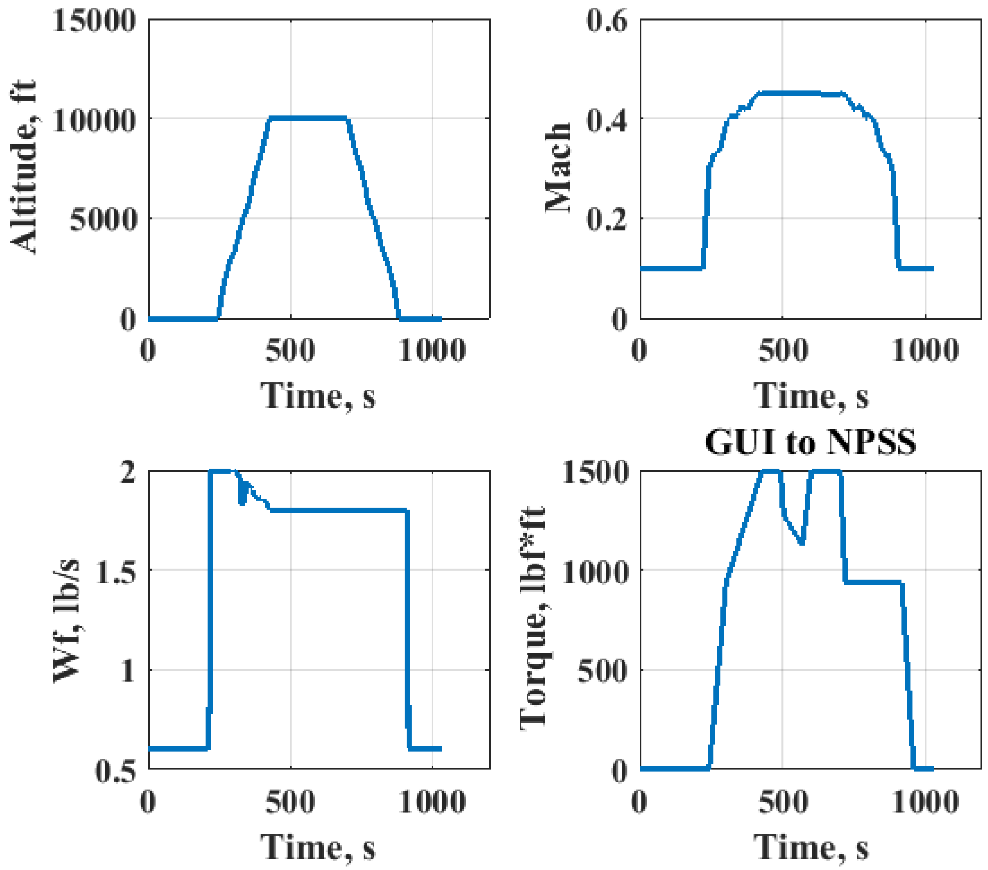
Torsional vibrations on motor shafts

Communications safe guards for erroneous NPSS values or loss of signal

NPSS Simulink Diagram

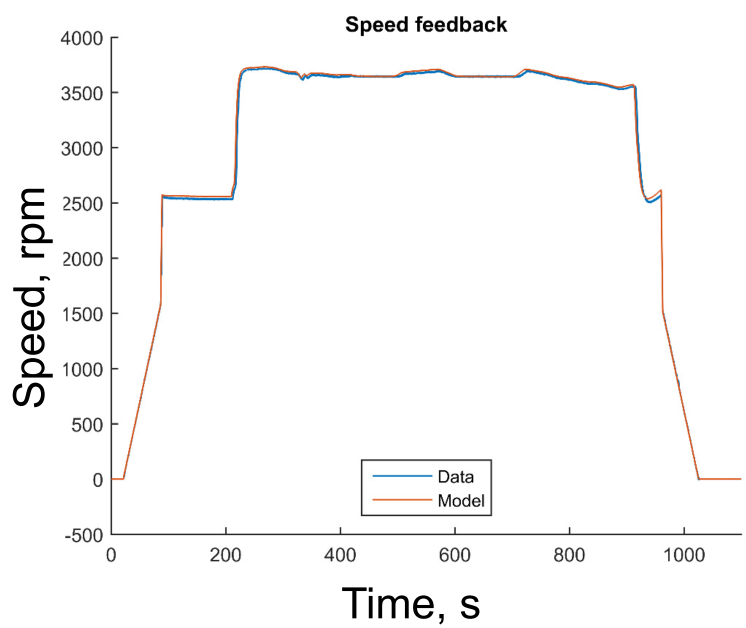


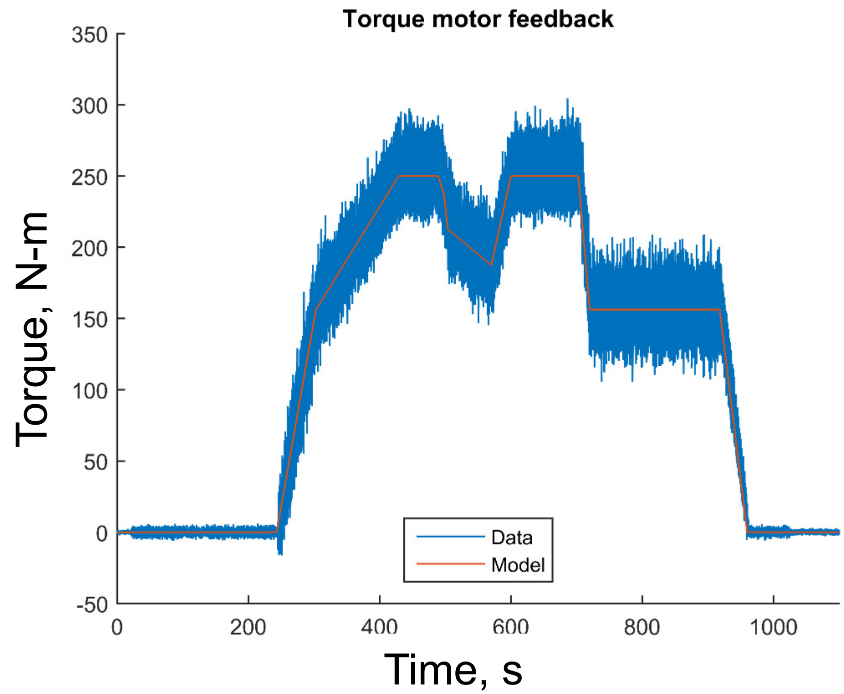
Flight Profile for Single String Test



Single String: Speed/Torque Response

- Model over predicts speed command since the model used load torque feedback while the test used drive torque feedback
- Test data shows slightly more noise than model





- Both the model and test hardware follow the command closely

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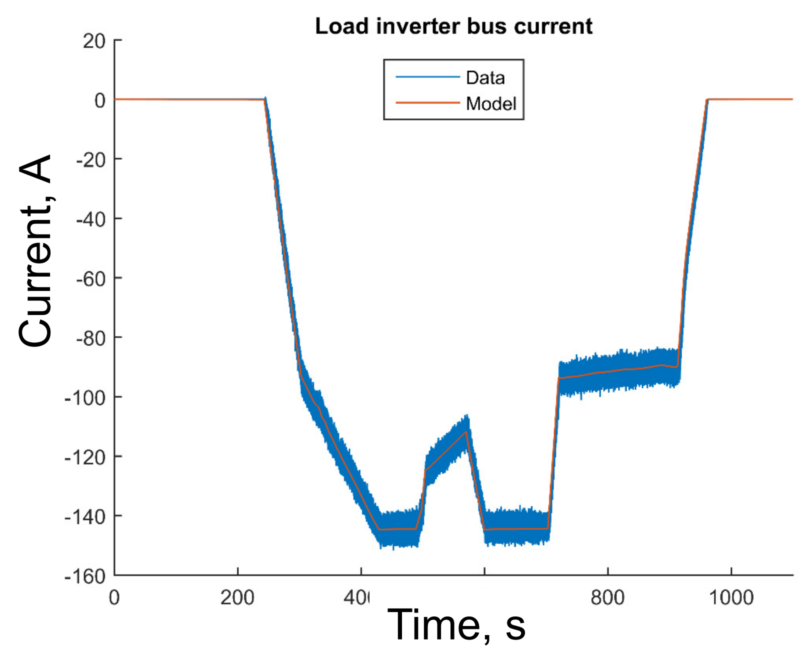
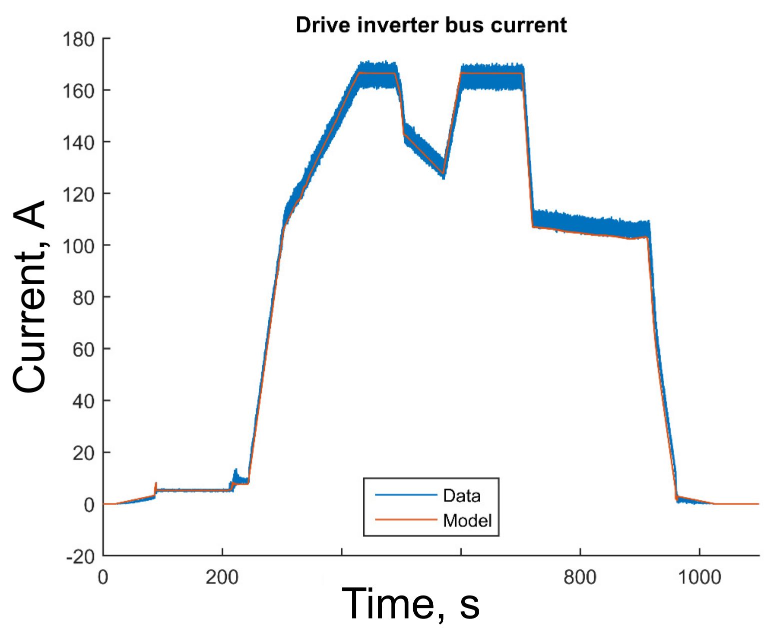
Single String: Current Response

- Test data shows much more noise than model since switching harmonics are not modeled
- Data shows higher current draw due to lack of inverter losses in model

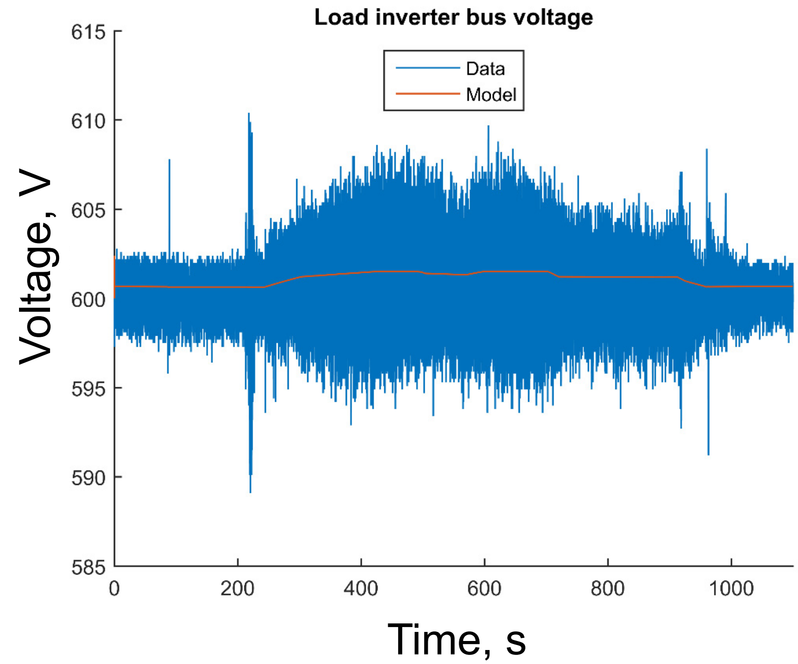


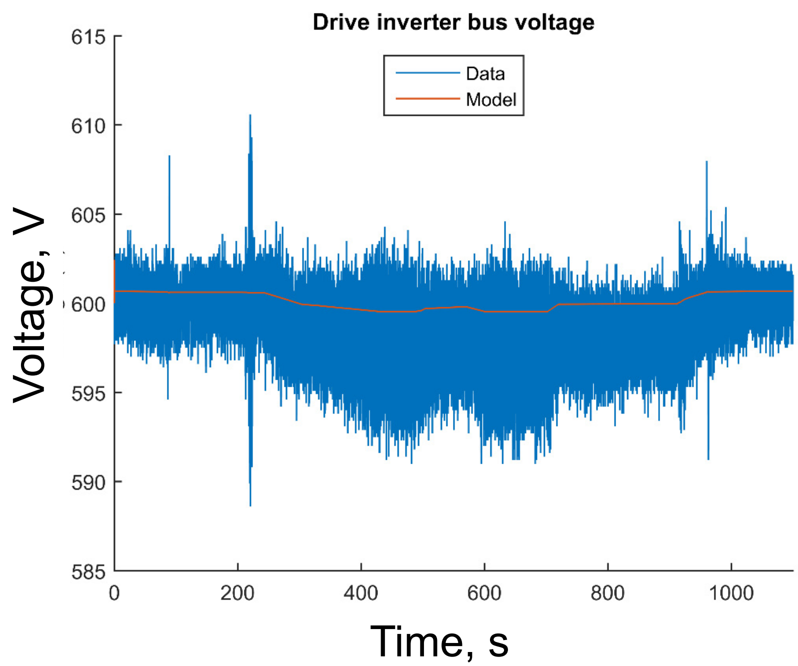


Simplified shaft model may over predict losses, offsetting under prediction of inverter losses

Single String: Voltage Response

- Test data shows more noise than model since switching harmonics and DC supplies are not modeled
- Model prediction follows same trend as data but does not capture spikes





- Model prediction follows same trend as data but does not capture spikes

Turbine/Generator Integration and Control

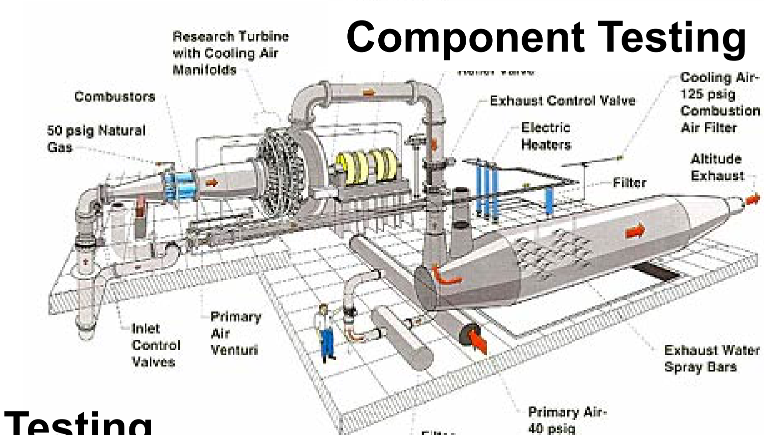
Objective

- Identify and demonstrate key technology challenges for extracting large percentages of gas turbine power while mitigating performance and efficiency detriments

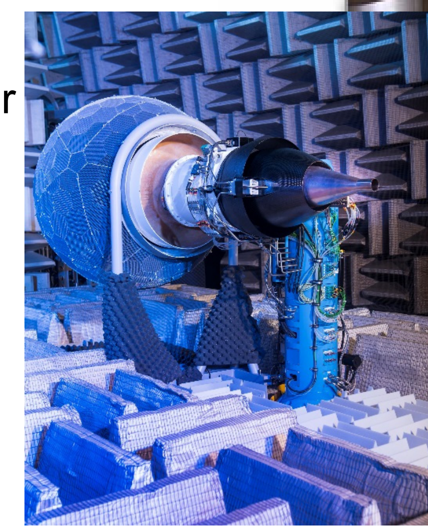
Overall Technical Challenges:

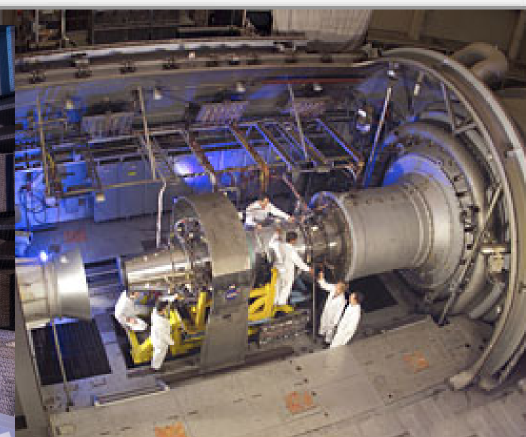
- Turbofan needs to provide propulsive thrust plus shaft power to power generator
- Understand and mitigate power extraction impact on turbomachinery, controls, dynamics, operability
- Mechanical integration
- Refine and validate STARC-ABL

Component Testing



Scaled Testing





Large Scale Testing

Conclusions

- Analysis conducted on N+3 hFan
  - Verified transient operability of both NASA concept engines with baseline control designs
  - Dynamic systems analysis suggests excess HPC surge margin typically built into designs can be reduced
  - Increasing hFan motor power during accel buys T40 margin

- NASA is exploring various ways to reduce the emissions of commercial aircraft. A key technology is moving toward more electric aircraft
  - Conducting studies of aircraft powered by turboelectric systems to better understand the benefits, component performance sensitivities, certification issues, and trade-offs related to key aircraft systems.
  - Developing research facilities and simulation tools for megawatt-class electric power and thermal management systems suitable for turboelectric aircraft propulsion systems.

- A near term goal is to develop and demonstrate critical technologies for hybrid gas-turbine electric propulsion by 2025 to impact the next generation of single aisle aircraft

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3. Welstead, J. and Felder, J. L., "Conceptual Design of a Single-Aisle Turboelectric Commercial Transport with Fuselage Boundary Layer Ingestion" AIAA 2016-1027
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Acknowledgments

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DGEN 380 Controls Testbed and Research Plans

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6th Propulsion Control and Diagnostics (PCD) Workshop
Ohio Aerospace Institute (OAI), Cleveland, OH
August 22, 2017

Outline

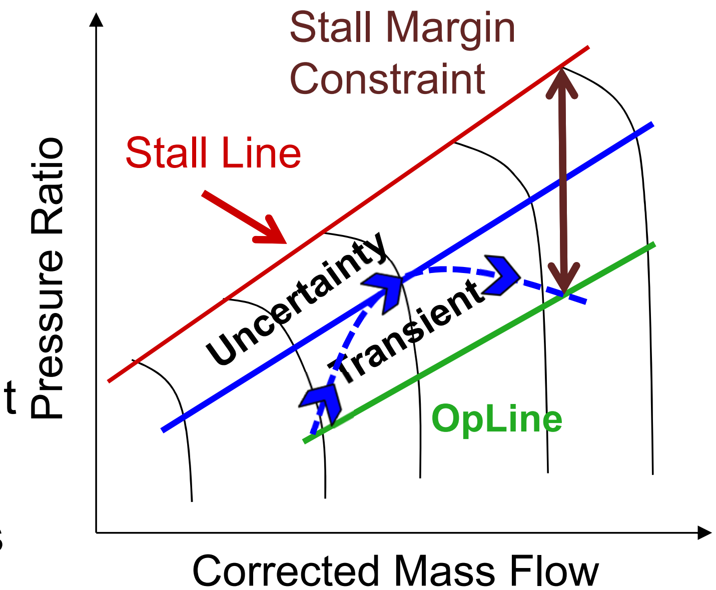
- Introduction and Motivation
- Engine Overview and Facility Development
- Model Development
- Baseline Control Design
- Results
- Research Plans
- Conclusions

Introduction and Motivation

- Advanced controls for turbofan engines is being supported under the Transformative Aeronautics Concepts Program – Transformational Tools & Technologies Project
- Focused on the NASA aeronautics strategic thrust for Ultra-Efficient Commercial Vehicles
  - With a goal of reducing fuel consumption for turbofan engines
- Typically, this has been accomplished through the development of technologies focused on the optimization of the steady state operation.

Introduction and Motivation

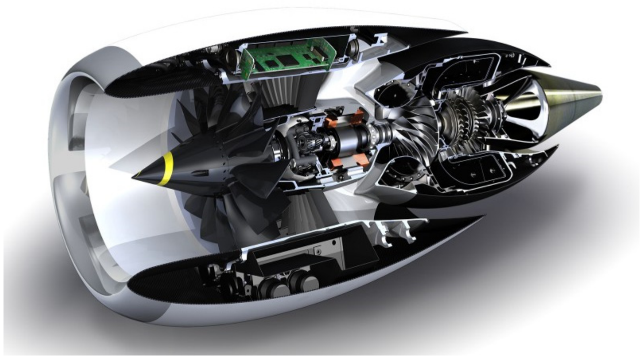
- Model-based engine control (MBEC) is being developed as an advanced control methodology to improve turbofan engine efficiency
  - Simulation studies have show approximately a 1% TSFC improvement
- Primary technology development issue has been that studies have largely been simulation based
  - Focus here is on how to advance the technology readiness level of advanced controls architectures that have typically been limited to simulation studies



A SM limiter can be developed to ensure that a lower threshold can be used for developing a new operating line while maintaining safe operation

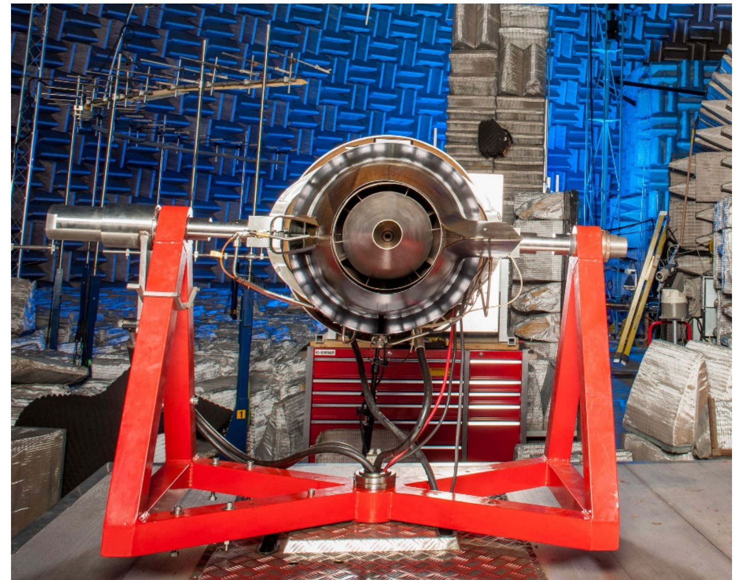
DGEN 380 Engine Overview

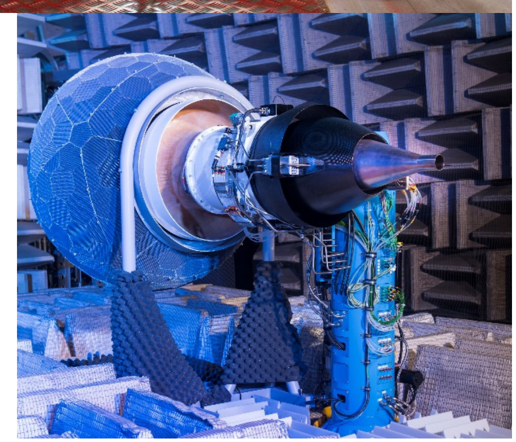
- The DGEN family of engines are small, dual spool, high-bypass, geared turbofan engines manufactured by Price Induction
  - Dual Spool, High-bypass (~7.5 ratio), Geared turbofan (~3.3 ratio)
  - Personal light jets, 4 to 6 seat aircrafts, Thrust ~570 lbf
  - Aircraft Max take-off weight
    - ~3,600 lbf (1650 kg) to 4,740 lbf (2150 kg)
  - Cruise design point
    - 10,000 ft / 0.33 Mach



DGEN 380 Facility Development

- DGEN Aero-Propulsion Research Testbed (DART)
  - Housed within the Aero-Acoustic Propulsion Laboratory (AAPL)
  - Enables technology studies at the system level to be examined on a relevant platform and move beyond simulation system studies
  - Initial single engine test on truck stand in AAPL, data from this test was used in model development
  - DART facility check out testing completed last month, research testing planned for early August





WESTT CS/BV Virtual Engine Test Bed

- Multipurpose test bench modeled after the DGEN 380 intended for practical education and research
- Features include:
  - Real time linear parameter varying simulation of the engine performance data
  - Dynamic 3D visualization of the engine
  - Thermodynamic and aerodynamic explorations
  - DGEN control system with access to the engine regulation code.

- Intelligent Control and Autonomy Branch
  - Purchased test bench
  - Integrate with distributed engine control technologies.
  - Interest in testing model-based engine control architecture

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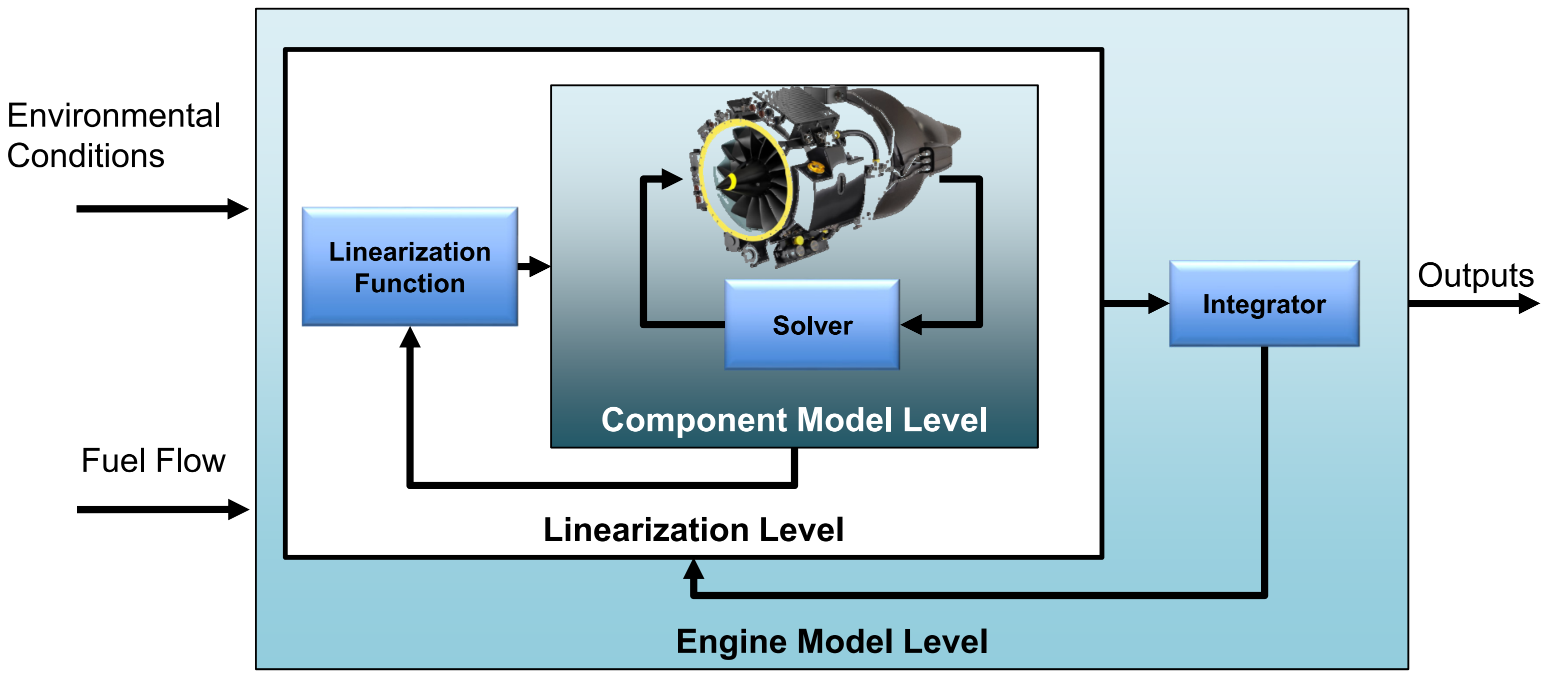
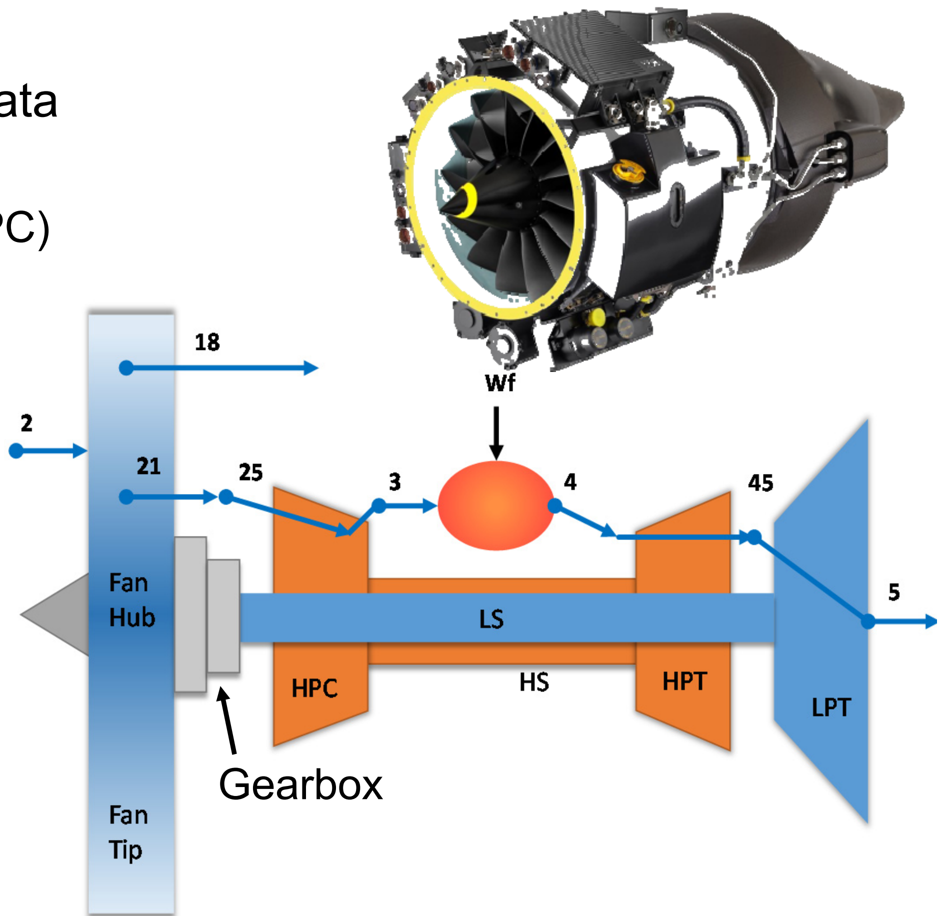
Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) Overview

- T-MATS abilities:
    - Iterative solving capability
    - Generic thermodynamic component models
    - Control system modeling (controller, actuator, sensor, etc.)



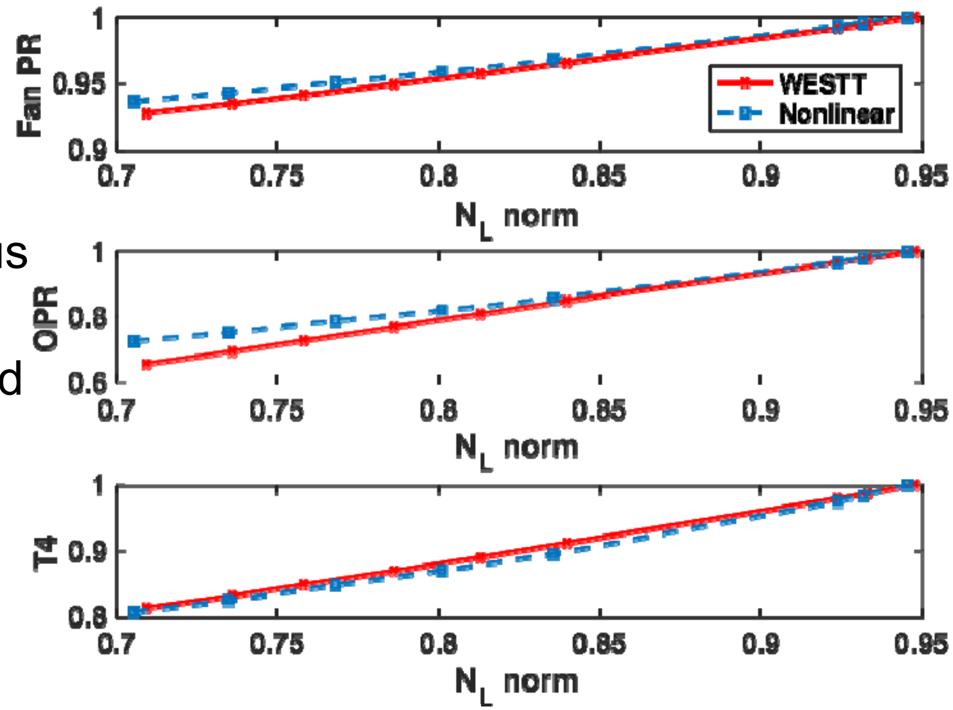
DGEN380 – Component Level Model

- Identify major turbo-machinery components of the engine and assign station numbering convention
- Model developed with limited data
  - Fan Tip / Fan Hub
  - High pressure compressor (HPC)
  - High pressure turbine (HPT)
  - Low pressure turbine (LPT)
  - Low speed shaft (LS)
  - High speed shaft (HS)
  - Burner
  - Gearbox
  - Power Management on HS



Model Comparisons: Steady State Cruise Simulation Data

- Comparisons of the nonlinear T-MATS developed model to the WESTT test bench
  - Cruise condition at various power settings
  - All data shown normalized by its maximum value
- Results shown for Fan PR, Overall PR, and T4
- In general the results show the model is more accurate at higher power, or design point



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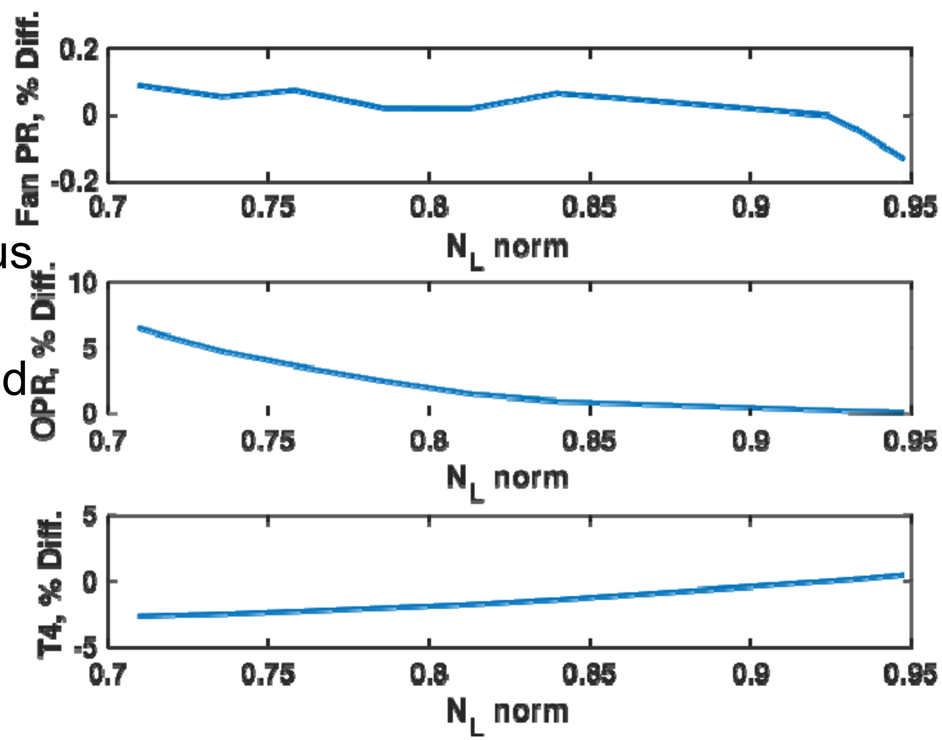
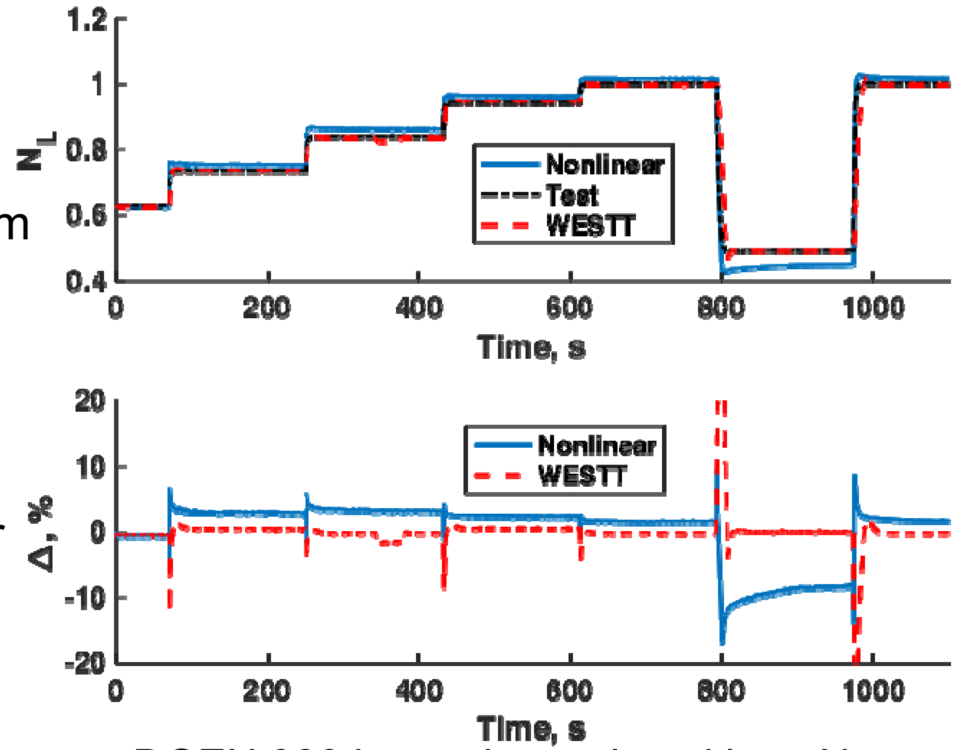


Percent difference typically less than 5%

Model Comparisons: Ground Engine Test Data

- An initial ground test of the DGEN 380 was conducted using a stair case transient step in the PLA starting from a flight idle condition to full power.

- N_L response shown is accurate during the smaller stair case transient maneuvers to within a few percent. During the larger transient maneuvers of the engine the error grows, but is still in general less than 10%



- DGEN 380 is running a closed loop N_L controller; however, for comparisons the fuel flow signal from the engine test is directly provided to the nonlinear T-MATS model running open loop

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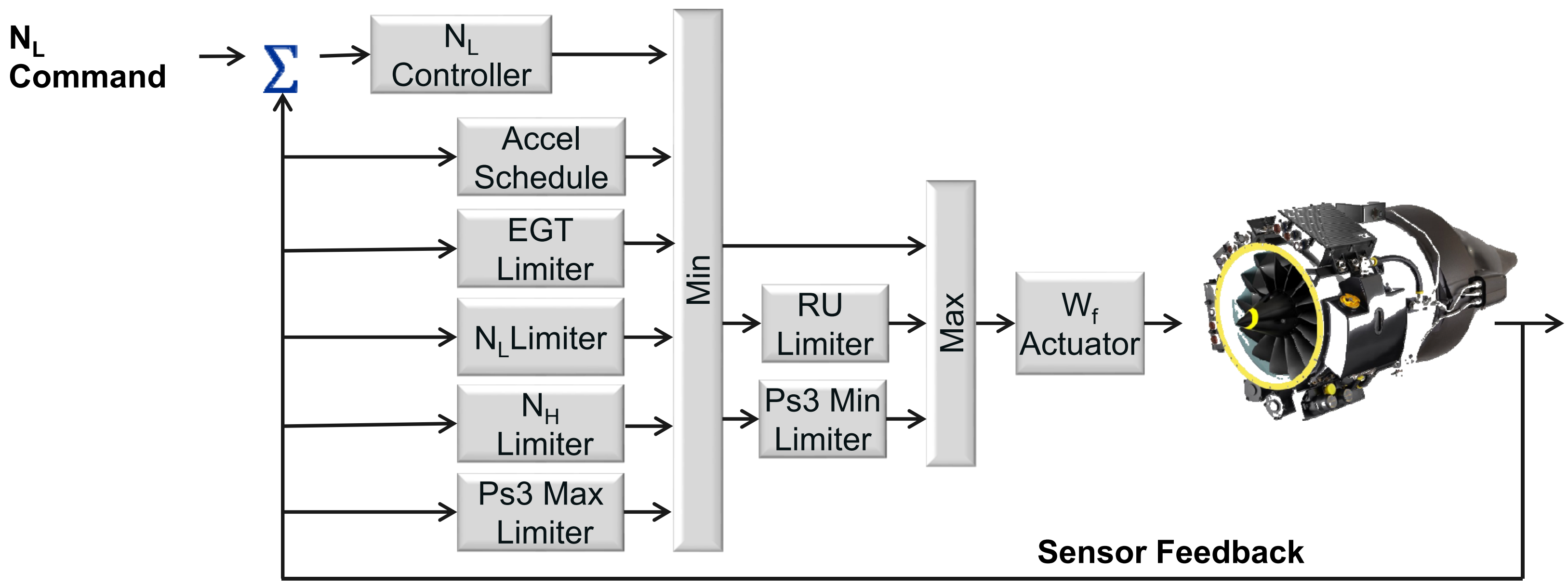
Baseline Control Architecture



- Thrust cannot be measured and hence is indirectly controlled through regulating a measured variable which correlates with thrust e.g. Low Speed Spool (N_L).
- For DART facility safety the key limiter to enable operation has been the N_L max limiter

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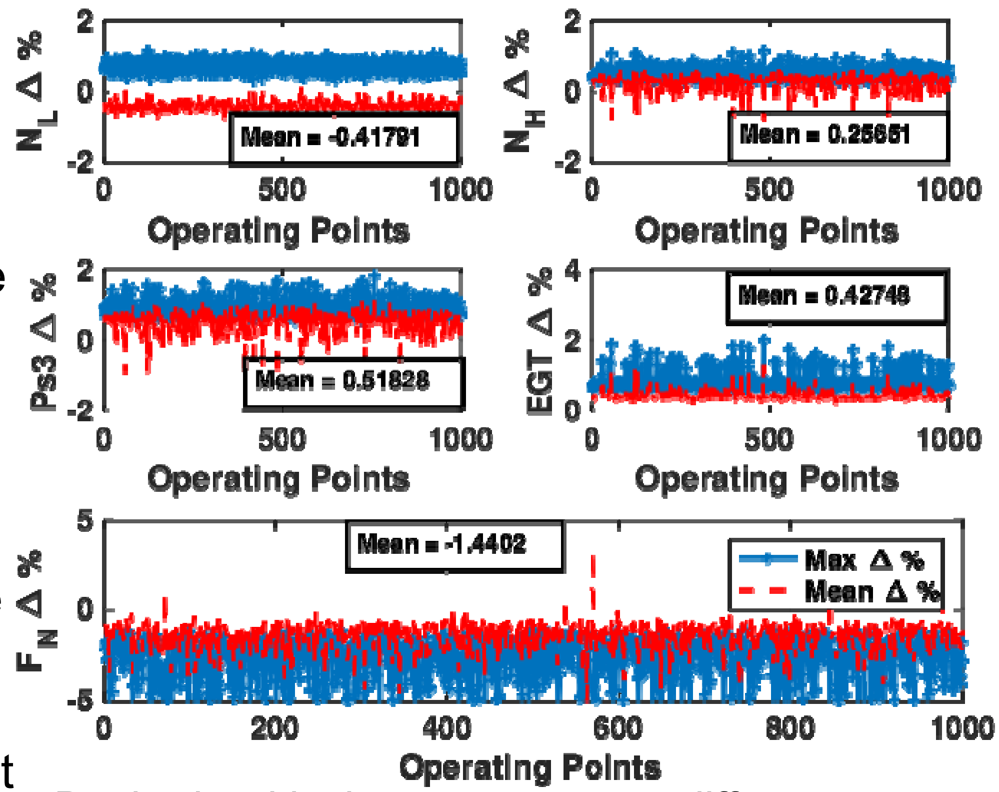
Model Comparison: Transient Piecewise Linear Model

- 1,000 random operating conditions are simulated for both the nonlinear and PWLM models spanning the full operating envelope
  - Simulated with a 20% fuel flow step change

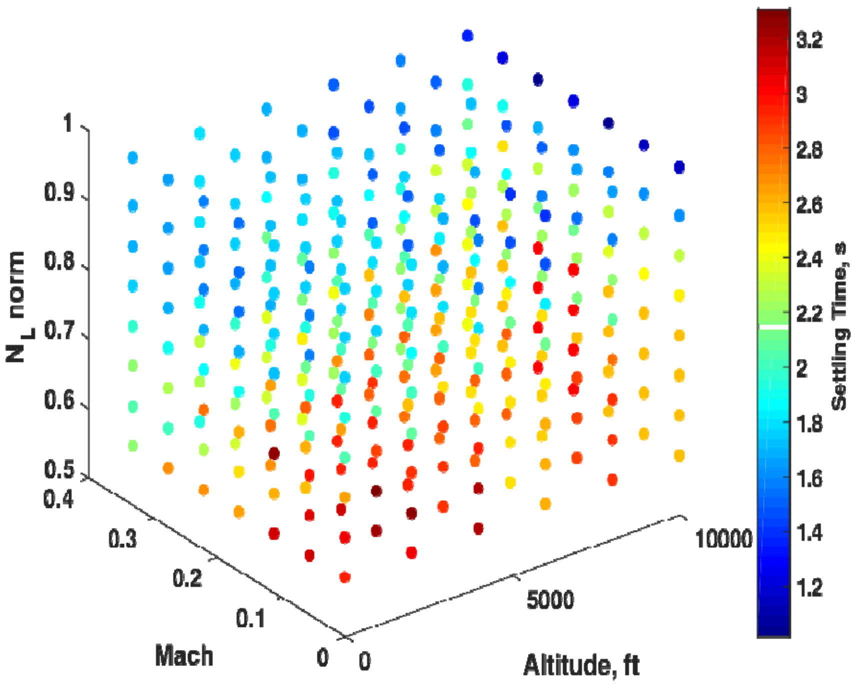


Dashed red is the mean percent difference and blue is the maximum percent difference

- For most of the parameters of interest, the maximum percent difference shown is less than 2%, where the largest errors are in the net thrust with a max error of 5%.

Controller Development: PWLM Controller Settling Time

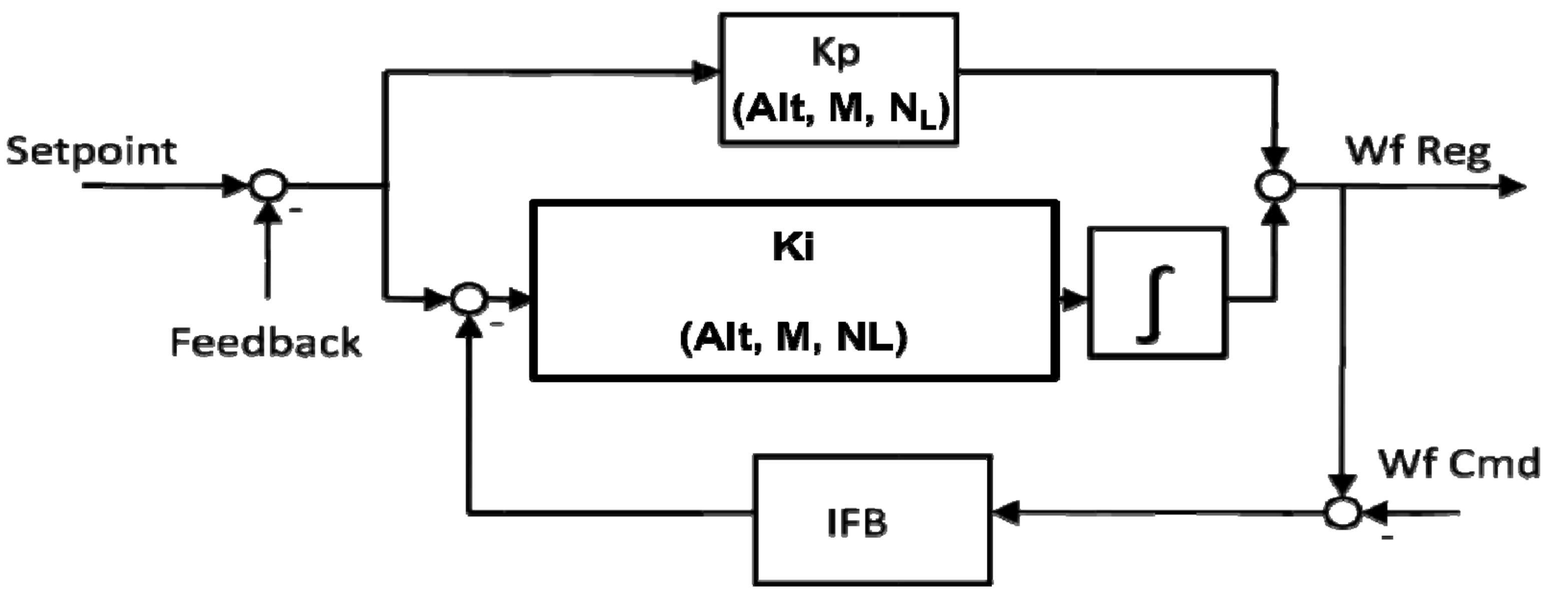
- The closed loop controller uses a PI gain approach, where the goal of the controller design is to obtain gains that provide the desired gain margin of 6 dB and phase margin of 60 degrees for the closed loop system across flight envelope
- Illustrates that conditions closer to flight idle, the settling time is longer 3.2 s max.
  - The lower starting speed of the engine shafts it will take longer to overcome inertia to speed up the turbofan engine.



3D color coded plot to illustrate changes in the settling time across the flight envelope, where red indicates less margin and blue indicates more margin.

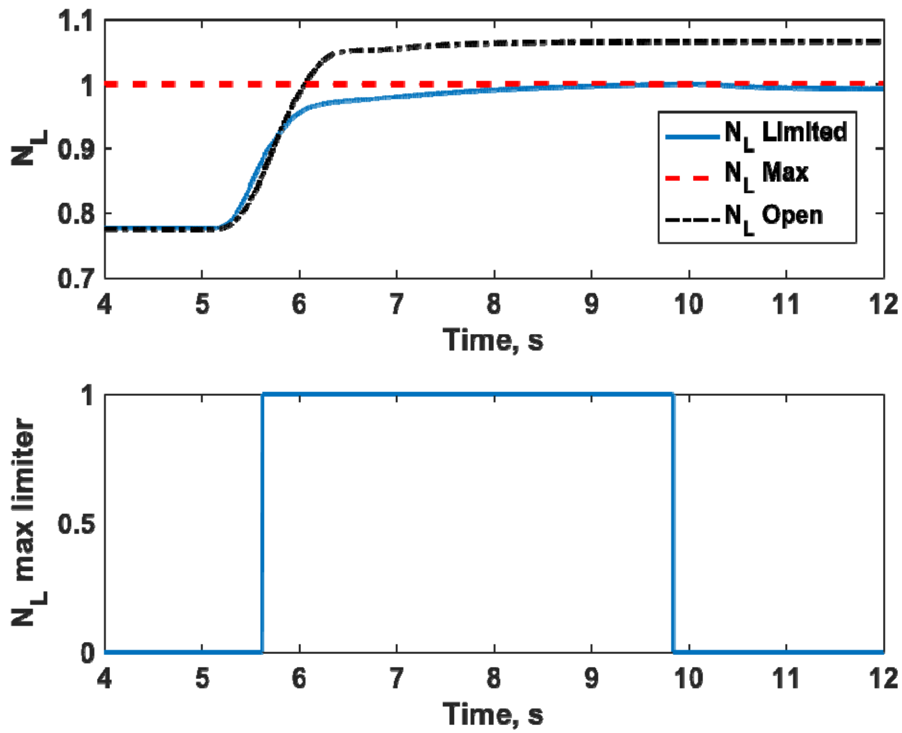
Fuel Flow Controller Design

- The main fuel flow controller design is a proportional-integral (PI) controller scheme that is gain scheduled based on operating conditions
  - Gain scheduled based on altitude, Mach number, and power
  - Contains integral anti-wind-up protection scheme



Results: N_L Max Speed Limiter

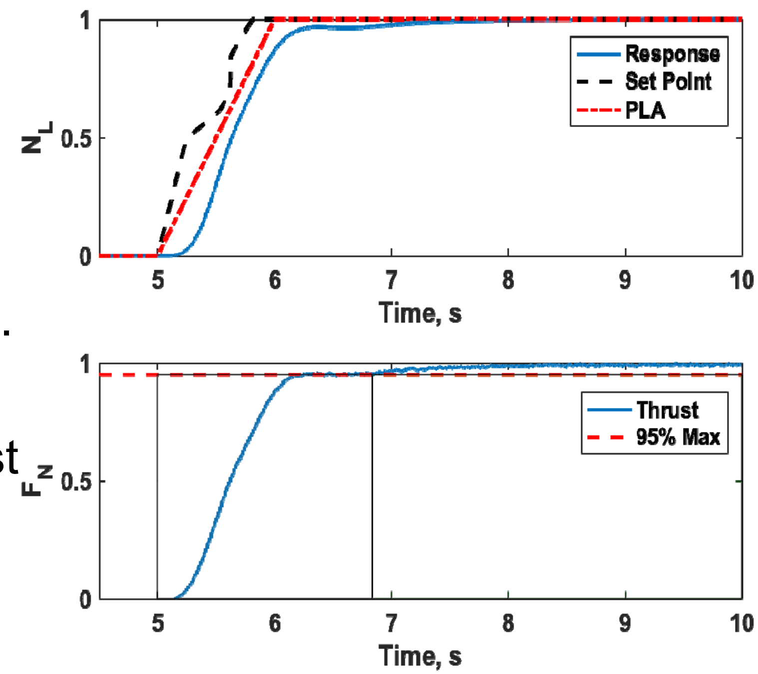
- Controller gains obtained from the design process on the PWLM are now applied to the nonlinear T-MATS model
- To illustrate the performance of the limit logic, the engagement of the max N_L limiter is shown due to a large fuel flow transient at five seconds.
- The control limiter was able to protect the engine by preventing the N_L response from exceeding the over speed value the N_L set point is commanding the engine to follow.



N_L response with the limiter (solid blue line), without the limiter (dashed teal line), and dashed red line indicates the limiter threshold

Results: FAA Transient Engine Requirement

- The FAA has a requirement that within 5 s, the engine should be able to go from idle to 95% power
  - Top plot shows the resulting N_L commanded set point and N_L response from the nonlinear model.
  - Bottom plot shows overall net thrust
  - The start of the transient is at 5s to meeting the FAA requirement



The closed loop response of the engine was able to meet the requirement within two seconds from the initial start of the transient. The initial controller design for the DGEN 380 meets the desired five second transient response applied to the nonlinear model.

Notional Controls DART Plans

- Phase I - Verifying Estimation Model with Acoustic Data Capture
  - Identify thrust measurement and data acquisition needs
  - Identify temperature casing sensors and data acquisition needs
  - Use data from DGEN 380 check out to verify T-MATS model
  - Install additional thrust and casing temperature sensors
  - Obtain thrust measurements during initial acoustic tests during transients
- Phase II – Verifying Estimation Model with Control Focus Data Capture
  - Determine dynamic sensor requirements
  - Develop dynamic pressure sensor
  - Develop compressor stall test plan and safety requirements
  - Obtain compressor stall measurements using dynamic pressure sensor
- Phase III – Model Based Engine Controls Test
  - Test MBEC on real-time hardware system
  - Develop safety plan for switching main controller to MBEC
  - MBEC Controls Test

Conclusions

- A nonlinear dynamic model and propulsion controller is developed for a small-scale turbofan engine, the Price Induction company's DGEN 380.
-
- During engine transients, the nonlinear model typically agrees within 10% error, even though the nonlinear model was developed with limited available engine data.
- The controller provides desired gain and phase margins and is tested to meet Federal Aviation Administration transient propulsion system requirements.
- The DGEN 380 provides a cost effective means to accomplish advanced controls testing on a relevant turbofan engine platform. The propulsion controller developed here provides a baseline from which future advanced controller development can be compared.
  - Plans are on going for engine modifications to test model based control and other advanced control architectures

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NASA/CP—2018-219891

184

Acknowledgments

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Advancements in Verification Methods

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6th NASA GRC Propulsion Control and Diagnostics Workshop
August 22-24, 2017

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Outline

- Motivation
- Recent Efforts
  - Run-Time Assurance
  - Design-Time Verification Tool Application
- Concluding Remarks

Motivation: Advanced Propulsion Algorithms

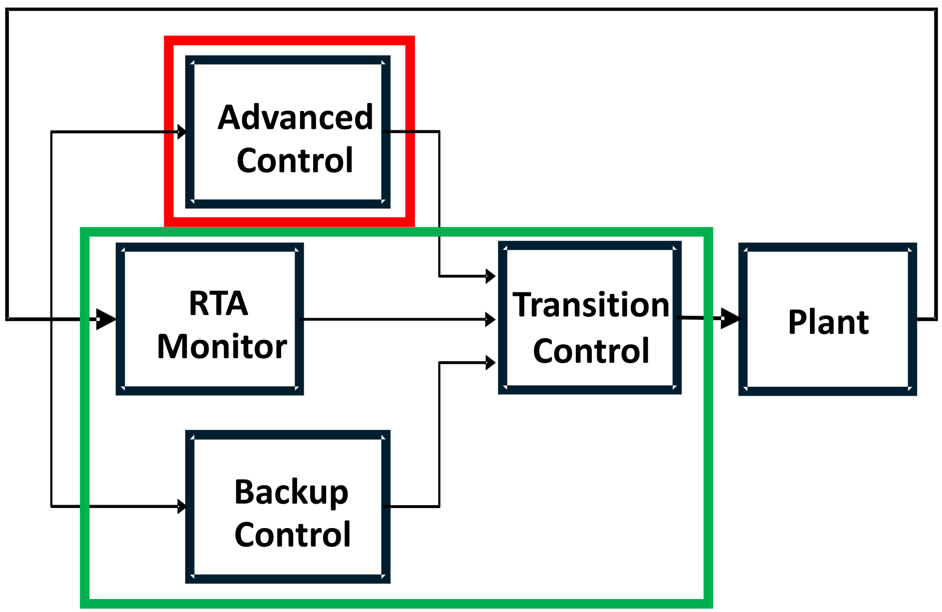
- Desire for increased capability has driven the development of advanced engine control and health management algorithms. Characteristics include:
  - Intelligent and autonomous
  - Adaptive, onboard learning, self-tuning and reconfigurable
- Potential to enable:
  - Increased performance and safety
  - Autonomous adaptation to accommodate:
    - Damage and wear
    - Hardware faults (sensors & effectors)
    - Uncertain environmental conditions

Motivation: Certification Challenge

- Current verification & validation (V&V) approaches cannot adequately certify these advanced systems
  - Increasingly difficult and cost-prohibitive using current practices due to complexity
  - Design-time V&V for some algorithms may not be feasible
    - Non-determinism or complexity preclude typical exhaustive testing
    - As a result, complete coverage cannot be achieved
- Efforts to address the problem
  - Advancements in design-time analysis (formal methods).
  - Advancements in run-time assurance
    - continually monitor execution of uncertified algorithms to insure overall system behavior remains constrained within safe bounds.
    - If unsafe conditions are impending, switch to trusted backup algorithm.
  - Advancements in design-time verification tools
    - Facilitate verification of safety and performance criteria for new controller designs

Run-Time Assurance

Run-Time Assurance Framework

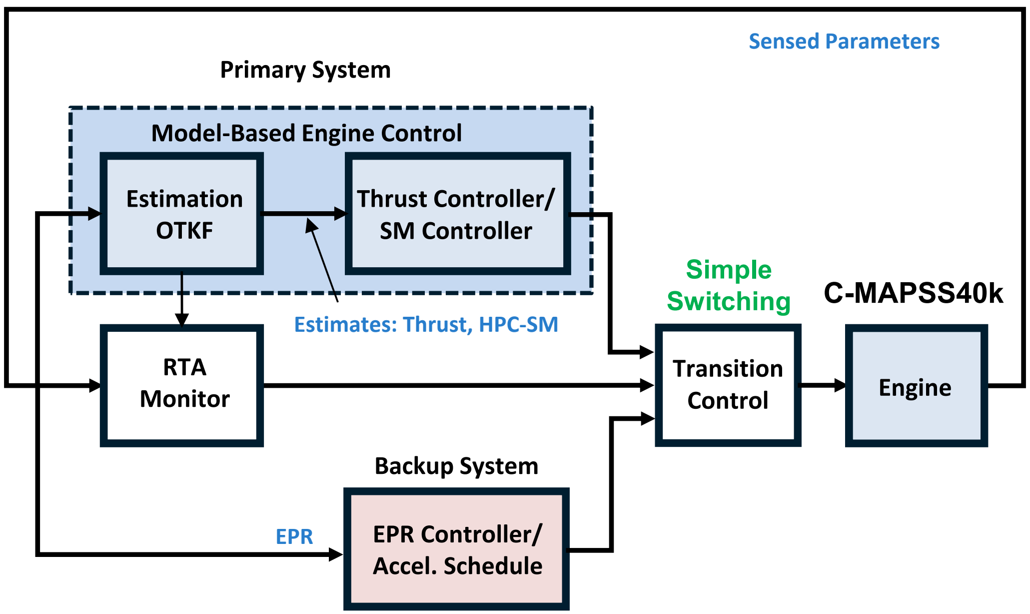


- Difficult or costly to fully certify at design time
- Certified at design-time using traditional methods

- Advanced Controller
  - Advanced controller responsible for achieving performance objectives
  - Intelligent, reconfigurable, adaptive, non-deterministic, etc.
- Backup Controller (Fail-Safe)
  - Simplified control system with emphasis on safety rather than performance
- RTA Monitor & Transition Control
  - Continually monitors overall state of the system
  - Compare against validated representation of safe operating envelope
  - If violation occurs, disables Advanced Controller and switch to Backup Control

Case Study: Model-Based Engine Control

- Investigated application of RTA framework to GRC's Model-Based Engine Control
- RTA employs simple switching between:
  – Advanced thrust controller and Backup EPR controller
  – Switching the type of stall margin limiter

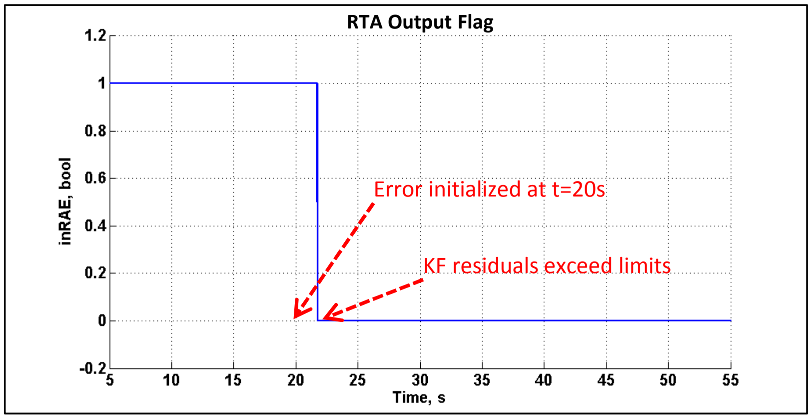


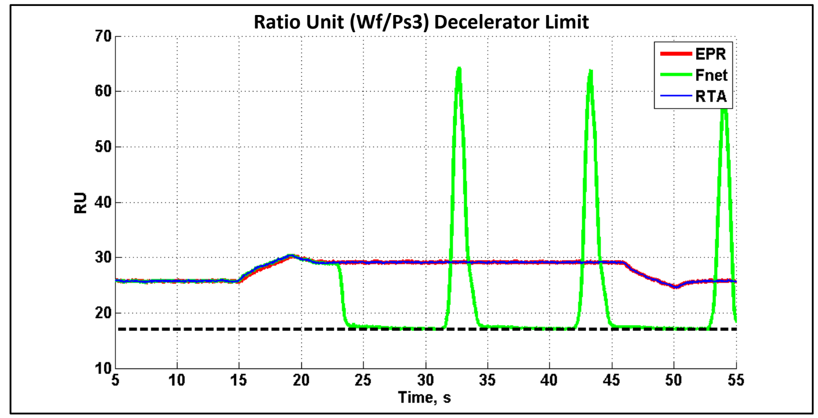
- Define Safety Boundaries
  - Monitored well-understood engine safety & operational limits
  - Monitored analytical parameters: Kalman filter residuals to assess performance

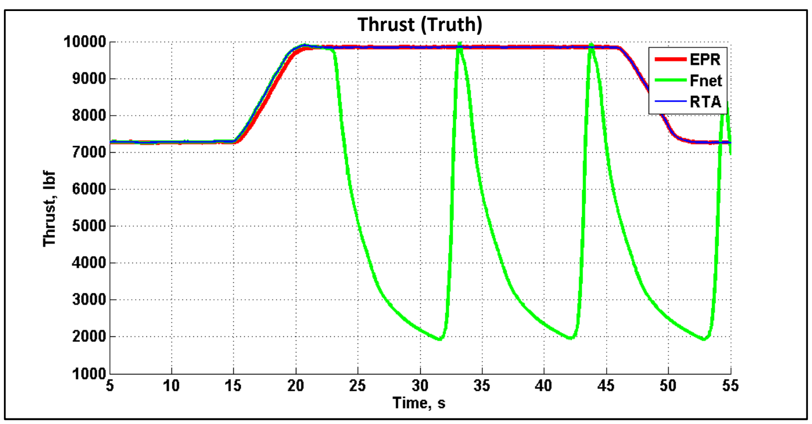
Limited Parameter	Value
Safety and Operational Limits	
Fan Speed (Nf)	max = 4200 rpm
Core Speed (Nc)	max=12200 rpm
HPC discharge pressure (Ps3)	max = 433 psi
HPC stall margin (smHPC)	min = 8%
LPC stall margin (smLPC)	min = 6%
RU limit	min = 17%
Kalman Filter Residual Limits (% error)	
Fan speed (Nf)	max = 3%
Core speed (Nc)	max = 3%
HPC discharge temperature (T30)	max = 3%
LPT discharge temperature (T50)	max = 3%
HPC discharge pressure (Ps3)	max = 3%
LPT exit pressure (P50)	max = 3%

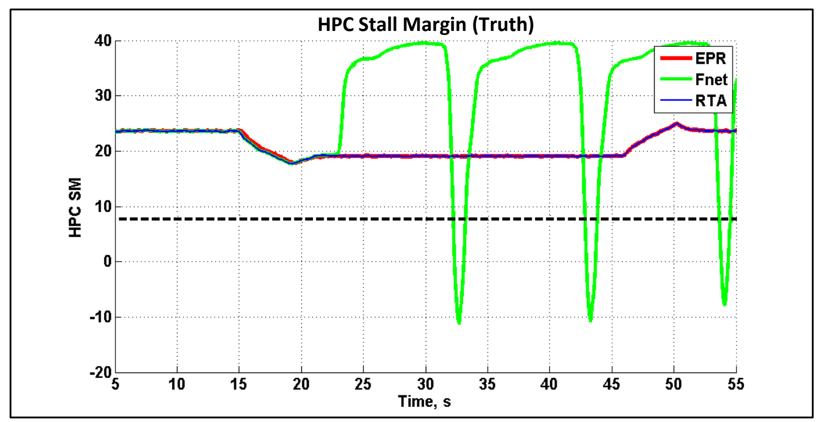
Induced Fault Experiment

- Seeded error: *Δy* coding error introduced @ t = 20 sec during <u>cruise</u>
  - RTA switches to EPR controller @ t = 22 sec 🡐 KF residuals exceed their limits









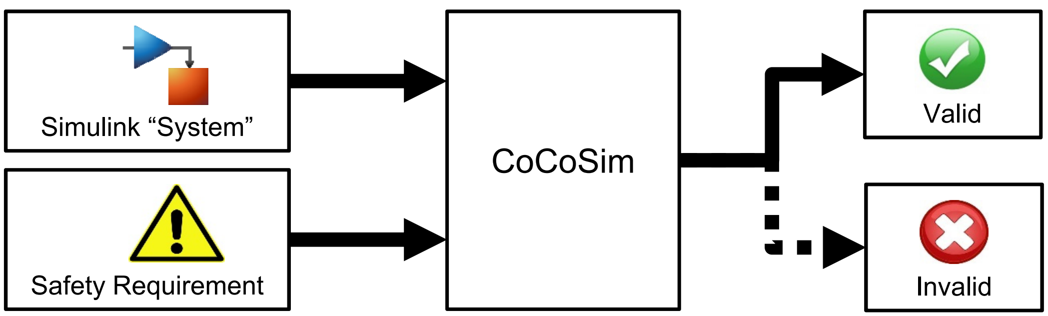
Ongoing Work

- RTA Diagnostics:
  - Investigating diagnostics/logic for RTA monitor to differentiate system anomalies from errors due to the advanced control
- Control Mode Switching Procedures
  - Developing more robust transition logic to replace the simple switching. Ensure stable transition from the advanced controller to the backup controller.

Design-Time Verification Tool

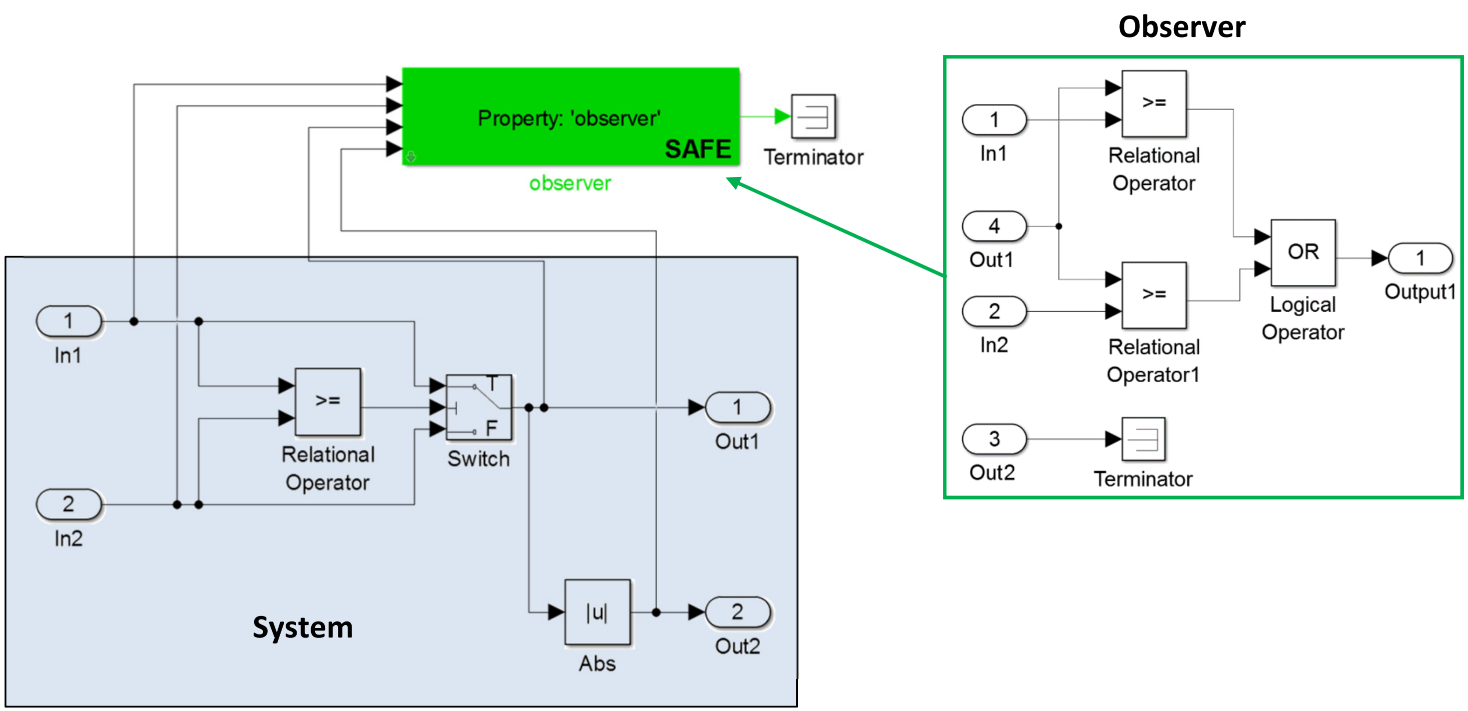
CoCoSim

- CoCoSim is a publically-available verification tool for Simulink models
  - Allows checking Simulink modeled “systems” against defined safety requirements.
  - Compiles a Simulink model and process it with underlying model checker (backend solver, e.g. JKind) [ref]
- An Observer is constructed for a Simulink model to be verified
  - Safety properties are defined as “assertions” – statements that are always true.
  - All system inputs and outputs are routed to the Observer
  - CoCoSim varies system inputs and checks validity of assertions against the output
    - A valid result implies that the assertions within the Observer are satisfied for all system operating points.
    - An invalid result implies that input values were found that falsify the assertions.



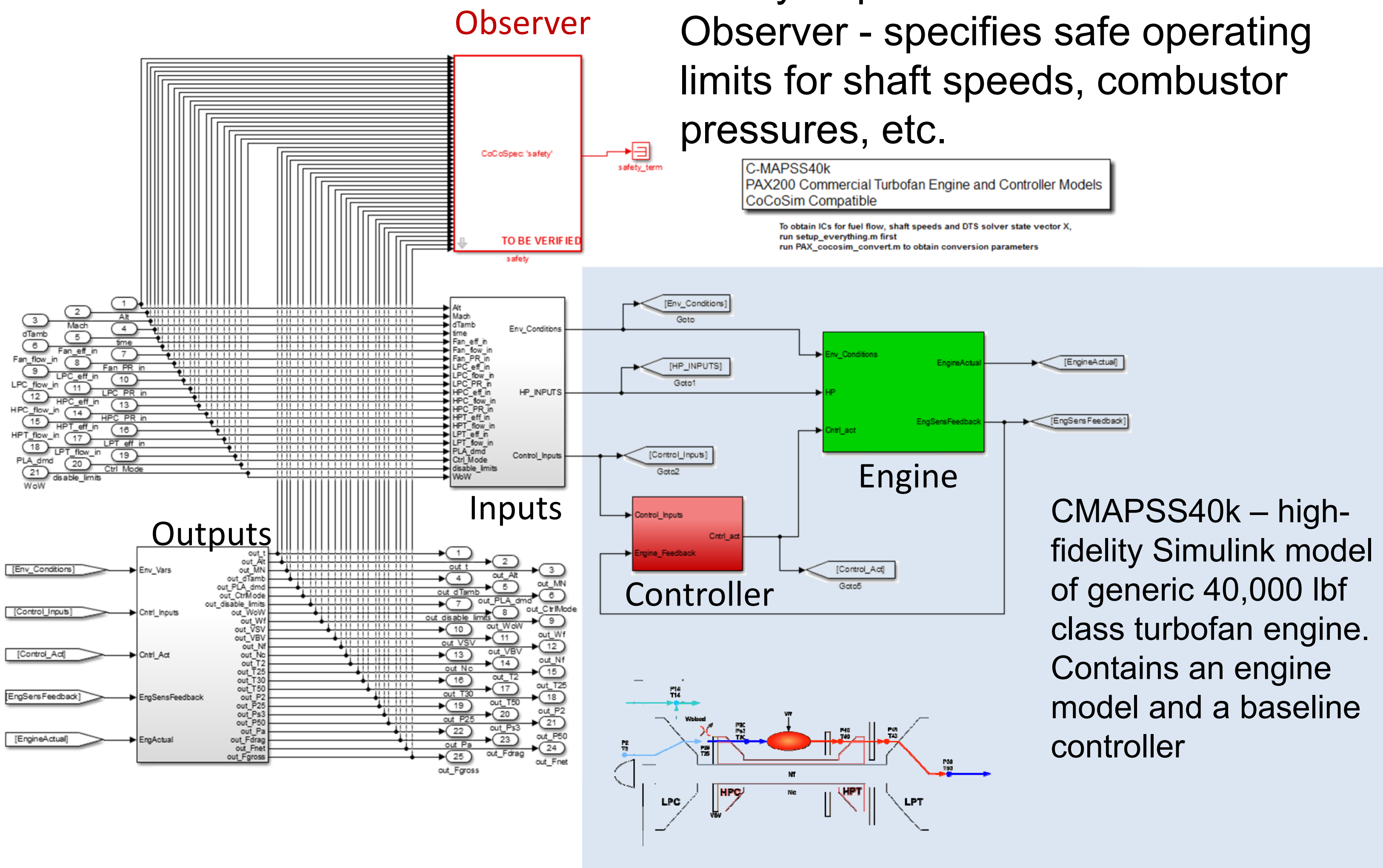
CoCoSim Example

- Simple system that outputs (Out1) the larger of the two inputs (In1, In2)
- Observer defined with assertion that: Out1 ≥ In1 OR Out1 ≥ In2
- Observer block displays GREEN color indicating a valid (safe) solution since property is true for all system inputs. RED if invalid.



Case Application: CMAPSS40K

- Safety requirements formulated in Observer - specifies safe operating limits for shaft speeds, combustor pressures, etc.



CMAPSS40k – high-fidelity Simulink model of generic 40,000 lbf class turbofan engine. Contains an engine model and a baseline controller

Safety Requirements

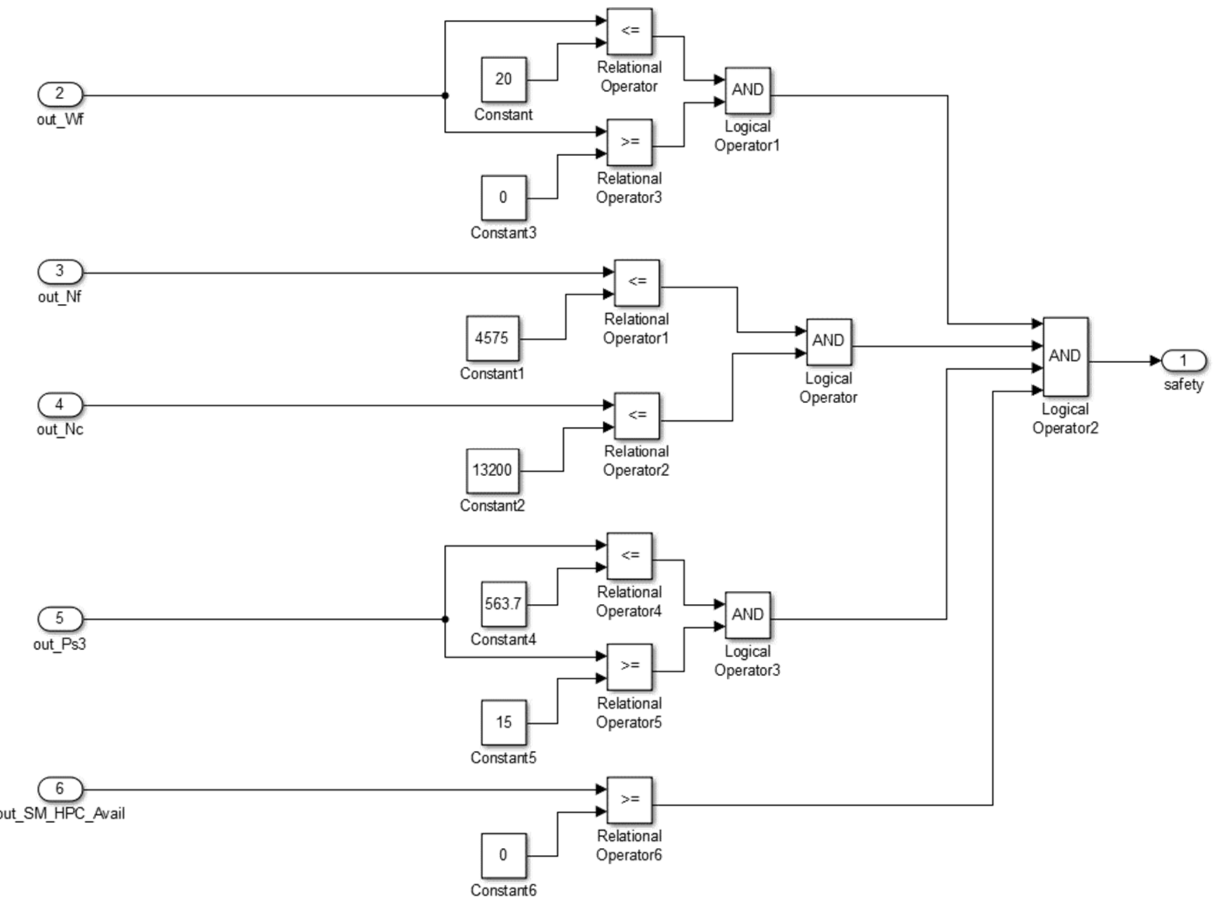
Fuel flow must be within safe limits

Fan speed must not exceed maximum

Core speed must not exceed maximum

Compressor pressure must be within safe limits

Stall Margin must be greater than zero



Safety Requirements – Example Result

- The CoCoSim (using the JKind backend solver) output is shown
- The fuel flow upper limit was reduced to see if CoCoSim can find the invalid case
  - Constant5 = 10
- At the 4th step, the fuel flow (out_Wf) of 14.947 exceeded the upper limit and triggered the invalid output

```
==========================================
  JKind 3.0.1
==========================================

There are 1 properties to be checked.
PROPERTIES TO BE CHECKED: [Safety]

+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
INVALID PROPERTY: Safety || bmc || K = 4 || Time = 18m 17.604s

                            Step
variable                      0           1              2               3

OUTPUTS
Safety                     true        true           true           false

LOCALS
Constant5                    10          10             10              10

LogicalOperator            true        true           true           false

RelationalOperator5        true        true           true           false
Fuel_Flow                 2.319       2.319          0.364          14.947

+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

    -------------------------------------
    --^^--        SUMMARY           --^^--
    -------------------------------------

INVALID PROPERTIES: [Safety]
```

Future Work

- Continue working with CoCoSim developers to:
  - Include support for remaining unsupported Simulink blocks and support for S-functions.
  - Add support to enable verification of properties that require time simulation, e.g. FAR 33.73(b) which stipulates a thrust transient requirement.

Concluding Remarks

- Provided motivation for pursuit of advanced verification approaches to address certification barrier for advanced propulsion algorithms
- Discussed effort to develop and apply run-time assurance framework to model-based engine control
- Discussed effort applying a design-time verification tool to model of turbofan engine and control

References

- Wong, E., Schierman, J., Schlaphohl, T., and Chicatelli, A., “Towards Run-time Assurance of Advanced Propulsion Algorithms,” 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference,” No. AIAA 2014-3636, 2014.
- Schierman, J., Neal, D., Wong, E., Chicatelli, A., “Runtime Assurance Protection for Advanced Turbofan Engine Control,” AIAA 2018 SciTech Forum (Submitted)
- Uth, P., Narang-Siddarth, A., Wong, E., “Investigation of a Verification and Validation Tool with a Turbofan Aircraft Engine Application,” AIAA 2018 SciTech Forum (Submitted)
- CoCoSim, [online] https://github.com/coco-team/cocoSim.
- JKind, [online] http://loonwerks.com/tools/jkind.html
- Connolly, J., Csank, J., Chicatelli, A., Kilver, J., “Model-Based Control of a Nonlinear Aircraft Engine Simulation using an Optimal Tuner Kalman Filter Approach,” 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference,” No. AIAA 2013-4002, 2013.
- Connolly, J., Chicatelli, A., and Garg, S., “Model-Based Control of an Aircraft Engine using an Optimal Tuner Approach,” 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, No. AIAA 2012-4257, 2012.
- Simon, D. L., “An Integrated Architecture for On-Board Aircraft Engine Performance Trend Monitoring and Gas Path Fault Diagnostics. NASA TM 216358, 2010.
- Csank, J., Ryan, M., Litt, J. S., and Guo, T., "Control Design for a Generic Commercial Aircraft Engine," Technical Report NASA/TM 2010-216811, 2010.
- May, R., Csank, J., Litt, J. S., and Guo, T., "Commercial Modular Aero-Propulsion System Simulation 40K," Technical Report NASA/TM 2010-216810, NASA, 2009.

Session 3

Active Component Control and Engine Icing Session

NASA/CP—2018-219891

National Aeronautics and Space Administration

Active Component Control & Engine Icing Session

Donald L. Simon
Kathleen M. Tacina
George Kopasakis
Jonathan L. Kratz
NASA Glenn Research Center

6th NASA Glenn Propulsion Control and Diagnostics Workshop
August 22-24, 2017
Cleveland, OH

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6th NASA Glenn Propulsion Control and Diagnostics Workshop

Active Component Control & Engine Icing

Time	Presentation Title		Presenter
3:20	Low-Emissions Engine Combustor: Challenges, Solutions and Opportunities		Kathy Tacina (NASA)
3:50	Fuel Modulators Testing and Instability Suppression		George Kopasakis (NASA)
4:20	Active Turbine Tip Clearance Control Research		Jonathan Kratz (NASA)
4:50	A Dynamic Model for the Evaluation of Aircraft Engine Icing Detection and Control-Based Mitigation Strategies		Don Simon (NASA)

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Active Component Control & Engine Icing

(Additional Related Activities Included in PCD Workshop Reception Poster Session)

High Bandwidth Liquid Fuel Modulators for Active Combustion Control
Joe Saus - NASA

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Low-Emissions Engine Combustor: Challenges, Solutions, and Opportunities

Kathleen M. Tacina

NASA Glenn Research Center

6th GRC Propulsion Control and Diagnostics Workshop

August 22-24, 2017

Cleveland, OH

1. Where we have been
2. Where do we go

    Bottlenecks

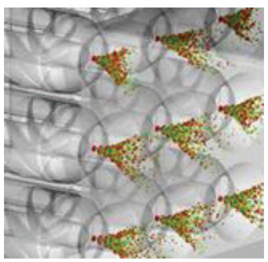
    Solutions

    Opportunities

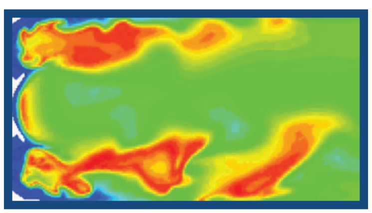
Engine Combustion Branch Interests

Combustion CFD

- Turbulence
- Chemistry
- Spray
- Radiation
- Emissions (CO,NOx, soot)



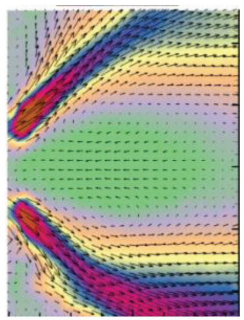
Simulation of first-generation lean burning injector concept



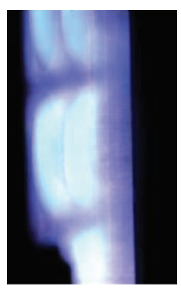
Simulation of third-generation lean burning injector concept

Optical Diagnostics

- Gas and spray
- Velocity, Temperature, Species Concentrations
- Flame Imaging



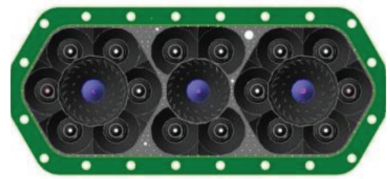
Spray velocity measurements



Flame imaging

Combustor Design and Testing

- Gas & Particulate measurements
- Flametube and sector test rigs
- Combustion Dynamics & Control (Passive and Active Control)
- Low-emission designs
- Alternative Fuels



Multi-element lean-burning injector concept

Emissions Measurement Systems

Intermediate-pressure Flametube

Sector Test Hardware

High-pressure Sector Test Rig

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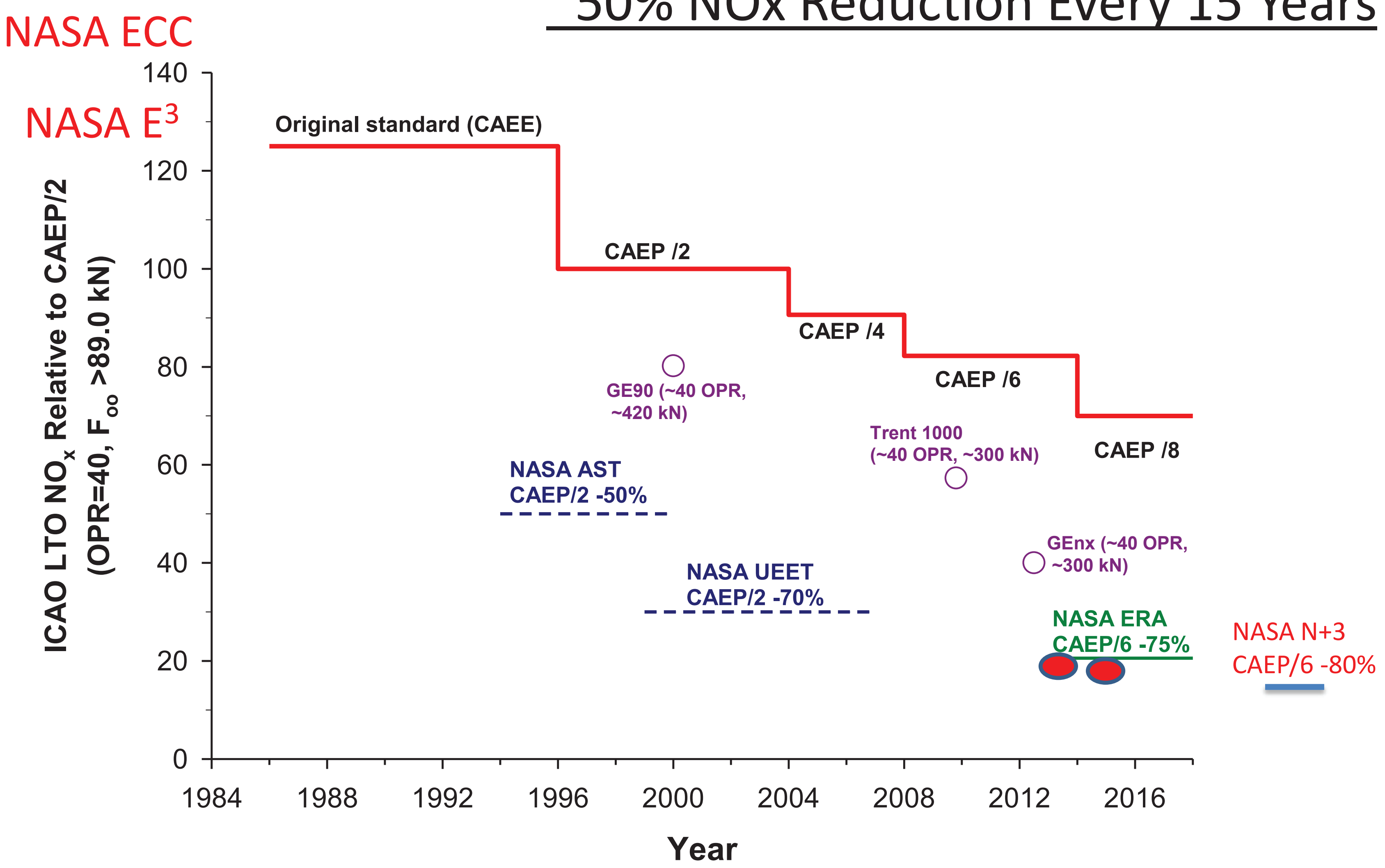
Where Have We Been:
~50% NOx Reduction Every 15 Years



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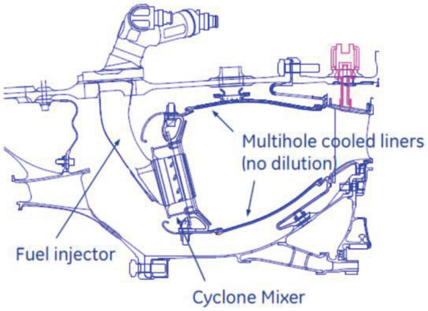
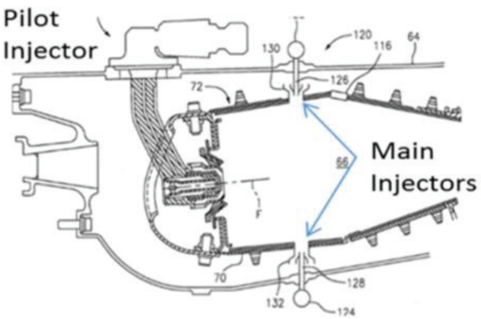
ERA Combustors
-75% CAEP /6 LTO NOx

GE TAPS 5-cup Sector Combustor



P&W ACS Annular Combustor



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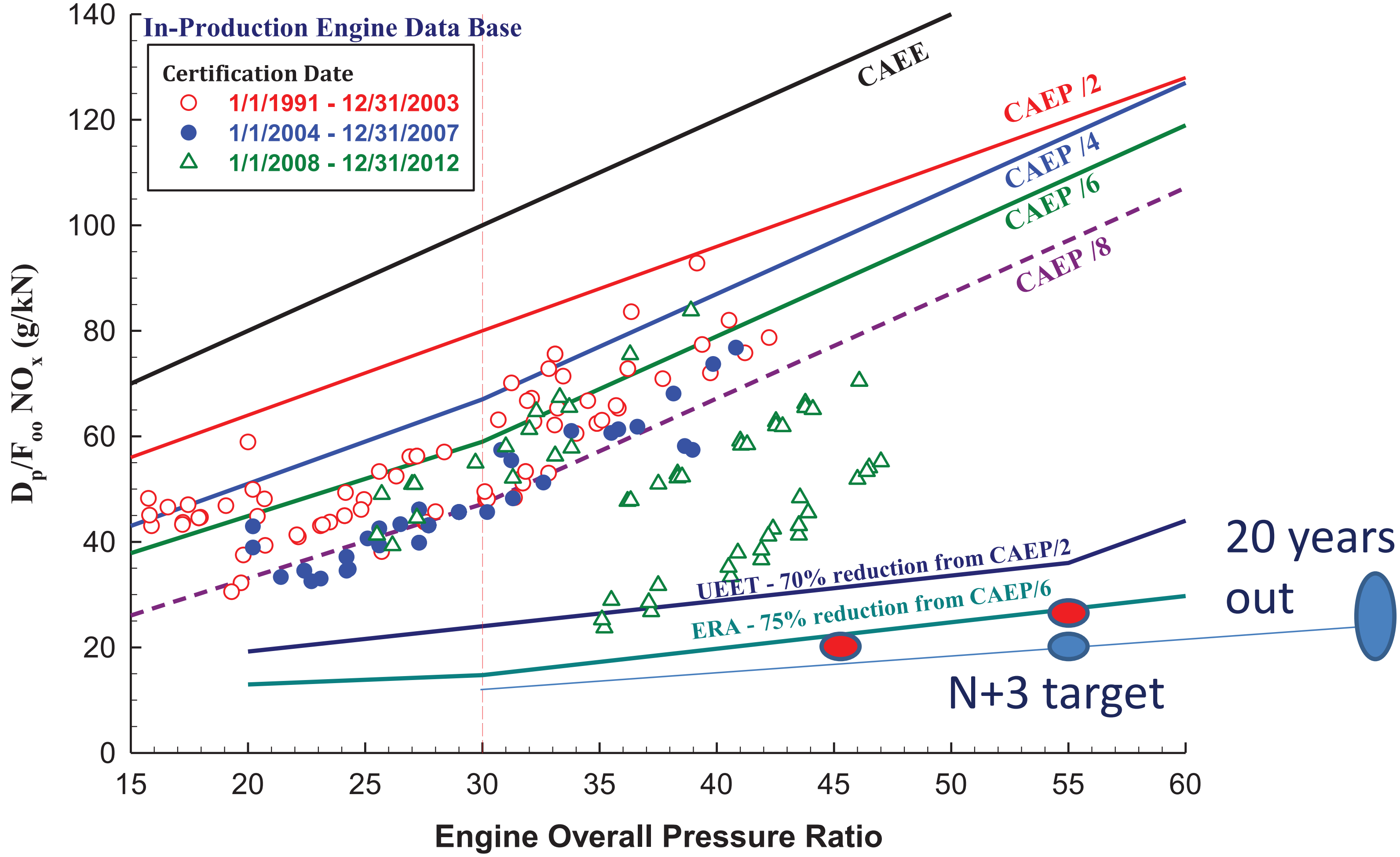
Emissions Targets



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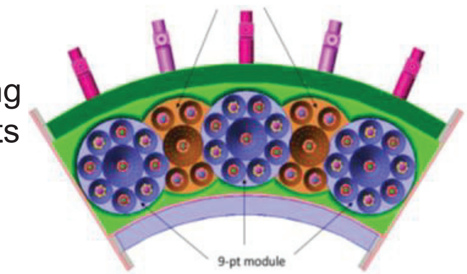
Lean Direct Injection (LDI)

Objective

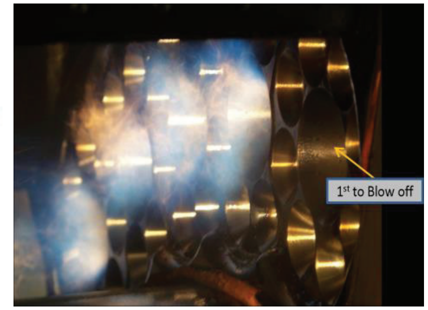
Design, fabricate and test in real engine operating conditions innovative injector concepts that meets N+2 goals.

Accomplishments

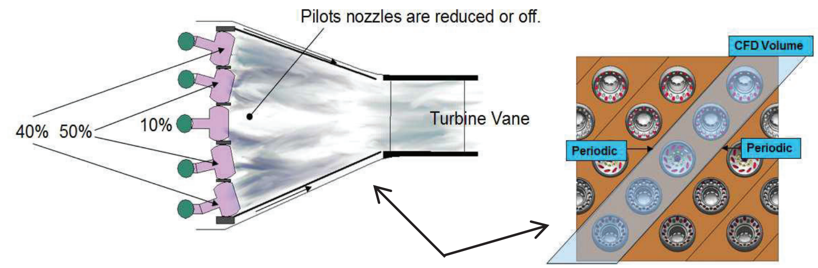
- All concepts designed for high OPR (50-70) engine cycles to meet N+2 emissions goals
- All injectors designed for alternative fuels flexibility (Up to 85% alt fuel blend)
- Goodrich, Woodward, and Parker down-selected most promising LDI concept
- All LDI injectors successfully completed lean blow-off testing
- Testing of the three concepts in NASA's high pressure facility (CE-5) were completed and emissions reduction goals met. Results presented at AIAA 2014 Joint Propulsion Conference.



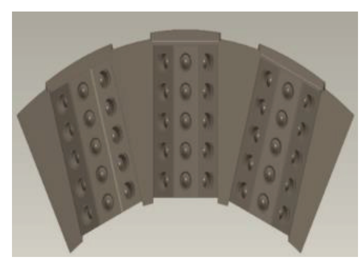
Woodward: 5-cup arc-sector concept



Woodward: Lean-blowout testing



GOODRICH LDI concept



Parker Hannifin: 3-cup arc installation concept

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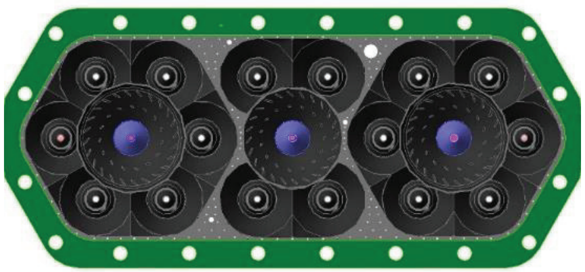
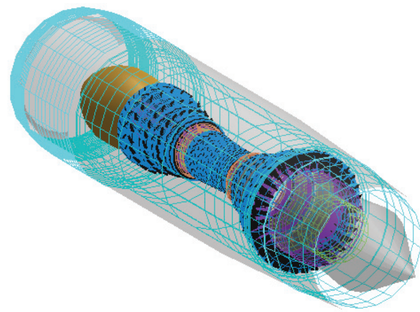
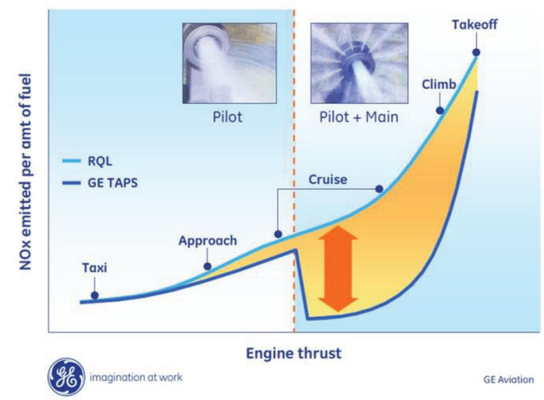
Future Direction



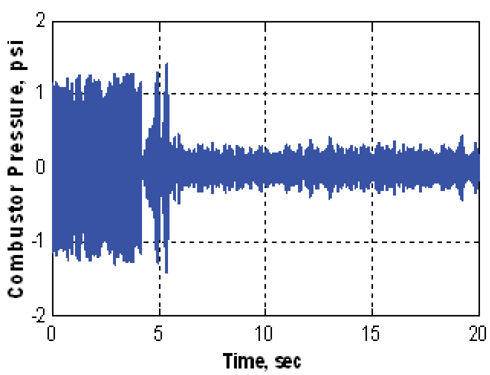
High-pressure Multi-point LDI



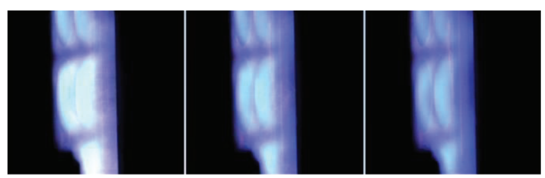
Smaller High Pressure Engine Cores



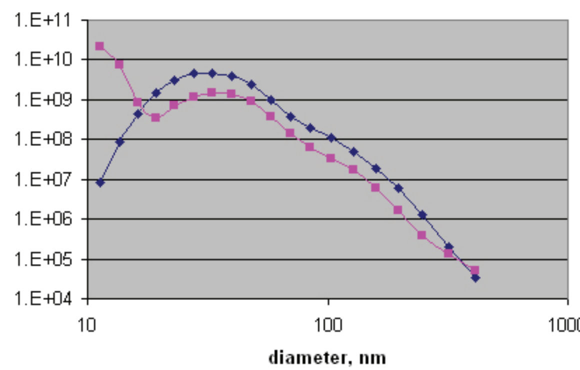
Cruise-Level NOx Reduction



Dynamics and control



Fuel-composition optimization



Particulate Reduction

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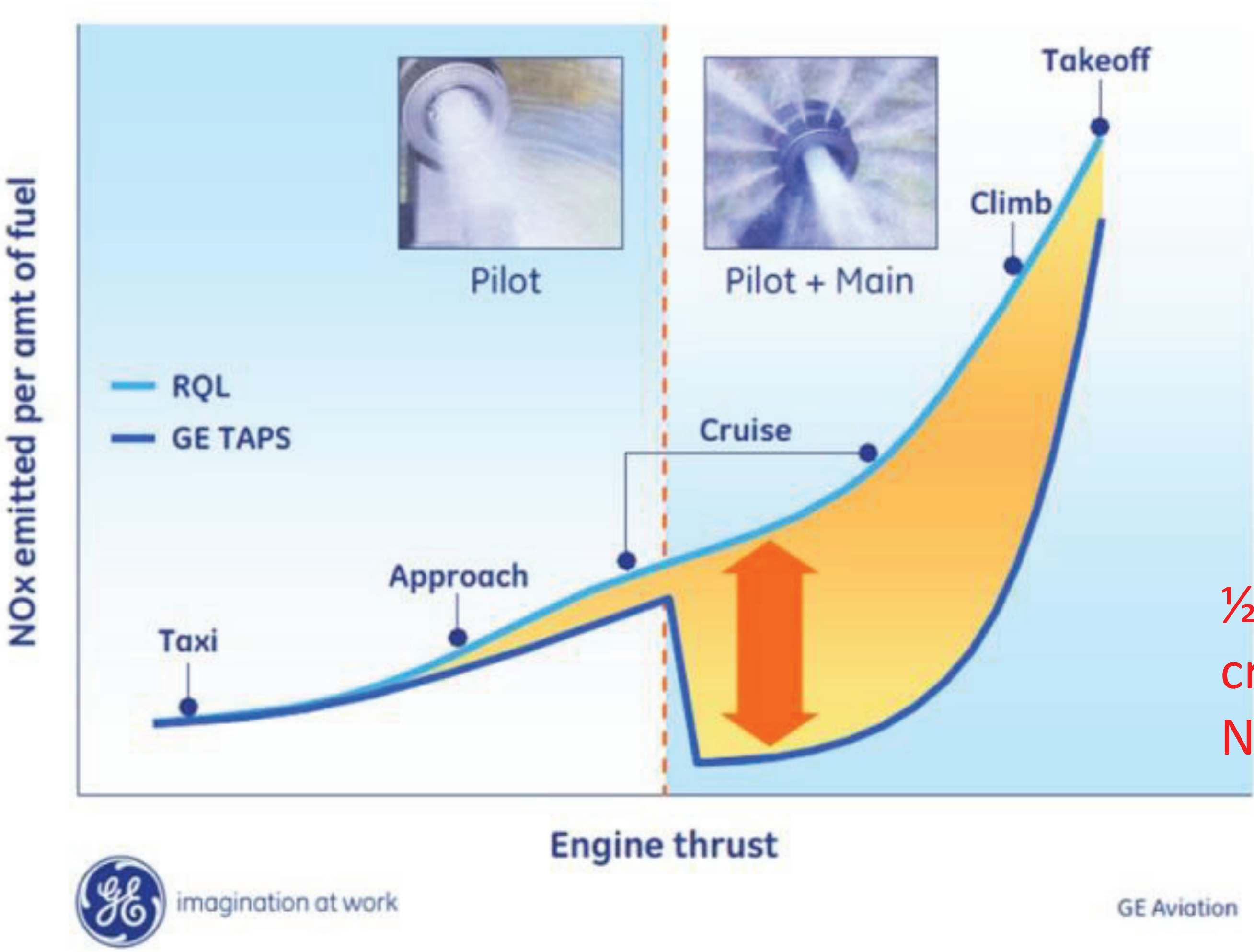
Lean-burn is the future

for

Civil Aeronautics

National Aeronautics and Space Administration

Lean-burn Advantage



½ to 1/3 less cruise-level NOx

Courtesy GE Aviation

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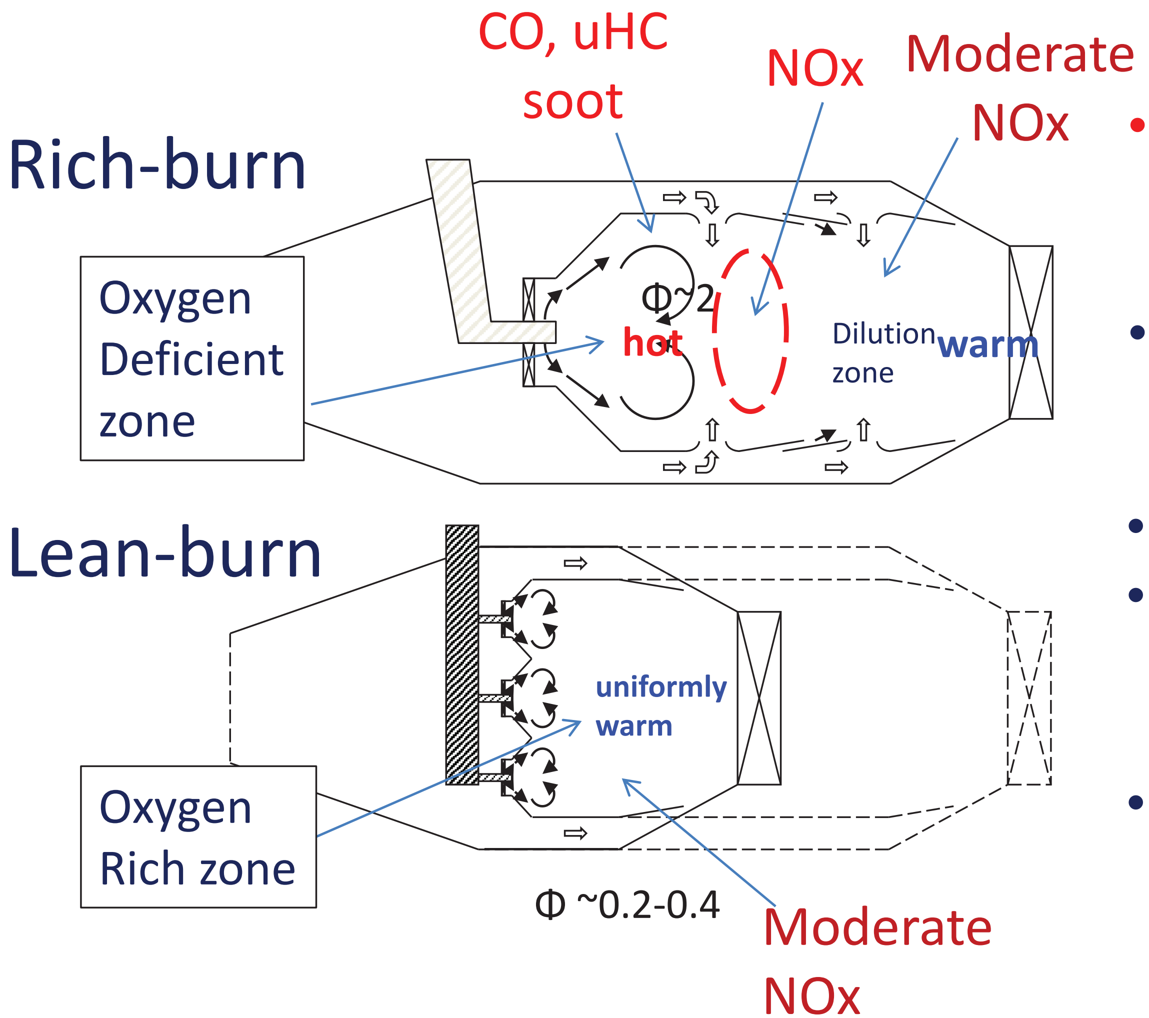
Lean-Burn: Avoid making CO & soot in the first place



- Makes CO, uHC, & nvPM in the front end
- burn them off

- Mix well, burn
- Stage fuel to maintain flammability
- hotter CMC liner

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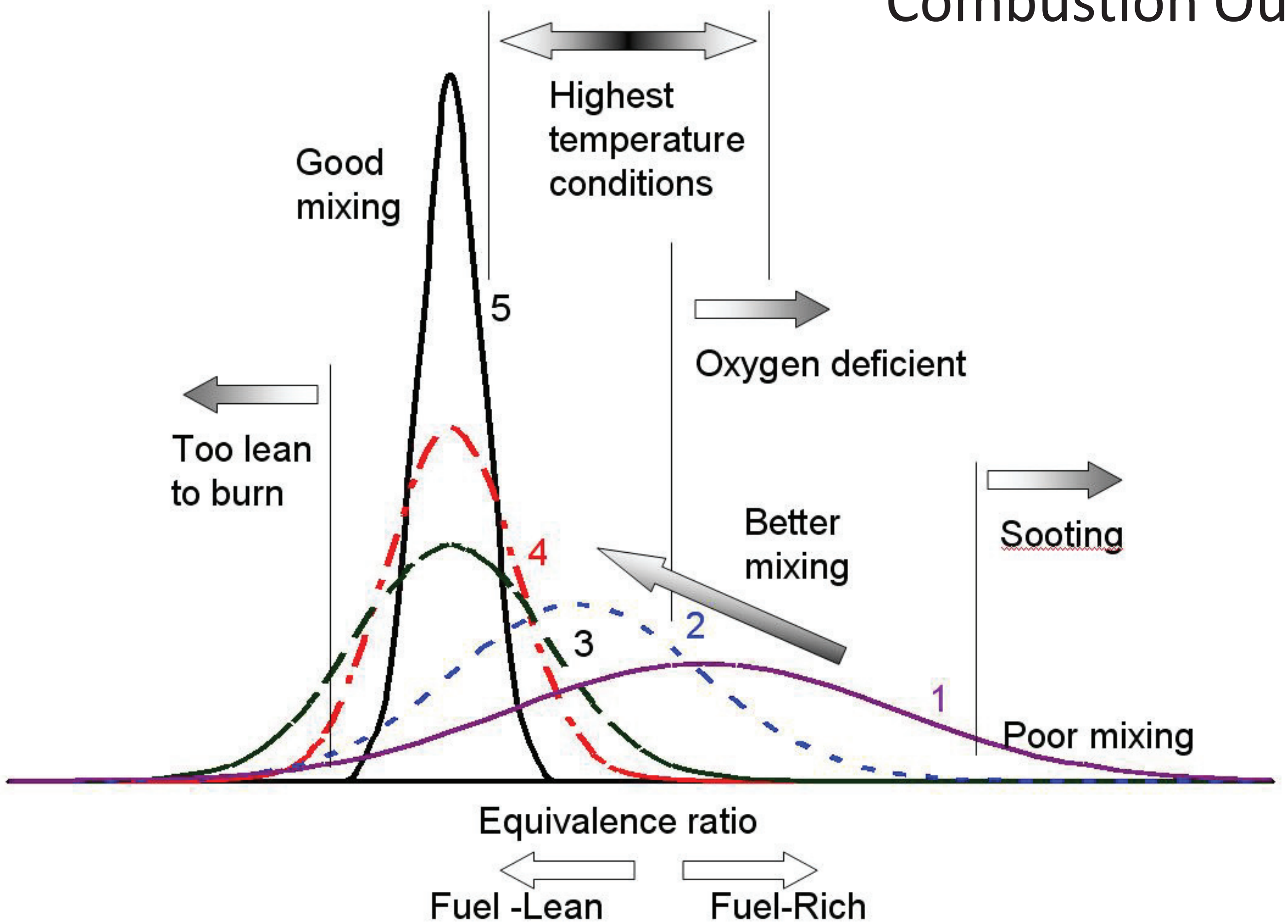
Fuel-Air Mixing Affects Combustion Outcome



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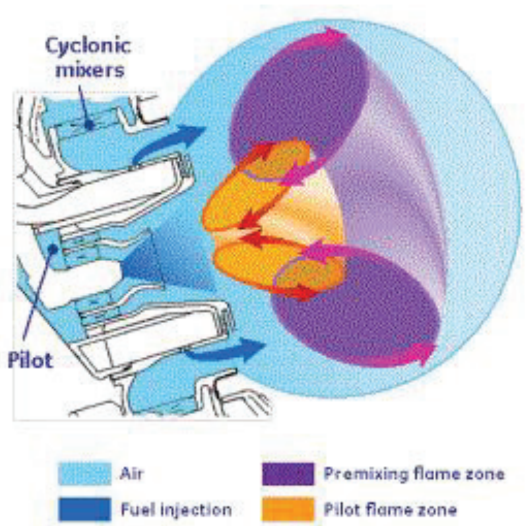
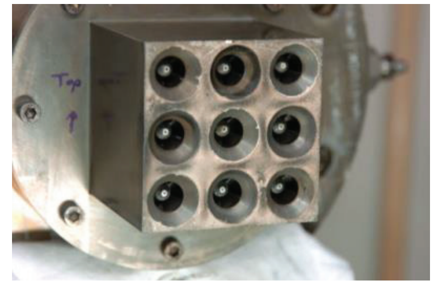
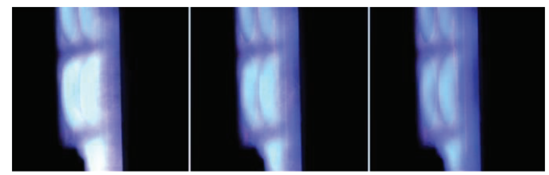
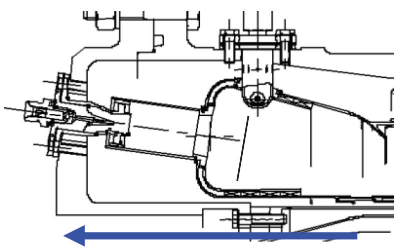
Maximum Combustor Pressure Dictates Viable Lean-burn Combustor Concept









Lean Direct Injection

Lean Partial-Premixed

Lean Premixed Prevaporized

ECC

25 35 45 55 65 75

Max Combustor Pressure

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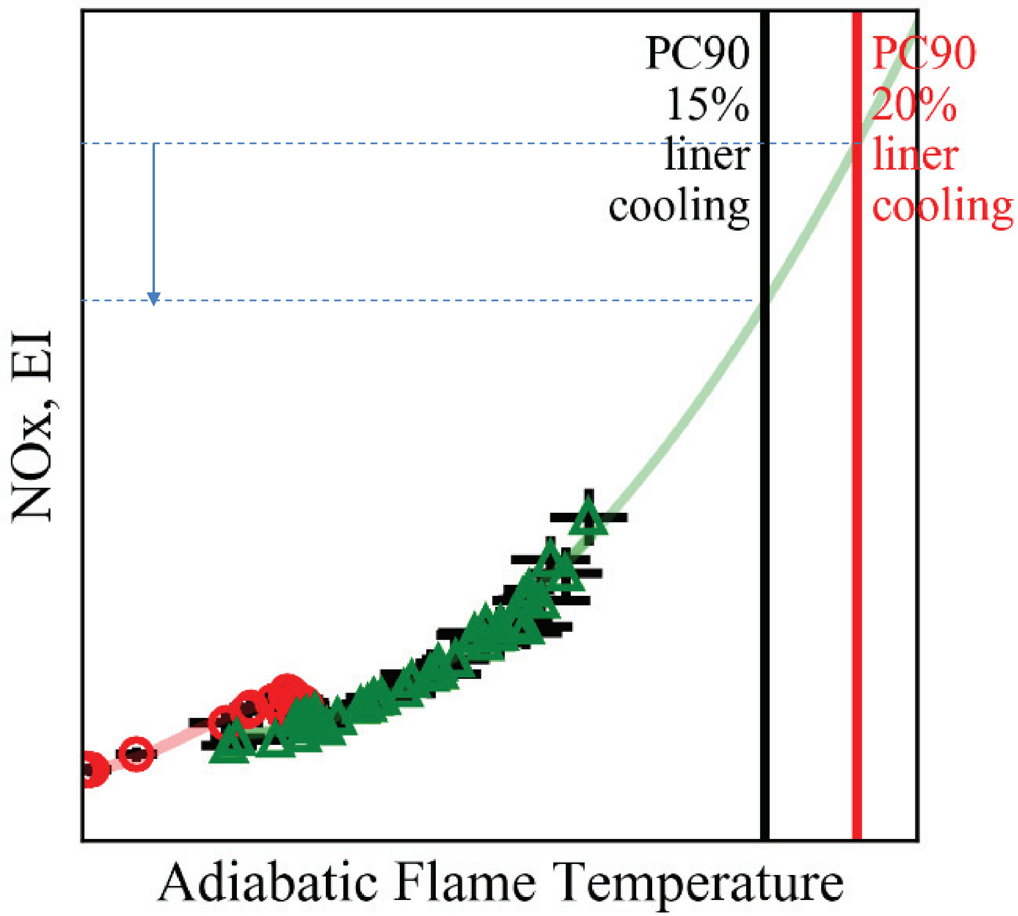
Second-generation CMC liner Enabling Technology for NOx Reduction



Combustor Outlook

	Takeoff P3	LTO NOx relative to CAEP/6	Fuel Injection mode	SOA combustor length	liner cooling budget	liner material
Current Single Aisle	30 bar	-	rich-burn, partial-premixed	20 cm	~1/3	super alloy
N+2 (twin-aisle)	55 bar	-75%	partial-premix, LDI	15 cm	20%	1st-gen CMC
N+3 small core	55 bar	-80%	Partial-premix	15 cm	15%	2nd-gen CMC
20 year out	70 bar	-80%	LDI	10 cm?	15%	2nd-gen CMC

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Mitigating combustor dynamics will be challenging

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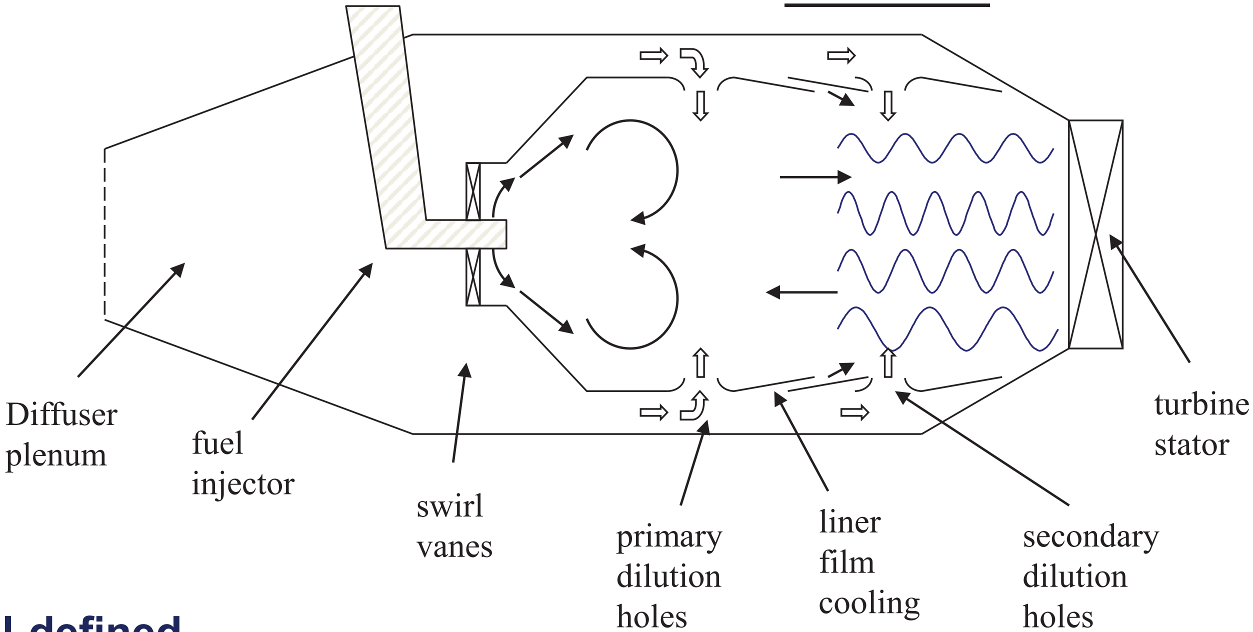
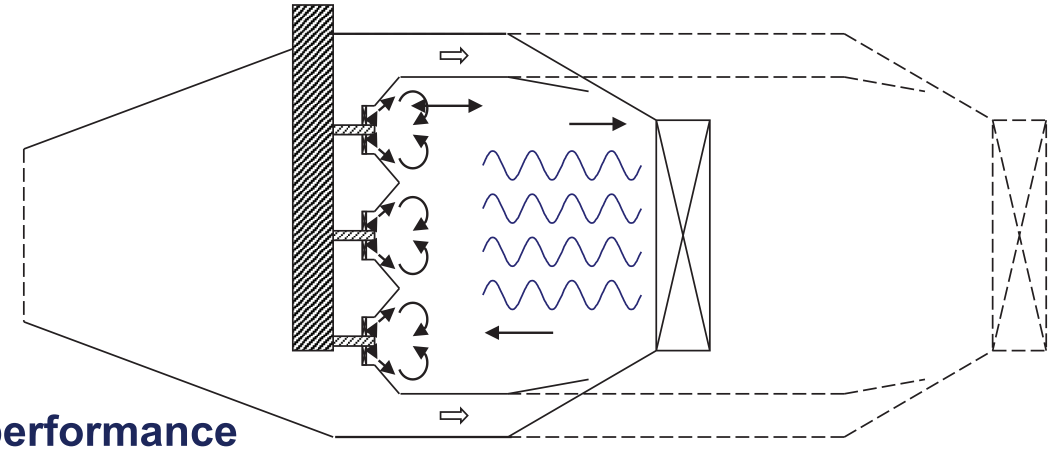
Issues that Affect Combustor Instability / Acoustics



1. **Well-defined acoustic boundary conditions**
2. **Perturbations from fuel-nozzle turbulence**
3. **Recirculation vortex provides flame-holding**
4. **Liner film-cooling provides damping**
5. **Multiple temperature zones**
6. **Φ’ interaction with P’**

Why is Lean-Burning Combustor More Sensitive?



1. Higher-performance fuel injectors: more turbulence
2. Reduced film cooling: reduced damping
3. More uniform temperature and composition: coherent transmission media
4. Fewer dilution holes: reduced physical constraint on flow motion and flame-holding anchoring
5. Threat: Flameout at throttle down
6. Threat: Flashback at throttle up

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Combustor Operability

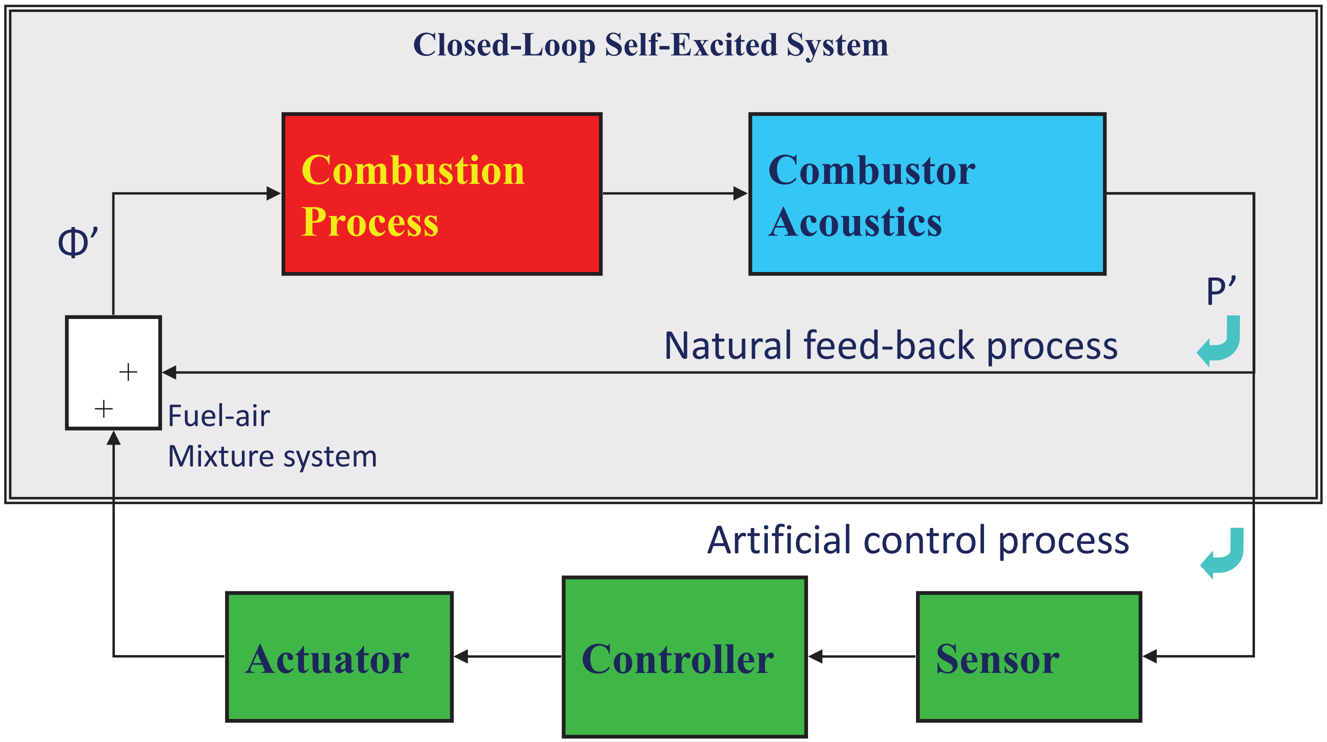
1. There is no substitute for good engineering

2. Sometimes that's not enough

3. Active-combustion control: Nanny in the background

Combustion Instability Control Strategy

Mimic the natural process and cancel it



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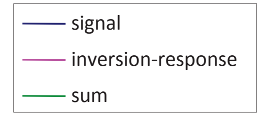
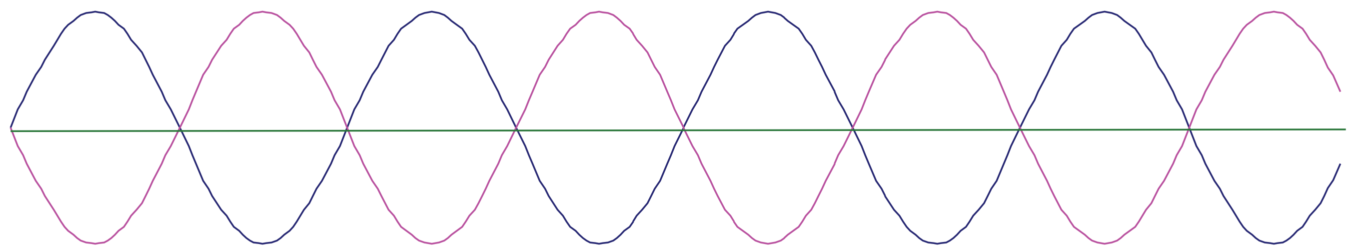
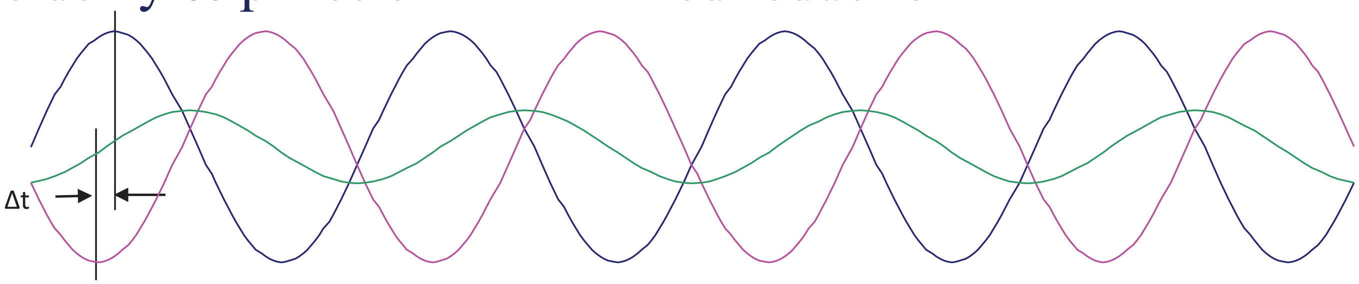
Why is instability control so difficult?



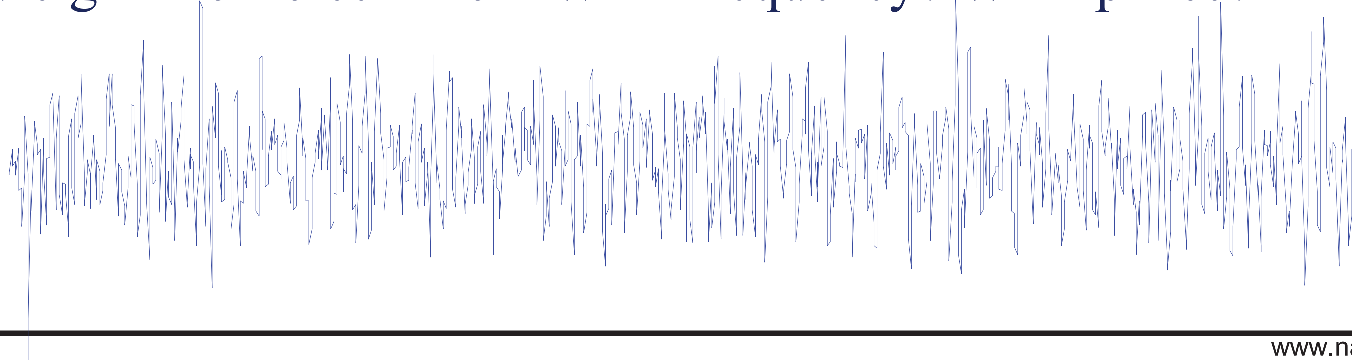
Perfect phase inversion



Time delay & phase shift – Limited reduction



Low signal-to-noise ratio – What frequency? What phase?



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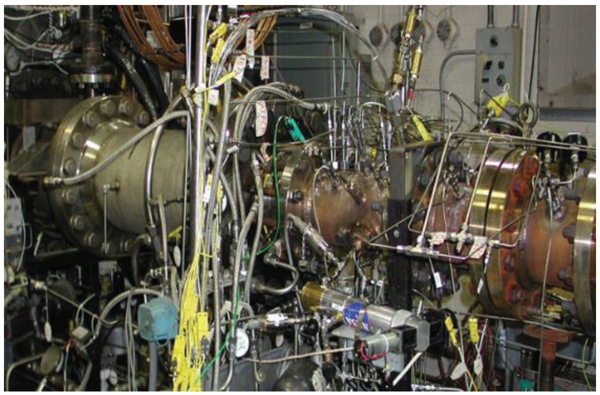
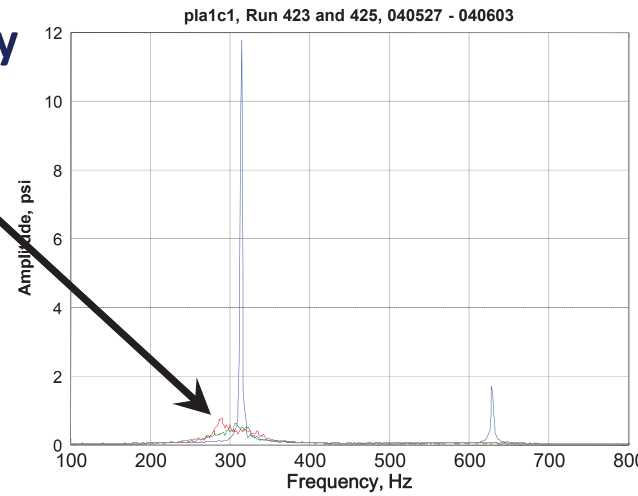
Instability Control Needs Strategy

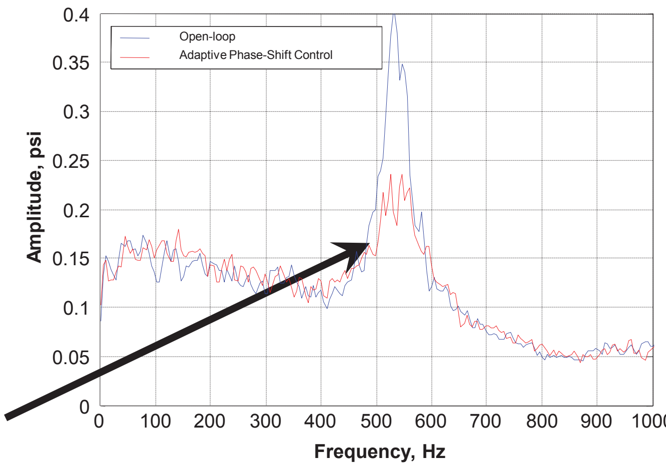
Large amplitude, low-frequency instability suppressed by 90% - TOO LATE!





Liquid-fueled combustor rig emulates engine observed instability behavior at engine pressures, temperatures, flows

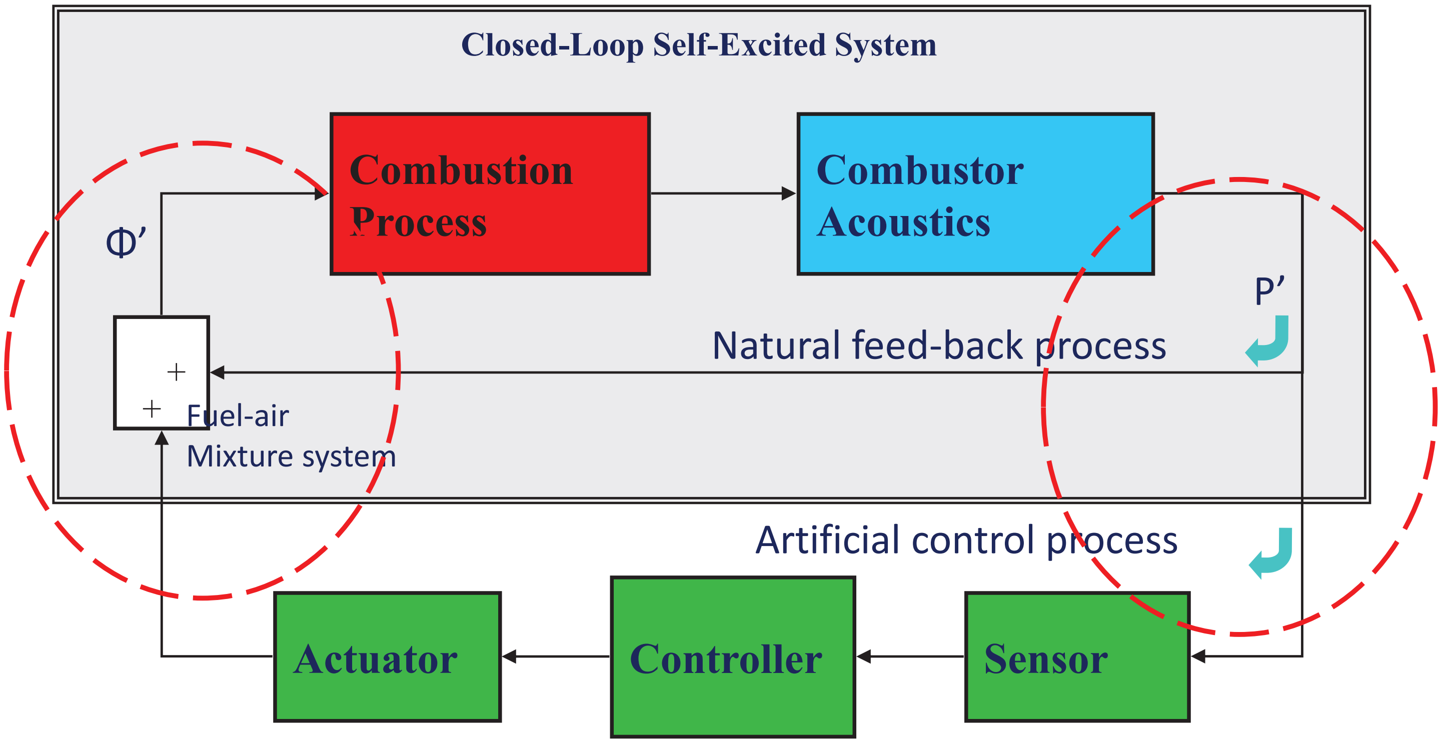
High-frequency, low-amplitude instability is identified, while still small, and suppressed almost to the noise floor.



Critical future research areas

What does it take to make a clean pilot injector dominant and suitable for control actuation on a lean-burn system?

What phenomenon (a) can a lean-burn combustor use to keep a combustor operable over a wide range?



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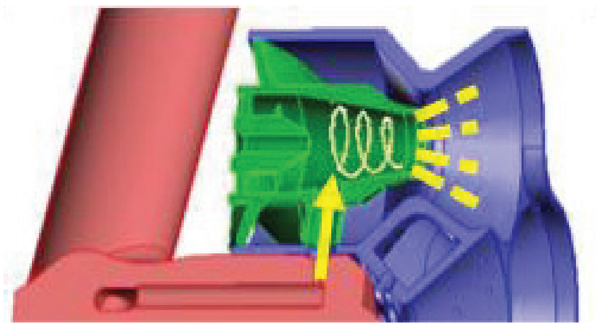
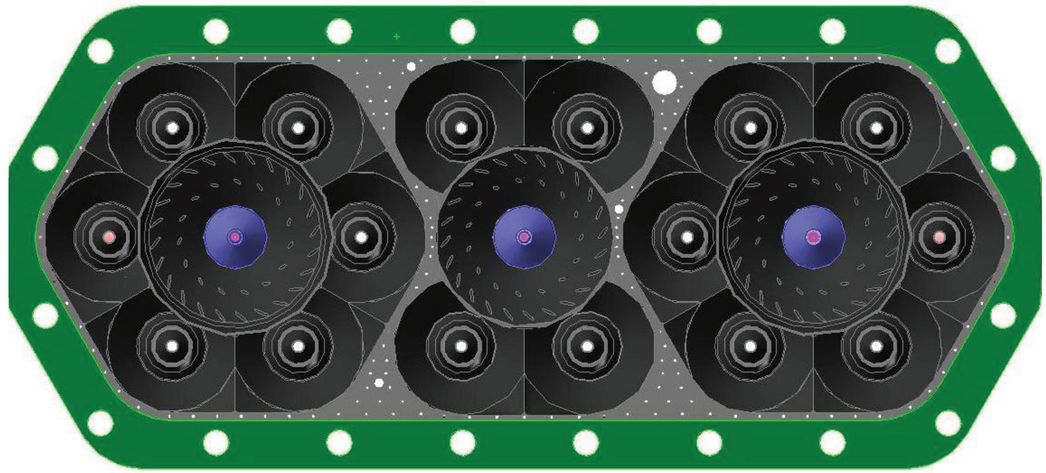
No guarantee of universal solution

Workable LDI Injector Layout





- Large decrease in fuel-injection module complexity with LDI-3 while maintaining effective area of individual injectors
- Much denser packing of injectors at combustor dome face
- Higher reference velocity for LDI-3 due to smaller annulus/dome area of combustor

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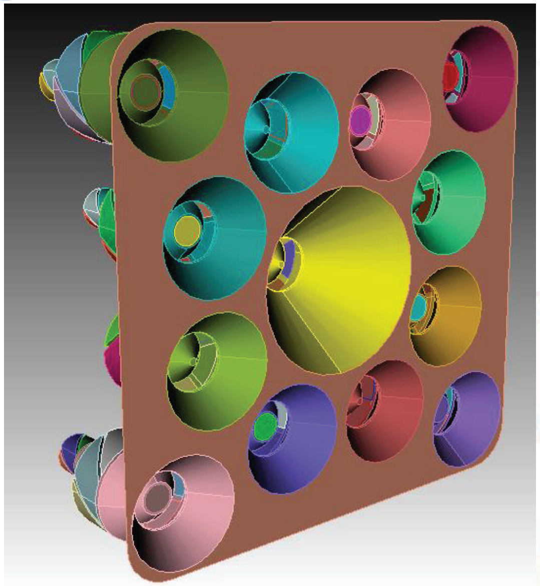
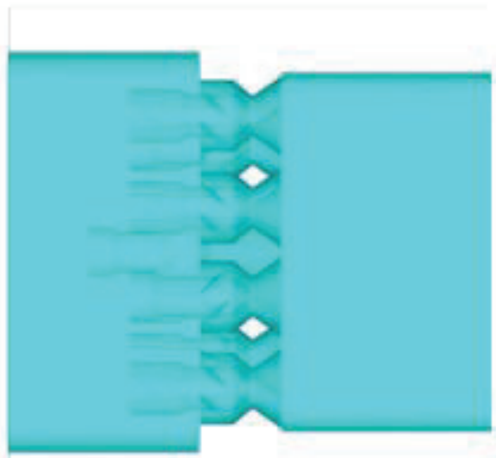
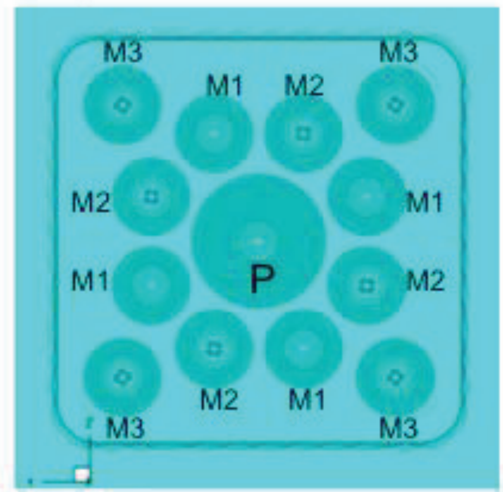
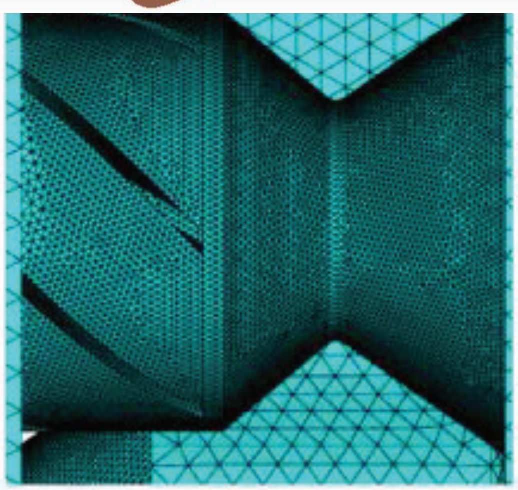
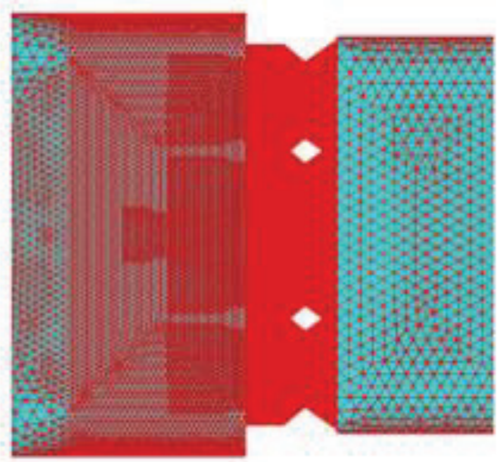
USE CFD to screen LDI Designs











M1 Simplex
M2 Airblast
M3 Airblast
P Simplex

17M element all-tetrahedral mesh

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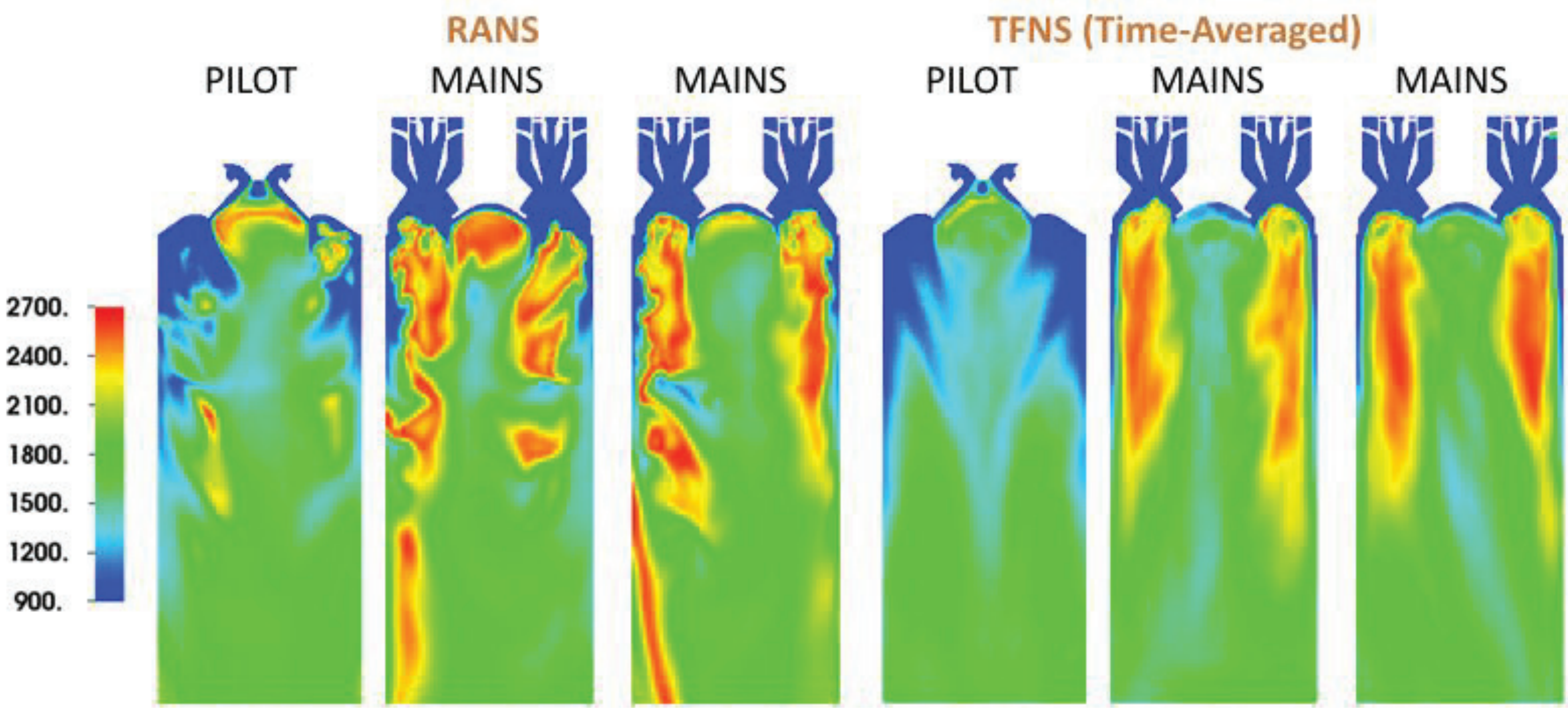
Time-resolved CFD needed to assess dynamics

Temperature Contours (K)



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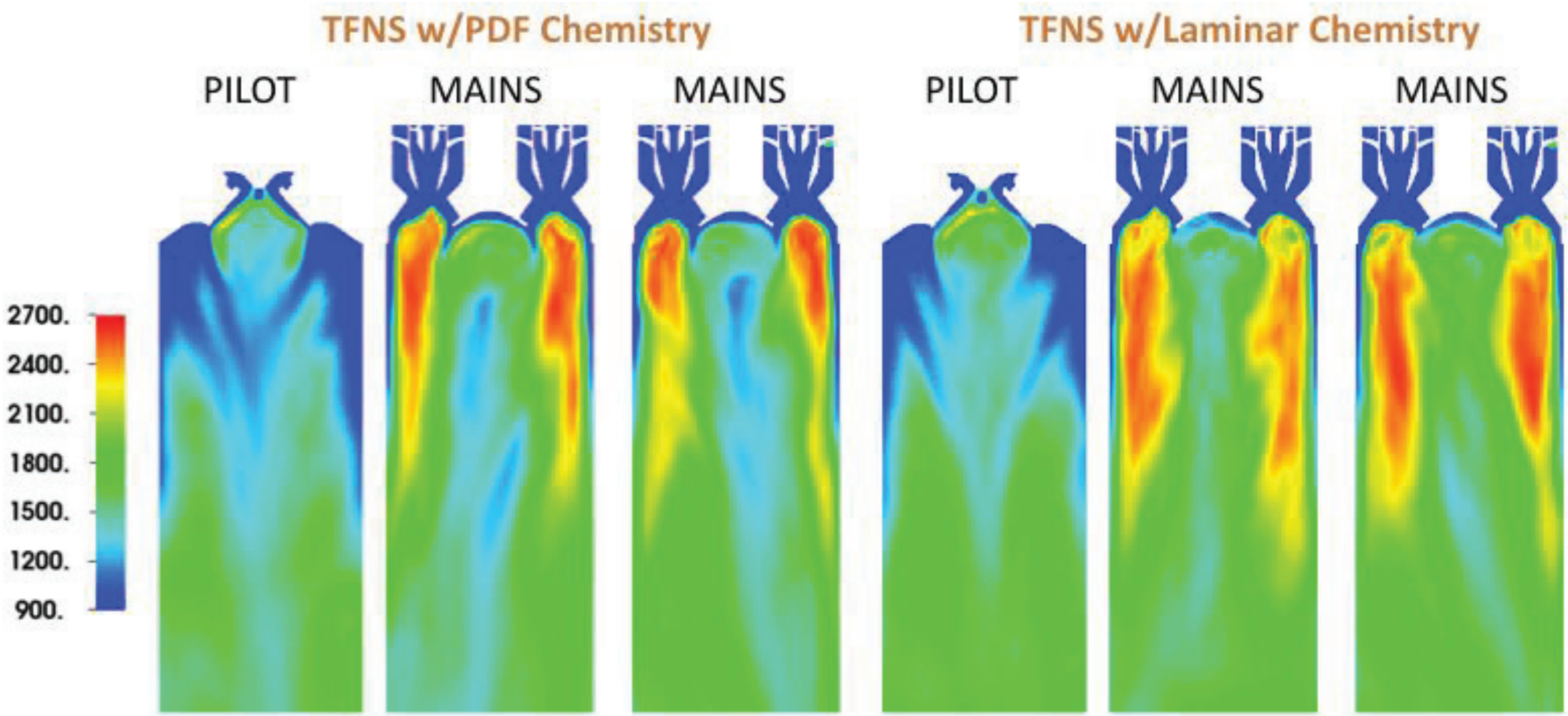
Turbulence-Chemistry Interaction Effects

Temperature Contours (K)

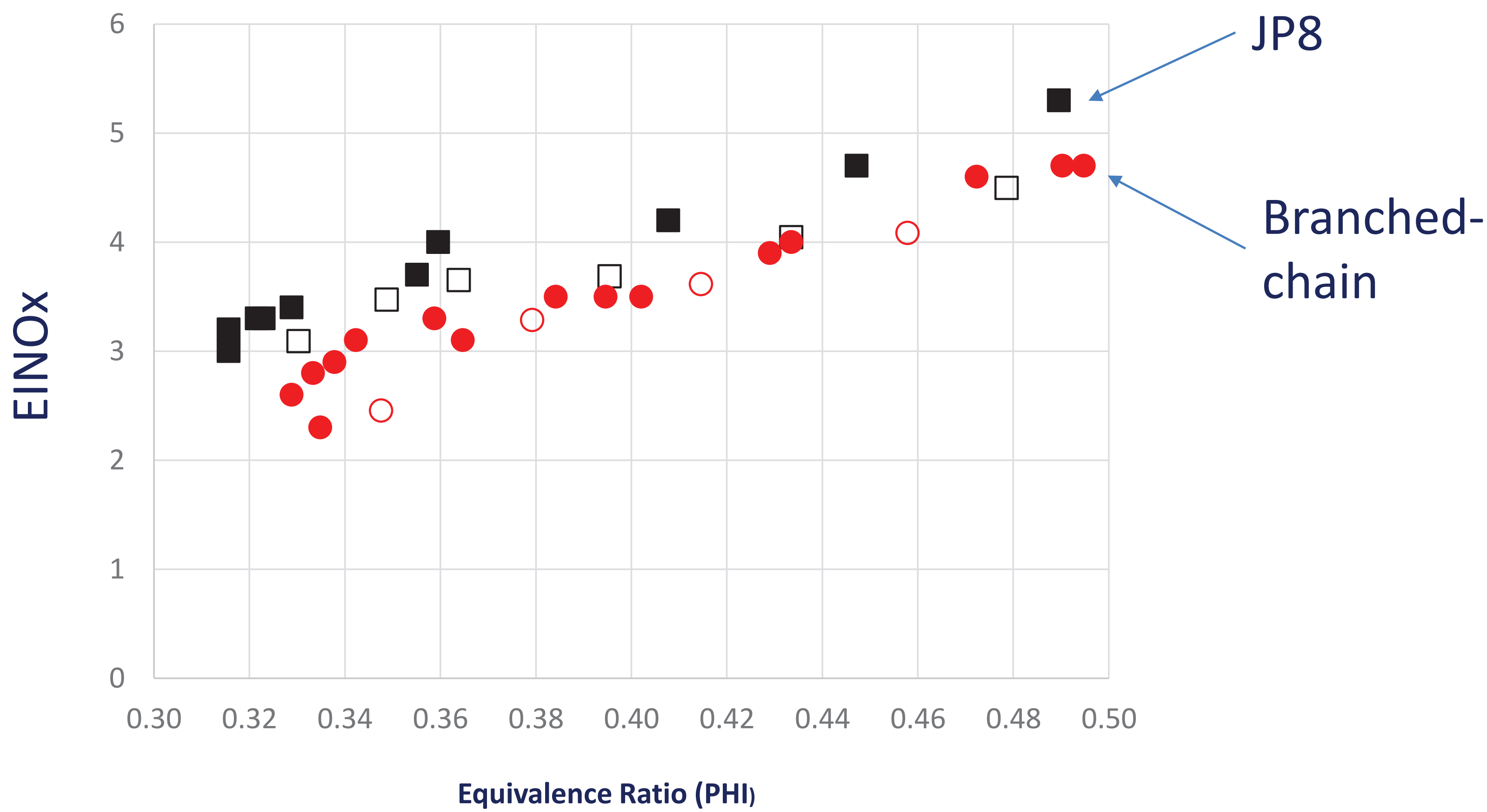


Opportunity:

Revised JP fuel composition an enabling technology

Aromatic reduction (Soot reduction)
Sulfur removal (Contrail reduction)
Fuel hydro-treatment (Injector coking reduction)
Limit paraffin content (Increase ignition delay)

Slower branched-chain pyrolysis delay lowers NOx



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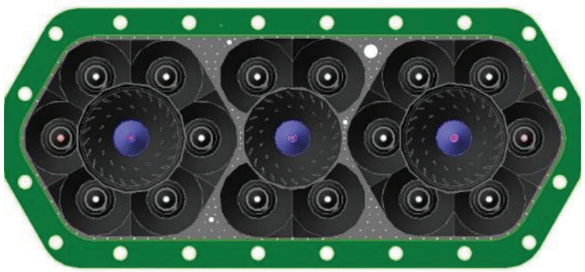
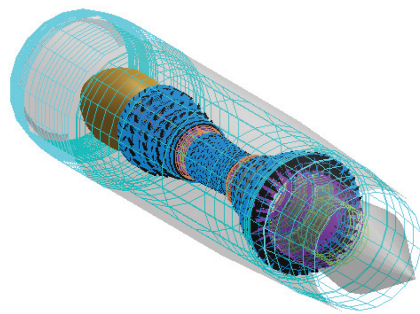
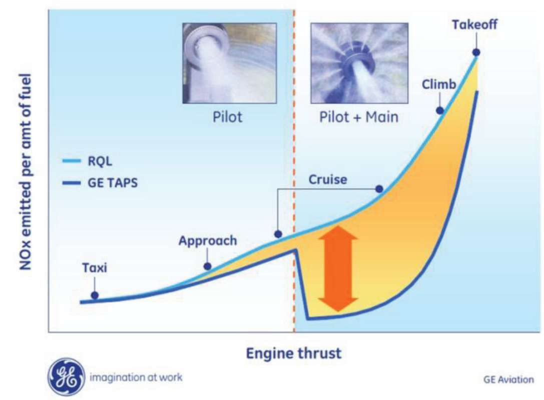
Future Direction



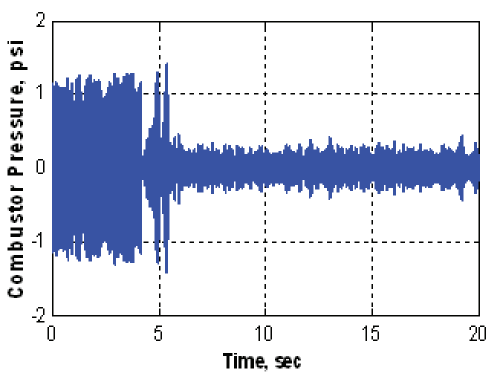
High-pressure Multi-point LDI



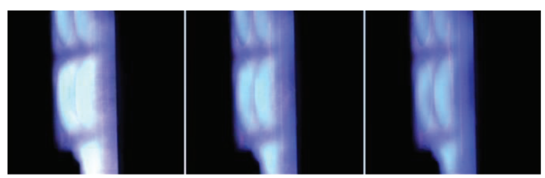
Smaller High Pressure Engine Cores



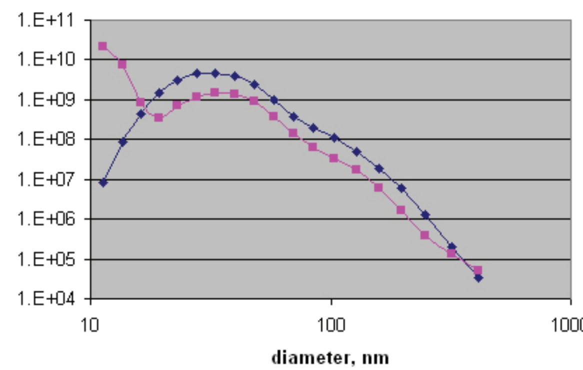
Cruise-Level NOx Reduction



Dynamics and control



Fuel-composition optimization



Particulate Reduction

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Summary

- Lean-burn to reduce cruise NOx and nvPM for the future
  - Second-gen CMC liner
  - Dynamics mitigation
  - Control strategies and technologies
  - Realistic CFD
  - Fuel formulation tweaking

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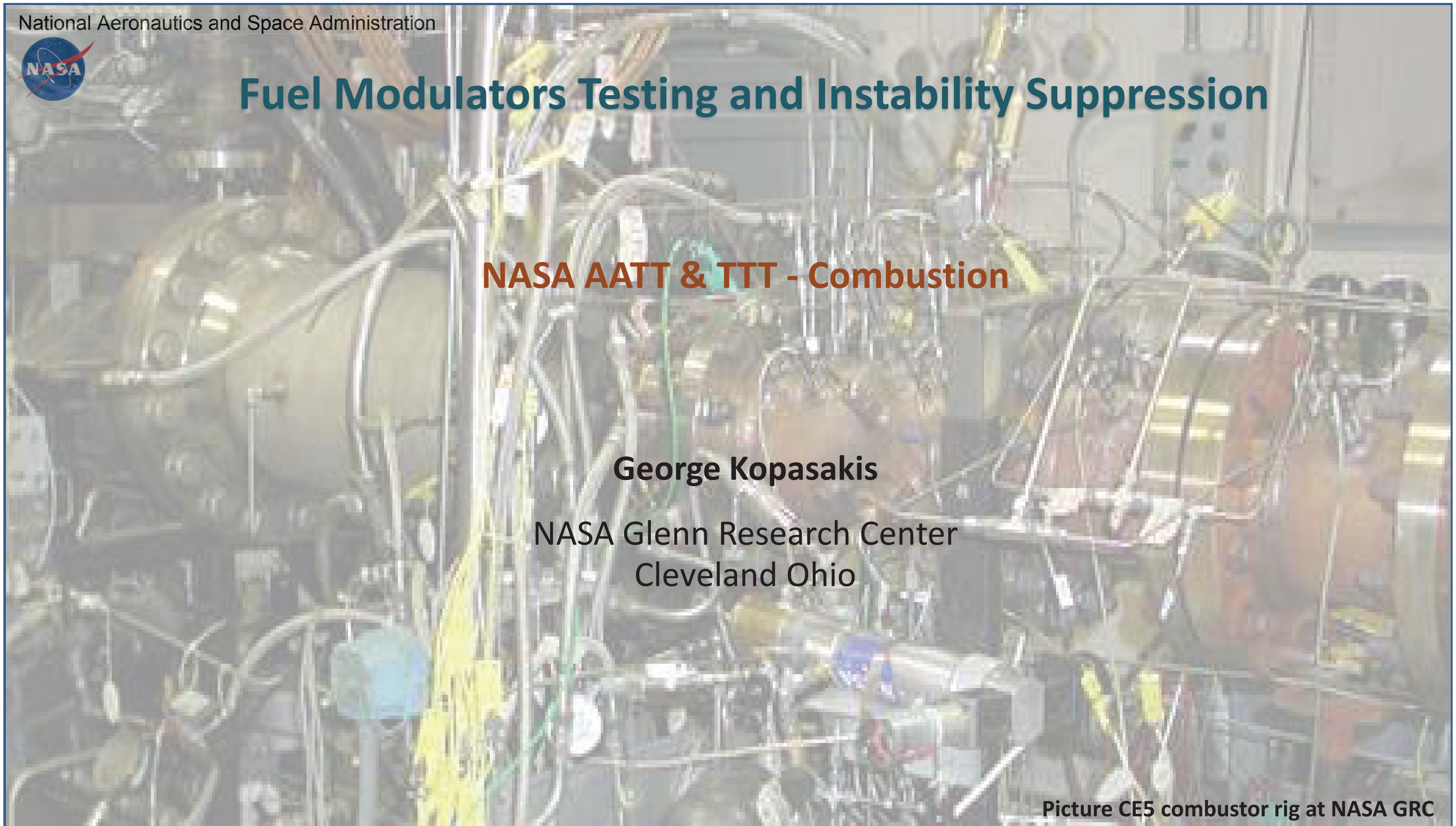
Fuel Modulators Testing and Instability Suppression

NASA AATT & TTT - Combustion

George Kopasakis

NASA Glenn Research Center
Cleveland Ohio



Picture CE5 combustor rig at NASA GRC

6th NASA Glenn Propulsion Control and Diagnostics Workshop
Aug. 22-23 2017, Cleveland, OH

www.nasa.gov

Team Members

<u>LCC Branch</u>

George Kopasakis

Randy Thomas

Joseph Saus

<u>LTC Branch</u>

Kathleen Tacina & team (TTT) – CE13

Clarence Chang & team (AATT) – CE5

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Outline

- **Background**
  - **-- History of Active Combustion control (ACC) at GRC by modulating the mains**
- **Small Fuel Modulator Development**
  - **-- Fuel modulation testing with the pilot**
- **Future Plans**
- **Conclusions**

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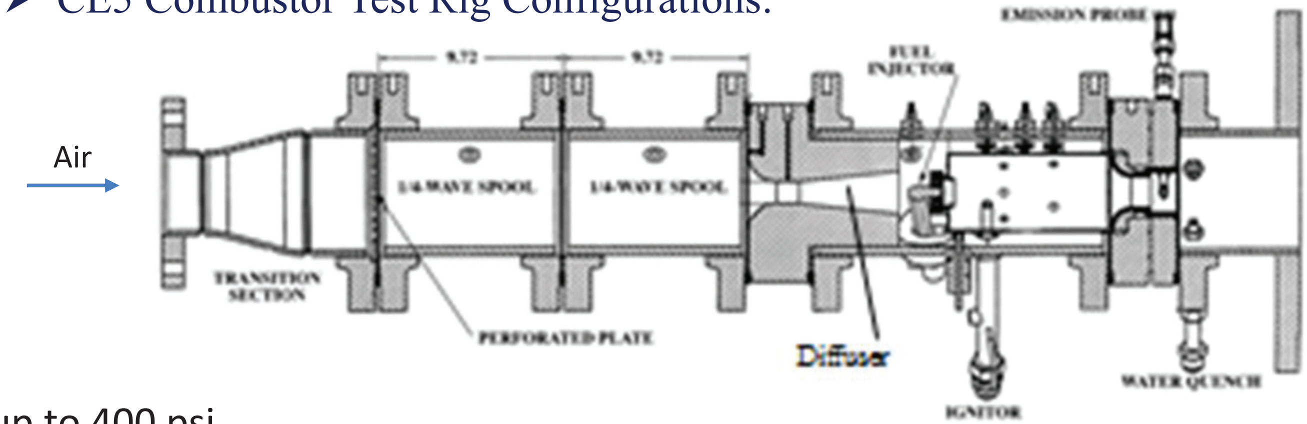
History of ACC at GRC - Modulating the Fuel Mains

- CE5 Combustor Test Rig Configurations:

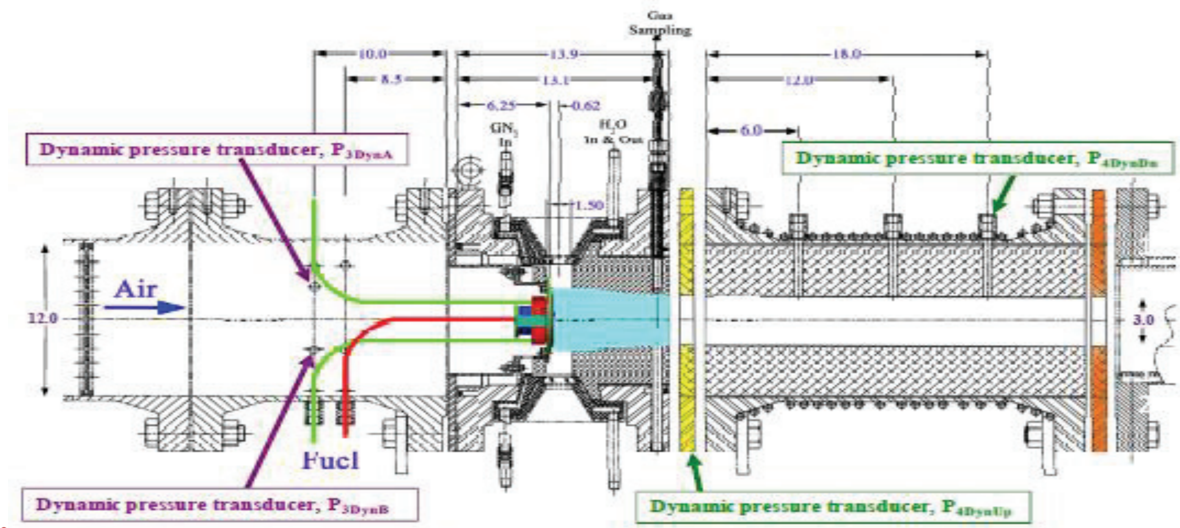


P3: up to 400 psi

T3: 1200° F

can go to 3000° F

Early 2000's rig Configuration – CE5 rig at GRC



Later 2000's

Advanced low-emissions combustor prototype installed in NASA flame tube. The pilot fuel line is shown in red and the main stage fuel lines are shown in green. Dimensions shown are in inches. Drawing is not to scale.

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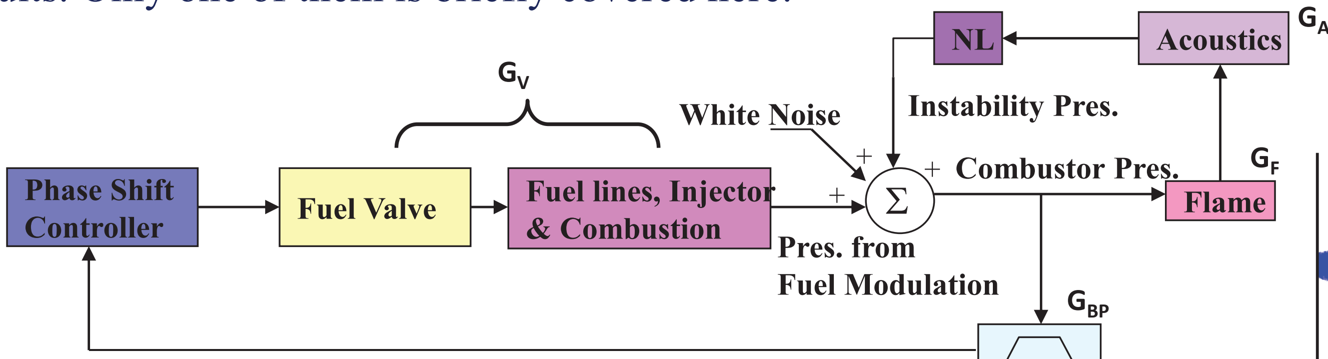
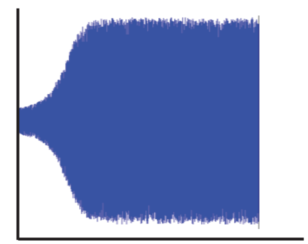
History of ACC at GRC – Controller Design

- Two different control methods were developed at GRC in early 2000's, with similar results. Only one of them is briefly covered here.

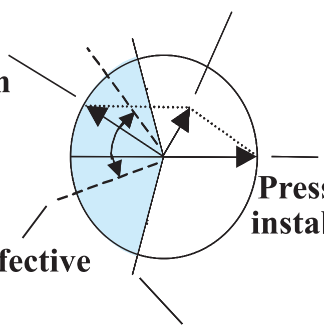


Combustor Instability Controls Diagram

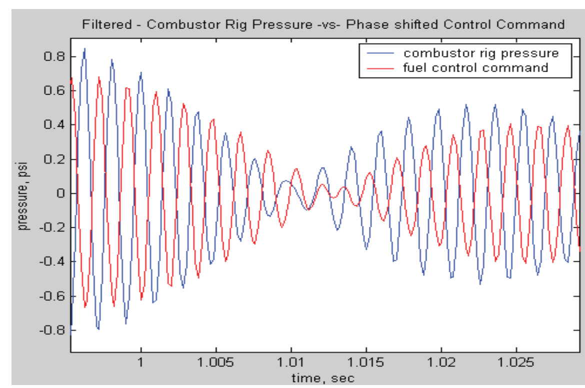
Filter



Combustor Instability Simulation



Control of relative phase angle of fuel nodulation and instability



Filtered instability signal and time shifted control signal to show apposing phase behaviour and instability inertia

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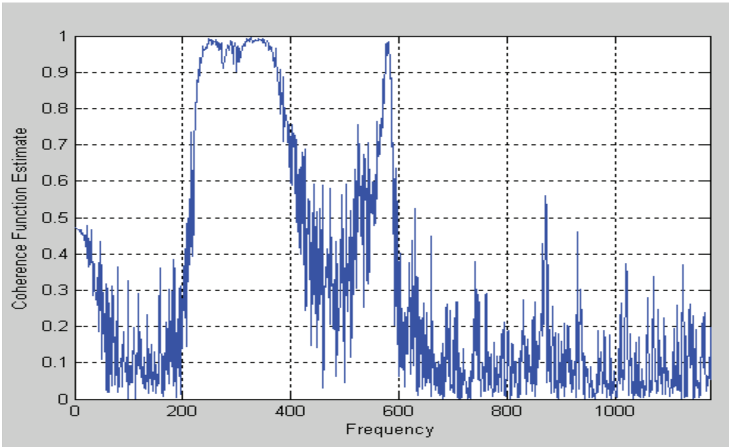
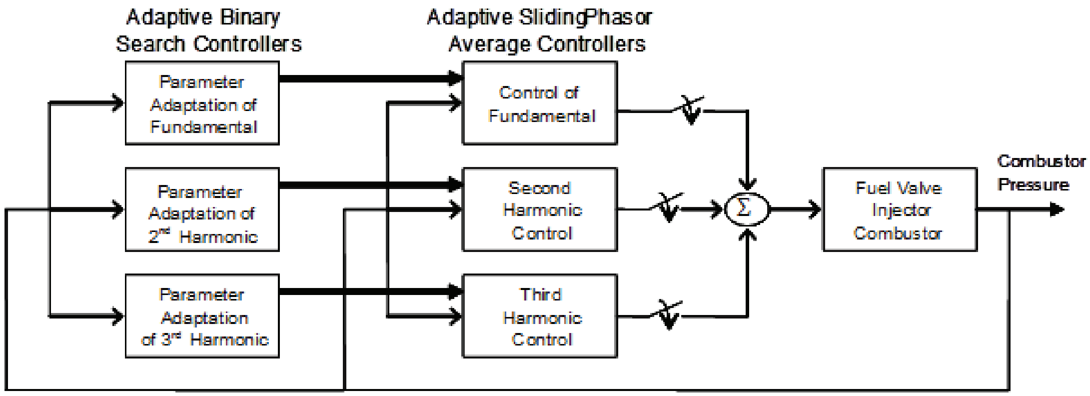
History of ACC at GRC - Controller Design



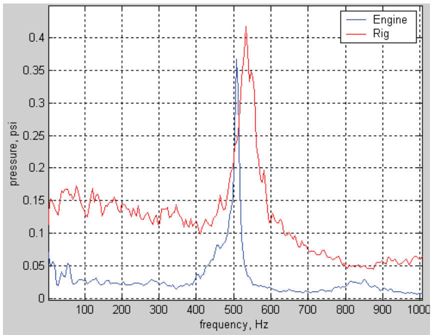
Harmonic Coherence (after some manipulation)
Showing strong coherence of fundamental and harmonics

❖ Added control parameter adaptation and control of harmonics

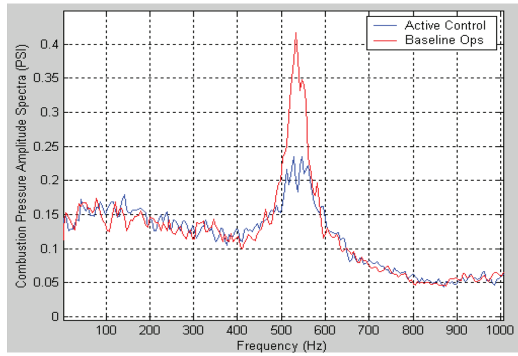


Overall Combustor Instability Controls Diagram

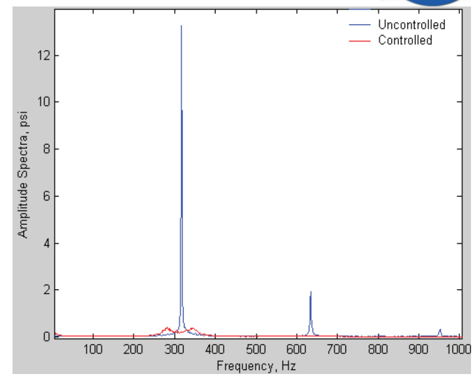
History of ACC at GRC - Prior Active Combustion Controls Testing



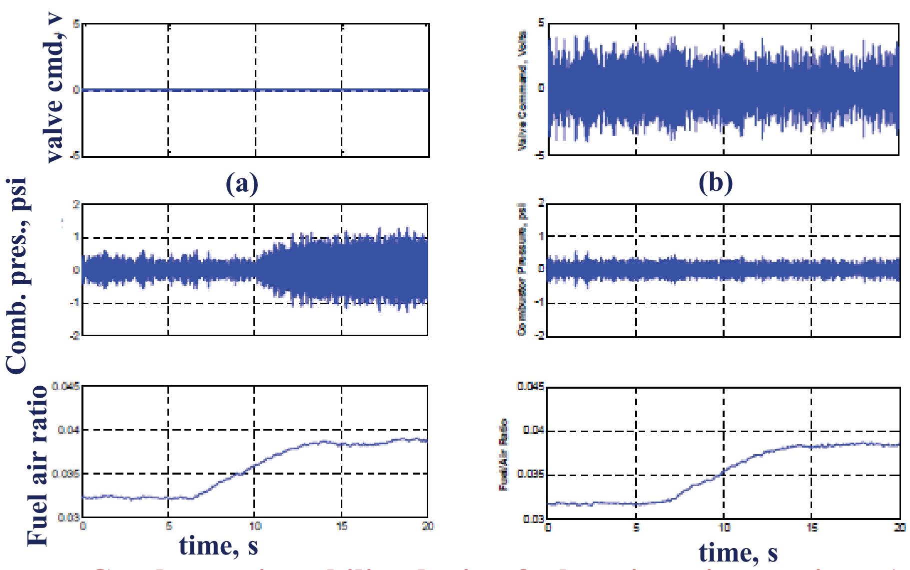
Amplitude Spectral of combustor instability of engine vs. rig at mid power



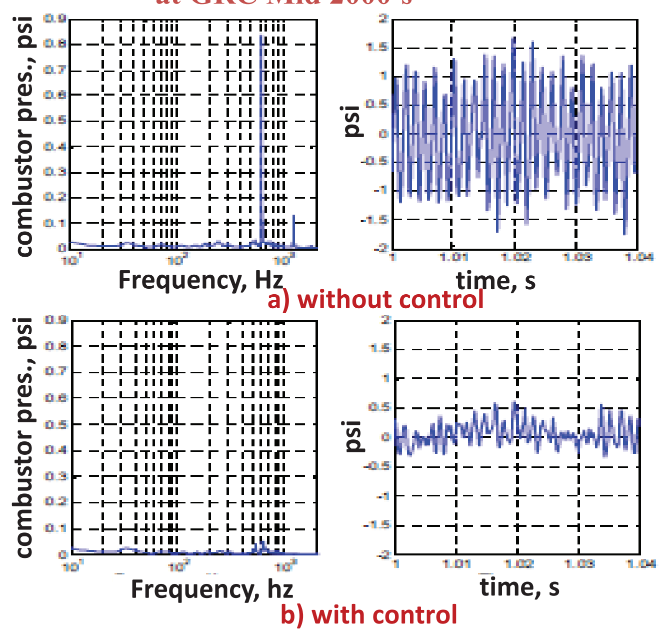
Uncontrolled vs. Controlled Instability. Testing at UTRC in early 2000's



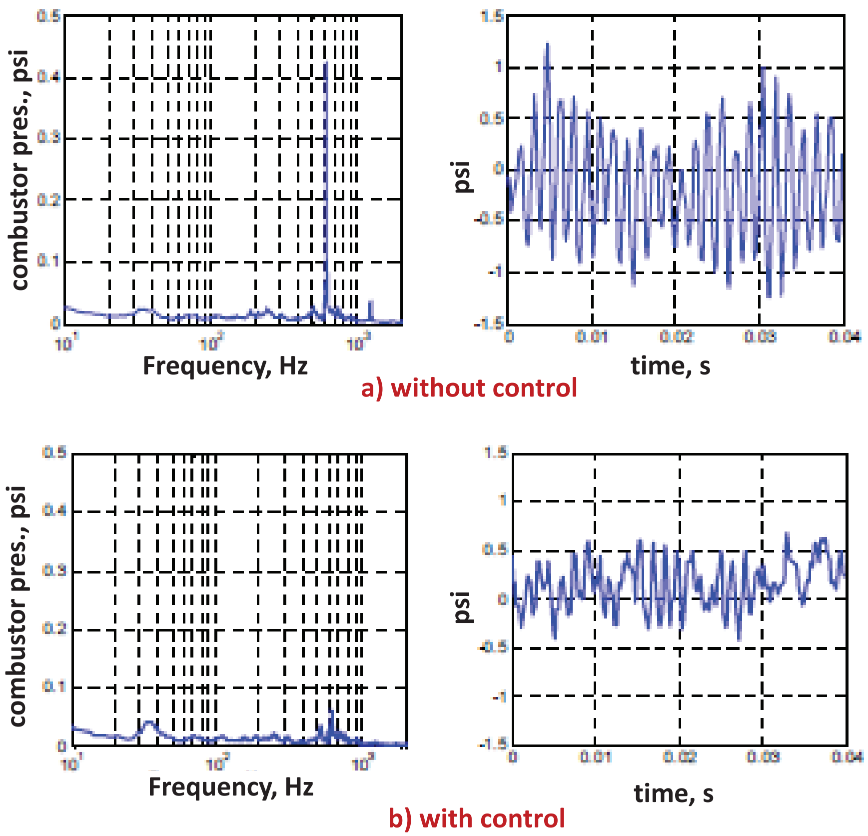
Uncontrolled vs. Controlled Instability by controlling the second harmonic Testing at GRC Mid 2000's



Combustor instability during fuel to air ratio transient a) without, b) with control – Testing at GRC 2011



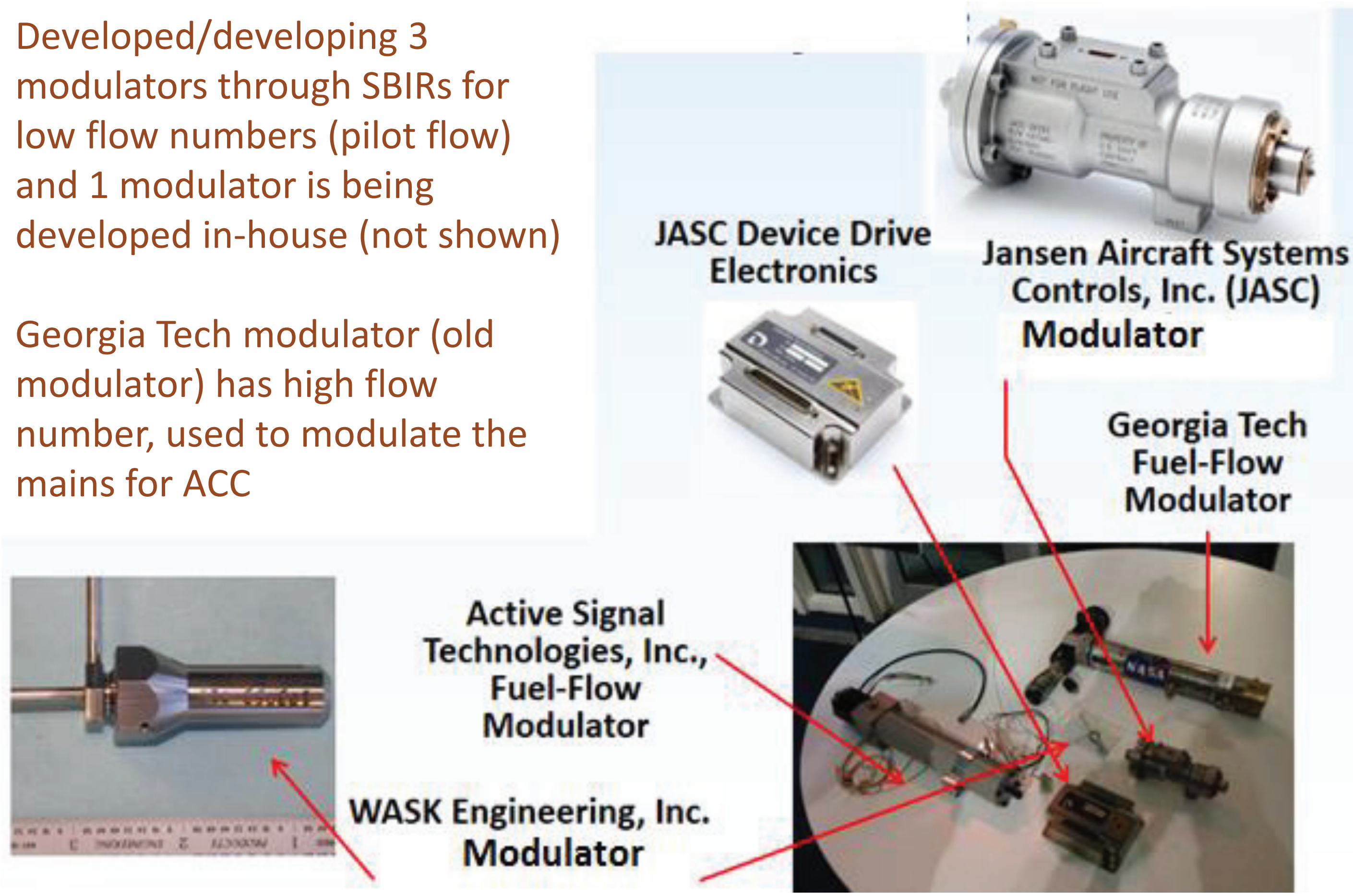
History of ACC at GRC - Prior Active Combustion Controls Testing



Combustor pressure amplitude spectral and time history showing combustor instability supressed by sensing reflected pressure oscillations upstream of the combustor – Advantageous for sensors to be located in less harsh environment

Small Fuel Modulator Development w/ Low Flow Numbers

- Objective: develop modulators w/ low flow numbers to modulate pilot flow & small size, w/ higher temperature materials/fuel cooling to potentially integrate with fuel injector assembly in harsh environment
  - Developed/developing 3 modulators through SBIRs for low flow numbers (pilot flow) and 1 modulator is being developed in-house (not shown)
  - Georgia Tech modulator (old modulator) has high flow number, used to modulate the mains for ACC



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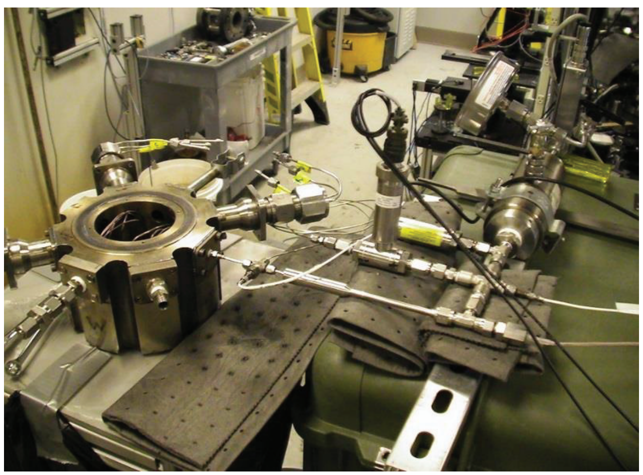
Fuel Modulator Testing to Establish Modulation Authority

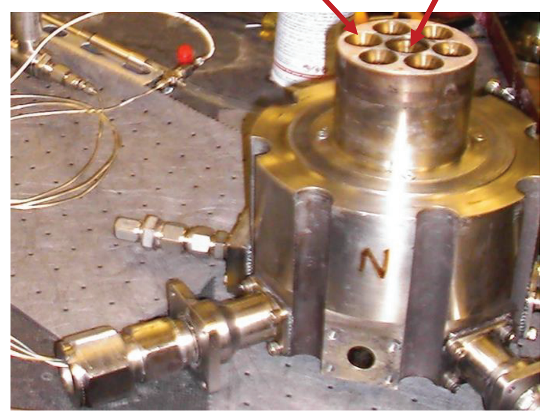
- Besides vendor testing and reports, modulators are hydro tested (pressurized testing) and then tested for operability in CE7 at GRC (water fluid facility) and/or at CE13 (hydrocarbon fuel).

- Modifying connectors and instrumentation ports to have the same ID's in order to maximize potential for modulation and simulating long fuel lines to understand the modulation pressure drop and acoustic impedance.

- Devices are then tested in CE13 and later in CE5 for their ability to modulate the combustor pressure through the pilot flow to establish their authority to effect the instability for ACC.



CE13 Cold Flow Test – Combustor Disassembled



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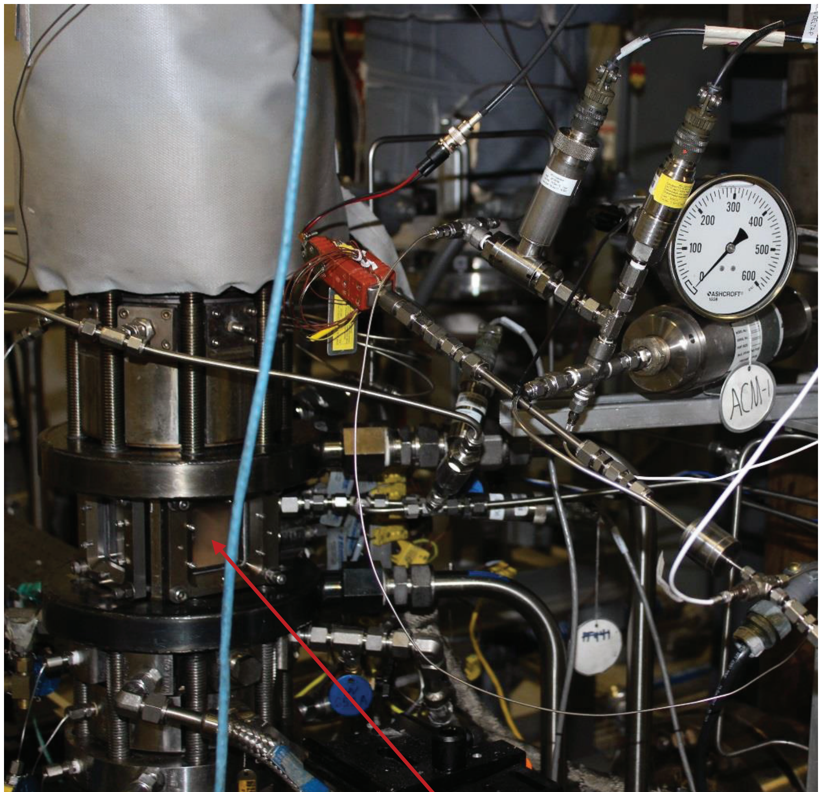
Fuel Modulator Testing in CE13 Combustor Rig at GRC

CE13:

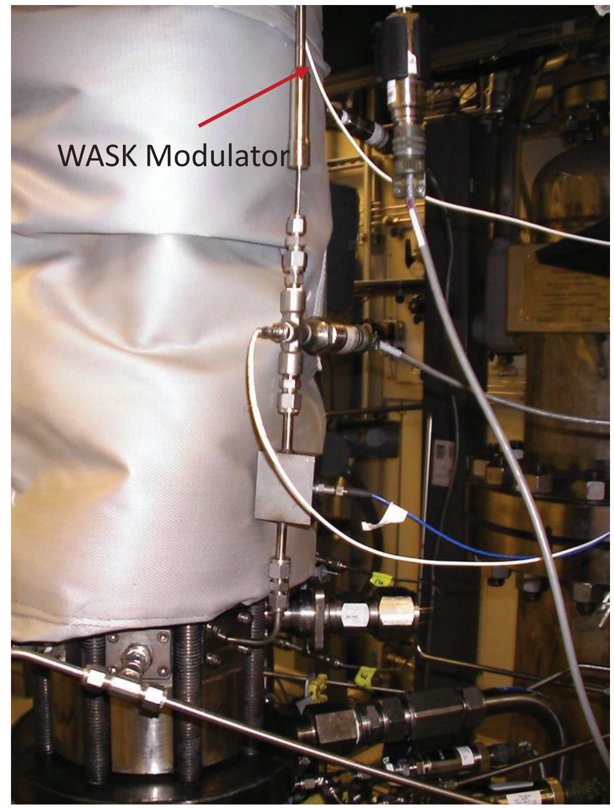
T3: 800º F; P3=75 psi

Fuel flow = 0-2lbm/min

In-House Modulator Testing



WASK Modulator Testing



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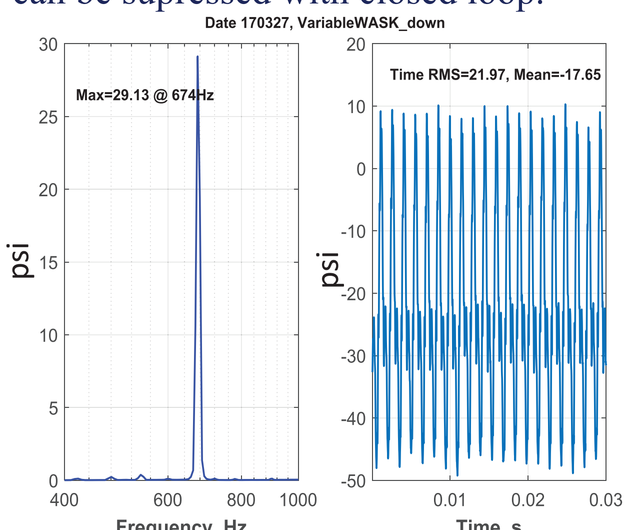
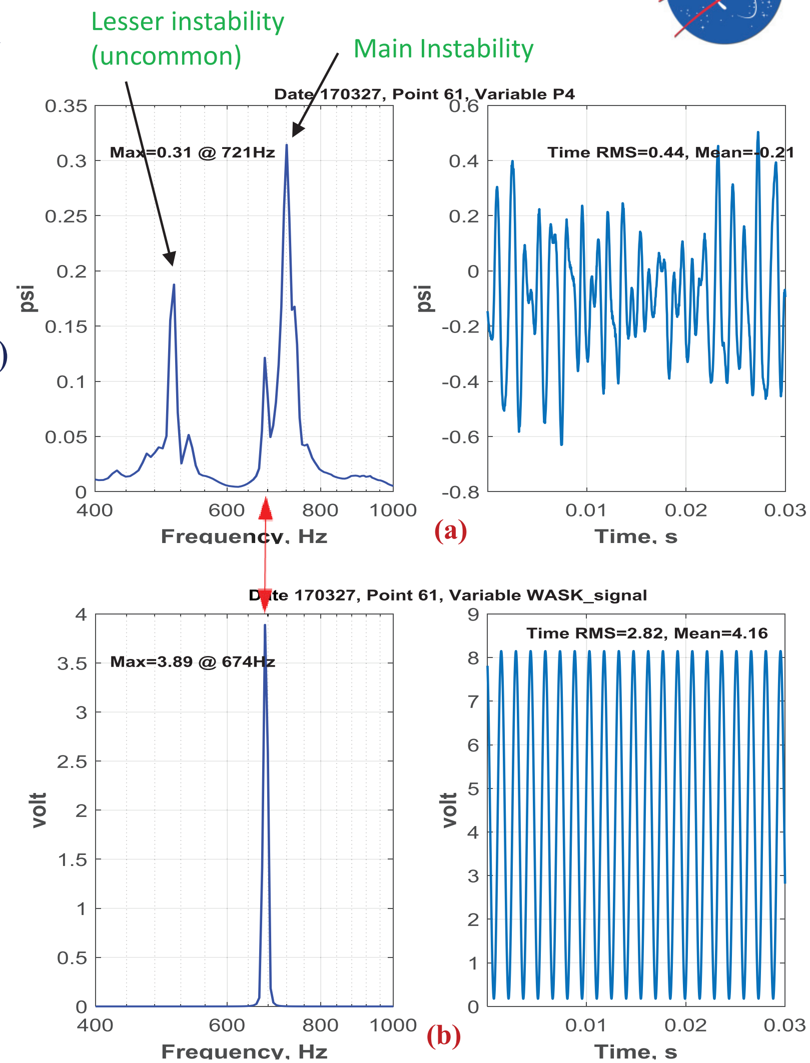
Fuel Modulator Test Results – CE13

- Modulating the pilot (~25% of fuel) with the WASK valve produced relative strong modulation downstream of the valve (upstream of the combustor).
- Discrete frequency modulation did not perturb combustor pressure, except near the instability frequency of 721Hz (500 Hz also present in this test)
- Modulating near the instability frequency show instability entrainment – indication that instability can be supressed with closed loop.



Modulator downstream pressure spectral varied from 25 to 35 psi at different frequencies.



(a) – Downstream Pressure spectral;
(b) - Applied modulator voltage

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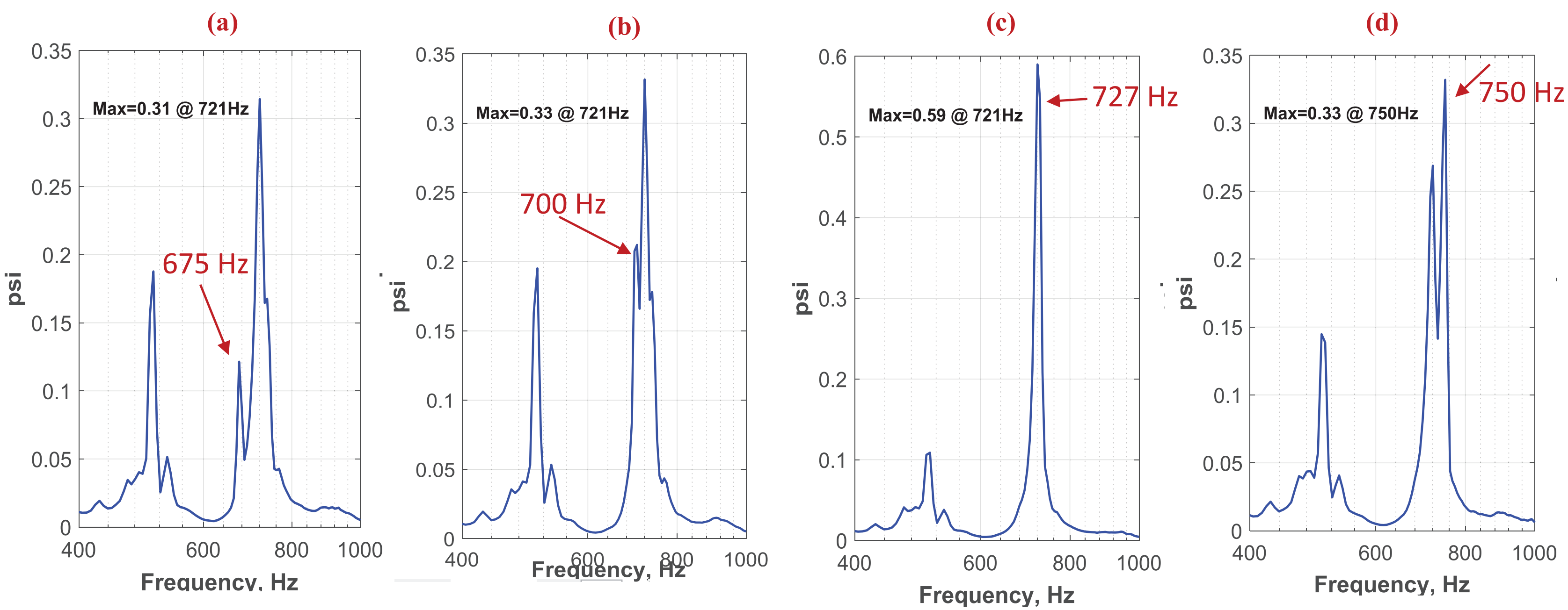
Fuel Modulator Test Results – CE13

- As shown in these figures, instability entrainment takes place when modulating near the instability, with progressively increased amount of entrainment nearer the instability frequency. In case (c), the 721 Hz instability is even amplified and the 500 Hz mode is reduced.



Future Plans

- Discrete frequency modulation testing with pilot in CE5
- Closed loop instability suppression testing in CE13
- Closed loop Instability suppression testing in CE5 (simulating real engine environment)
- Open and closed loop testing in CE5 with modulator installed inside the injector assembly
- Smart fuel management for emissions reduction and/or pattern factor
- Organize ACC under JANNAF: Airbreathing Propulsion Committee (APS); Mission area IX: Advanced Combustion Control for possible joint research and maturation of these technologies. Government, Industry, and academia input welcomed.

Conclusions

- Closed loop ACC control has been done before successfully at NASA GRC under simulated engine combustor conditions by modulating the fuel mains
- Low flow number modulator development has been done to be able to modulate the pilot flow to see if sufficient instability authority exists for closed loop control
- So far modulator testing shows that sufficient instability authority exists to attempt ACC control using the pilot (~25% of the fuel) in a low pressure combustor with the modulator coupled closer to the injector

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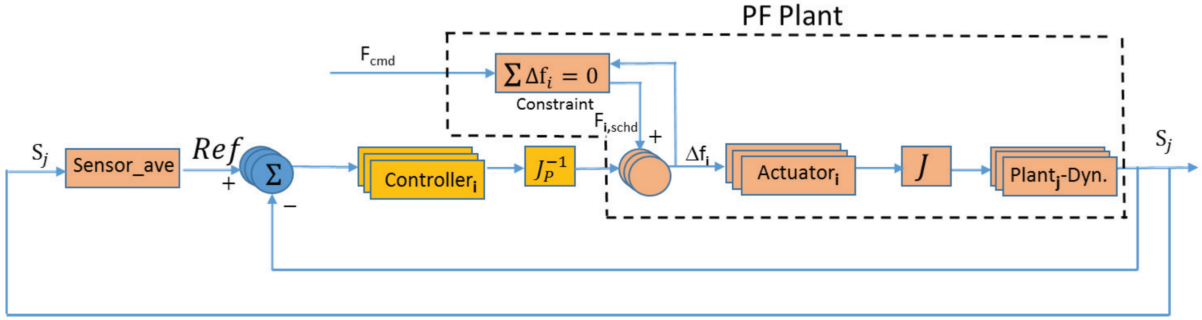
Backup Slide

Pattern Factor:

Preliminary control scheme



$$\Delta S_j = \sum_i \left(\frac{\partial S_j}{\partial f_i}\right) \Delta f_i = J \Delta f_i$$

$$S_{ave} = \frac{(1/j) \sum S_j}{\tau s + 1}$$

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ACTIVE TURBINE TIP CLEARANCE CONTROL RESEARCH

2017 PCD Workshop

Jonathan Kratz (NASA GRC) &
Jeffryes Chapman (Vantage Partners LLC)

Intelligent Control & Autonomy Branch (LCC)

August 22, 2017

Outline

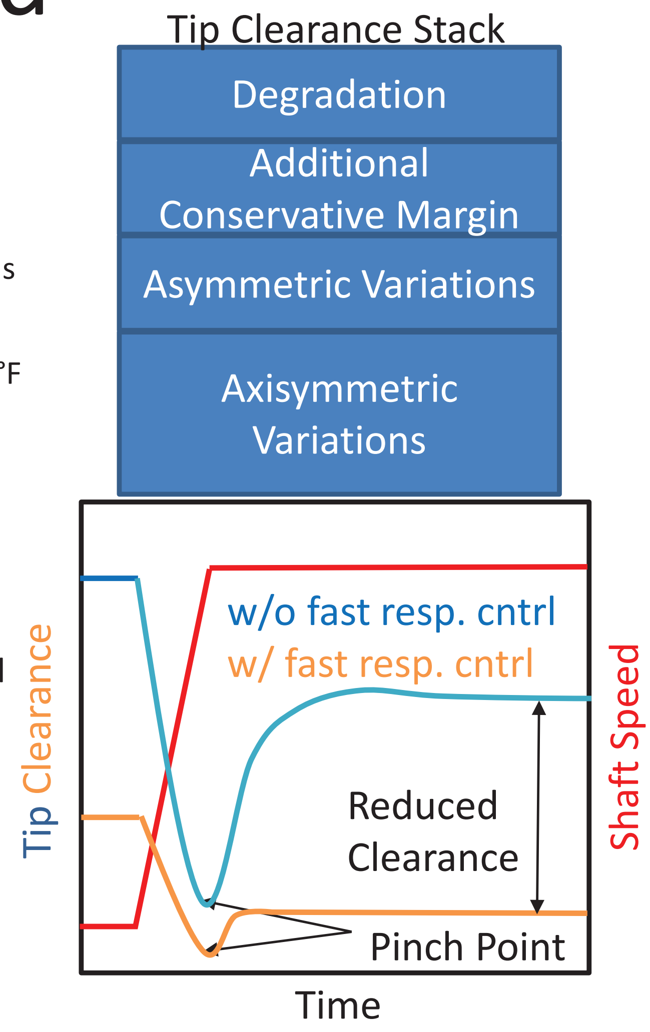
Research Summary: Developing dynamic turbine tip clearance models and integrated engine simulations + performing sensitivity and actuator studies

Outline

- Background
- Objectives
- Tip Clearance Model Overview
- Integration with Engine Model
- Sensitivity Studies (C-MAPSS40k)
- Actuator Requirement Studies (C-MAPSS40k)
- Preliminary studies for Compact Gas Turbines (CGTs)
- Summary

Background

- What are you trying to do?
  - Actively control HPT tip clearance to achieve higher HPT efficiency
- Reduced HPT tip clearance correlates to:
  - Increased turbine efficiency → Reduced fuel burn (For large gas turbine 10mils → 1% efficiency)
  - Reduce turbine inlet temperature → Longer time on wing & reduced maintenance cost (For large gas turbine 10 mils → 18°F reduction in EGT)
- How it's done today?
  - *Open-loop scheduled* control through thermally induced contraction of the casing via forced convection using bleed air from a cooler air stream in the engine
  - *Slow dynamics* → conservative clearances designed into the engine → less efficient performance (particularly at cruise)
- Value of Higher-Bandwidth Active Turbine Tip Clearance Control (HB-ATTCC)
  - Tighter clearance regulation (@ cruise and elsewhere)
  - Removal of conservative design decisions
  - Mitigation of tip clearance growth due to degradation
- Impact on future compact gas turbines
  - Smaller HPT annulus height → greater tip clearance sensitivity
  - Higher speeds and temperatures could exacerbate the tip clearance dynamics and relative variations



Background

<u>Challenges</u>

- Actuator Development
  - Sufficiently fast, accurate, high temperature, durable, low weight, fail-safe operation, able to exert a significant force
  - Actuator-Case Integration (seals dev., innovative design)
- Sensor Development
  - Sufficiently fast, accurate, high temperature, durable
- **Control/Estimation**
  - ***Development of tip clearance estimators***
  - ***Investigation of control challenges***
  - ***Control strategy development, control law development, and control system implementation***
- CGT Characterization
  - Understand CGT HPT environment & environment of actuator, sensor, and control components
- **Model Development & Validation**
  - ***Re-usable validated models characterizing tip clearance, engine performance, and actuation systems***

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Objectives

Over-arching objective: Support technologies that enable and improve performance of CGTs

- Create a framework for building a gas turbine engine simulation that includes fully integrated tip clearance effects
- Study the sensitivity of the tip clearance and the resulting engine performance to various design parameters
- Study tip clearance dynamics and the requirements it places on the active actuation systems
- Develop simulation environment that can be use to evaluate different actuation concepts

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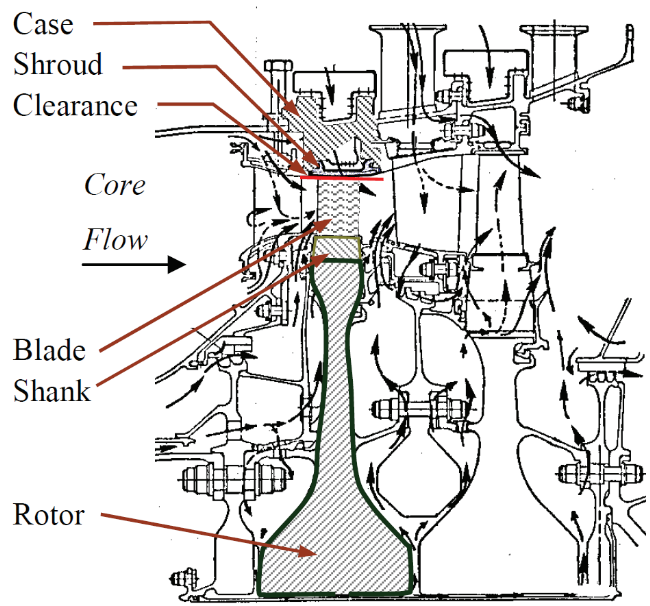
Tip Clearance Model Overview

- Considers axisymmetric tip clearance variations
- Models the following components
  - Blade
  - Rotor Disc (Includes Shank)
  - Shroud/Case
- Models expansion/contraction due to:
  - Centrifugal forces
  - Thermal expansion
- Tip clearance is a function of the component deformations



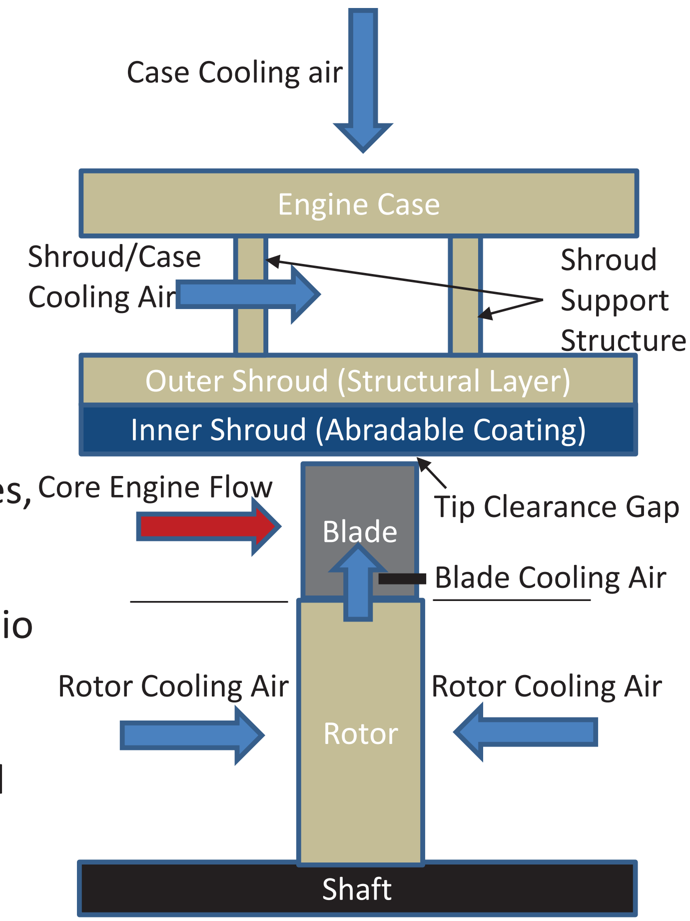
- Chapman, J., Kratz, J., Guo, T.H., Litt, J., "Integrated Turbine Tip Clearance and Gas Turbine Engine Simulation," Proceedings of the 52nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, 2016
- Kratz, J., Guo, T.H., Chapman, J., "A Parametric Study of Actuator Requirements for Active Turbine Tip Clearance Control of a Modern High Bypass Turbofan Engine," Proceedings of the 2017 ASME Turbo Expo Conference, Charlotte, NC, 2017

Tip Clearance Model Overview

Tip clearance contributors
- Thermal Expansion
  - Rotor Disc & Shroud/Case – 1-D finite difference method
  - Blade – Lumped mass model
- Centrifugal Forces
  - Modeled with algebraic equations under the assumption of simplified geometries

Significant Modeling Parameters
- Thermal: thermal conductivities, heat capacities, thermal expansion coefficients, heat transfer coefficients
- Mechanical: modulus of elasticity, Poisson's ratio
- Dimensional: lengths, radii, thicknesses, etc.

Special Features
- Temperature dependent thermal & mechanical properties
- Dynamic heat transfer coefficients



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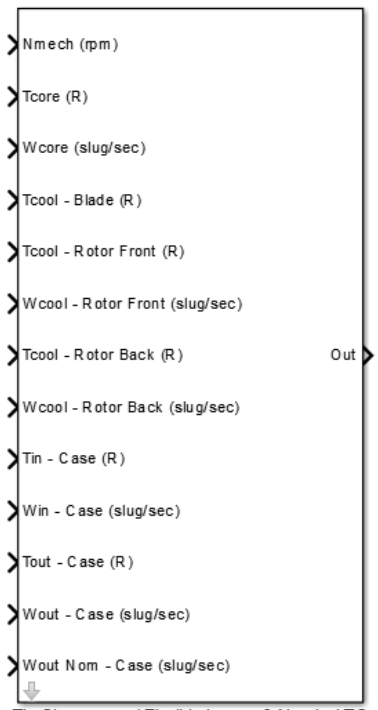
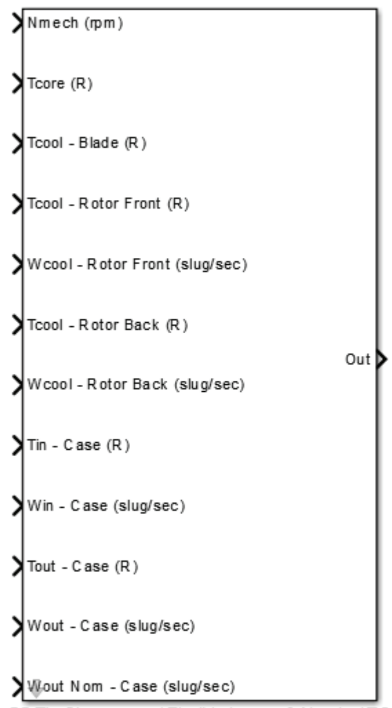
Tip Clearance Model Overview

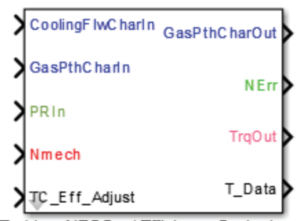
- Generic tip clearance modeling tool have been developed in the MATLAB/Simulink Environment
- Aiming to release these tools within the year



Tip Clearance w/ Flexible Inports & Nominal TC



SS Tip Clearance w/ Flexible Inports & Nominal TC



Turbine_NPSS w/ Efficiency Scalar Input

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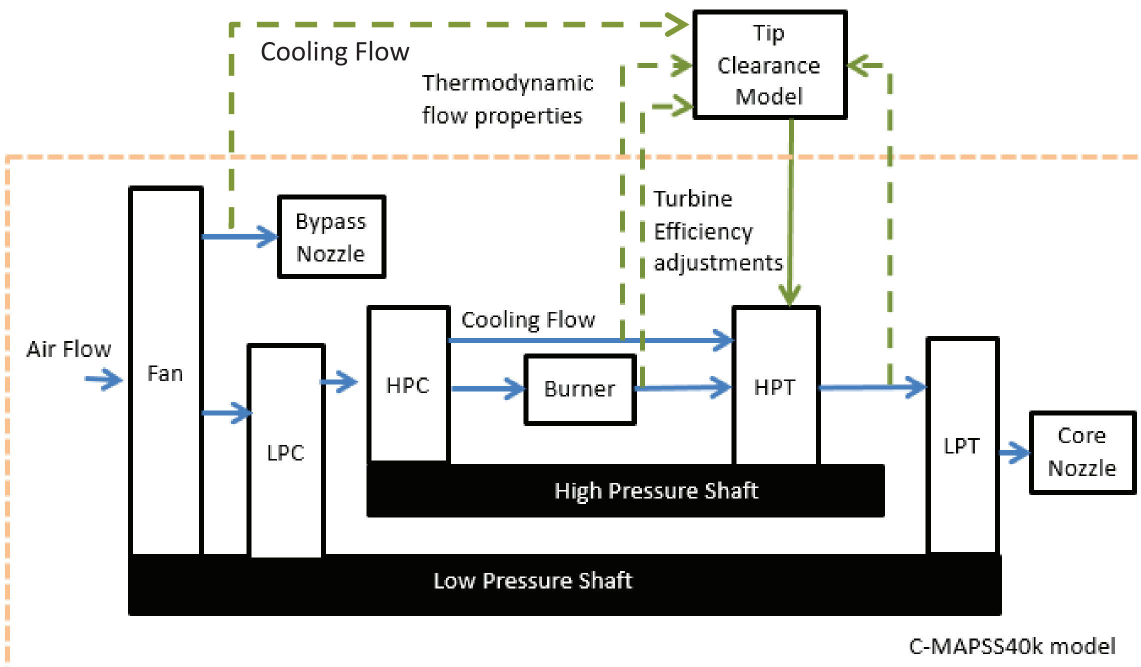
Integration with Engine Model

- Engine simulation supplies inputs and boundary conditions for the tip clearance model (temperatures, mass flow rates, etc.)
- Tip clearance model supplies in turbine efficiency adjustment to the engine model creating a coupled effect
- Applications: C-MAPSS40k (modern large gas turbine) & AGTF30 (NASA CGT)



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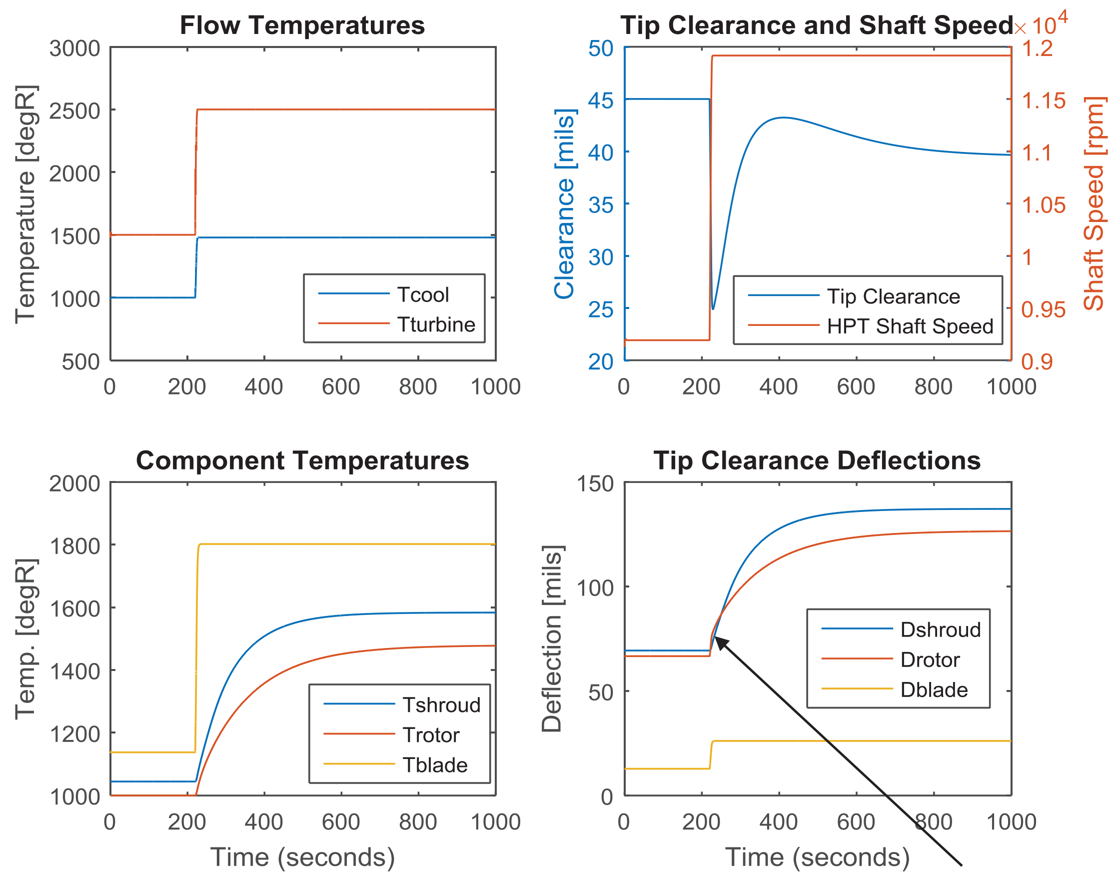
Integration with Engine Model

<u>C-MAPSS40k</u>

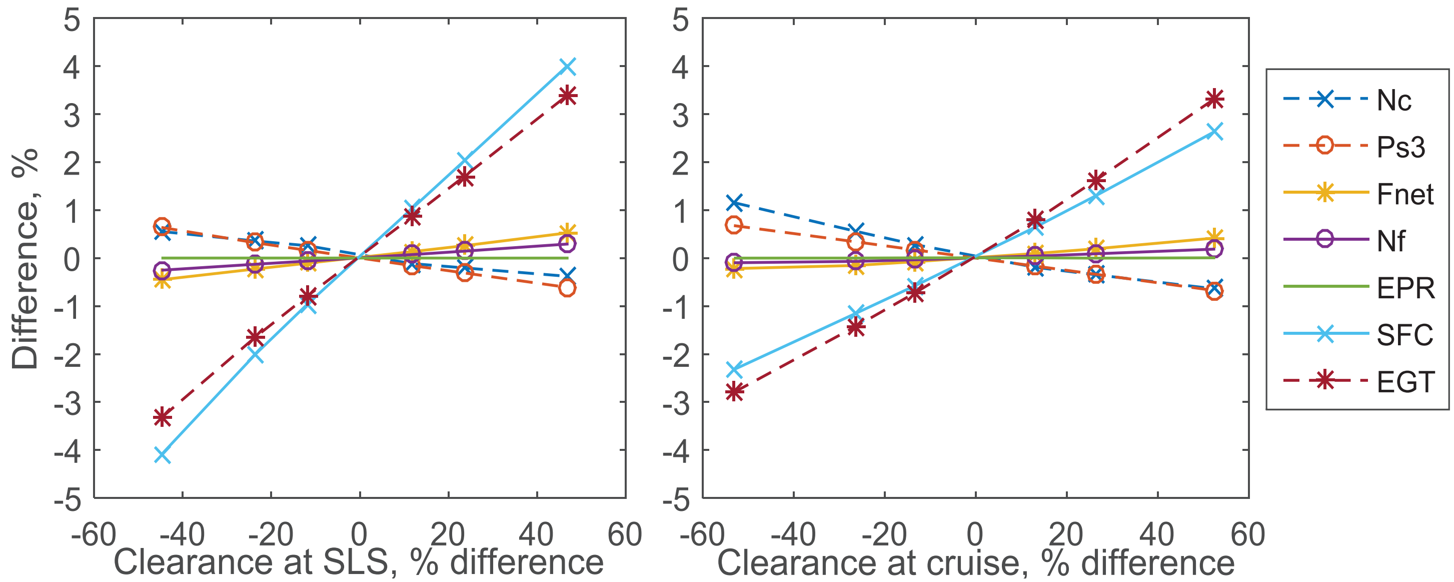
- Acceleration from idle to full power at time 200sec
- Shroud and Rotor temperature changes relatively slowly
- Blade deflection and shaft effects occur relatively quickly
- Pinch point location and depth determined by relative deflection responses



High time constant shaft rotor effects

C-MAPSS40k: Sensitivity Studies

- Develop understanding of link between tip clearance and performance



- Linear response shown for non-linear model.
- EGT and SFC have the largest change in performance (large benefit at cruise conditions)

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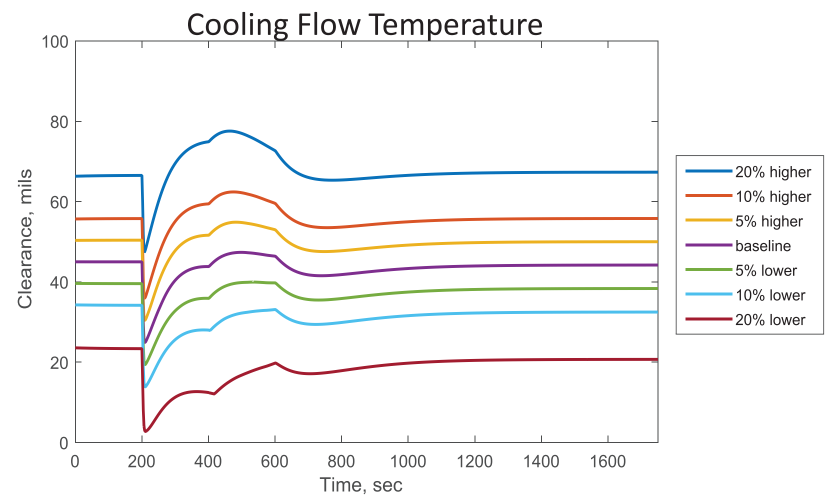
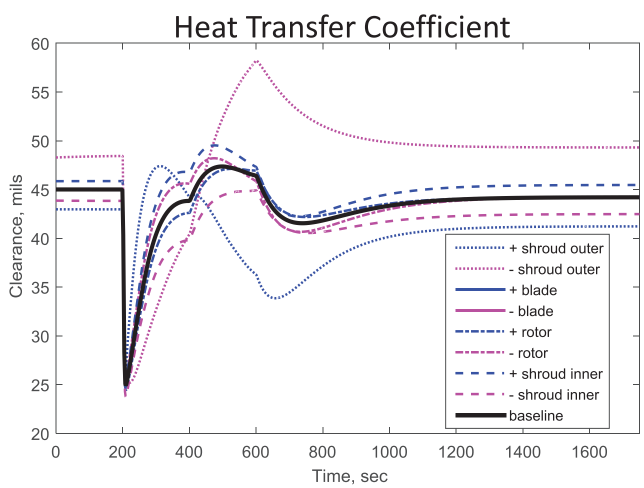
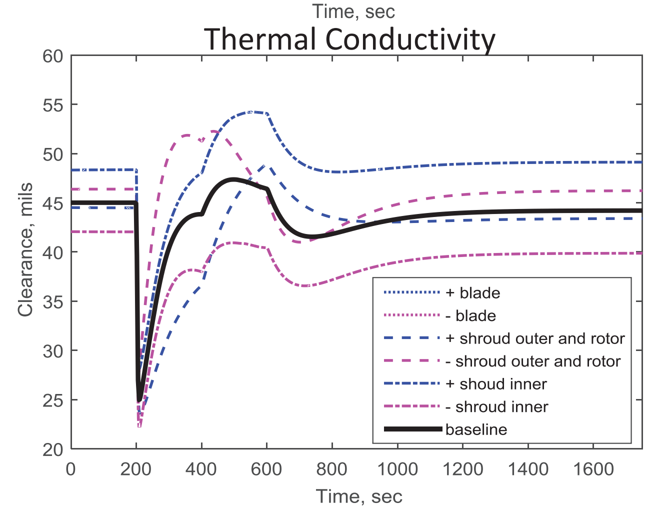
C-MAPSS40k: Sensitivity Studies

- Explore modeling sensitivity to changes in assumed values
  - Cooling flow temperature
  - Convective heat transfer coefficient
  - Thermal conductivity of materials



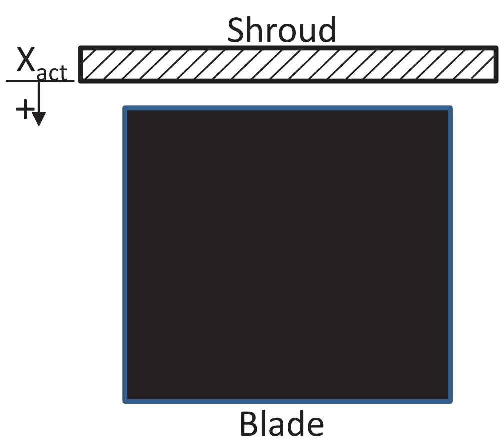


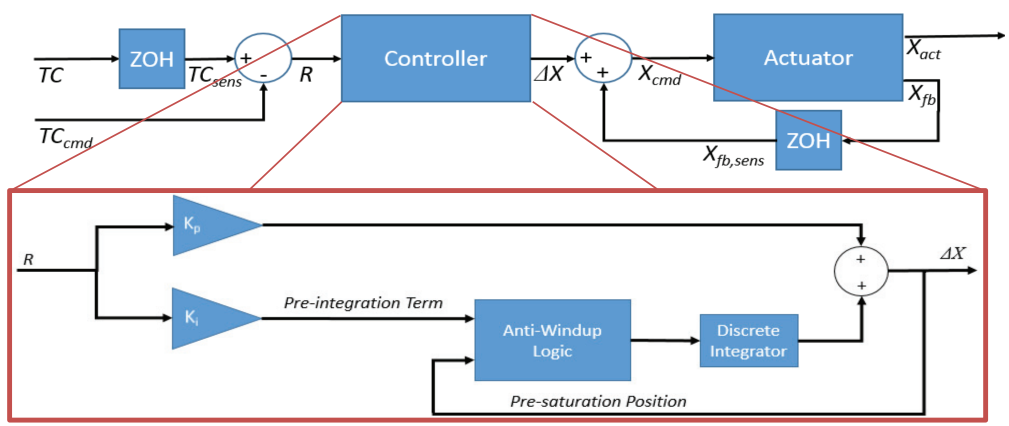


C-MAPSS40k: Actuator Studies

Actuator, Sensor, & Controller Modeling

- Actuator
  - Generic 1st Order Dynamics
  - Linear Properties: Bandwidth
  - Nonlinear Properties: Rate Limit, Saturation Limits, Deadband (applied to feedback position)
- Sensors
  - Measurements - Tip Clearance & Actuator Feedback Position
  - Zero order hold (no dynamics and exact)
- Controller
  - Proportional Integral (PI) control logic
  - PI gains tuned with same algorithm
  - Clamping circuit implemented for integral wind-up protection

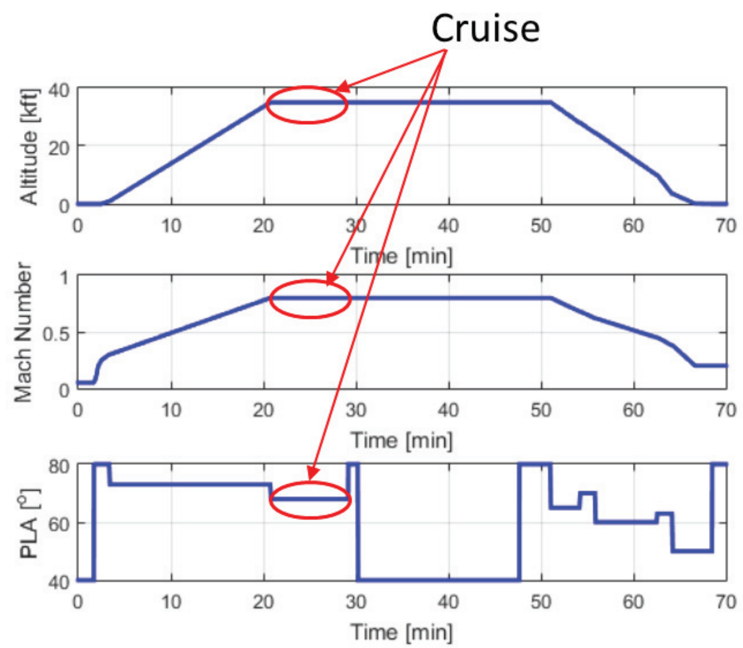




C-MAPSS40k: Actuator Studies

Simulation Description

- Goal: Identify the minimum maintainable tip clearance and corresponding cruise performance such that the an acceptable tip clearance is maintained during transients
- Actuator only seeks to address axisymmetric variations
  - Seeks to assure a margin of ~20mils is present at all time Baseline tip clearance at ground idle: ~55mils
- Simulation: For each actuator
  - Ran a simulation through a defined flight profile
  - The commanded tip clearance was adjusted to achieve a minimum tip clearance of ~20mils while considering all transients



Variable	Value
Tip Clearance, *TC*	50.31mils
Turbine Efficiency, η	0.8922
Fuel Flow Rate, w_f	1.401lb$_m$/sec
Thrust Specific Fuel Consumption, *TSFC*	0.2428
Turbine Inlet Temperature, T_4	2840°R

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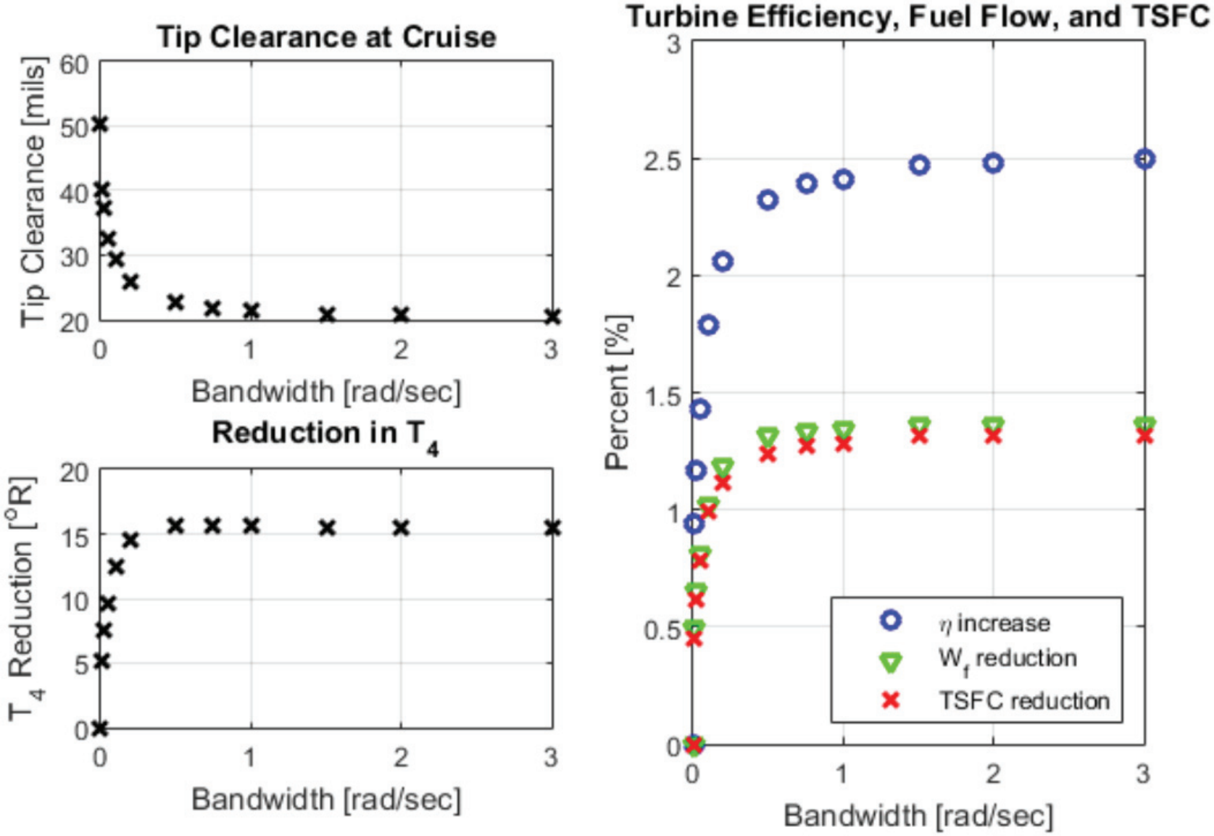
C-MAPSS40k: Actuator Studies

Bandwidth Studies



Relevant Bandwidth (BW) Range: 0.1 – 1rad/sec

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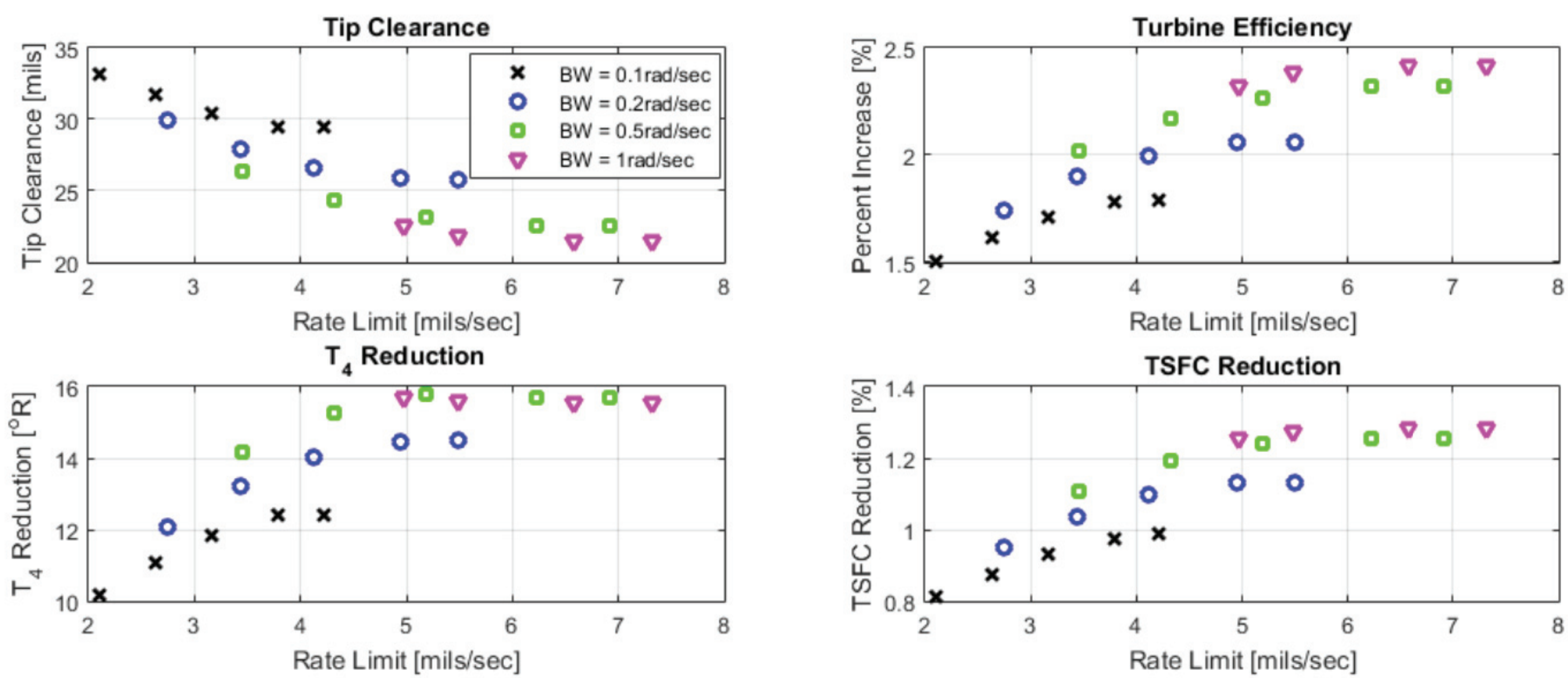
C-MAPSS40k: Actuator Studies

Rate Limit Studies



Relevant Rate Limit (RL) Range: > 4mils/sec

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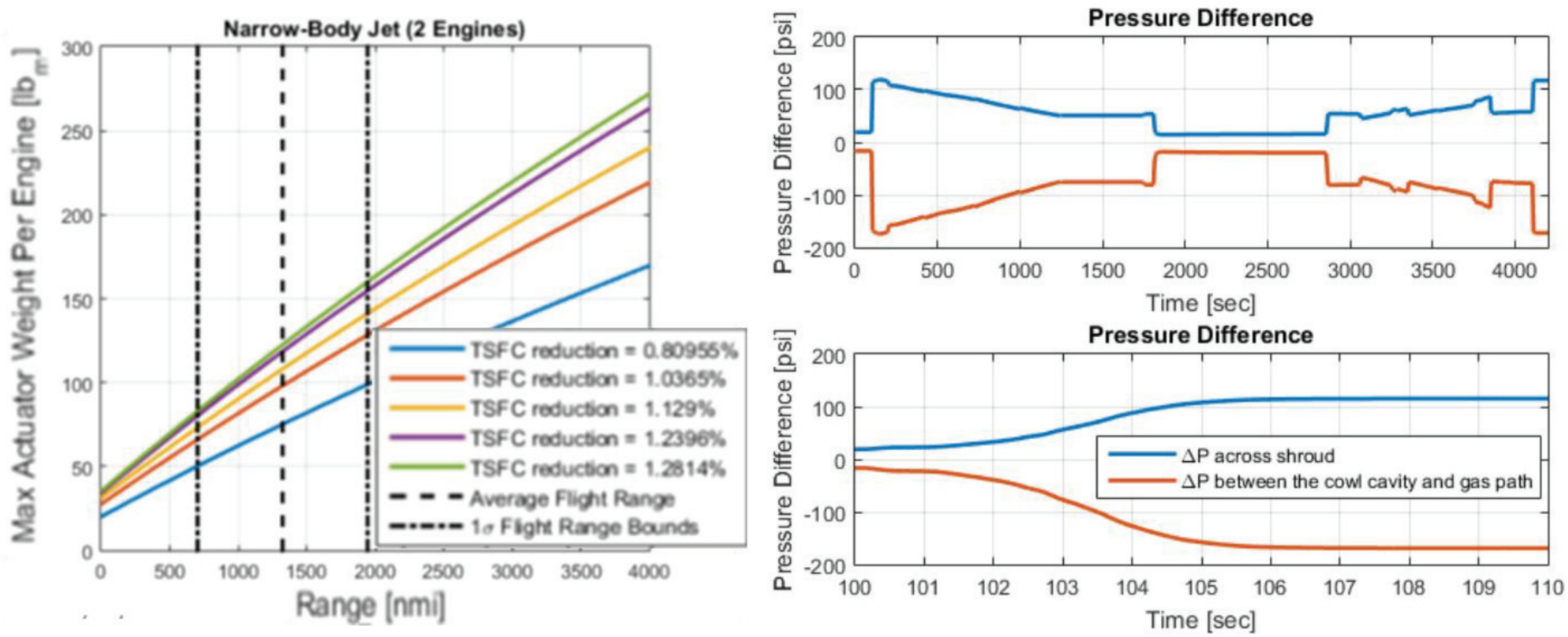
C-MAPSS40k: Actuator Studies

Weight & Force

- Range based weight analysis – weight that can be added to the system to offset the effect of carrying less fuel (conservative estimate)
- Force evaluation looks at the variation of the pressure differential in two scenarios – (1) modulation of the shroud, (2) modulation of the shroud & casing assembly



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C-MAPSS40k: Actuator Studies

- Appropriate actuator parameters:
  - Bandwidth: 0.1 – 1rad/sec
  - Rate Limits: ≥ 4mils/sec
  - Range: ≥ 40mils
  - Deadband: ≤ 2mils
  - Weight & Force: Application specific
- Used the results to select appropriate actuator parameters that respect the 20mil tip clearance margin

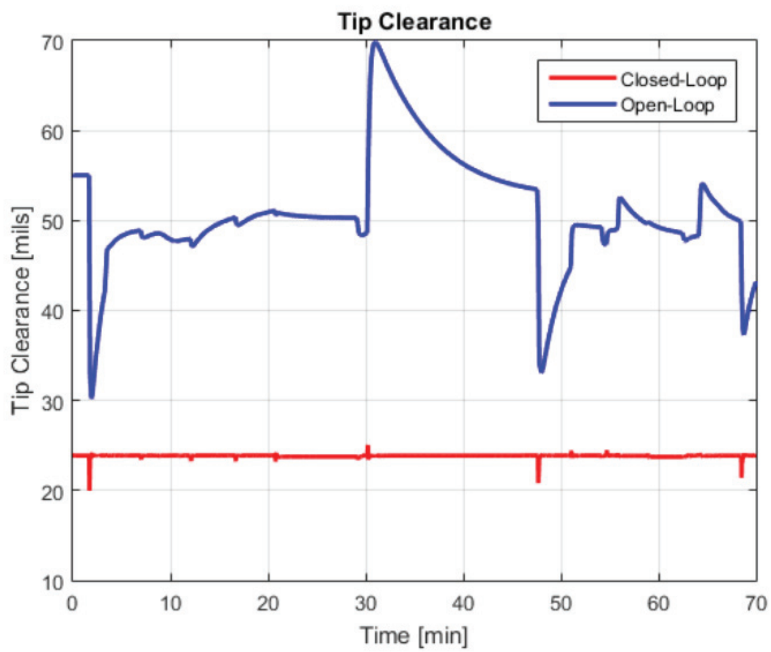
Parameters Chosen Based on Comprehensive Study

Bandwidth = 0.5rad/sec

Rate Limit = 5mils/sec

Range = 40mils

Deadband = 1mil



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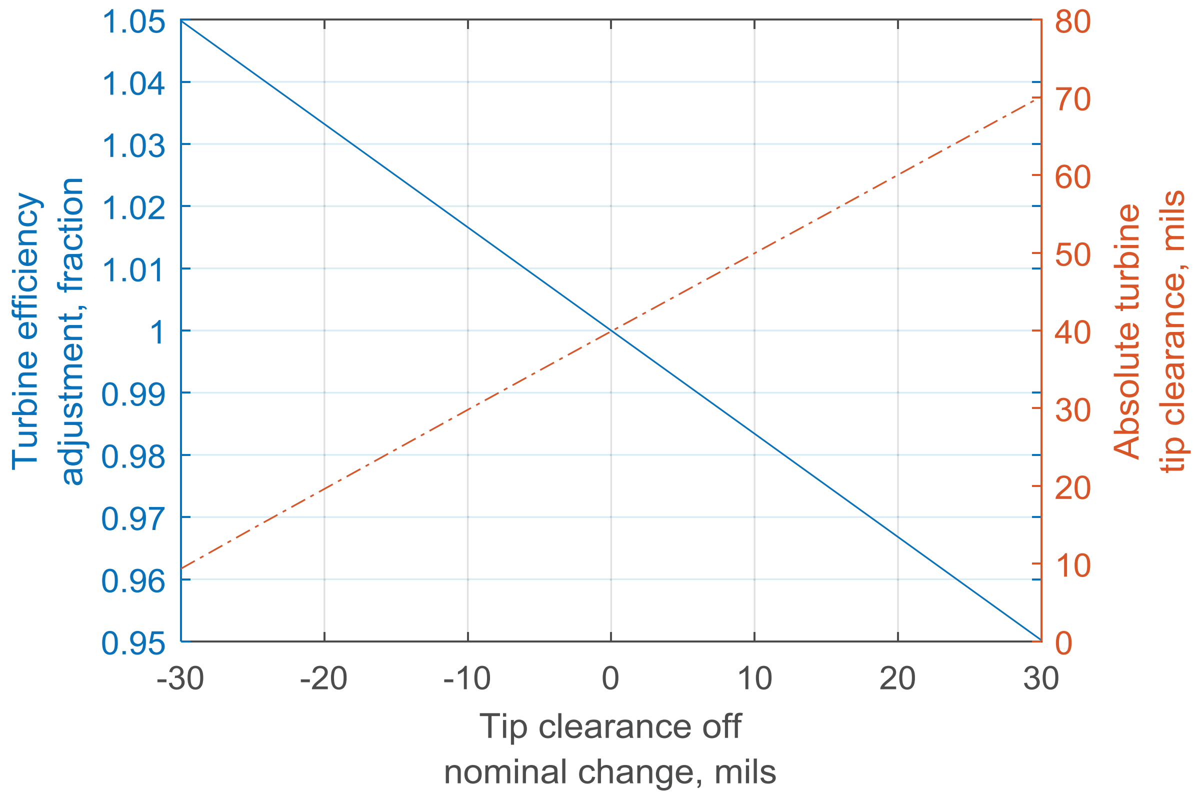
Compact Gas Turbine Studies

- Off-nominal tip clearance effects the turbine efficiency in a linear fashion.



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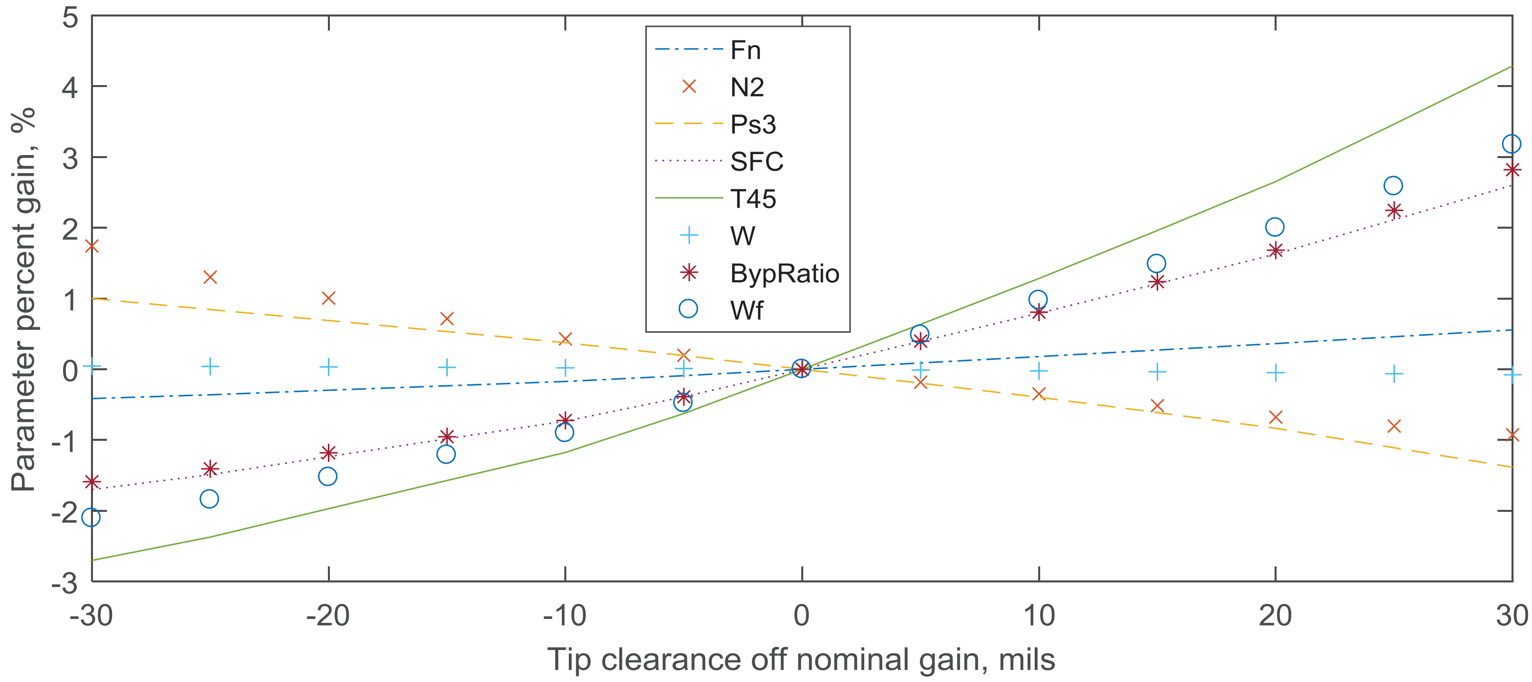
Compact Gas Turbine Studies

- Engine performance shifts as component operating point is adjusted. With decreasing tip clearance:

Core speed increases
Ps3 increases
T45 decreases
SFC decreases
Bypass ratio decreases



Summary

- Developed tip clearance modeling tools
- Developed and integrated tip clearance models with engine simulations
- Performed sensitivity studies
- Performed parametric actuator studies

– Wrapping up sensitivity and parametric actuator studies for a CGT

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Acknowledgements

The authors would like to acknowledge the creators of C-MAPSS40k & T-MATS. This work supports the objectives and goals of NASA's Advanced Air Transportation Technology (AATT) Project funded by the Aeronautics Research Mission Directorate (ARMD).

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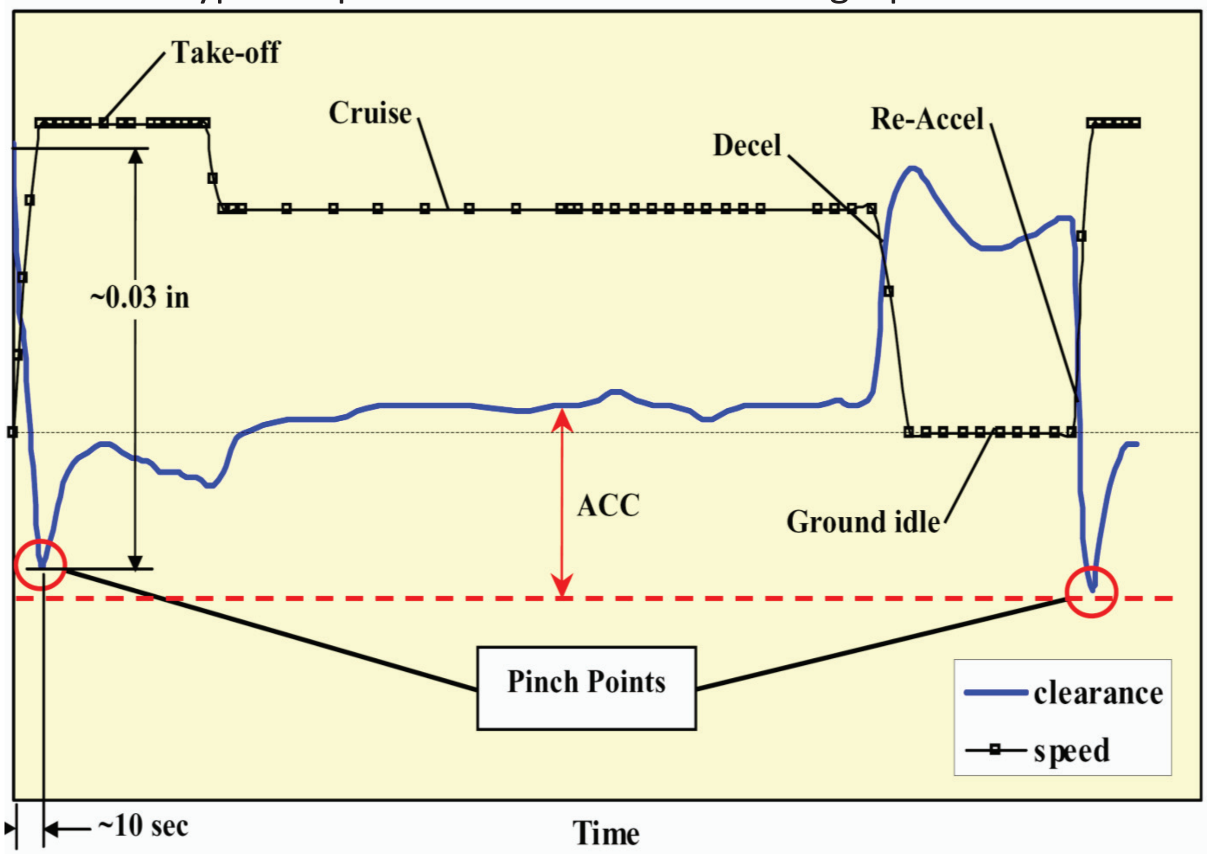
EXTRA SLIDES

Background

Typical Tip Clearance Variations during Operation



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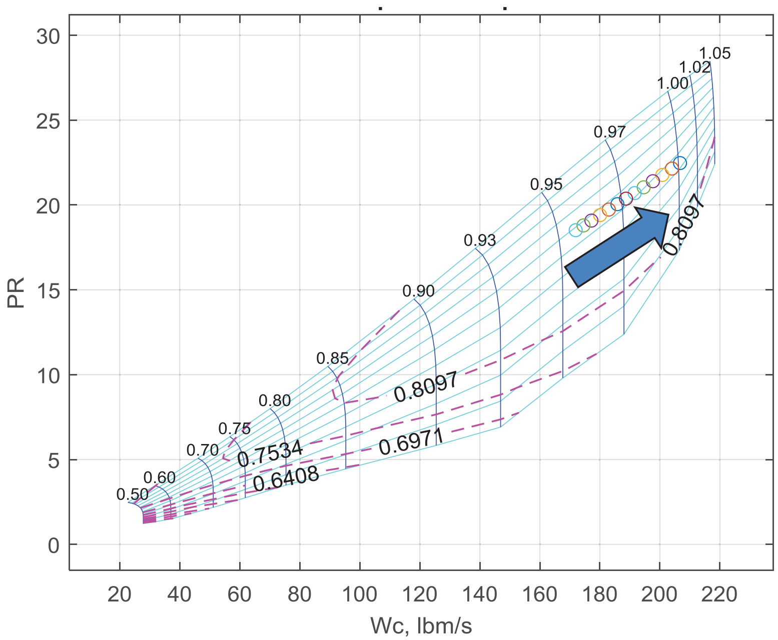
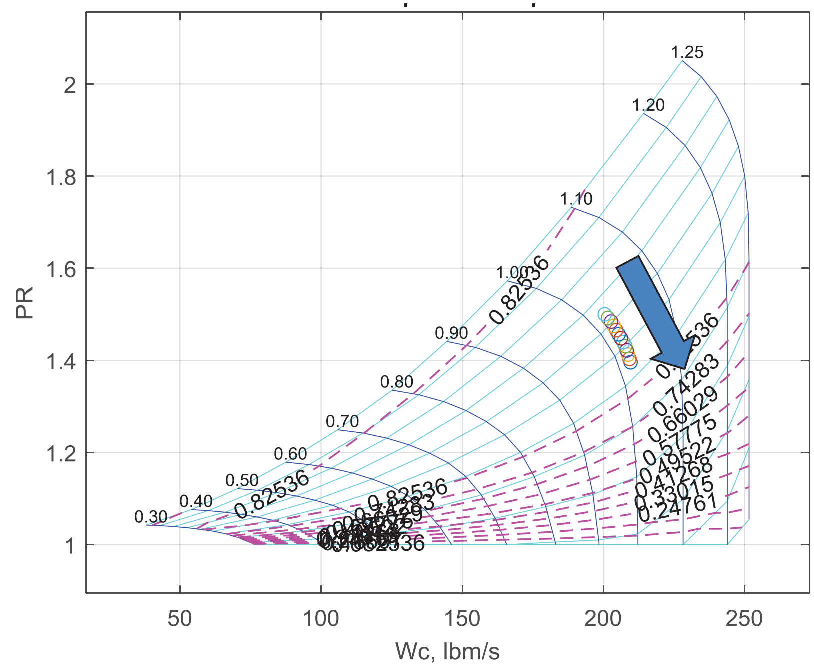
Compact Gas Turbine Studies

- Decreasing tip clearance from +30 mils to -30 mils at cruise on a fan speed controlled engine.

The rising turbine efficiency causes the HPC speed and flow within the core to rise.





Pressure at the back end of the LPC is reduced as more air is drawn through the core.

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A Dynamic Model for the Evaluation of Aircraft Engine Icing Detection and Control-Based Mitigation Strategies

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6th GRC Propulsion Control and Diagnostics Workshop
August 22-24, 2017
Cleveland, OH

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Outline

- Background:
  - The ice particle threat to engines in flight
  - A control-based approach to icing risk mitigation
- Dynamic engine model overview and features
  - Closed-loop control logic
  - Heat extraction due to ice particle ingestion
  - Flow blockage due to ice buildup in engine compression system
  - Engine actuators
- Comparison of dynamic engine model to engine ice crystal icing test cell data and manufacturer's customer deck
- Summary

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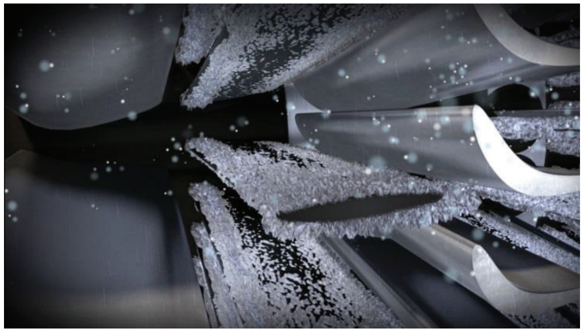
The Ice Particle Threat to Engines in Flight

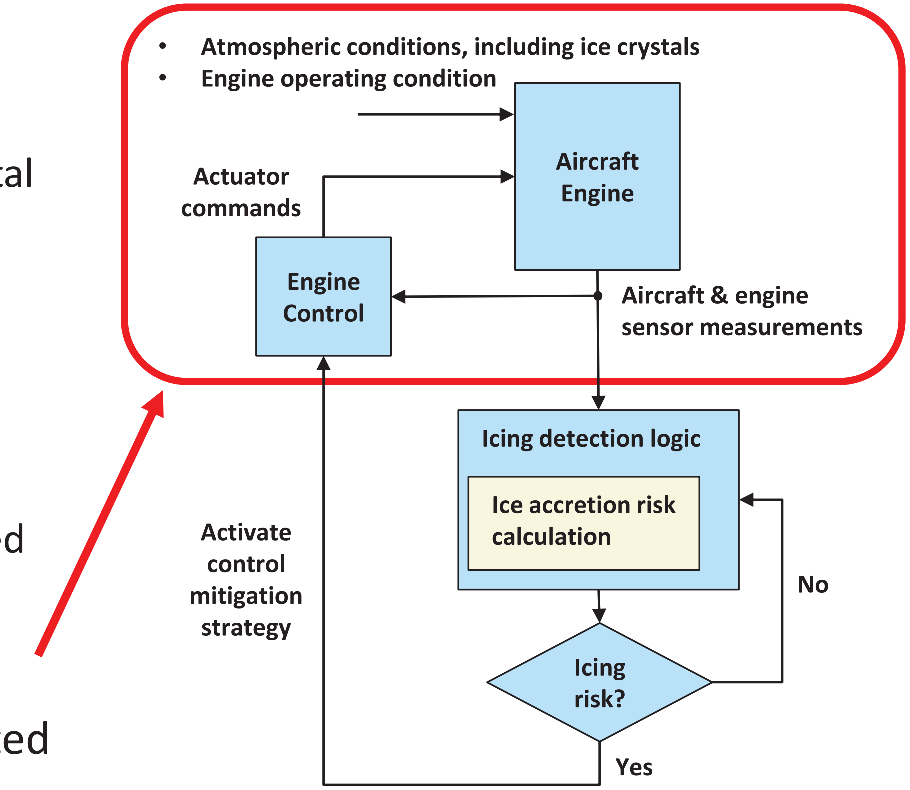
- Since 1990, there have been a number of jet engine powerloss events reported on aircraft operating in ice particle conditions
  - Temporary or sustained power loss, engine uncontrollability, engine shutdown
- Ice crystals enter the engine's core, melt, and accrete on engine components during flight
- Many possible causes of power loss:
  - Damage due to ice shedding
  - Flame-out due to combustor ice ingestion
  - Compressor surge
  - Sensor icing
  - Engine rollback
- Within the aviation community, research is ongoing to:
  - Characterize the environmental conditions under which engine icing can occur
  - Understand the mechanisms by which ice particles can accrete on engine components
  - Develop mitigation strategies for engine icing



Images courtesy of NASA

Control-Based Icing Risk Mitigation

- Potential mitigations to engine icing problem include
  - Avoidance of flight through ice crystal atmospheric conditions
  - Re-design of engine hardware
  - Ice protection systems
- Active control icing risk mitigation architecture
  - Includes detection and control-based mitigation logic
- This presentation will focus on a dynamic aircraft engine model created for the initial development and evaluation of aircraft engine icing detection and control-based mitigation strategies.



Active Control Icing Risk Mitigation Architecture

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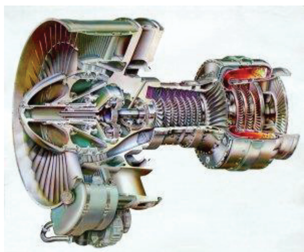
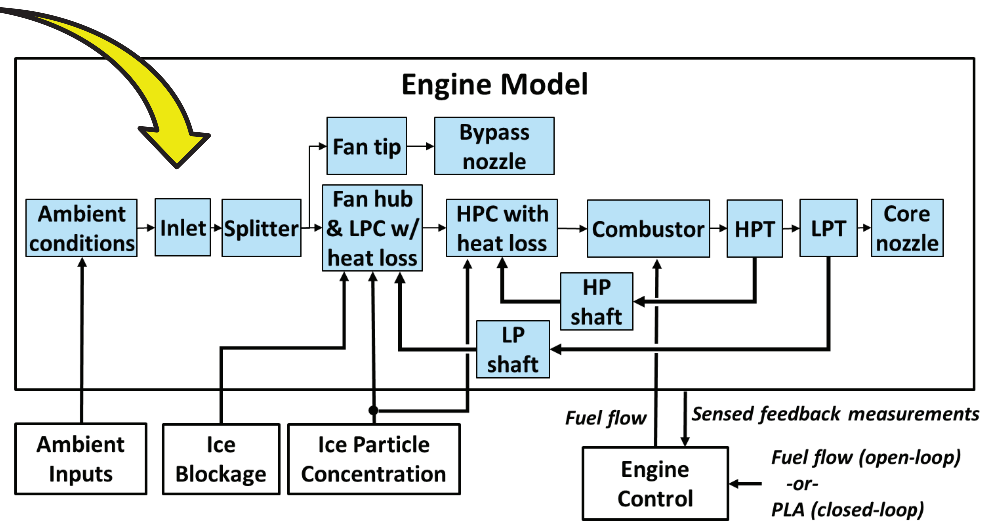
Dynamic Engine Model Overview

Image courtesy of Honeywell



ALF502R-5 Turbofan Engine

Experimental versions of this engine underwent engine icing testing at NASA Glenn in 2013 and 2015



Engine model block diagram

- Dynamic model of Honeywell ALF502R-5 turbofan engine
  - 0D component level model
  - Derived from Numerical Propulsion System Simulation (NPSS) model of the ALF502R-5
  - Coded in the Matlab/Simulink environment using a NASA-developed open-source thermodynamic simulation package – Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)
  - Includes performance losses caused by heat loss due to ice particle ingestion and ice blockage in the engine's compression system
  - Includes engine control logic enabling the simulation of transient engine operation

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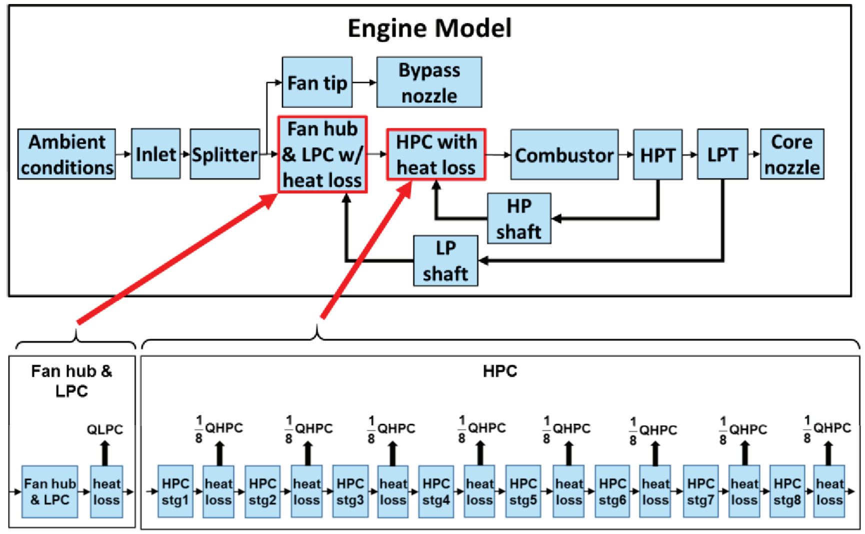
Heat Extraction Due to Ice Particle Ingestion



- Model includes heat (enthalpy) extraction effects to account for the phase transition (ice→water→vapor) that ingested ice particles undergo as they pass through the engine's compression system.
- Heat extraction is modeled to occur both within the LPC and the HPC:

$$\textit{LPC heat extraction}: \quad Q_{LPC} = w_{ice}c_{ice}\left(T_{melt} - T2\right) + w_{ice}H_f + w_{ice}c_{water}\left(T25 - T_{melt}\right)$$

$$\textit{HPC heat extraction}: \quad Q_{HPC} = w_{ice}c_{water}\left(T_{boil} - T25\right) + w_{ice}H_v + w_{ice}c_{steam}\left(T3 - T_{boil}\right)$$

w_{ice} = ice mass flow rate
T_{melt} = ice melting temp
T_{boil} = water boiling temp
c_{water} = specific heat of water
c_{ice} = specific heat of ice
H_f = heat of fusion of ice
H_v = heat of vaporization of water

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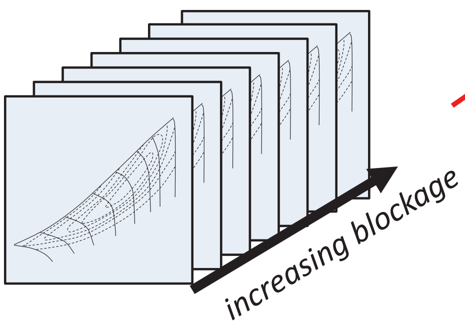
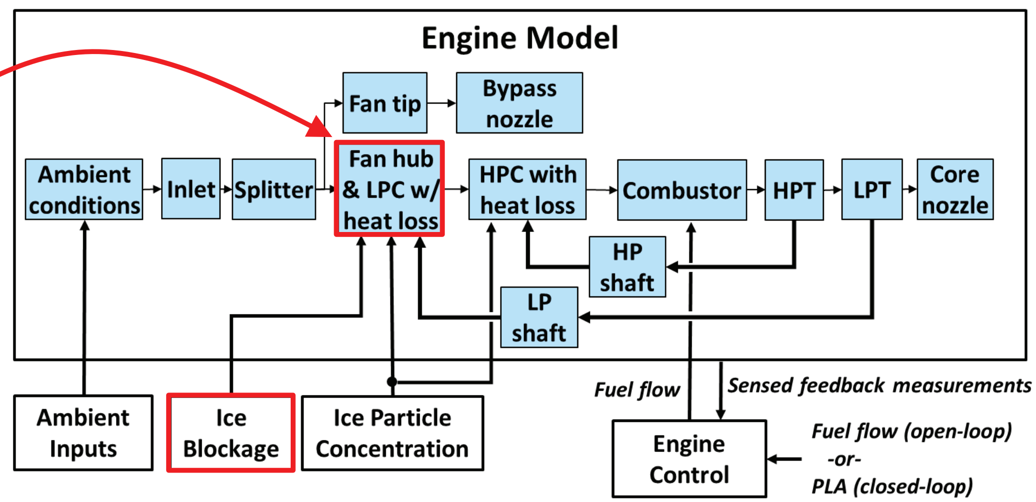
Flow Blockage Due to Ice Buildup in LPC

- Model includes an “LPC ice blockage” input, a lumped parameter that captures LPC performance changes due to ice accretion
- Captured through a series of modified LPC maps, each representing a different amount of ice blockage (maps generated from NASA-developed mean line compressor code (COMDES))
- Results in a series of maps that can be stacked and interpolated between to simulate changing levels of ice blockage

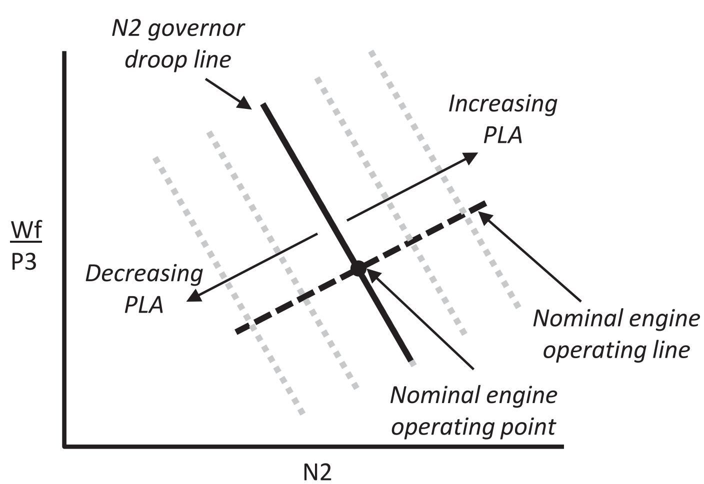


Stacked series of LPC compressor maps reflecting increasing levels of ice blockage

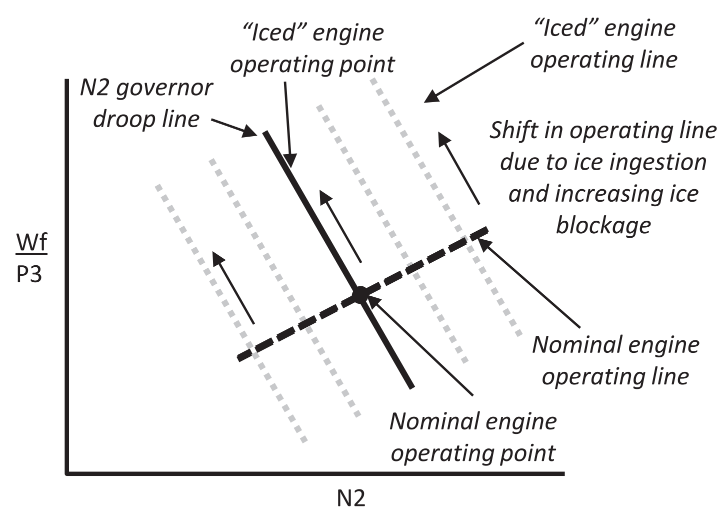


Engine Control Logic

- User can operate the engine in either open-loop or closed-loop control mode
  - In open-loop operation, user supplies fuel flow input
  - In closed-loop operation, user specifies power lever angle (PLA), and engine operates on core speed (N2) governor droop line
  - Closed-loop control logic allows the model to emulate the ALF502R-5 engine's response to ice particle ingestion and ice blockage in the LPC



Movement of N2 governor droop line with changing PLA



Movement of engine operating line caused by heat transfer due to ice ingestion and increasing ice blockage

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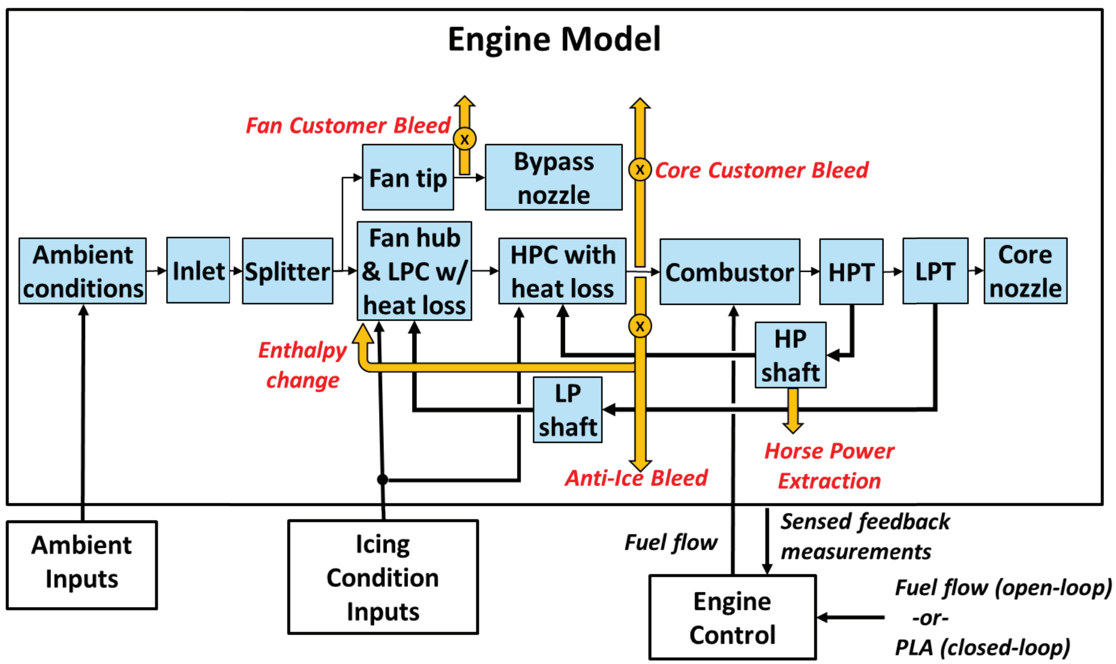
Auxiliary Actuators

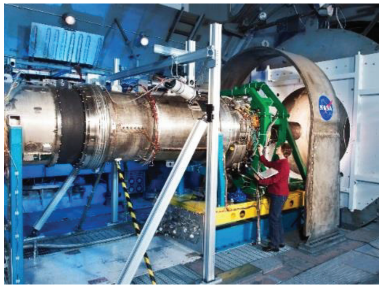
- Four auxiliary actuators added to model – enables future studies to assess how modulation of these actuators impacts ice accretion risk.
  - Fan customer bleed
  - Core customer bleed
  - Anti-ice bleed
  - Horsepower extraction



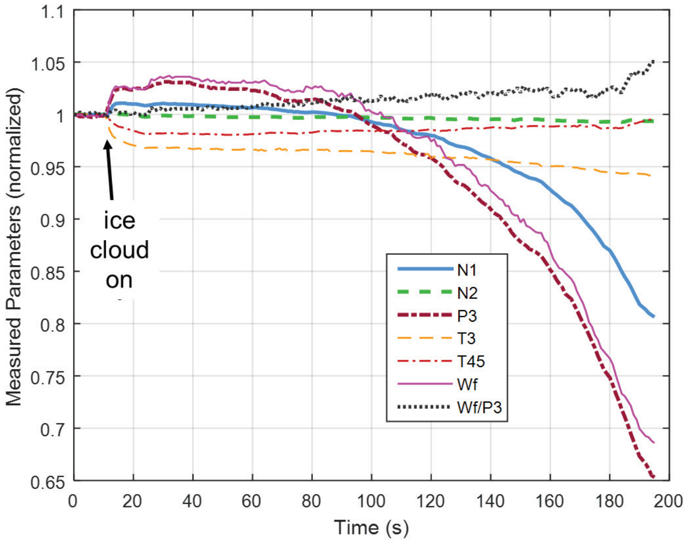
Aircraft Engine Ice Crystal Icing Testing in NASA Glenn Propulsion Systems Laboratory (PSL)

- The NASA Glenn PSL is an altitude simulation facility for experimental research on air-breathing propulsion systems
- A PSL test cell has been upgraded to include a water spray nozzle array system to produce simulated ice crystal cloud conditions
- Experimental versions of Honeywell ALF502R-5 engine underwent ice crystal icing testing in PSL in 2013 (LF01) and 2015 (LF11).

Water injection spray bars installed in PSL test cell



Experimental ALF502R-5 engine installed in PSL test cell



Normalized measurement parameters recorded during uncommanded engine rollback event caused by ice crystal icing (LF01 Run 193)

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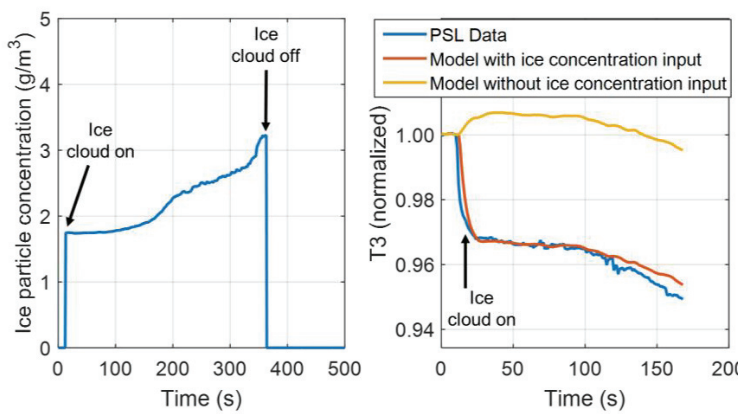
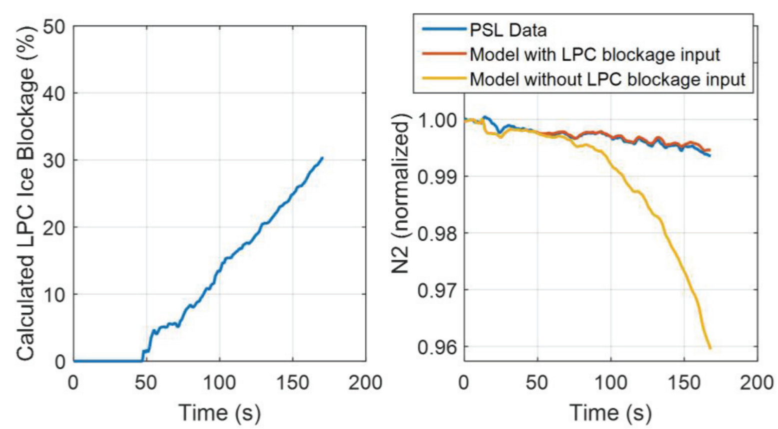
Comparison of Dynamic Engine Model to LF01 Engine Experimental Data

- Model was run under both open-loop and closed-loop control mode
  - Recorded parameters of altitude, Mach, dTamb, Wf (open-loop only), and PLA (closed-loop only) were supplied as model inputs
  - Additional model input parameters of ice particle concentration and LPC ice blockage were determined based on experimental data
    - Ice particle concentration profile is calculated as a function of measured spray bar water flow rate and engine volumetric flow rate, with scale factor adjustment to produce a comparable temperature drop as that observed in recorded HPC exit temperature (T3)
    - The percentage of LPC ice blockage was not measurable during the test. Model input of this parameter was selected to match measured engine core speed (N2) response.



a) Calculated ice particle concentration b) Engine and model T3 response

Calculated ice particle concentration and T3 response during LF01 Run 193 rollback event

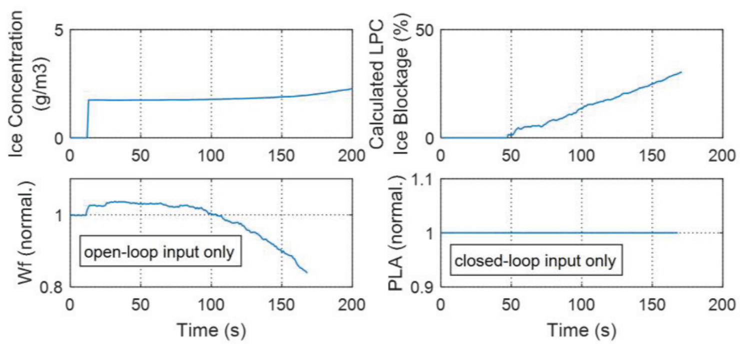


a) Calculated LPC ice blockage b) Engine and model N2 response

Calculated LPC ice blockage and N2 response during LF01 Run 193 rollback event

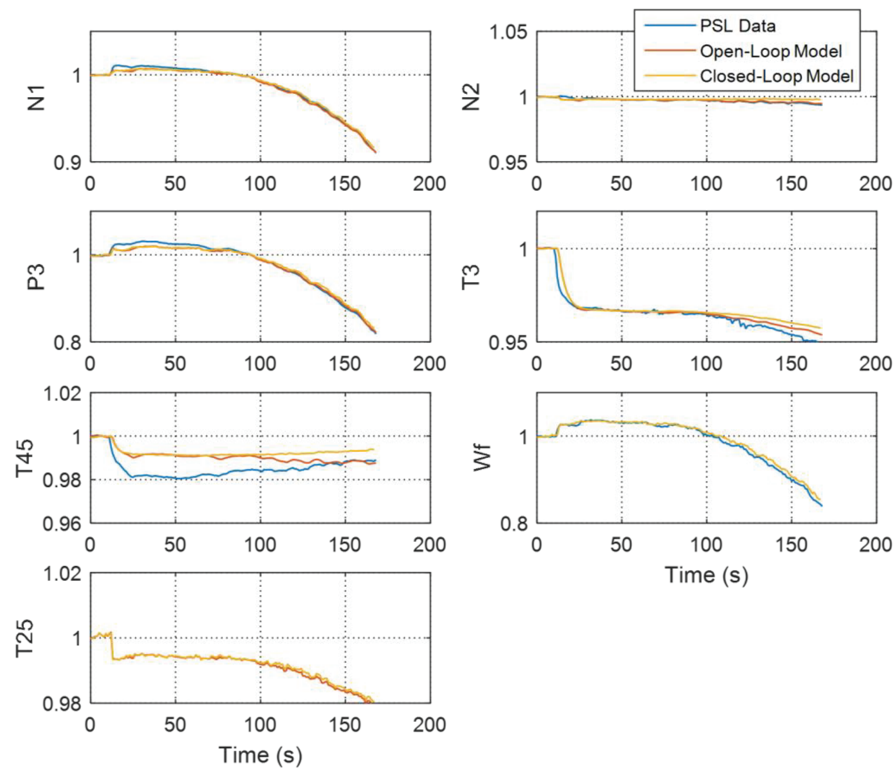
Modeling of LF01 Run 193 Engine Rollback Event

- Run 193 rollback event was simulated by running the dynamic engine model in both open-loop and closed-loop control mode
- Flight condition for Run 193 was 28K feet, 0.5 Mach, and ISA +28°F



Model Input Parameters (in addition to Alt, Mach, and dTamb)

- Ice concentration
- % ice blockage
- Fuel flow (Wf): *open-loop only*
- Power lever angle (PLA): *closed-loop only*



Normalized Engine and Model Output Parameters

- Fan speed (N1)
- HPC exit pressure (P3)
- Exhaust gas temp (T45)
- LPC exit temp (T25)
- Core speed (N2)
- HPC exit temp (T3)
- Fuel flow (Wf)

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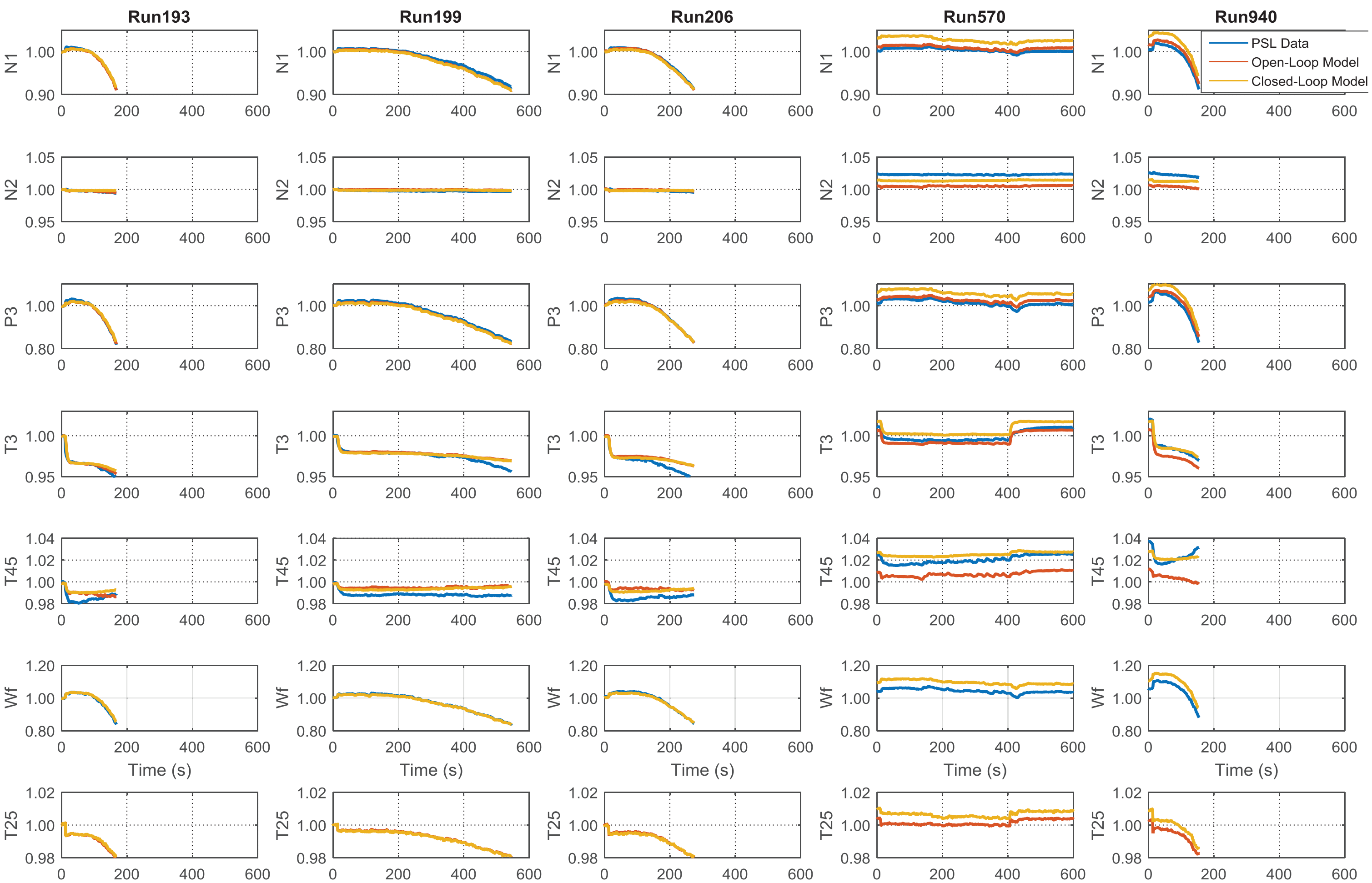
Modeling of Additional LF01 Engine Rollback Events (cont.)



Model Output Parameters

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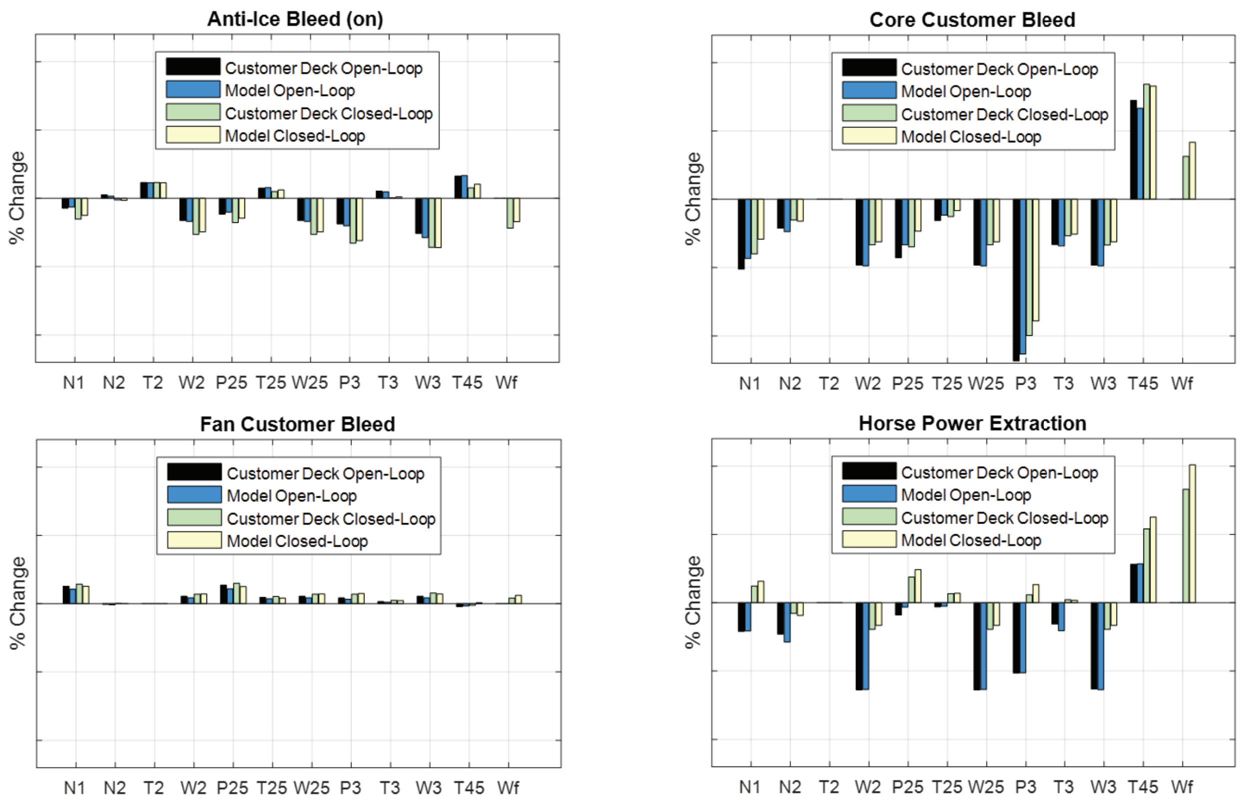
Comparison of Engine Model to Customer Deck

- In follow-on studies, the developed engine model will be used to evaluate the feasibility of control-based strategies for mitigating the risk of engine icing. This will entail modulation of the model's auxiliary actuators and assessing the corresponding impact on icing risk.
- The manufacturer's steady-state customer deck was used to assess correct implementation of auxiliary actuators within the model.



Comparison of Model and Customer Deck Steady-State Response to Actuator Modulation

Summary

- A dynamic model of the ALF502-5R turbofan engine has been developed and evaluated
- Model was shown to emulate engine system-level behavior during ice crystal icing test cell evaluations as well as the steady-state outputs produced by the manufacturer's customer deck
- Key features of the model include
  - Closed-loop controller allowing the simulation of engine transients
  - Heat extraction effects reflecting the heat loss the engine experiences as ingested ice crystals melt and vaporize in its compression system
  - Flow blockage effects reflecting the buildup of ice in the engine's low pressure compressor
  - Auxiliary actuators enabling the modulation of engine performance
- Potential follow-on work
  - The model can be used in follow-on studies to develop and evaluate potential icing risk detection and control-based mitigation strategies

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Acknowledgments

• This work was conducted under the NASA Advanced Air Vehicles Program, Advanced Air Transportation Technologies Project. The authors graciously acknowledge Honeywell Engines and the Ice Crystal Consortium for their support of the engine testing that enabled this work.

Reference

• Simon, D.L., Rinehart, A.W., Jones, S.M., "A Dynamic Model for the Evaluation of Aircraft Engine Icing Detection and Control-Based Mitigation Strategies," *ASME Turbo Expo Conference*, Paper ASME-GT2017-65128, Charlotte, NC, June 26-30, 2017.

Industry Perspective on Propulsion Control and Diagnostics (PCD) Research

NASA/CP—2018-219891

Next Generation Engine Control

Shreeder Adibhatla, GE Aviation
August 23, 2017

Next Generation Engine Control – The Environment

- Controls have been getting more complex in response to engine turbomachinery changes to get more performance (better fuel burn, lower noise, lower emissions). That means more actuators, more sensors, more control logic.
- But, airline customers want high reliability and low maintenance costs
- So, simplification, weight reduction, and cost out are ever-present themes

Next Generation Engine Control - Themes

- Model-based control and diagnostics to add state-awareness
- Advanced sensors (clearance, dynamic pressure, blade health, vibes, high temperature, …). But, sensors add cost!
- Distributed engine control
- Controls for future systems: VCEs, more electric aircraft, UAVs
- Certification concerns, failure modes
- Software: Validation and verification methods, cyber security
- Integration of Controls with PHM

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Rolls-Royce Controls Future Technology Perspective

NASA GRC Propulsion Control and Diagnostics Workshop

August 22-24, 2017

Nathan Payne
Controls Technical Specialist
Controls Supply Chain Unit, Rolls-Royce Corporation

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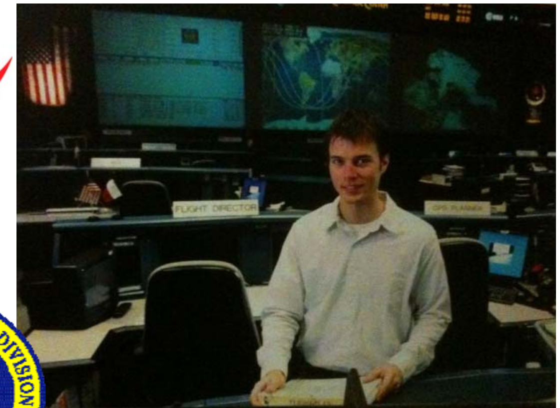
Nathan Payne

Controls Technical Specialist, Rolls-Royce Corporation










Rolls-Royce

Rolls-Royce Controls Future Technology Perspective

Rolls-Royce Controls Future Technology Perspective

HYBRID ELECTRIC PROPULSION

Model-Based Engine Control

DECWG
Distributed Engine Controls Working Group
consortium

Rapid prototype flight testing

Rolls-Royce

Session 4

Distributed Engine Control Technologies

Session 4: Distributed Engine Control Technologies
10:20-12:20 PM

10:20 **Session Overview**
Dennis Culley

10:30 **Modeling, Simulation, & Hardware-in-the-Loop Capabilities**
George Thomas

11:00 **Dynamic Thermal Modeling Capabilities**
Jonathan Kratz

11:30 **Advanced Smart Node Capabilities**
Norm Prokop

11:55 **Durable, Extreme High Temperature Integrated Circuit Capabilities**
Glenn Beheim

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- Intelligent Control and Autonomy Branch (LCC)
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  - Jonathan Kratz
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  - Shane Sowers (Vantage Partners LLC)
  - Samuel Mohler (Portland State University, Student)
  - Chao Li (Florida A&M, Summer Faculty)
- Optics and Photonics Branch (LCP)
  - Norm Prokop
  - Mike Krasowski
  - Larry Greer
  - Joe Flatico (OAI)
- Smart Sensors and Electronics Systems Branch (LCS)
  - Glenn Beheim
  - Phil Neudeck
  - Robert Okojie
  - David Spry

Distributed Engine Control Overview

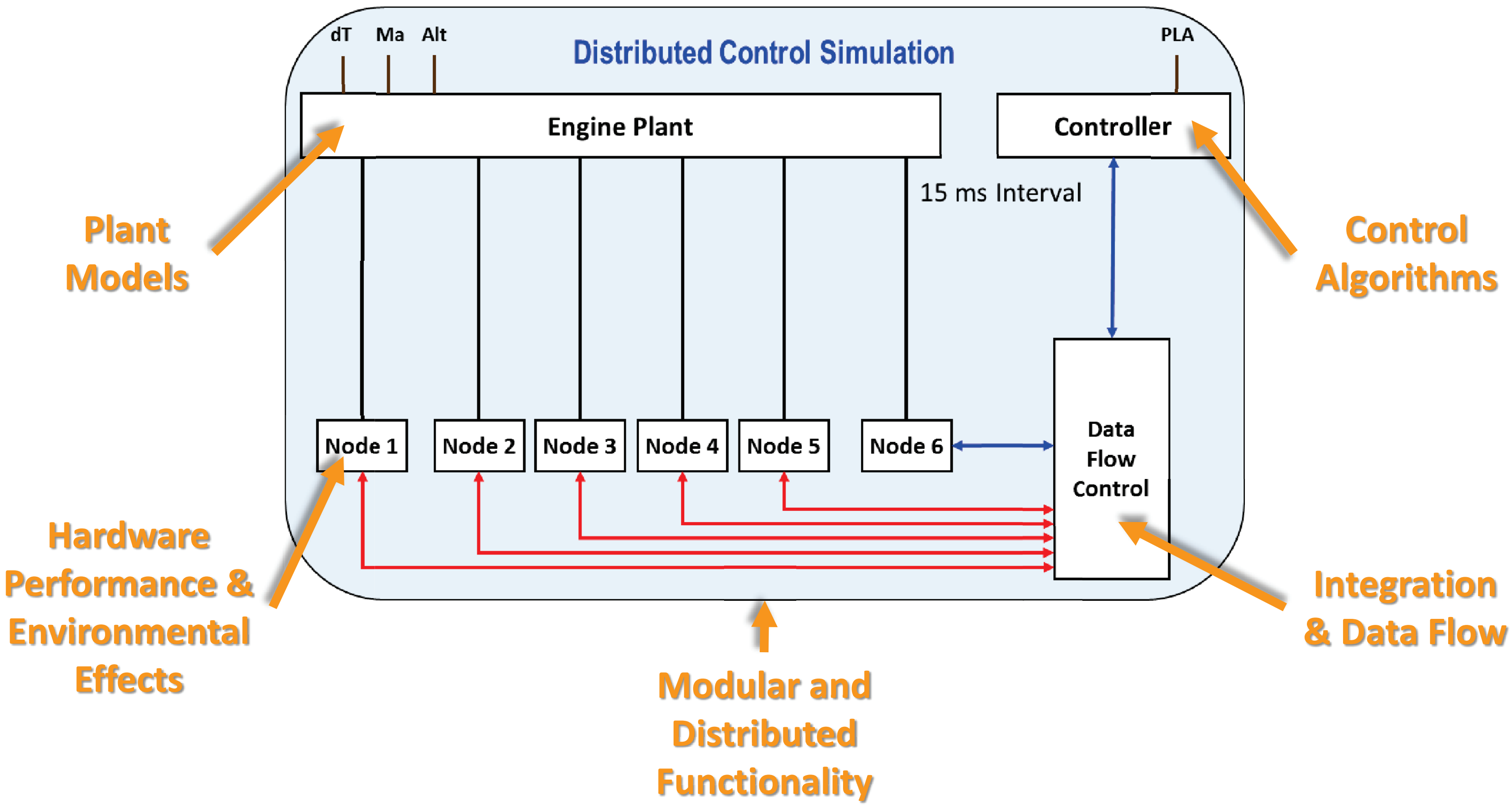
NASA is member of a larger community focused on addressing the control challenges of next generation propulsion engine systems. Modular and embedded control technologies are being developed to respond to new system constraints while enabling advanced capabilities that offer improved overall system efficiency and performance.

New Technology only matters when it brings a New Capability that outweighs the cost and risk of the old technology

NASA's investment in propulsion control affords two roles:

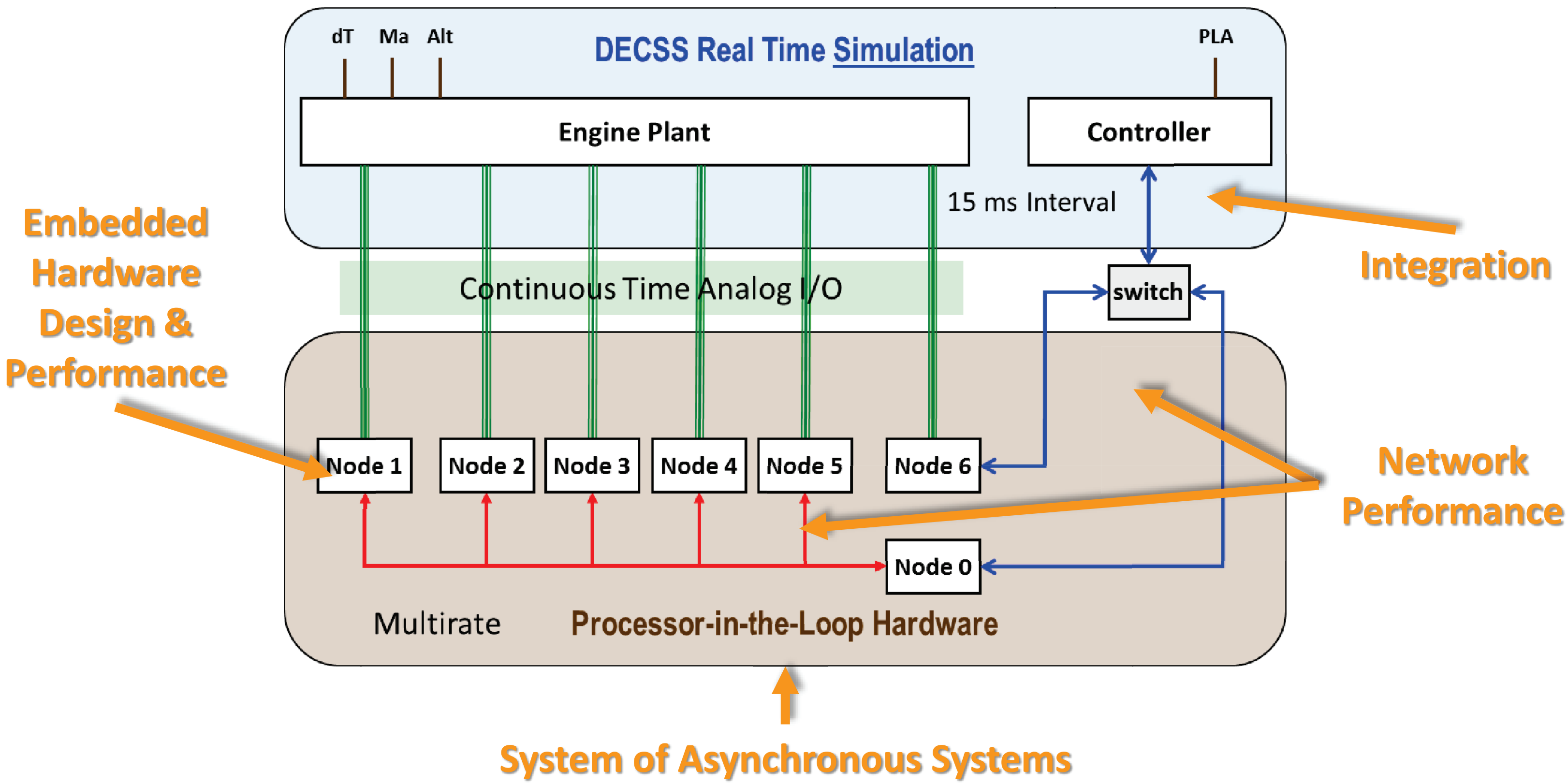
- to create tools and technologies that help understand & demonstrate the capability & performance of these new control technologies to inform system level metrics
- provide a leading but complimentary role, using NASA competencies, to reduce barriers for long-term technology growth

Modeling & Simulation of Distributed Control



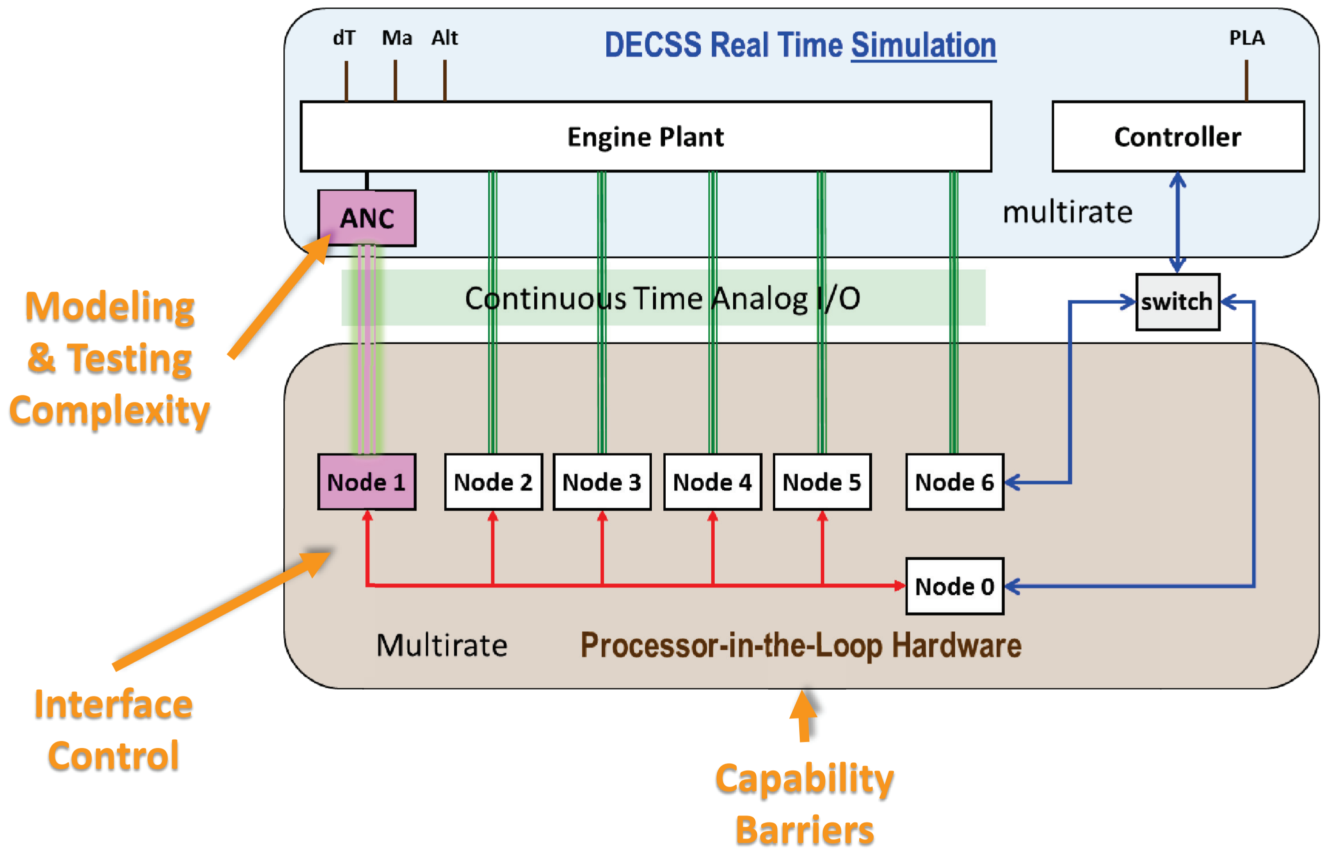
Goal: Rapidly build & model a representative hardware control architecture around any engine system

Real Time Simulation with Hardware



Goal: Understand real performance limitations of hardware architectures

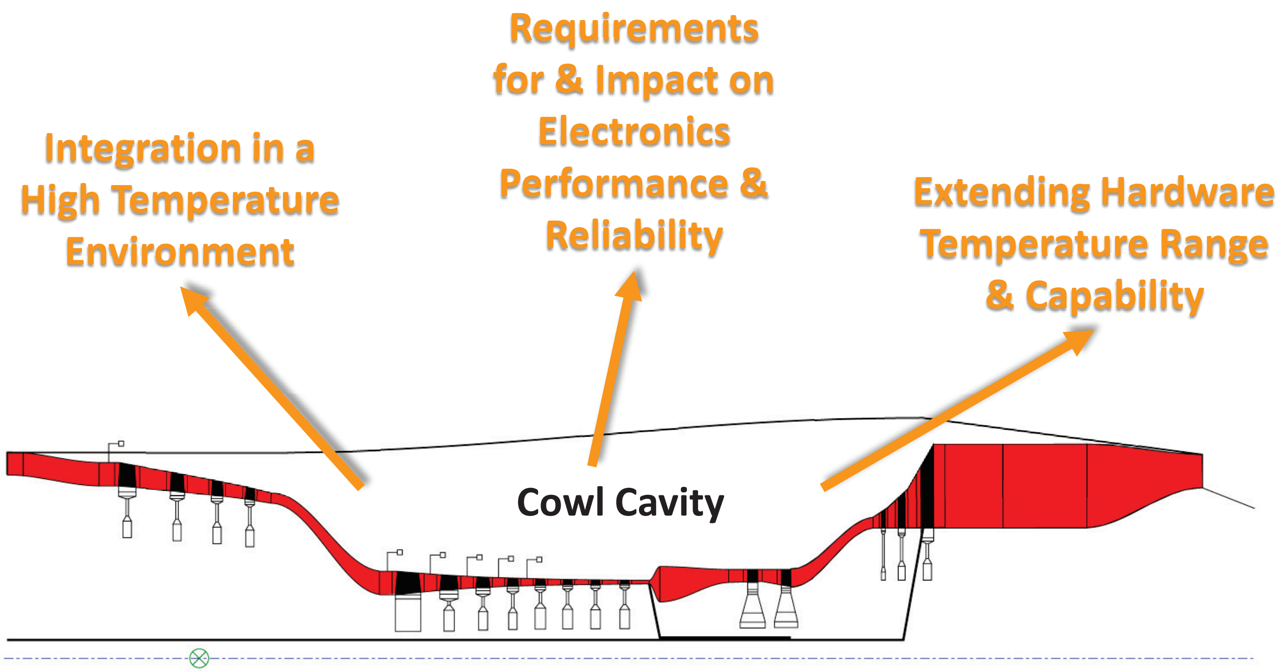
Real Time Simulation with Advanced Controls



Goal: Provide an open platform for early testing and integration at low TRL

Embedded Hardware Development & Capability

System constraints on control hardware



Engine Core Cross Section

Goal: Push the boundaries of propulsion control capability

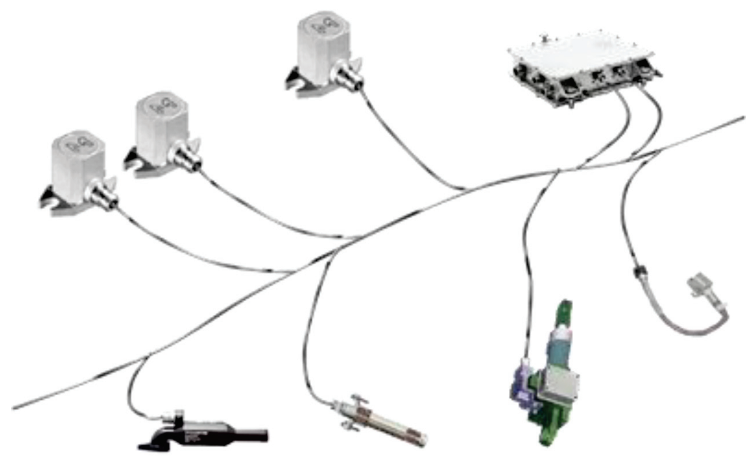
MODELING, SIMULATION, AND HARDWARE-IN-THE-LOOP CAPABILITIES

Outline

- Introduction
  - Modeling Capability and Approach
  - Distributed Engine Control System Simulator
- Applications
  - Simulation Studies
    - CMAPSS40k Communication Schedule Simulation Study
  - Hardware-in-the-Loop Test Studies
    - Sporian P3 Test Article
    - AGTF30 DEC Hardware-in-the-Loop Testing
- Additional HIL capabilities
  - Flight Simulator + Engine HIL Test Infrastructure
  - Multidisciplinary Control+Thermal+Propulsion Model
- Conclusions

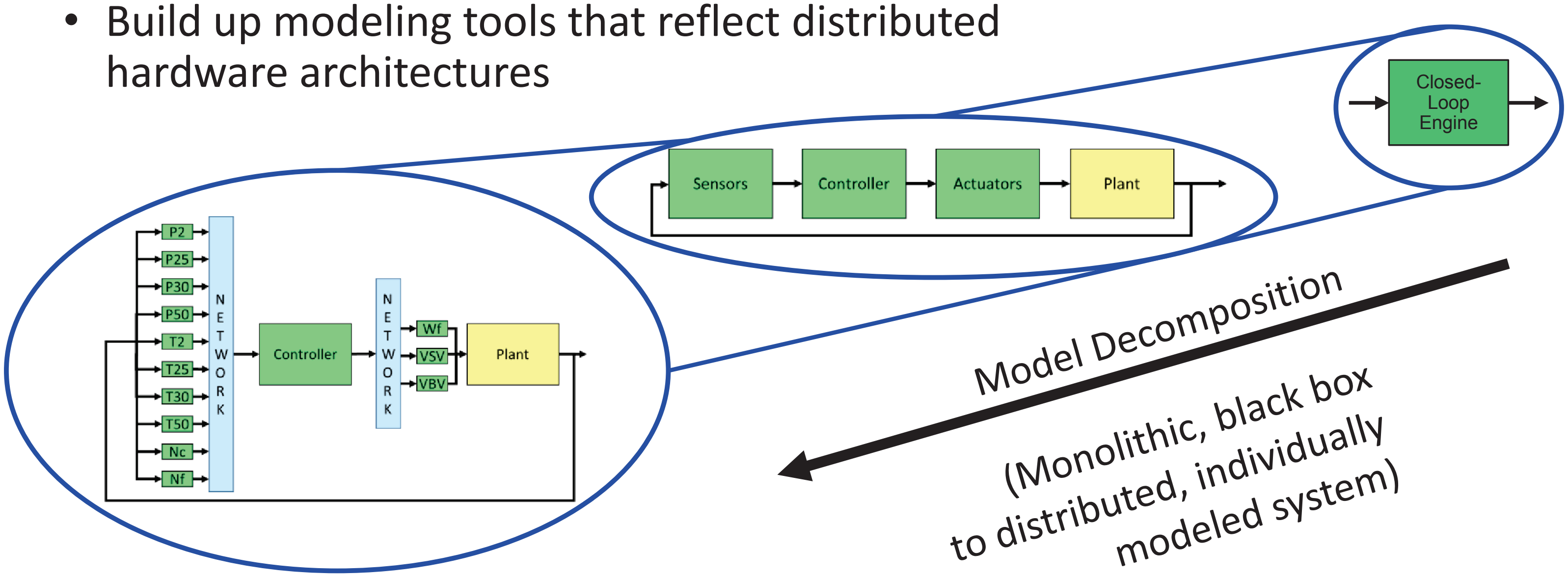
Introduction

- Objectives
  - Inform shareholders of the benefits and constraints of DEC
  - Investigate performance and capabilities enabled by DEC
    - e.g.,: high bandwidth local control
  - Develop tools/infrastructure for testing/building DEC systems and devices
    - Both generic NASA ones and proprietary ones
- Plan
  - Develop models and tools to accurately represent and test DEC systems
  - Focus on future engines of interest to NASA (e.g., AGTF30)
  - Conduct HIL tests for DEC research
    - Use existing DECSS capabilities adding more if necessary



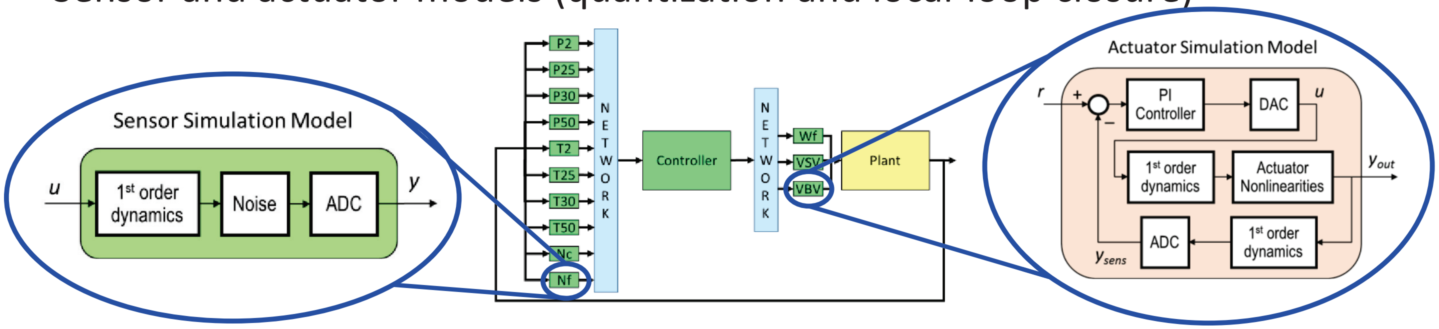
Introduction – Modeling Approach

- Past work: decompose existing, monolithic closed-loop engine models
  - Produces distributed model (system of asynchronous systems)
- Identify salient features of DEC
  - Functional modularity
  - Asynchronous execution and data flow
- Build up modeling tools that reflect distributed hardware architectures

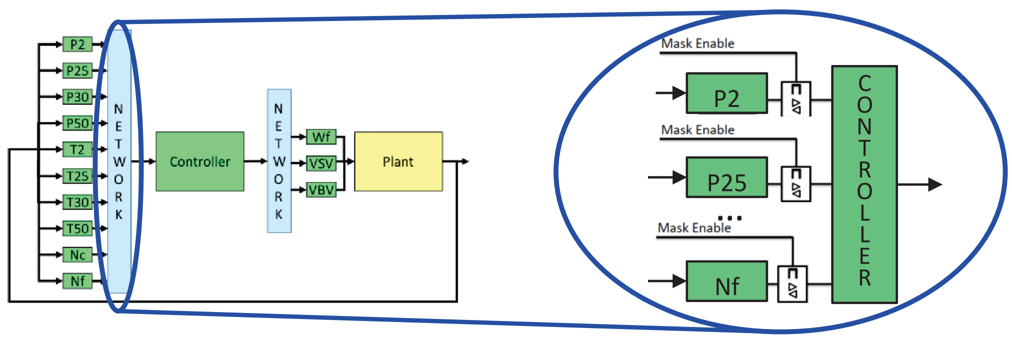


Introduction – Modeling Capability

- Additional modeling fidelity to reflect DEC system elements
  - Sensor and actuator models (quantization and local-loop closure)

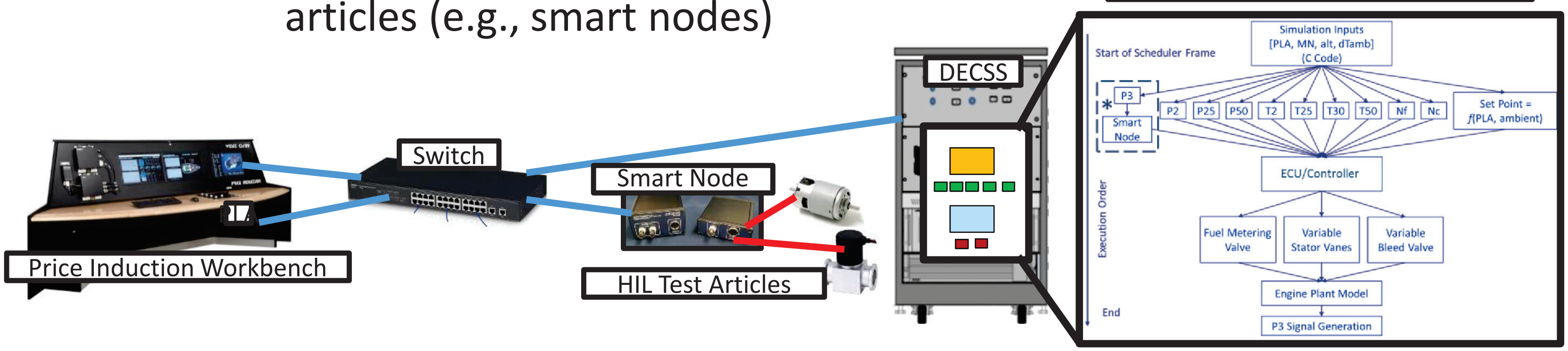


- Data flow through DEC network modeled as **switched subsystem**
  - Represents communication schedule balancing finite network throughput



Introduction – HIL Test Capabilities

- Distributed Engine Control System Simulator
  - 16-core Intel rack mounted server
  - Real-time Linux with “Sim Workbench” IDE
  - Variety of digital, analog, serial I/O
    - Capacity to add more (e.g., PCIe expansion chassis)
  - HIL LAN w/ Price Induction test bench
    - “Virtual Test Cell”
    - LAN also connects test articles (e.g., smart nodes)

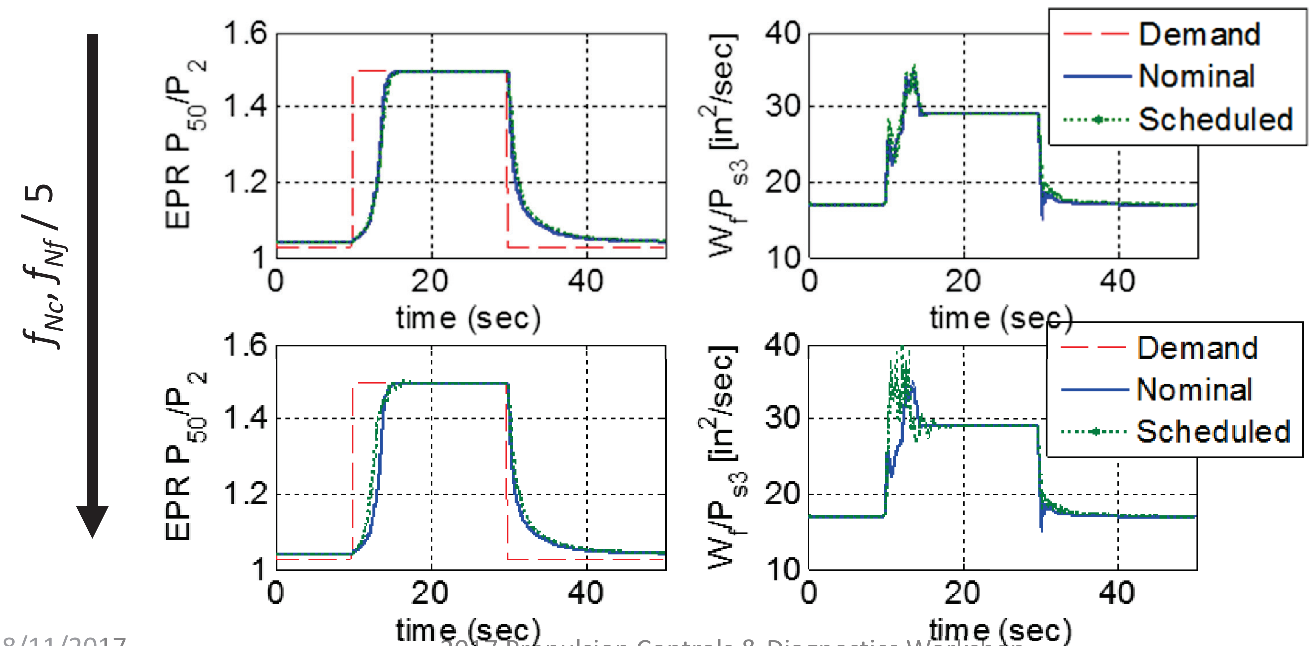


Applications

- Simulation studies
  - **C-MAPSS40k + DEC Communication Schedule (Simulation Study)**
    - Investigates effects of communication scheduling on closed-loop
- Hardware-in-the-loop test studies
  - **C-MAPSS40k + Sporian P3 Test Article**
    - Article is a high bandwidth capable smart sensor for P3/Ps3
    - Demonstrates low bandwidth HIL system test running closed-loop
    - Open-loop high bandwidth device unit test
  - **AGTF30 + Network of Processors-in-the-Loop (AGTF30 NIL)**
    - Demonstrates proof of concept DEC network with advanced engine
    - Shows properly designed DEC network successfully controls engine
    - Does so despite smart node hardware limitations discovered

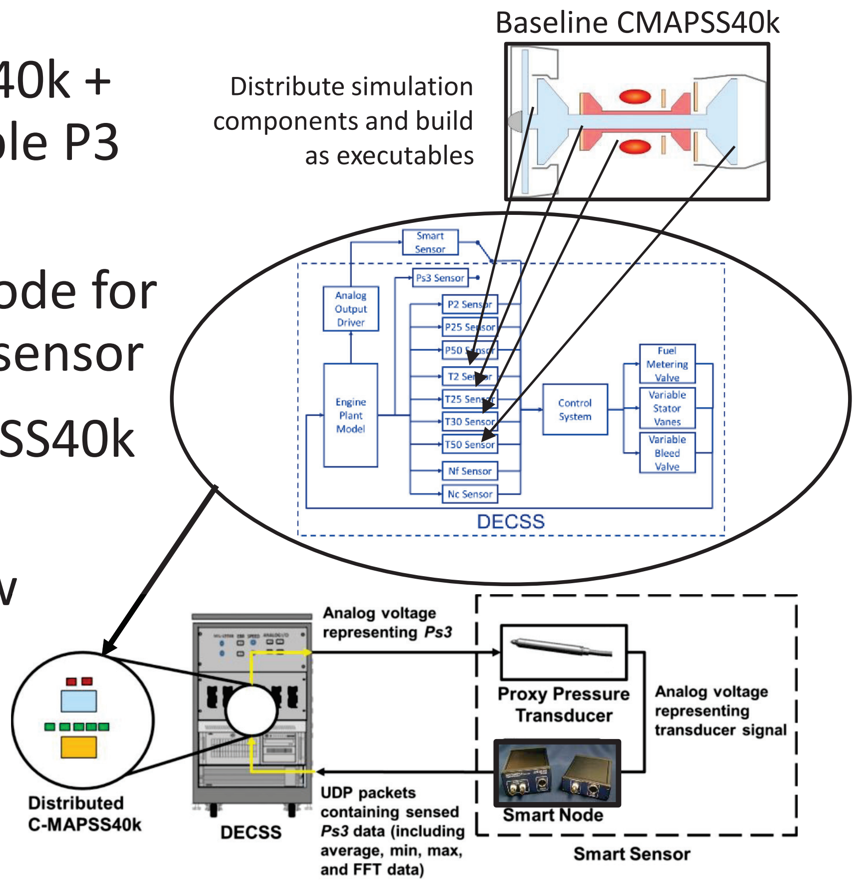
C-MAPSS40k +
DEC Communication Schedule Simulation Study

- Simulation studies showing that reducing shaft speed sampling rates by a factor of five causes limit chattering
- Indicates that control design must take communication scheduling into account



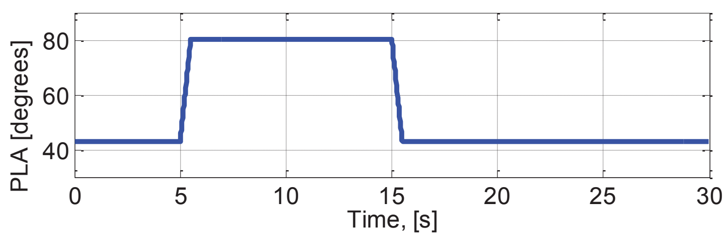
C-MAPSS40k + Sporian P3 Test Article

- HIL test designed for CMAPSS40k + Sporian high bandwidth capable P3 test article
- Device under test is a smart node for measuring P3/Ps3 with proxy sensor
- Study done with older, C-MAPSS40k engine, purely software
- Figures to right show workflow to design HIL test
  - NASA HIL tests generally follow similar workflow (e.g., AGTF30)

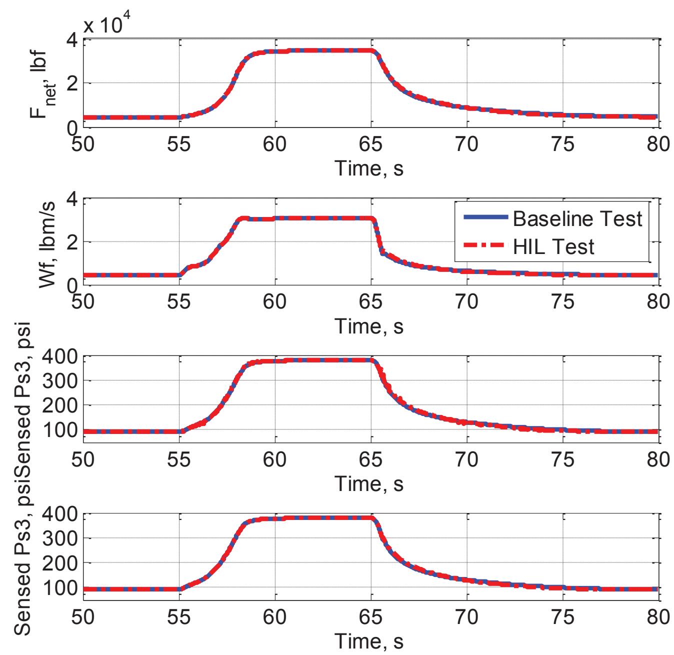


C-MAPSS40k + Sporian P3 Test Article

- HIL Test Conditions
  - Sea-level static, throttle burst and chop
  - Ran test with simulated Ps3 sensor and with HW smart P3 sensor
  - Smart sensor is fed analog signal corresponding to truth data for P3

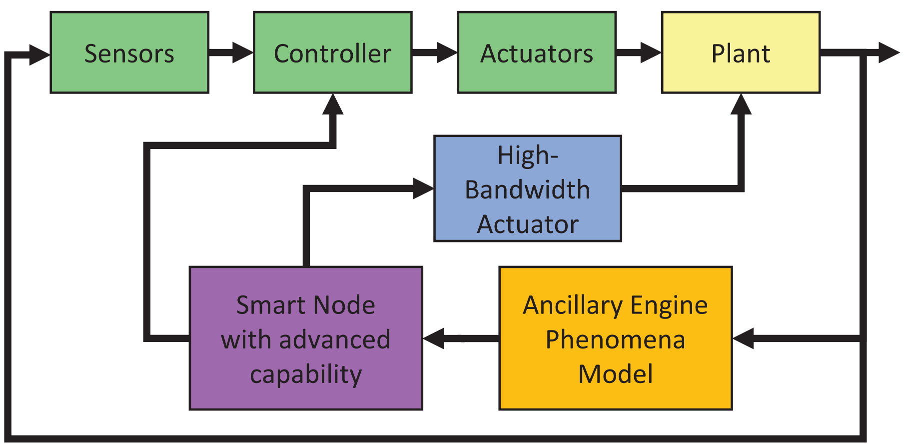


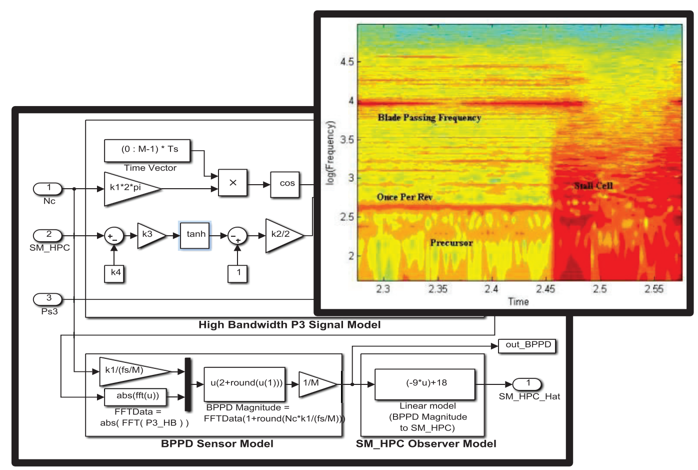
- Results:
  - Insignificant performance difference!
  - Means the HW sensor performs same function as baseline simulated one
  - Demonstrates successful HIL test



C-MAPSS40k +
Sporian P3 Test Article

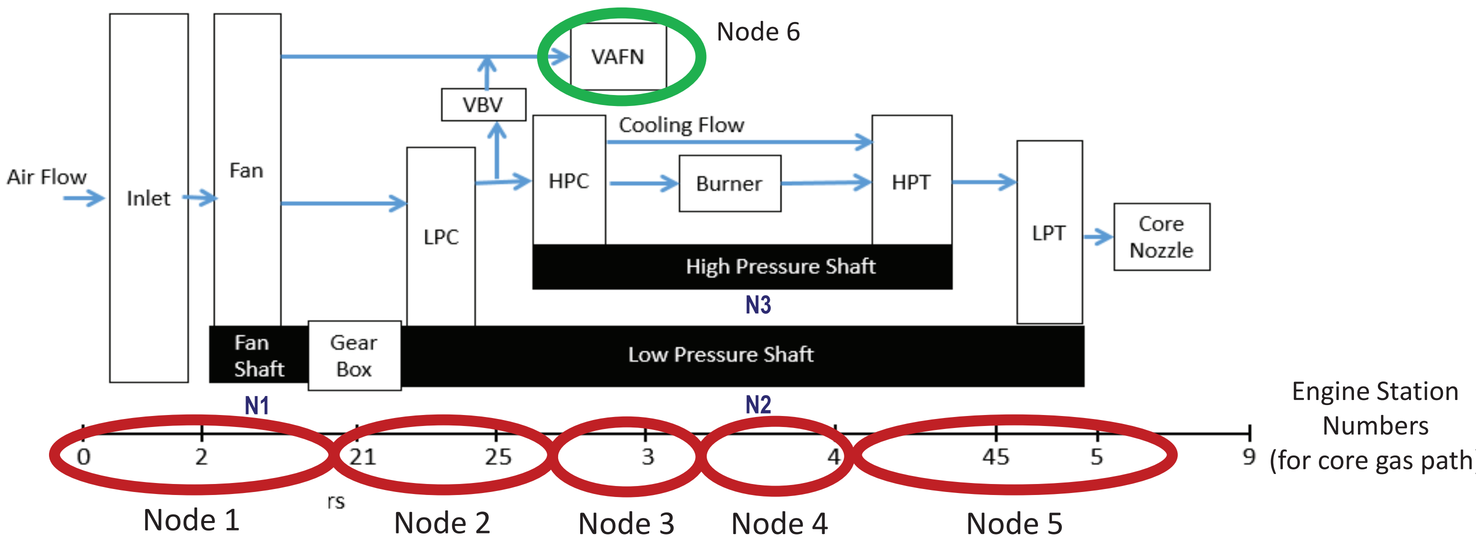
- Smart nodes (e.g., Sporian node) have capabilities beyond legacy nodes
  - May include high bandwidth sampling, local processing (FFTs) and control, etc.
  - Can enable aggressive engine designs via tight, active local loop closure
- Unpublished high bandwidth bench tests of Sporian P3 node performed
- Future work: Test advanced smart node capabilities with ancillary models
  - E.g., high bandwidth, pre-stall compressor pressure signals with pips, etc.
  - Feed ancillary model with data from 0-d, engine performance models
  - Close loop around ancillary model to demonstrate advanced control SW/HW



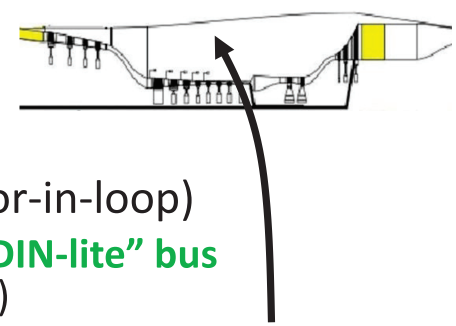


AGTF30 + NIL (Network of Processors-in-the-Loop)

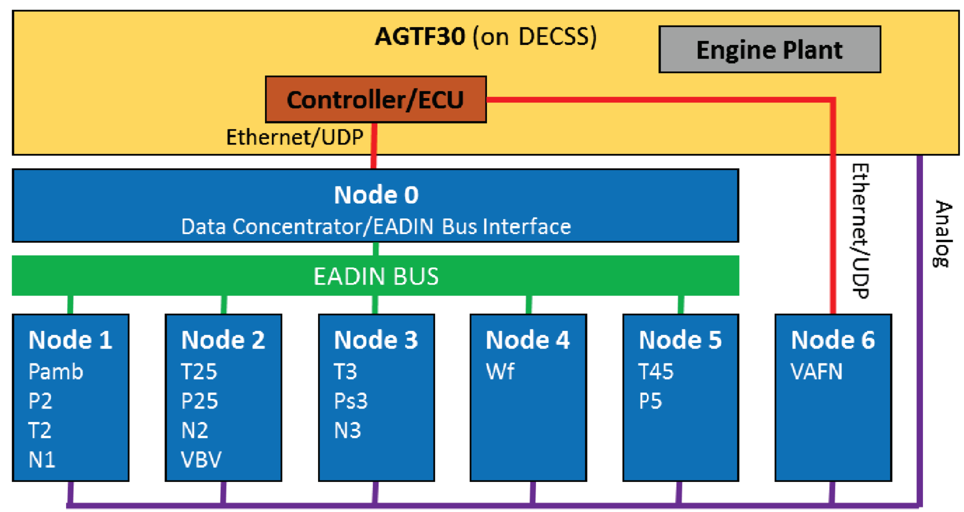
- AGTF30: Advanced Geared Turbofan concept engine simulation
  - Concept/demo DEC architecture built around this engine
  - Sensing and actuation responsibilities grouped by station location
  - Groups shown w/ circles, (red = core locations, green = nacelle/bypass)
  - Each group is assigned a particular smart node



AGTF30 + NIL
Distributed Control Architecture



- **Controller (ECU)** simulated in **DECSS**
- Smart nodes represented with **MCU boards** (processor-in-loop)
  - Engine core related nodes connected via **physical "EADIN-lite" bus** to ECU via data concentrator (EADIN master, "Node 0")
    - **EADIN-connected** nodes intended to be mounted in relatively hot **cowl cavity**
  - Bypass duct/nacelle related variable fan nozzle node "Node 6" connected via **Ethernet/UDP**
  - ECU also connected to data concentrator via **Ethernet/UDP**
  - Engine & actuator truth (response) data represented by **analog signals**
  - Smart nodes contain comms/simulation logic
  - Possible DEC architecture



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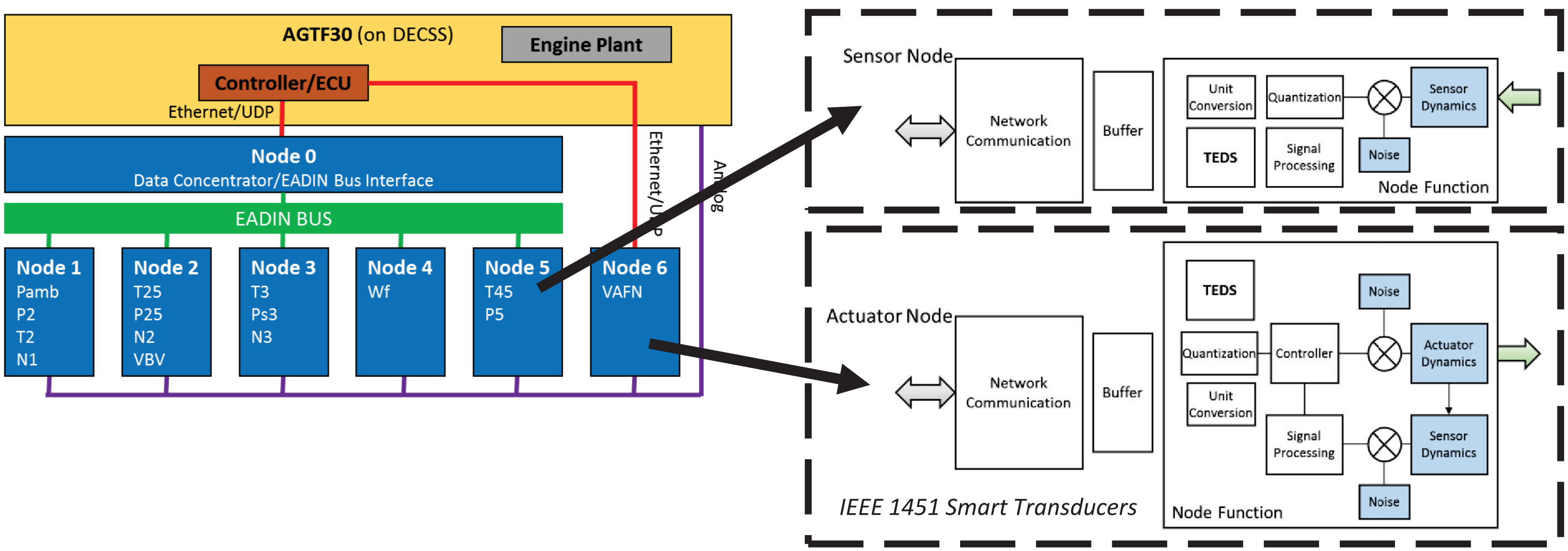
AGTF30 + NIL
Smart Node Functions

- Processor-in-the-Loop Smart nodes roughly based on IEEE 1451, containing
  - Peripherals such as (Network communication, ADCs/DACs)
  - Simulation of a transducer (Linear sensor/actuator dynamics, Nonlinearities)

Architecture —> Individual Nodes

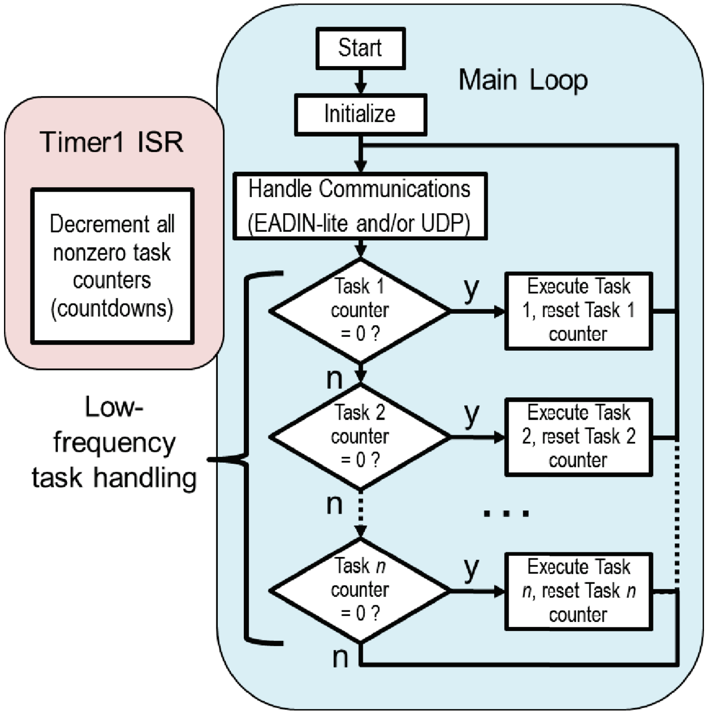


AGTF30 + NIL
Smart Node Transducer C code

- Both sensor and actuator models were developed as classes in C++
- Generic objects with specific properties loaded during initialization
- AGTF30 Distributed Simulink model was used as the basis from which to develop the C++ code

AGTF30 + NIL
Smart Node Communication Logic

- DEC communication logic (polling-driven):
  - Each node polls its slave receive buffers for **as often as possible.**
  - This minimizes time nodes spend running consecutive task handlers in between responding to messages.
  - Not doing so compromises responsiveness of slaves to queries from master



AGTF30 + NIL
Smart Node Communication Schedule

- Communication schedule (EADIN Master to EADIN Slaves)
  - Each 15 ms minor frame, master exchanges data with three slave nodes
  - Each packet exchanged contains all sensor/actuator data for that slave
- Visualization of schedule (variables exchanged with ECU each frame)
  - Arbitrary schedule for constant traffic on 1 Mbaud EADIN bus
    - (18 bytes/packet)(8 bits/byte)(2 packets/query)(3 queries/frame)(1 frame/15 ms) = 57.6 kbps effective data rate
    - 57.6 kbps / 1 Mbps = ~5% utilization (**system theoretically able to support more**)
    - Hardware and comms library **limitations** make achieving more utilization **challenging**

Node ID	(1)				(2)				(3)			(4)	(5)		(6)
Variable	Pa	P2	T2	N1	P25	T25	N2	VBV	T3	Ps3	N3	Wf	P5	T45	VAFN
Frame 1															
Frame 2															
Frame 3															
Frame 4															
Frame 5															

  - All other communication channels (e.g., UDP) exchange all data each interval

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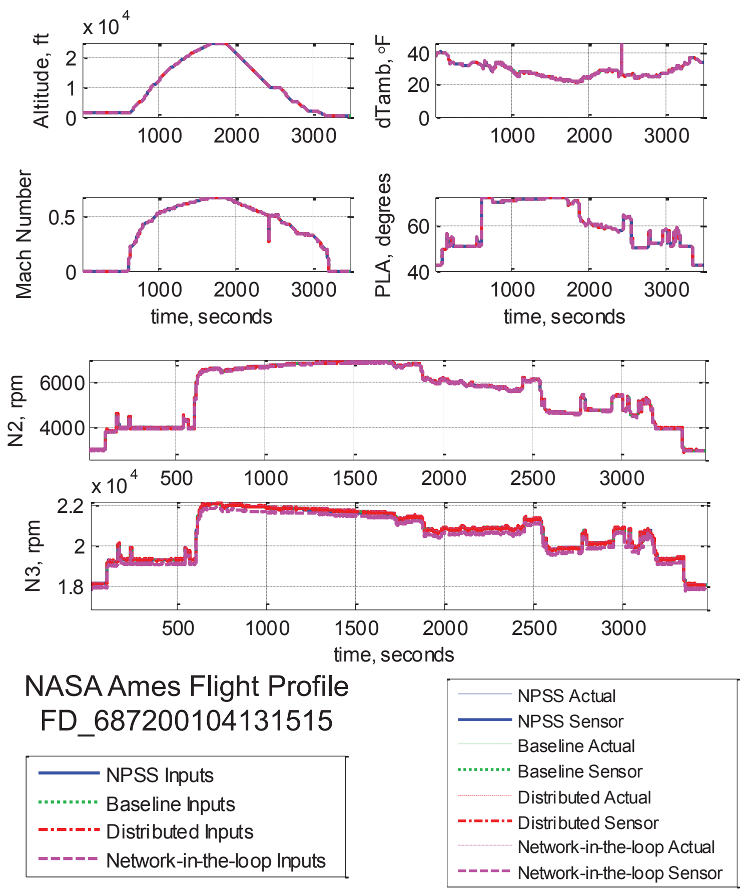
AGTF30 + NIL Results

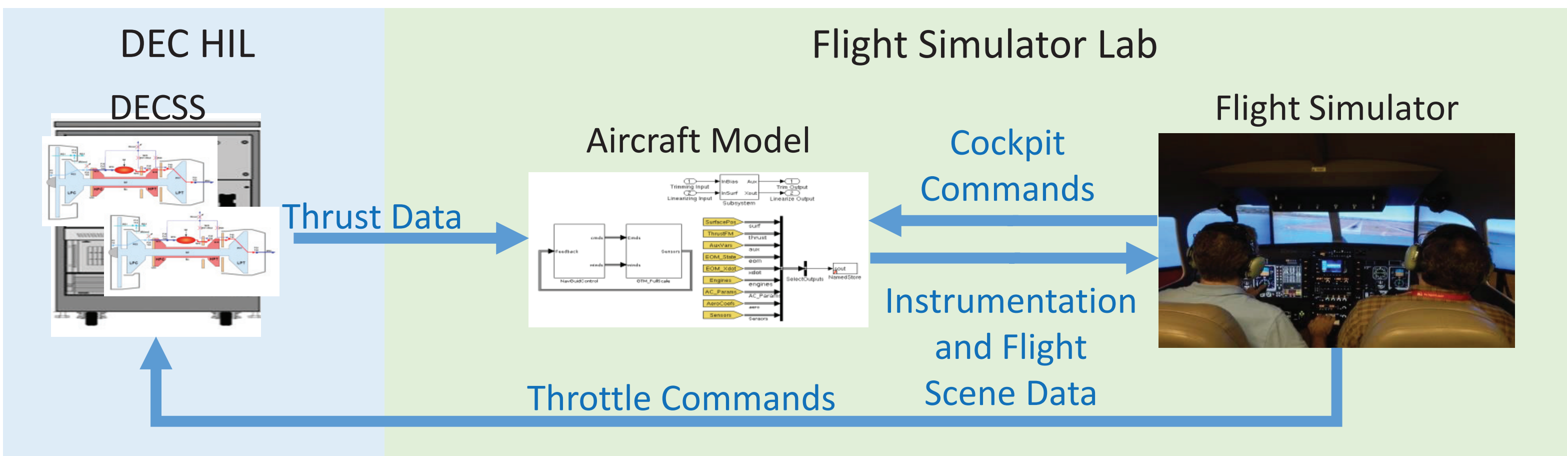


Results:

- **NPSS** (s-function) engine plant model with TMATS controller on Microsoft Windows® platform
- **Baseline** TMATS AGTF30 engine model & controller, real time HIL platform
- **Distributed** TMATS AGTF30 engine plant model & controller with **simulated** DEC nodes and network on real time HIL platform
- **Network-in-the-Loop** TMATS AGTF30 engine plant model & controller with **physical** nodes and network on real time HIL platform
- Shows several capabilities
  - Can bring engine described in NPSS into TMATS-based HIL environment
  - Approach applies to any engine system
  - Can add DEC modeling fidelity to simulated control elements and compare with hardware
  - Appropriately designed DEC system (**Network-in-the-Loop**) successfully performs same function as centralized

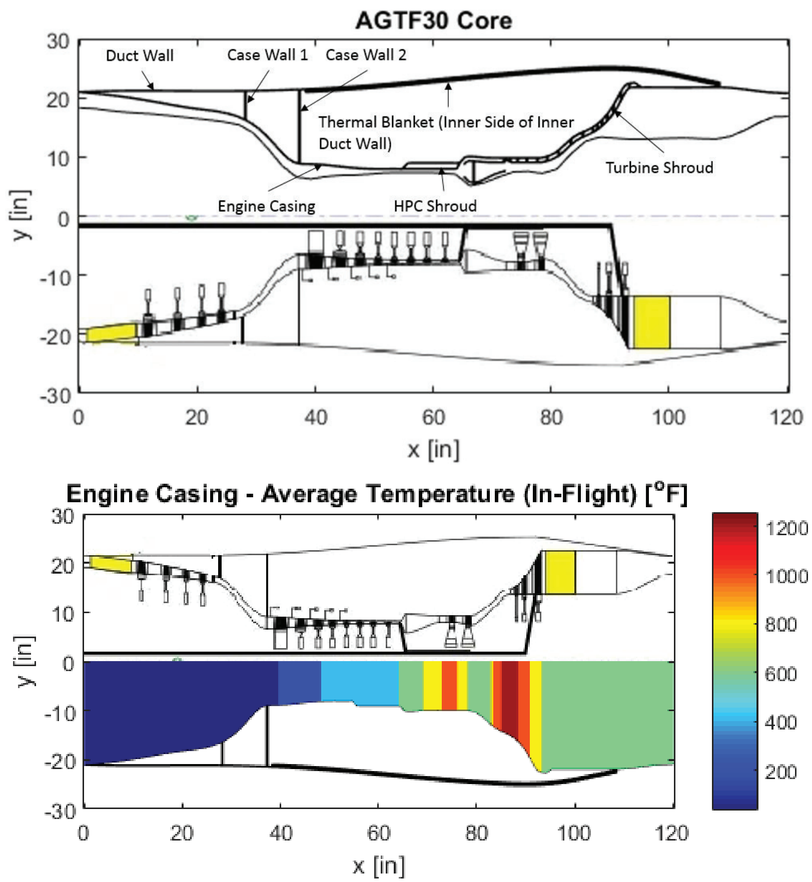
Additional HIL Capabilities
Flight Simulator + Engine HIL Test Infrastructure

- The DEC HIL and Flight Sim labs connected via Ethernet network using UDP
  - The DEC HIL Lab operates a pair of CMAPSS40K (or other) engine models.
  - The Flight Sim Lab utilizes the Transport Class Model (TCM) as the aircraft model and an enclosed cockpit for pilot command input.
- Enables realistic flight scenarios that exercise engine performance throughout all phases of flight (i.e., takeoff, climb, cruise, descent and landing).
- Capacity to incorporate other aircraft and engine models.



Additional HIL Capabilities AGTF30 Control+Thermal+Propulsion Model

- Multidisciplinary structural, thermal AGTF30 model
- Thermal model originally ran off-line
- Adapted for real-time, fed by real-time AGTF30 outputs
- Multi-rate sim on DECSS
    - Ts = 15 ms for engine
    - Ts = 1 s for thermal model
- Potential to support HIL test of active turbine tip clearance control system, etc.



Conclusions

- Models developed represent a capability at NASA GRC
  - Tools allowing one to
    - Design, analyze, and optimize DEC system architectures
    - Evaluate system benefits with DEC compared to centralized
    - Determine DEC related hardware constraints and requirements
  - Testbed to evaluate advanced control concepts (HIL)
    - Proof of concept/prototype tests can identify hardware constraints
    - Generic or proprietary engine models
    - Hardware (smart nodes)
      - Including high-bandwidth and/or local-loop closure capability
    - Advanced control strategies
      - New features (e.g., active component/stall control)

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DYNAMIC THERMAL MODELING CAPABILITIES

Outline

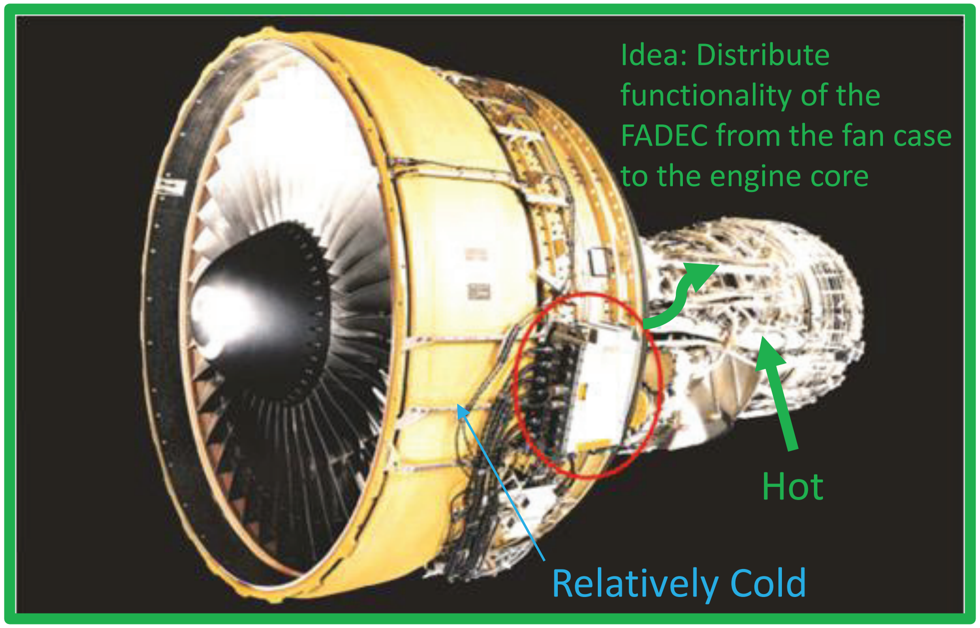
Research Summary: Developing dynamic thermal models to approximate the thermal environment of gas turbine engines relevant to the placement of electronics that enables distributed engine control

Outline

- Background on DEC & High-Temp Electronics
- Dynamic Thermal Modeling Methodology
- Tools Development
- Applications
- Real-Time Simulation
- Architecture Optimization
- Summary

DEC & High-Temp. Electronics

- Current control approach
  - Centralized control performed through a full authority digital engine controller (FADEC)
  - Constrains the control system topology
  - Limits the capability of the control system
- DEC
  - Modularizes the control system
  - Introduces a lightweight digital data network
  - Benefits include **flexibility in designing controls**, enabling **more functionality and adaptability, reducing weight**, & allowing for a **more aerodynamic profile**



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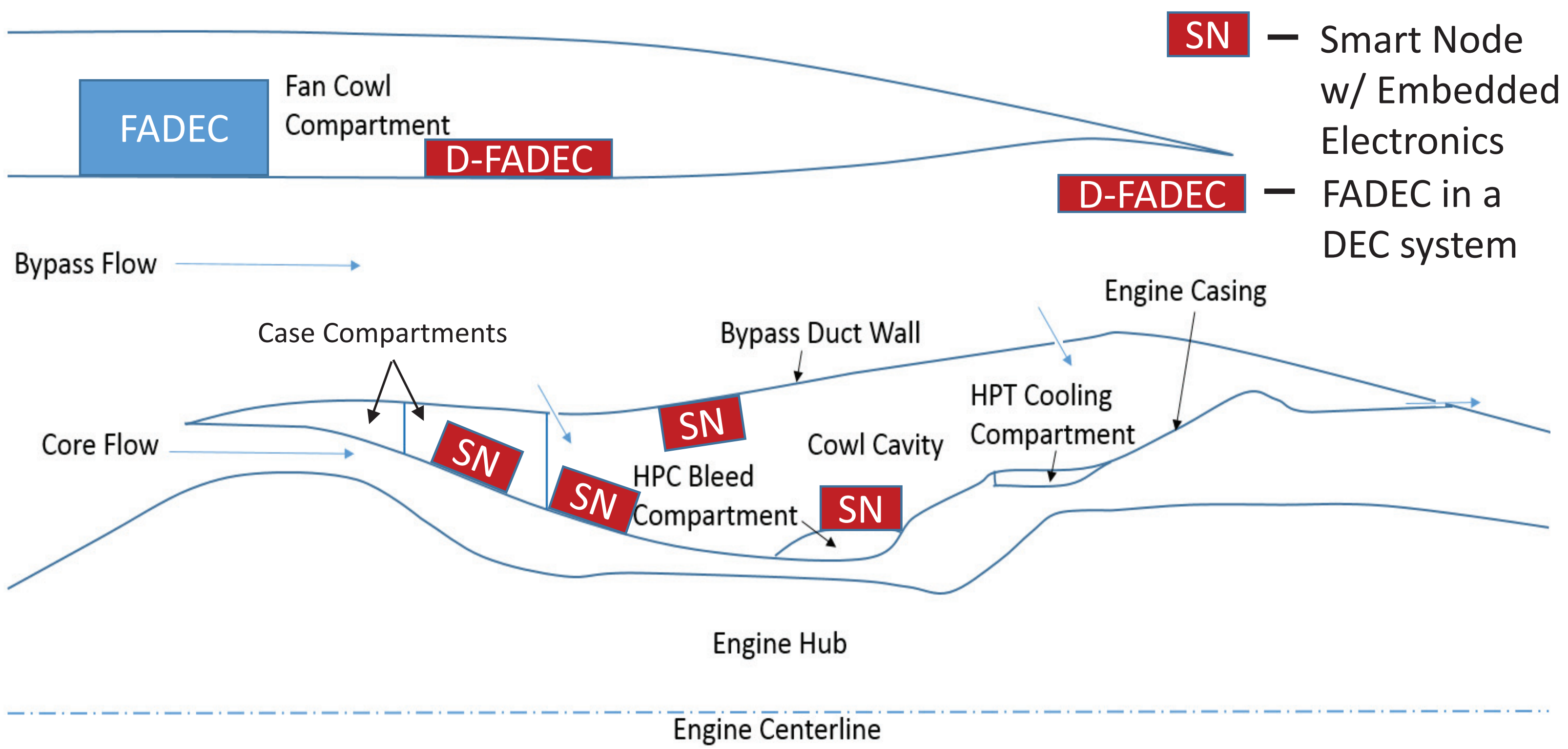
DEC & High Temp. Electronics



Where can we mount hardware?

- SN mounting surfaces could include those exposed to the cowl cavity or case compartments (engine casing, bypass duct wall, & various supports structures)

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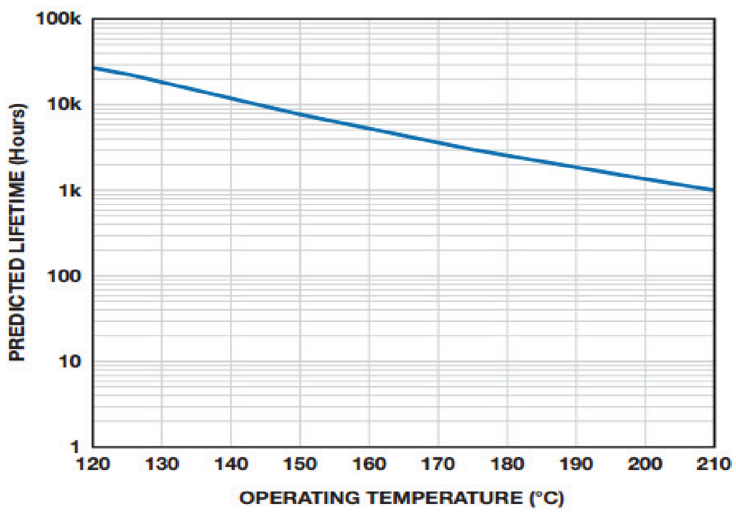
DEC & High-Temp. Electronics



Example of the reliability vs. temperature relationship for an electronic device http://www.analog.com/library/analogdialogue/archives/46-04/high_temp_electronics.pdf

- Desire to mount smart nodes on the engine core
- Challenging thermal environment
  - State-of-art material for internal gas path exceed 1500 °C
  - Common consumer electronics operate reliably <70 °C, sometimes 150°C
  - Inverse relationship between temperature and electronic reliability
- High-Temp electronics
  - Silicon-On-Insulator (SOI): Up to 300 °C (225 °C near term)
  - Silicon Carbide: 500 °C +

- Important considerations: Max & min temperature (steady-state), rate of change in temperature (dynamic), & temperature cycling (dynamic)
- Objective: Develop thermal models of the relevant engine structure to estimate the environment in which DEC electronics will be placed + aid industry through producing non-proprietary modeling tools and simulation results

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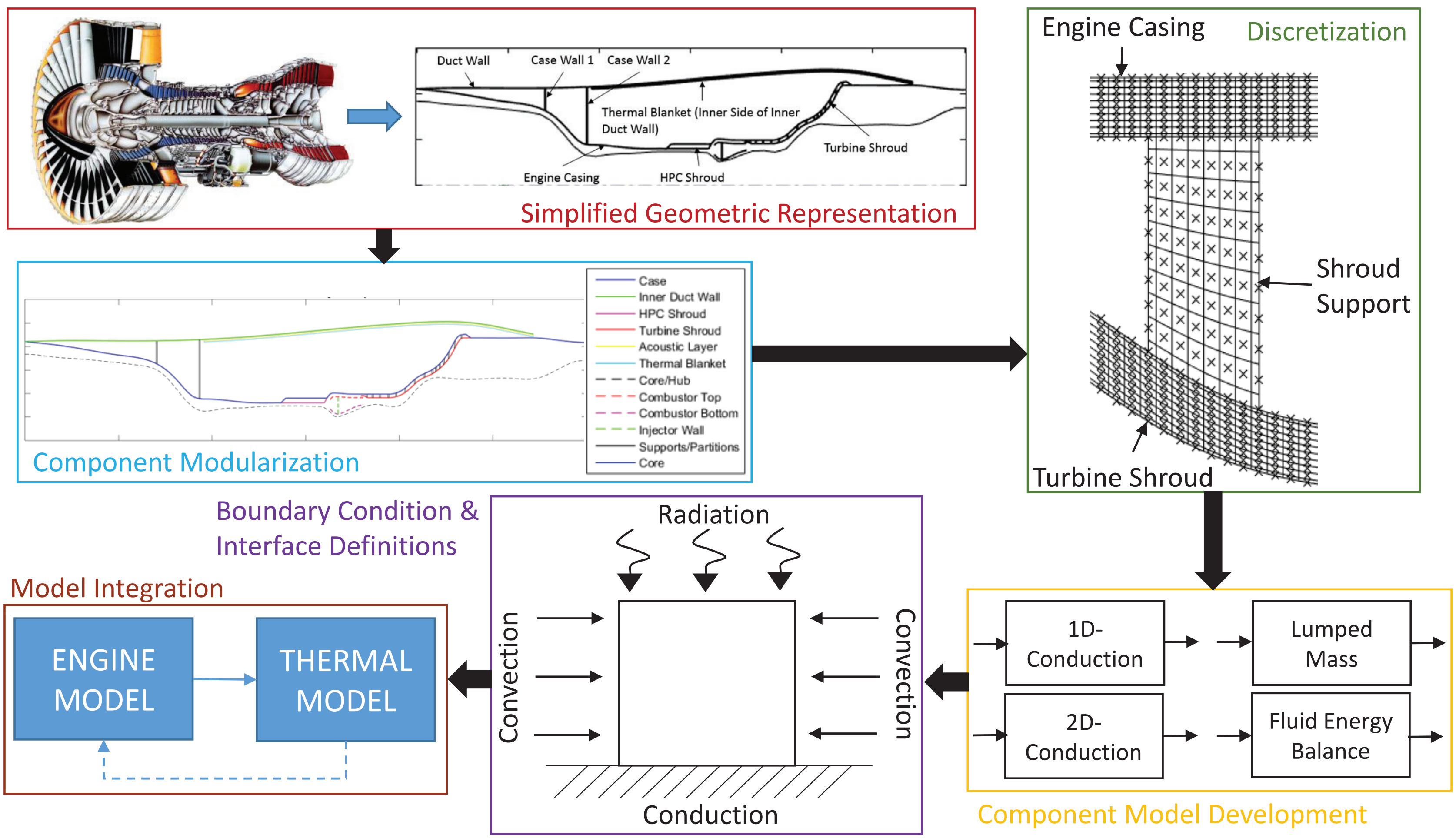
Thermal Modeling Methodology



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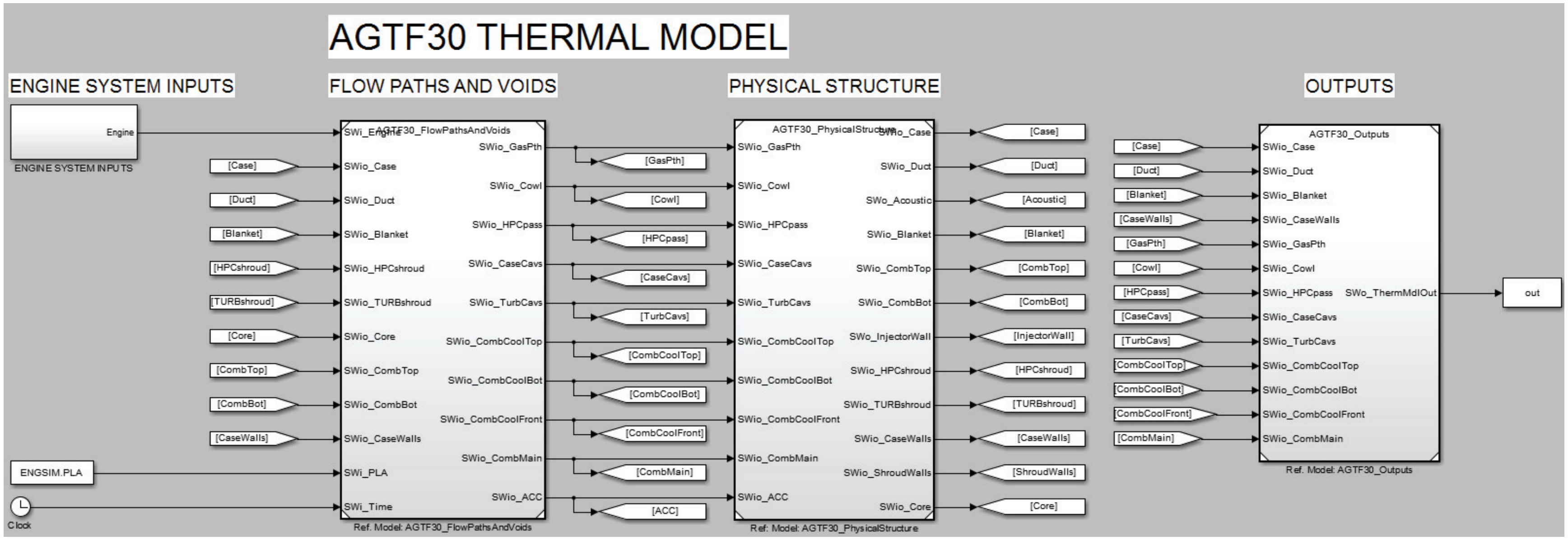
Thermal Modeling Methodology

- Modeled in the MATLAB/Simulink environment



Special Features

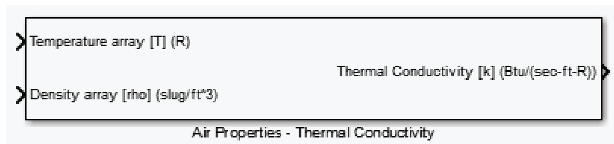
- Temperature dependent material & fluid properties
- Dynamic heat loads
- Ability to capture a variety of planar and axisymmetric geometries
- Integration of some bleeds and cooling systems effects
- Heat soak back

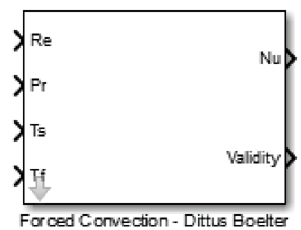
NASA/CP—2018-219891

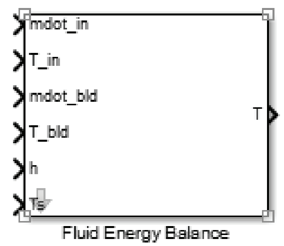
Tools Development

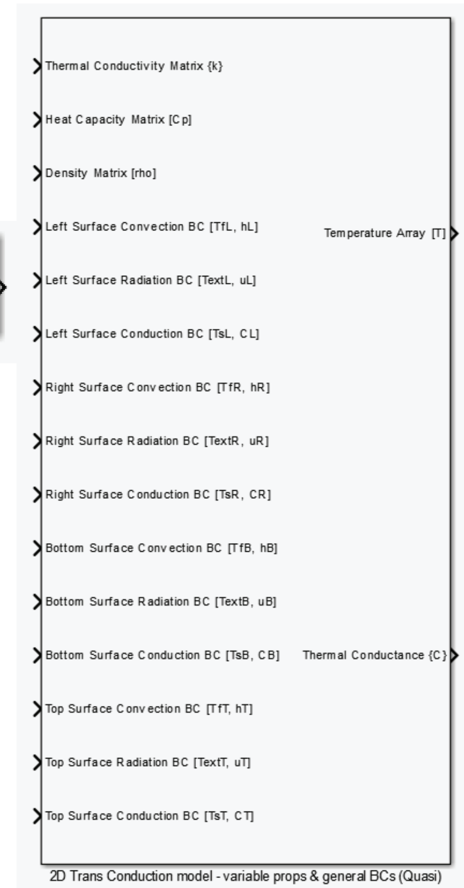
Thermal System Analysis Toolbox (TSAT)

- Library of tools developed in the MATLAB/Simulink environment
- Topics modeled
    - Conduction
    - Convection
    - Radiation
    - Deformation
    - Air Properties
    - Fluid Heat Transfer
    - General Tools
- Provides building blocks for building up and modeling dynamic thermal systems
- Provides some tools for generating geometries and meshes









*A public release of the software is planned within the next several months

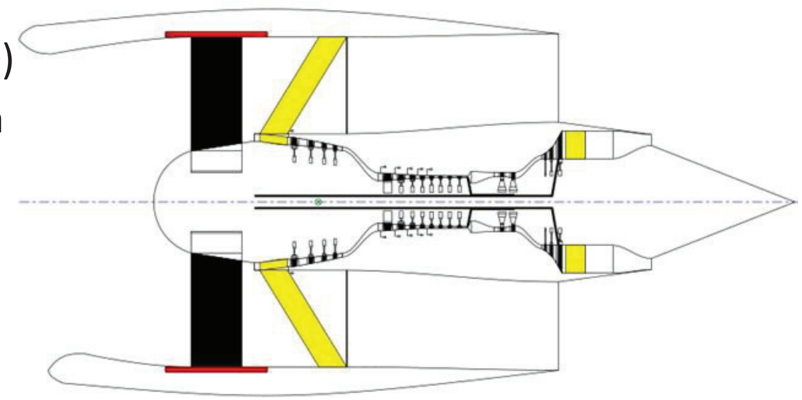
Applications: Overview

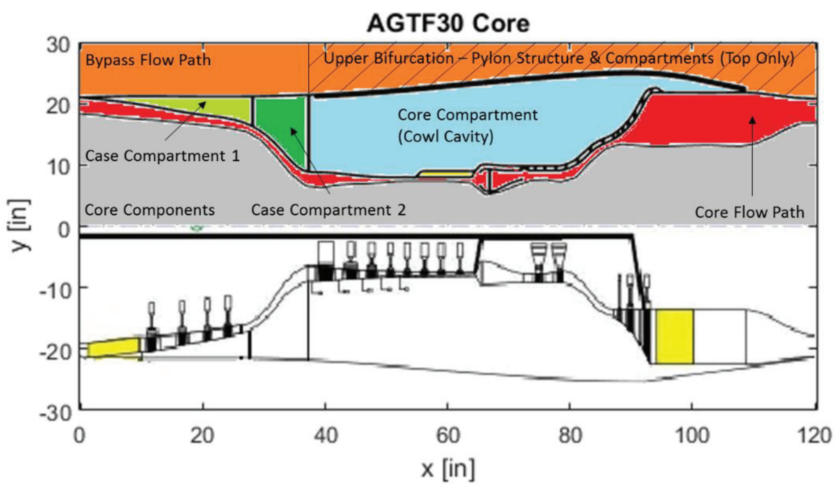
- Large Commercial Turbofan – C-MAPSS40k
  - Presented at AIAA Propulsion & Energy (2016)
  - Paper: *Kratz, J., Culley, D., Chapman, J., "Approximation of Engine Casing Temperature Constraints for Casing Mounted Electronics," Proceeding of the 52th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, 2016*
- Low Bypass Afterburning Engine – T-MATS developed engine model
  - Presented at Turbine Engine Technology Symposium (2016)
- NASA N+3 Commercial Turbofan with a Compact Gas Turbine (CGT) – AGTF30

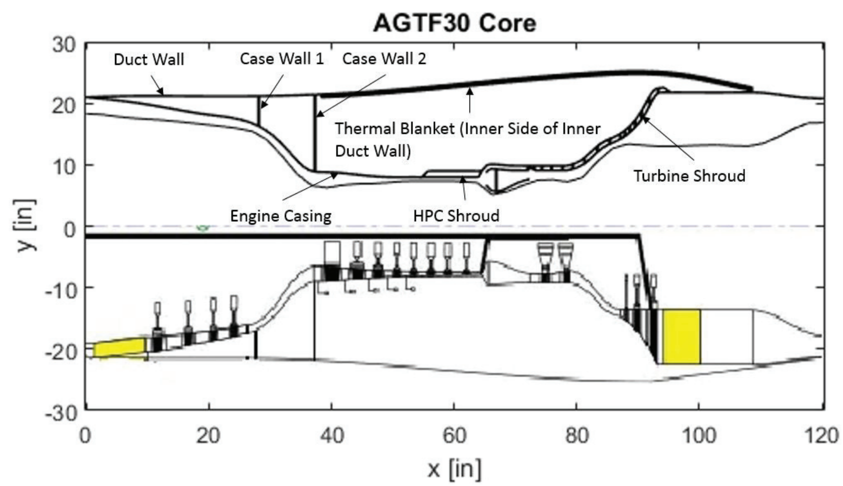
Application: NASA CGT Concept

Advanced Geared TurboFan 30,000 lb_f (AGTF30)

- Developed using T-MATS based on NPSS data
- Features:
    - Geared turbofan
    - Variable area fan nozzle
    - Compact gas turbine (CGT)
    - Full flight envelop controller







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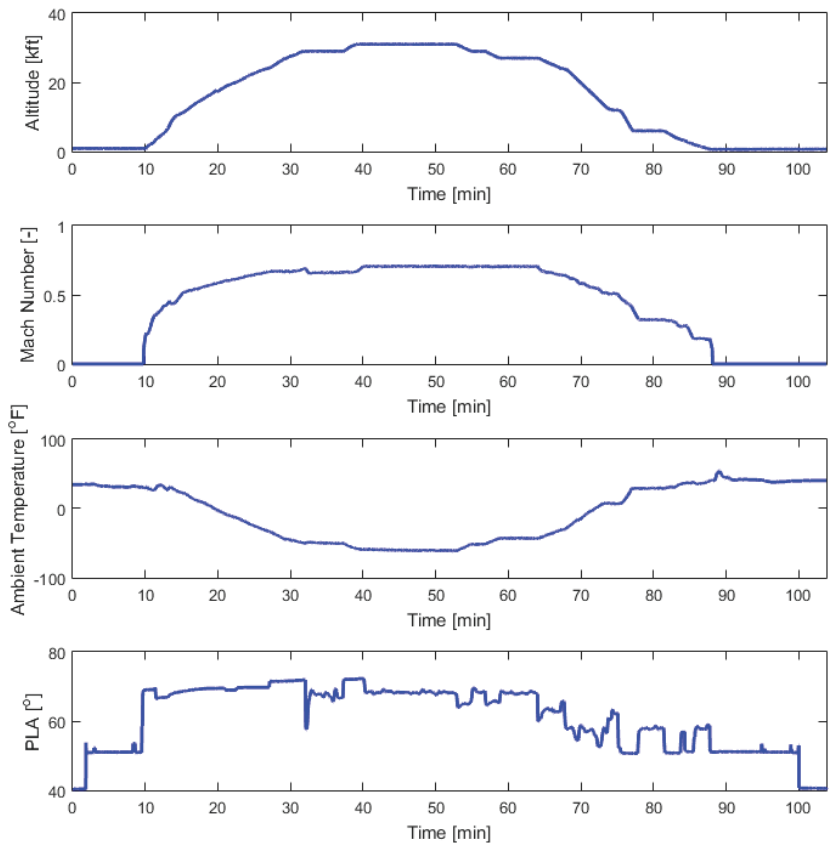
Application: NASA CGT Concept

FLIGHT PROFILE



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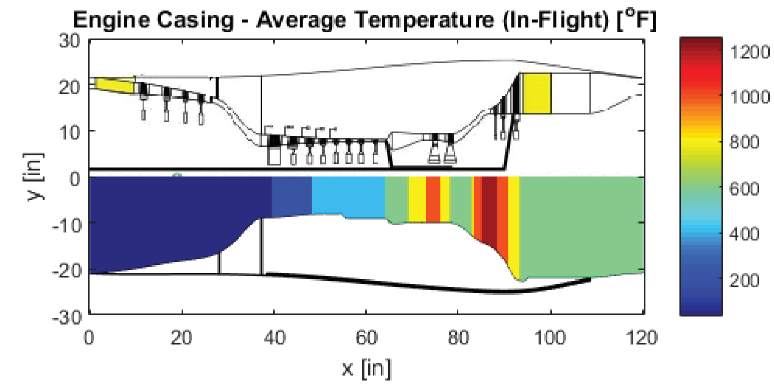
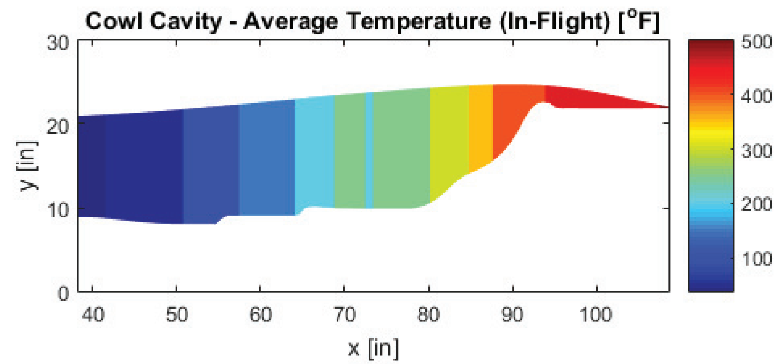
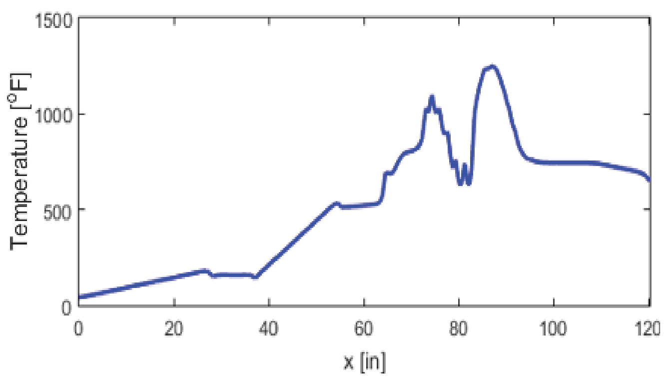
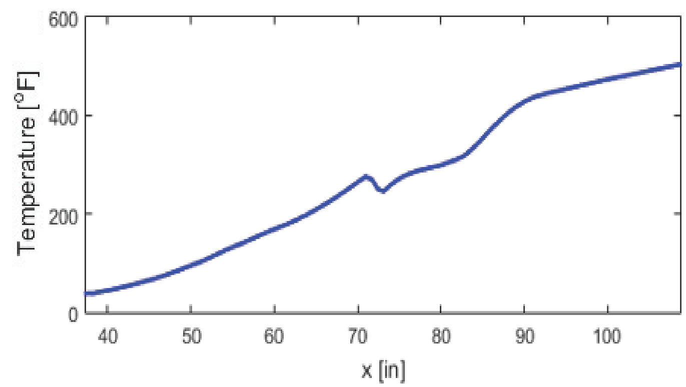
Application: NASA CGT Concept

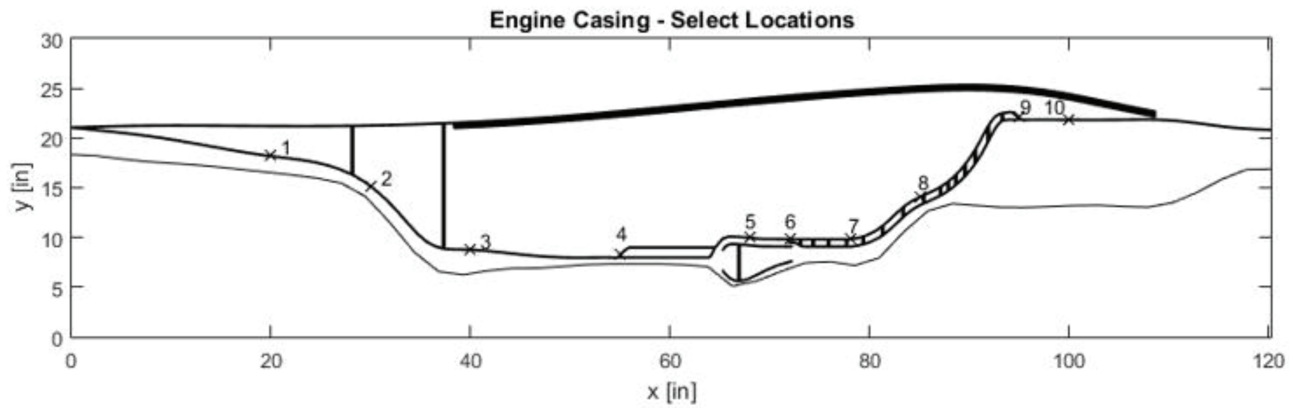


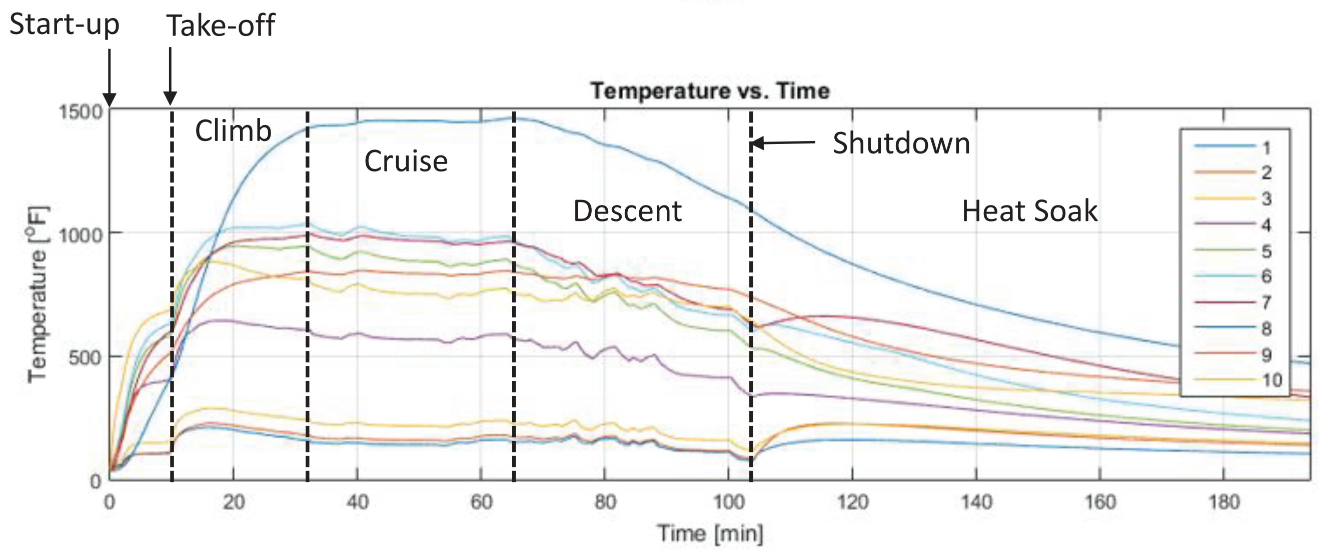




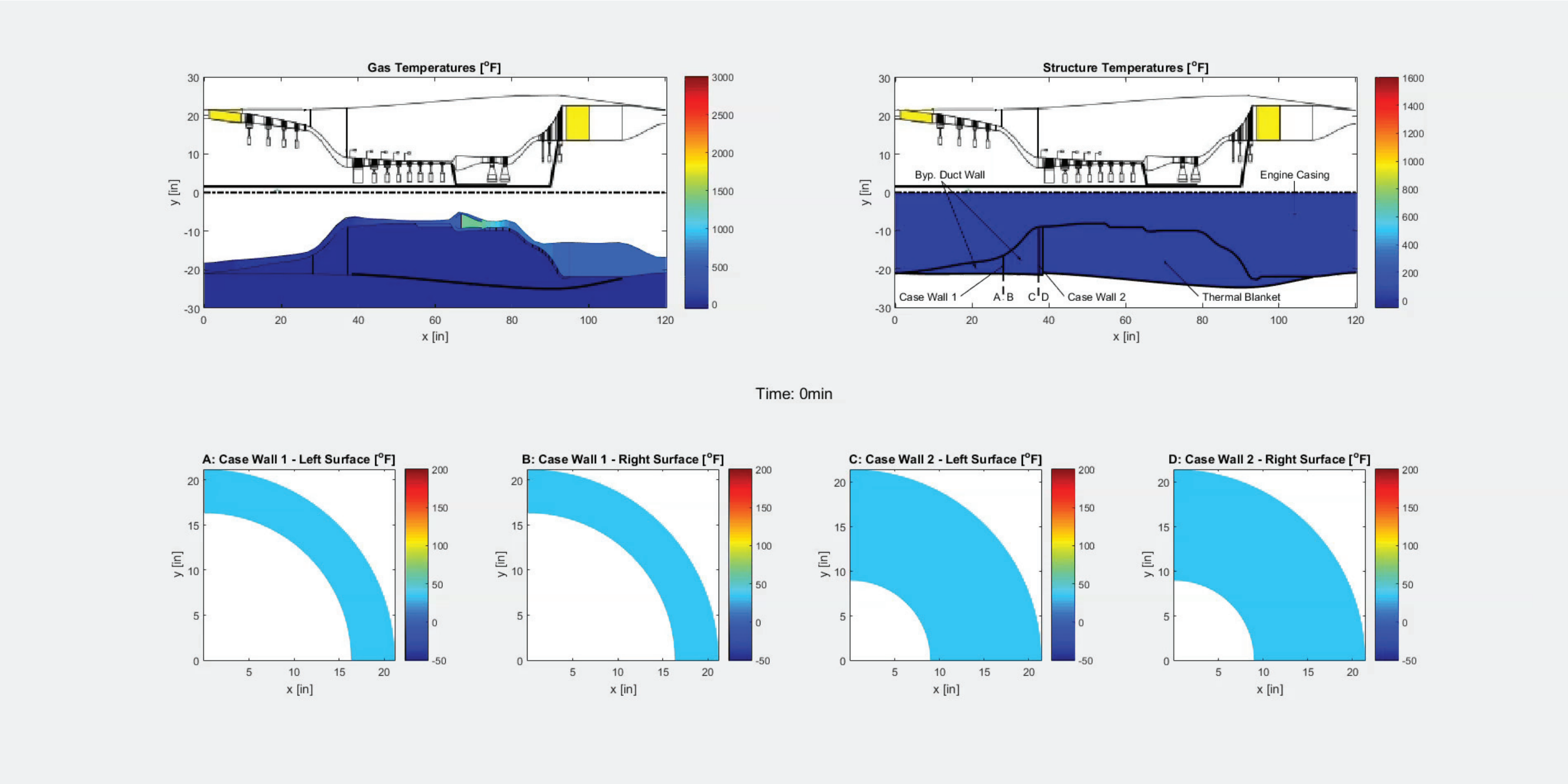


Application: NASA CGT Concept



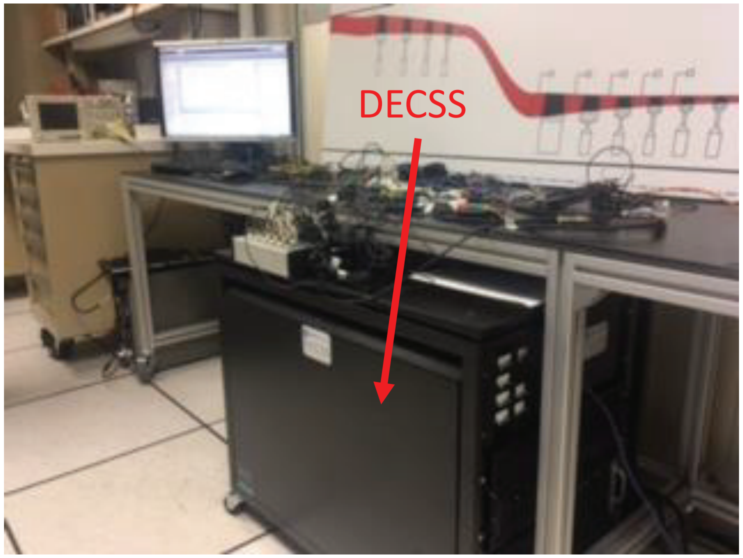


Applications: NASA CGT Concept

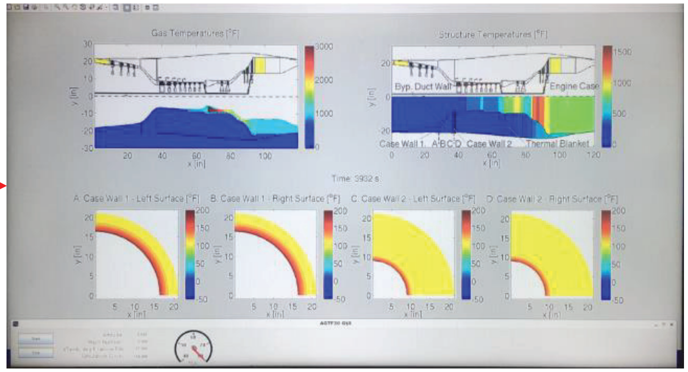


Real-Time Simulation

- Real-time integrated engine performance, distributed engine control, and thermal model simulation
  - Engine model runs in hard real-time
  - Thermal model runs in soft real-time in Simulink
  - Real-time plotting code runs in MATLAB
  - Data is transferred via UDP
- Demonstrates ability to:
  - Run complex multi-disciplinary simulations
  - Drive a heating source in real-time for component testing



Real-Time Display



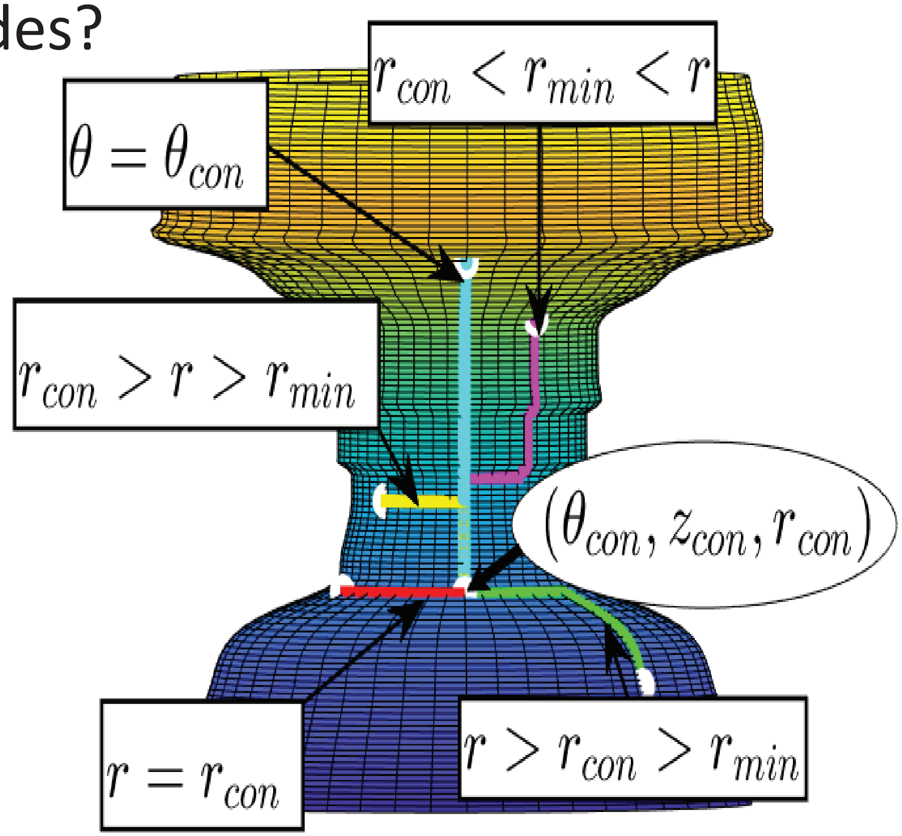
National Aeronautics & Space Administration

Architecture Optimization

Where to place smart nodes?

<u>Placement Constraints</u>

- Geometric/volumetric
  - Must fit inside the volume it occupies
  - Must not overlap with other nodes or engine components
- Functional
  - Must not prevent crucial functions from being performed (ex. blocking cooling flow)
- Environmental
  - **Temperature**
  - ***Vibration (Created code that generates dynamic power spectral density test profiles based on MIL-STD-810G)***



*Temperature places a hard constraint on component placement & impacts system reliability & availability which can impact the *optimal* control system configuration

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Architecture Optimization

Objective

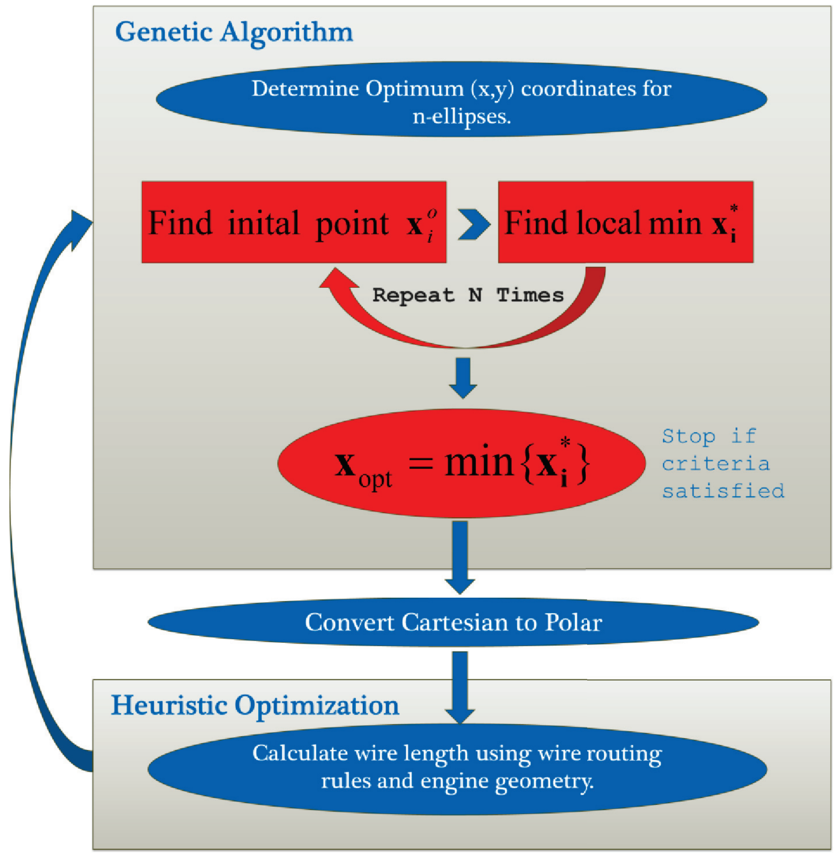
Find the placement of control system components that minimizes the control system weight under geometric and **environmental constraints** given a control system architecture, wire routing rules, and linear wire densities.

Optimization Layers

- *Minimum wire length & path between nodes* – heuristic optimization
- *Placement of nodes* – genetic algorithm
- *Architecture selection* – comparison of various optimizations

Future Work

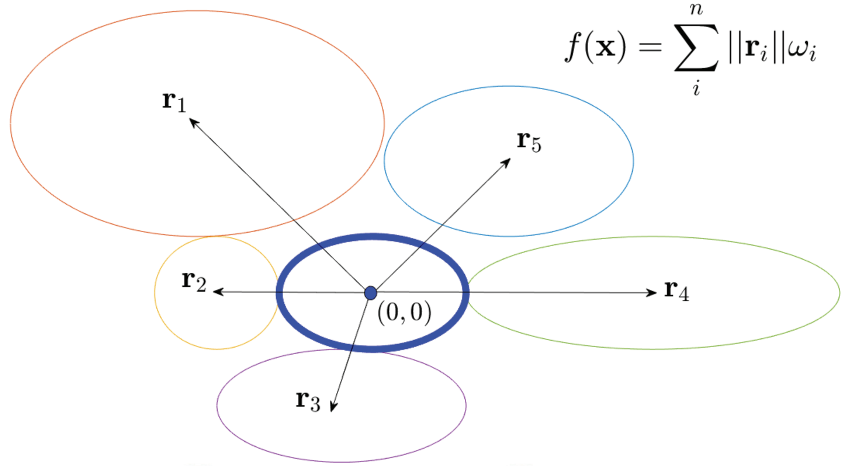
Bring reliability & availability into the optimization function



Credit: Samuel Mohler (Portland State University)

Architecture Optimization

$$f(\mathbf{x}) = \sum_{i}^{n} ||\mathbf{r}_i||\omega_i$$

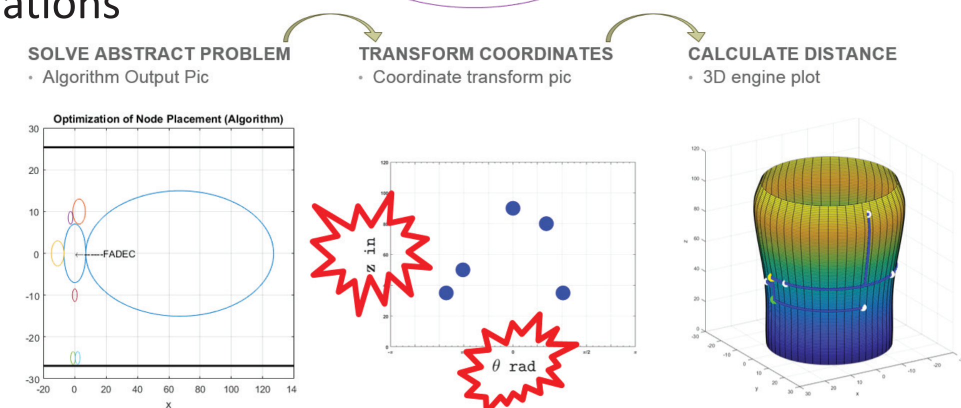


<u>The abstract problem</u>

Given *n* ellipses of arbitrary major and minor radii, minimize the sum of the of the vectors lengths from the origin multiplied by some arbitrary linear density such that the ellipses do not intersect.

<u>Parts to the problem</u>

- Generate feasible configurations
- Convert coordinates
- Calculate wire lengths
- Calculate weight
- Iterate



Credit: Samuel Mohler (Portland State University)

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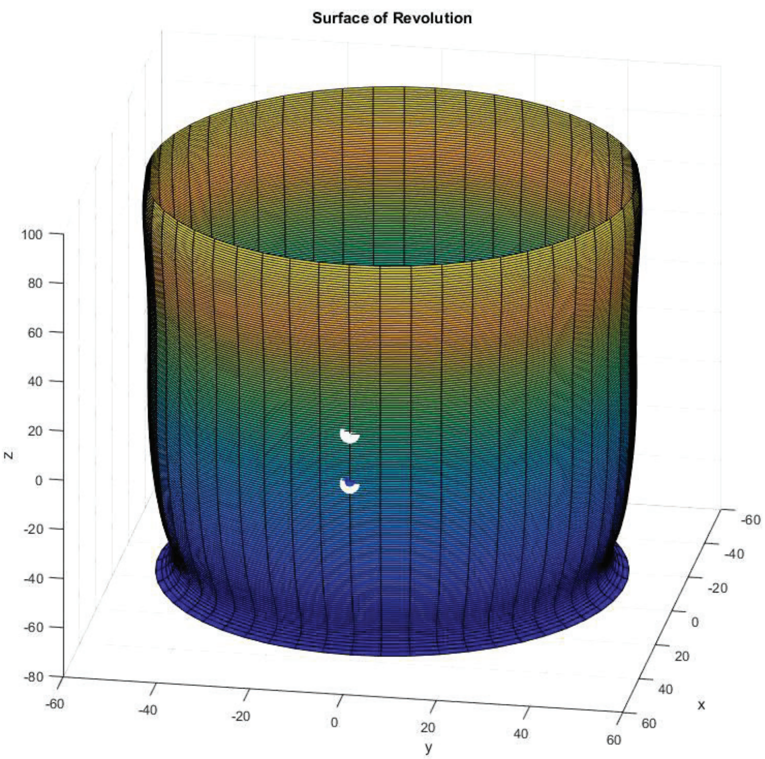
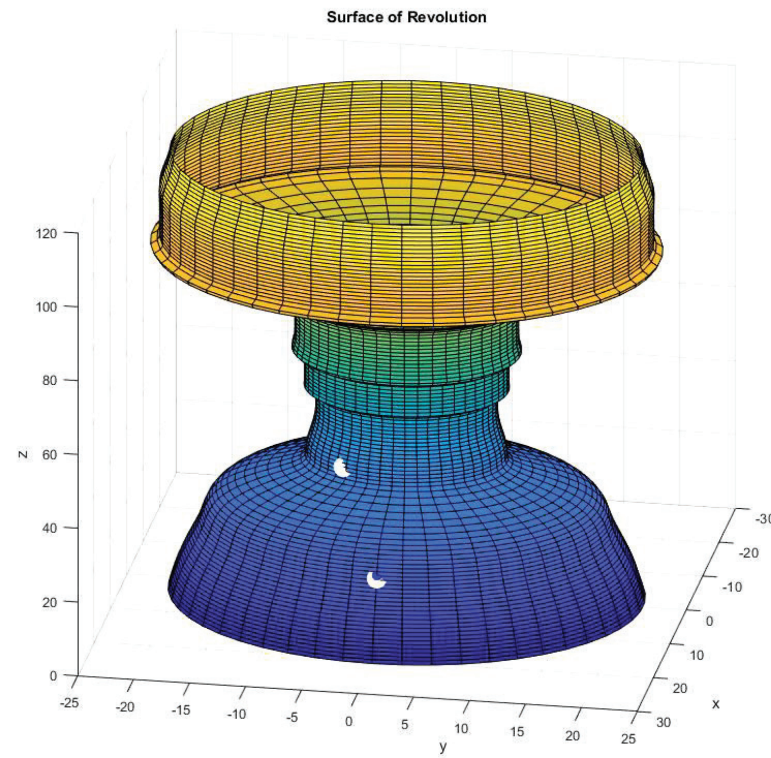
Architecture Optimization

FAN Case

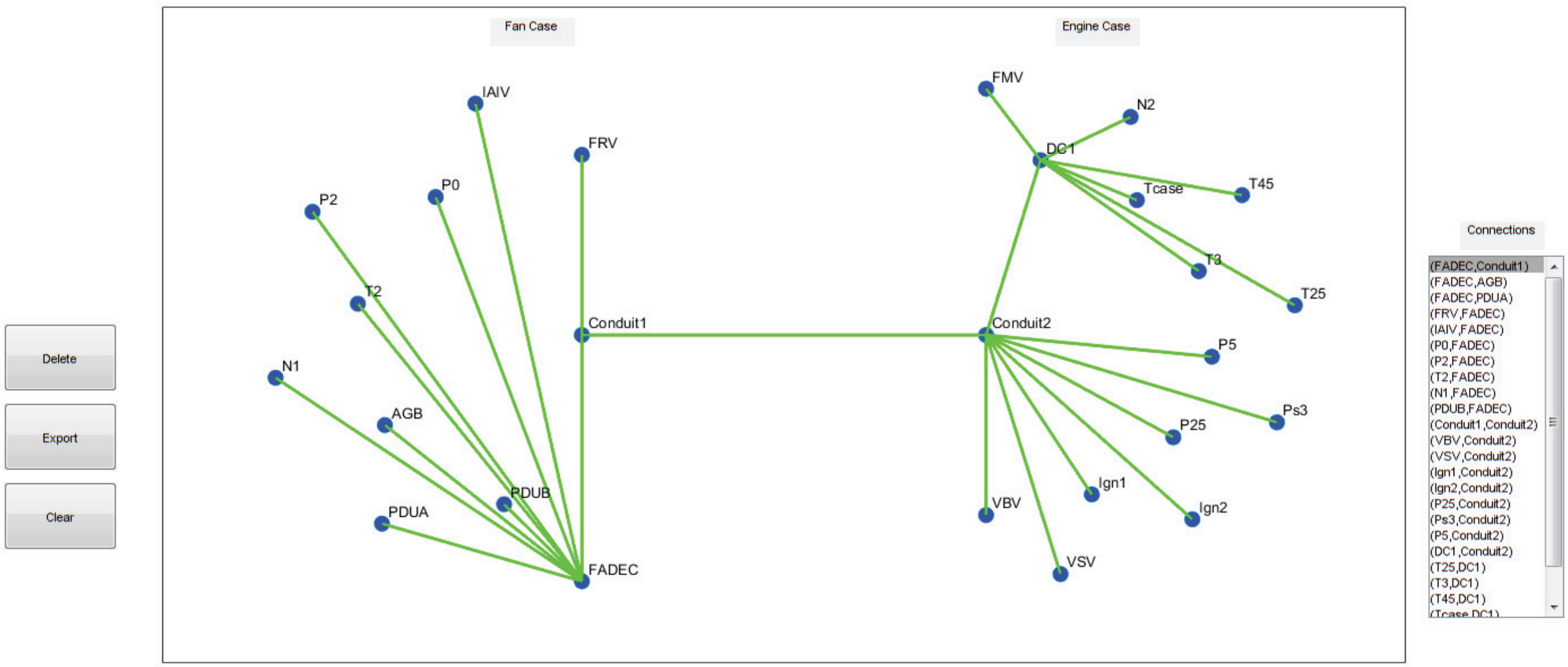


Engine Case



Credit: Samuel Mohler (Portland State University)

Architecture Optimization



Credit: Samuel Mohler (Portland State University)

Summary

- Developed a modeling methodology to serve the DEC problem
- Developed various dynamic thermal models
- Demonstrated real-time capabilities
- Applying thermal model results to direct decisions in DEC architecture design
- Future paths
  - Continue to improve the thermal modeling tools
  - Build-up temperature and hardware testing capabilities
  - Develop tools to facilitate decision making regarding DEC system configuration and architecture selection

Acknowledgement

- Transformational Tools and Technologies (TTT) project at the NASA Glenn Research Center as part of the Aerospace Research Mission Directorate (ARMD).
- NASA GRC: Dennis Culley, George Thomas, Don Simon, Roger Meredith, Jeff Csank, Jonathan Litt, Jeff Chapman, Dan Paxson, and Sanjay Garg
- Distributed Engine Controls Working Group (DECWG): Bruce Wood, Jay Kokas, Ed Dodd and Bill Rhoden
- Portland State University: Samuel Mohler

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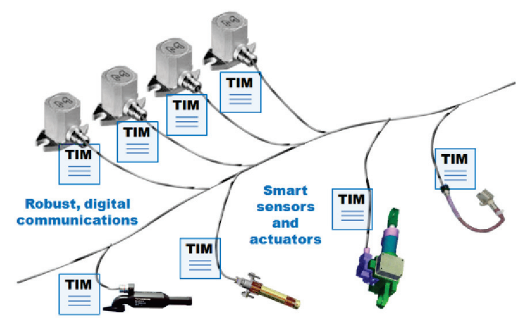
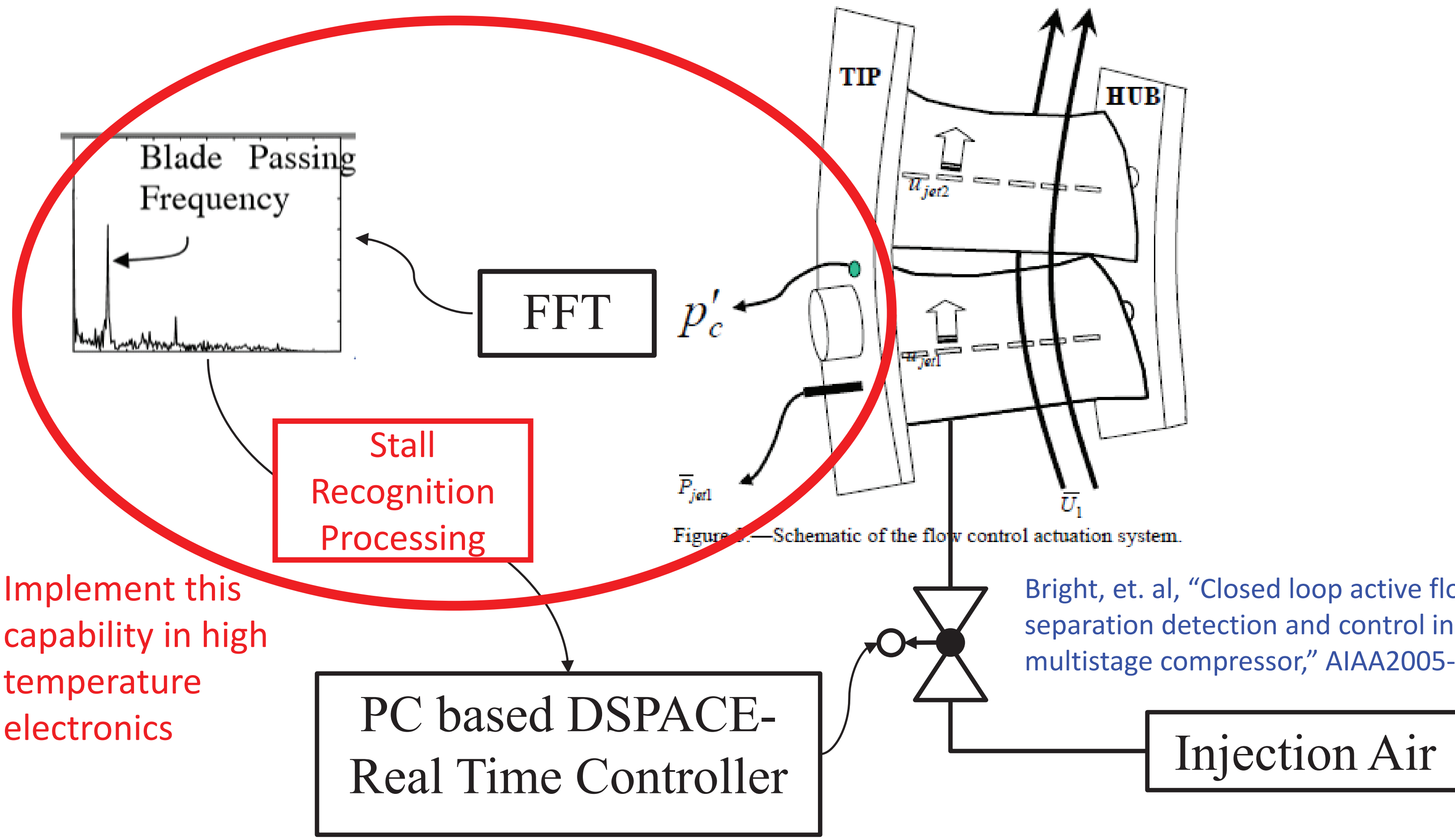
ADVANCED SMART NODE CAPABILITIES

What is a smart node?

- Distributing control from the FADEC to smart nodes enhances system
  - Augments total control system processing capability
  - Frees up FADEC processing to be used elsewhere
  - Distributes analog circuitry closer to sensors, on the smart nodes
- Advanced control technologies like Active Combustion Control or Active Stall Control will require Distributed Engine Control
  - Not practical to implement if loop closure is through the Engine controller
  - Smart node moves processing closer to sensor/actuator, allowing for higher bandwidth sensors
  - Instead of 1 or 10 Hz sensors, now 10 to 100 kHz with signal processing
- But, distributing control functions to smart nodes requires new hardware based on high temperature electronics
  - *What can we do with currently available hardware???*
  - *Can we detect stall precursors?*



Active Stall Control Scenario

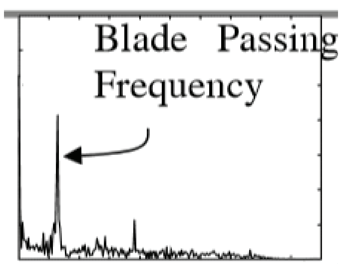


Implement this capability in high temperature electronics

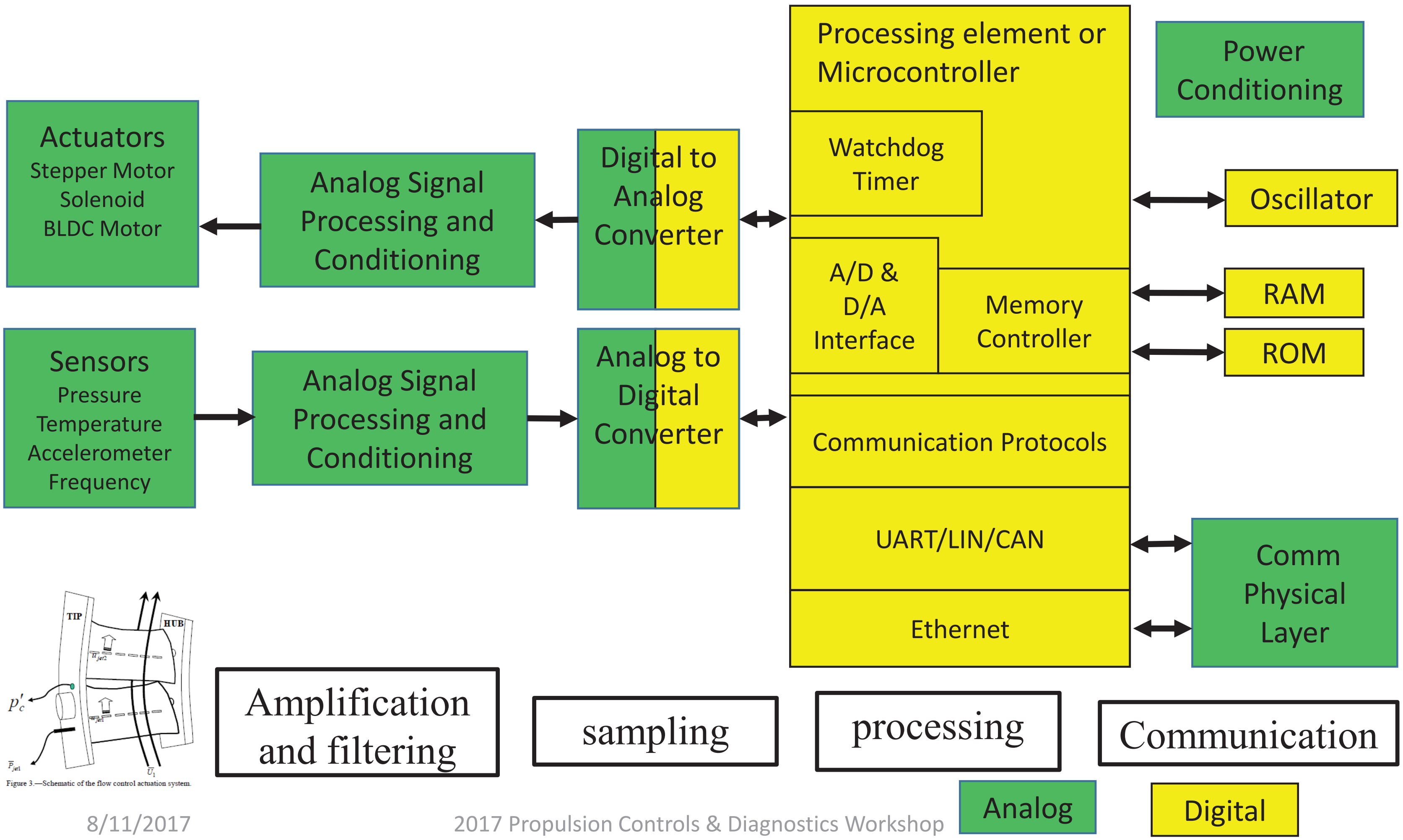
Bright, et. al, "Closed loop active flow separation detection and control in a multistage compressor," AIAA2005-849

NASA Smart Node

- Demonstrate a high temperature smart node for a distributed control environment
- To demonstrate a smart P3 sensor, Develop a Smart Node design incorporating available SiC and Si components for sensing and processing of P3 pressure sensor signals operating at >175 °C. (Highest possible temp with available components.)
- Outcome: Reference design of high temperature smart node hardware for demonstration in the HIL simulator.
  - Understand capabilities of hardware and needs for processing
- As part of active stall control, P3 smart node will:
  - Condition and sample high bandwidth pressure signal for processing
  - Process recognition of stall pressure signatures
  - Communicate with Hardware in the Loop controller



Smart Node Architecture

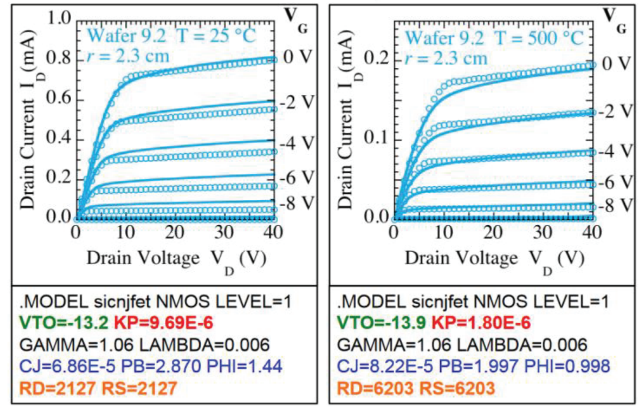


High Temperature Processors

8051 (+225 °C)	Relchip RC10001 (+300 °C)	Vorago Technologies (+200 °C)	SiLabs EFM32ZG222 (+85 °C)
Honeywell HT83C51 Tekmos TK80H51 • **8 bit** • **16 MHz** • Performance relies on peripherals • << 1 DMIPS • Need external ROM and RAM	• Cortex-M0 • **4 kB RAM** • UART and LIN 2.0 • Two 16-bit timers with PWM • Two 32-bit timers with PWM • **32 bit hardware multiplier** • **8 MHz operation** • Need external ROM • 5V supply	• Cortex-M0 • **32 kB RAM** • 128 kB Code Memory loaded from external SPI Flash at boot time • UART, no LIN or CAN • 24 timers with PWM • **32 bit hardware multiplier** • **50 MHz Crystal Oscillator** • 1.5 V core and 3.3 V IO supply	• Cortex-M0+ • **4 kB RAM** • UART, no LIN or CAN • Two 16-bit timers with PWM • **32 bit hardware multiplier** • 1-28 MHz RC Oscillator, or 1-**32 MHz Crystal Oscillator** • 12 bit – 1MS ADC (SAR) w/ mux • 2 to 3.8 V supply

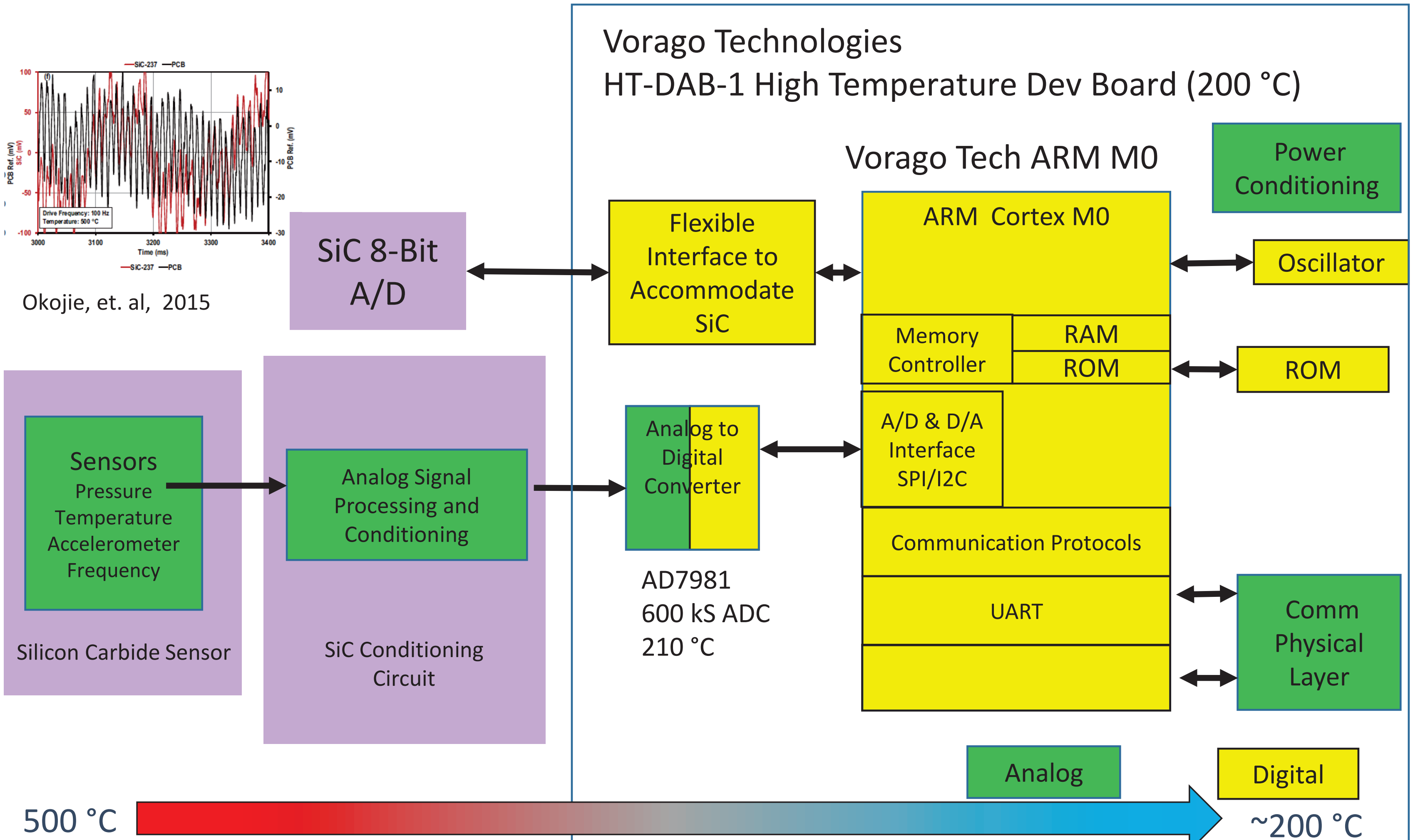
Silicon Carbide Circuits 500 °C

- Silicon Carbide transistor models have led to more accurate simulations
- Currently have designed and demonstrated logic gates, oscillators, counters
- New designs simulated in SPICE include operational amplifier and 8-Bit ADC
- Future designs currently in work include an arithmetic logic unit



Neudeck, et. al., "First-Order SPICE Modeling of Extreme Temperature 4H-SiC JFET Integrated Circuits," IMAPS International High Temperature Electronics Conference, New Mexico, USA, 2016.

NASA High Temperature Smart Node



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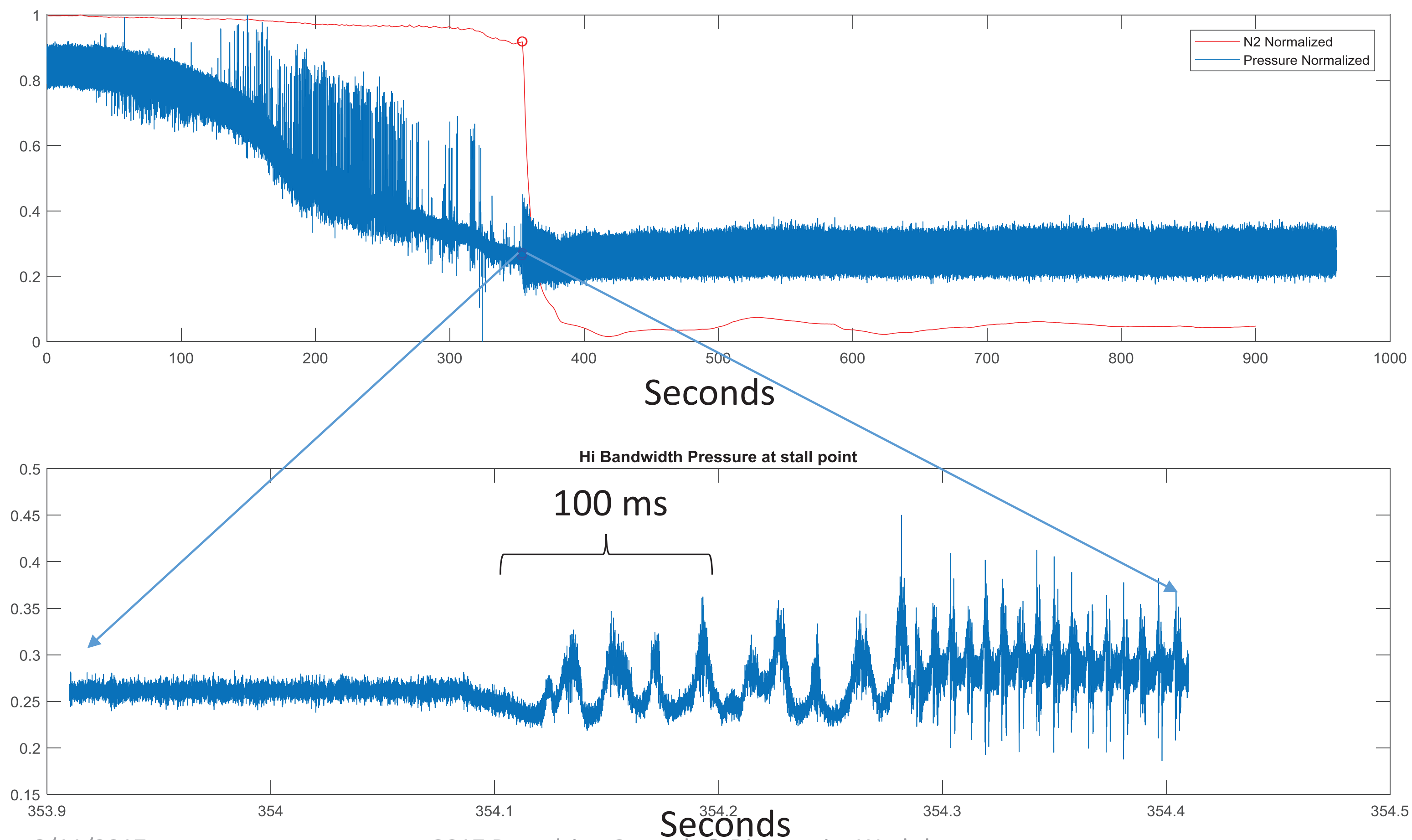
Stall Detection Test



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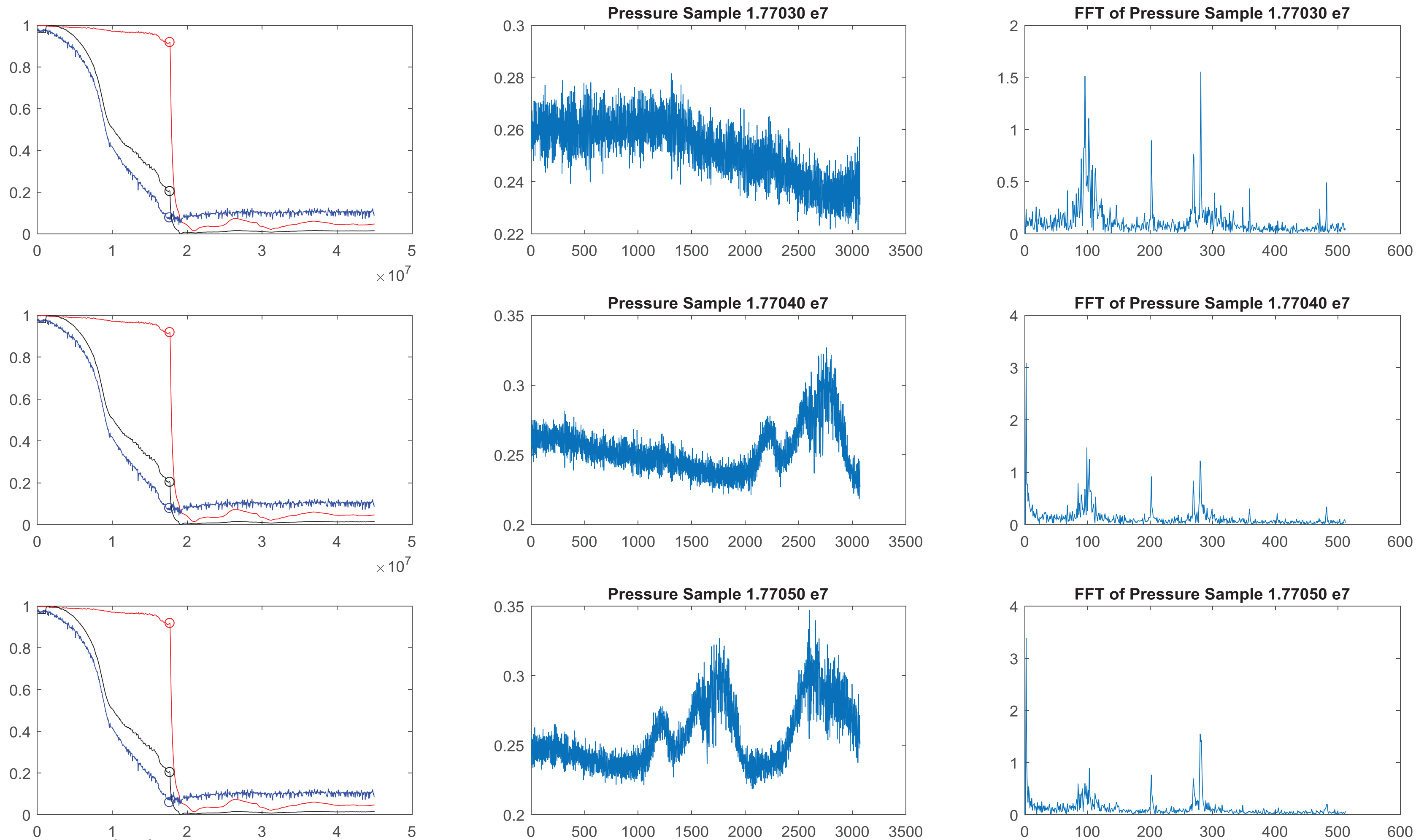
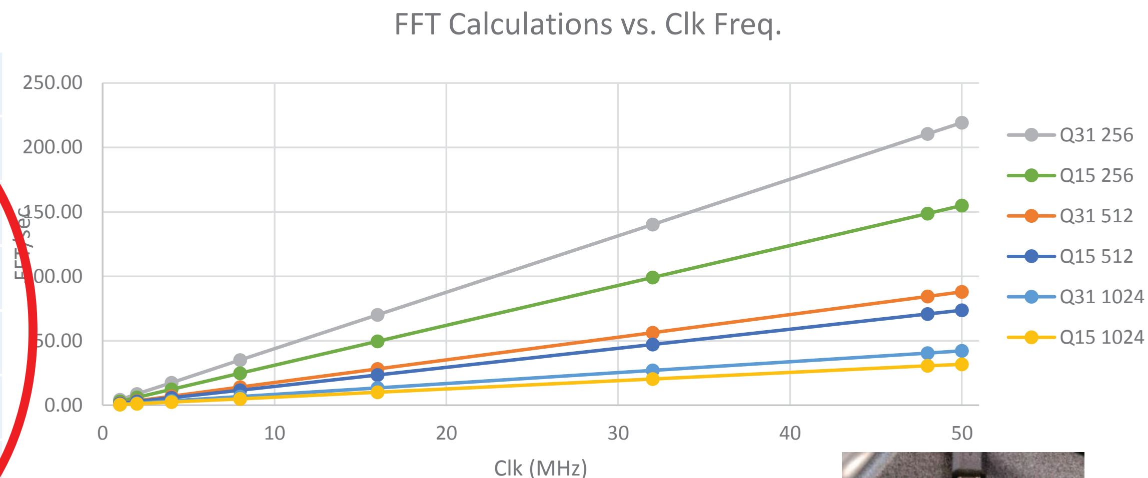
Stall Detection Problem



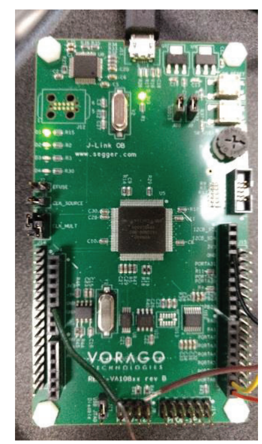
FFT Calculations on Vorago Technologies ARM M0

Memory Usage

		Flash (Bytes)	RAM (Bytes)
Q31	1024	51,572	20,672
Q31	512	47,492	10,432
Q31	256	45,476	5,312
Q15	1024	50,452	12,480
Q15	512	47,892	6,336
Q15	256	47,892	3,264

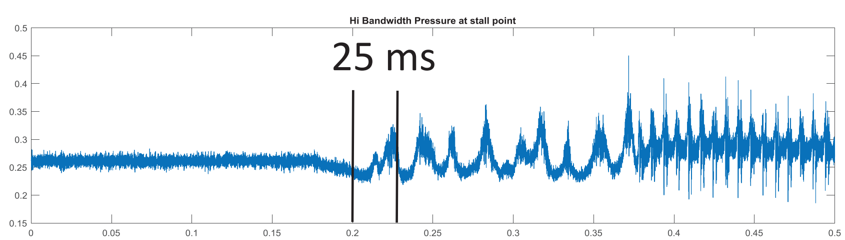


- FFT run on Vorago REB1-VA10800 Development Board
- FFT from ARM CMSIS library
  - arm_cfft_q15(&arm_cfft_sR_q15_len1024,fftOutputComplex,0,1);
- Program Size is significant and may not fit into memory
- Algorithm constraints of program size, ram usage, and speed
- 16 bit calculations less efficient



How fast can we run an FFT algorithm?

- If we ping pong data buffers, sample collection time should be negligible, happening on an interrupt
- Communication happens at 1Mbaud, so if common UART (8 data bits, with start and stop bit)
- 1 Byte transfers at 10 uS, 100 Bytes at 1 ms
- Will have new FFT data every 25 ms with 1024 point FFT
- So we should be able to detect stall precursors in 25 ms



		Calc Period (ms)	100 kS Sample time
Q31	1024	23.70	10.24
Q31	512	11.40	5.12
Q31	256	4.60	2.56
Q15	1024	31.90	10.24
Q15	512	13.60	5.12
Q15	256	6.50	2.56

Alternative Algorithms
A Reprogrammable Smart Node

- Correlation based algorithm
- Manuj Dhingra, Yedidia Neumeier, J.V.R. Prasad, and Hyoun-Woo Shin. "Stall and Surge Precursors in Axial Compressors", 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Joint Propulsion Conferences, 2003.
- Current Test
  - arm_correlate_q31(fftOutReal,512,fftOutImag,512,fftOutputComplex)
  - ~12.4 M clock cycles, so ~4 correlations per second
  - Will try smaller buffers for correlation

Conclusion

- We're developing this node and will test it at temperature as part of a HIL simulation.
- Algorithms depend on available high temperature hardware (memory and speed)
  - There are not a lot of options
- FFT method should work in planned high temperature hardware demonstration
- Correlation algorithm may not work
- Open to other algorithms

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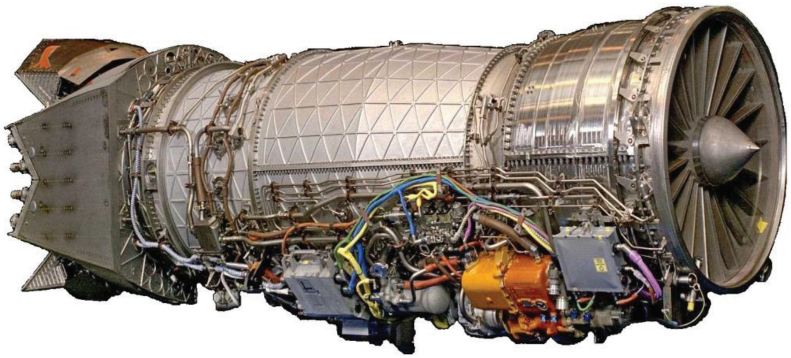
DURABLE, EXTREME HIGH TEMPERATURE INTEGRATED CIRCUIT CAPABILITIES

Role for Extreme High Temperature Electronics in Distributed Engine Control

Centralized control architecture with FADEC has been used since the mid 1980's

Distributed engine control features:

- Data concentrators
- Smart sensors/actuators
- Local loop closure
- Digital I/O
- Plug and play
- Sensor bus
- Reduced wire count and weight
- Increased reliability
- Expandability, flexibility, modularity



P&W public release

Implementation of distributed control inhibited by lack of high temperature electronics

- Active cooling of distributed modules is impractical
- Catalog of 225 °C silicon-on-insulator (SOI) electronics needed
- Use SiC for T > 300 °C
  - In-package sensor signal conditioning
    - Smart P3 sensor

Engine Applications for High Temperature SiC Electronics

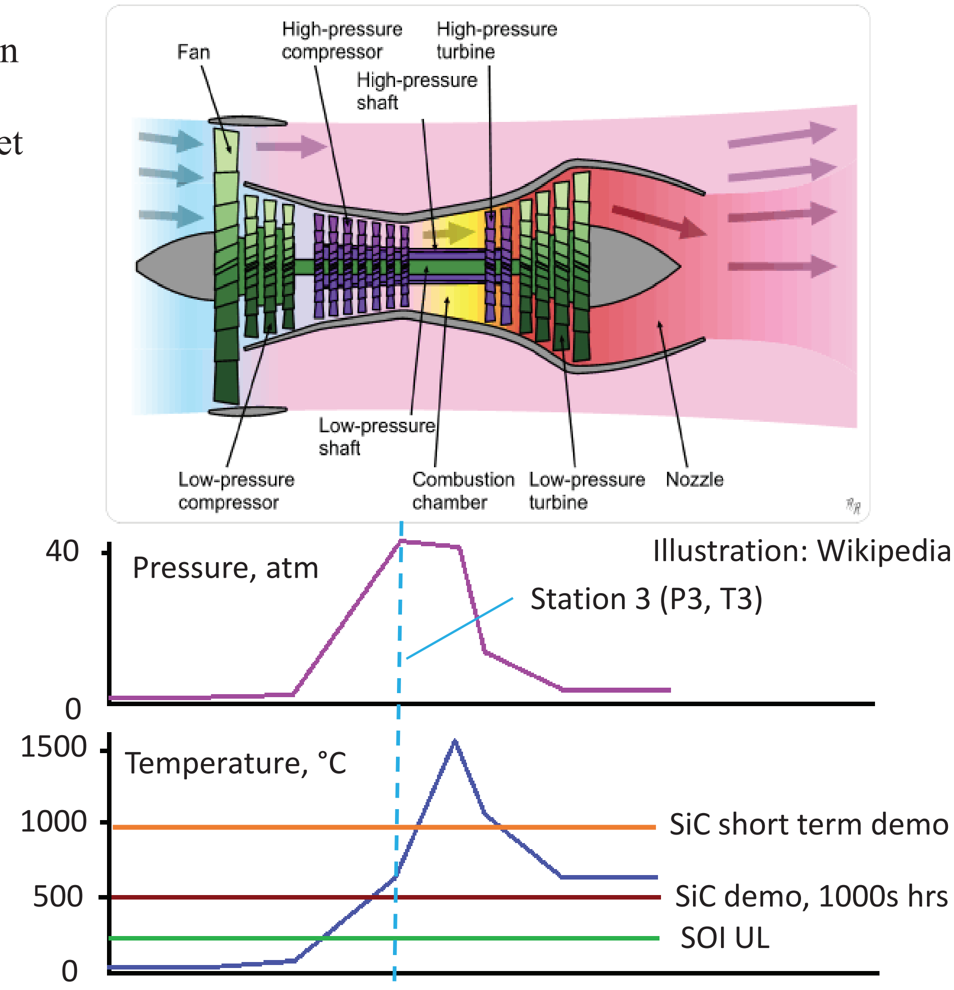
- 500 °C durable SiC electronics enable in-package sensor signal conditioning in hot regions of engine:
- **Electronics in core gas path**; from inlet to last stages of compressor
- **Electronics outside core, at back of sensor probe**; additional locations accessible, including compressor discharge and front part of combustor

- Desirable to withstand compressor discharge temperature (T3):

P3/P1	T3
30	540 °C
40	615 °C
50	675 °C

(T1=59 °F, P1=1 atm, 90% comp. eff.)

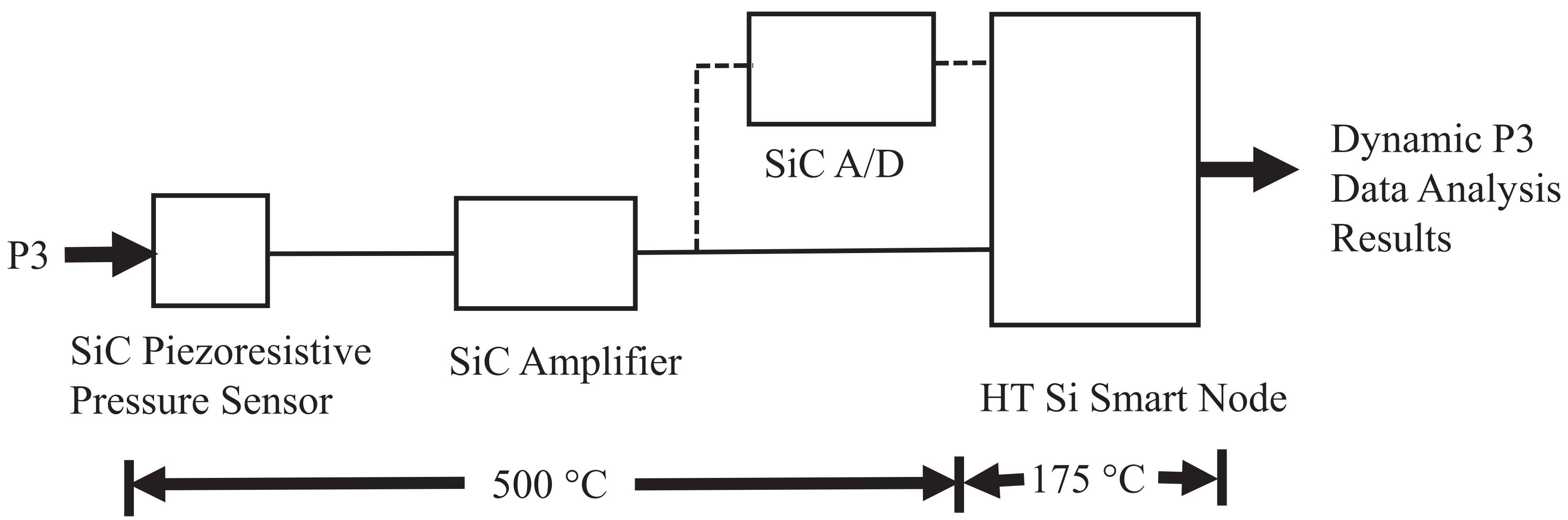
- SiC electronics being pushed to temperatures > 500 °C
- Recently GRC has demonstrated operation of a SiC IC at 960 °C



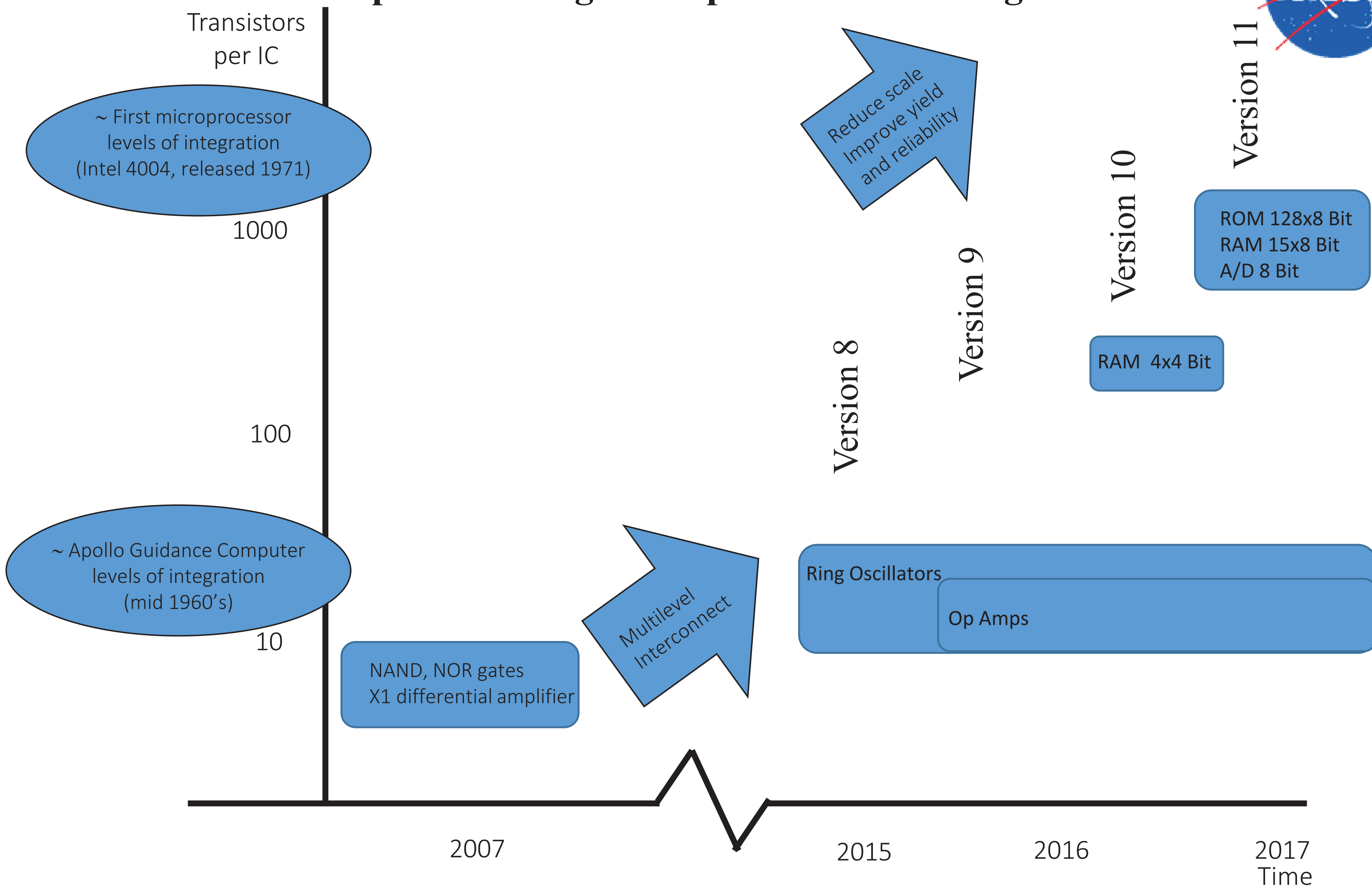
Core gas path pressures and temperatures for 42:1 pressure ratio engine

Stall Precursor Detection Using High Temperature Smart P3 Sensor and Smart Node

- High bandwidth SiC sensor installed in existing P3 port (sensor can withstand 800 °C)
- 500 °C capable SiC signal conditioning electronics mounted in back end of sensor housing
- Analog or digital (depending on availability of 8 bit A/D) data transmitted to smart node
- Smart node processes dynamic P3 data to determine proximity to stall



Development of High-Temperature SiC Integrated Circuits



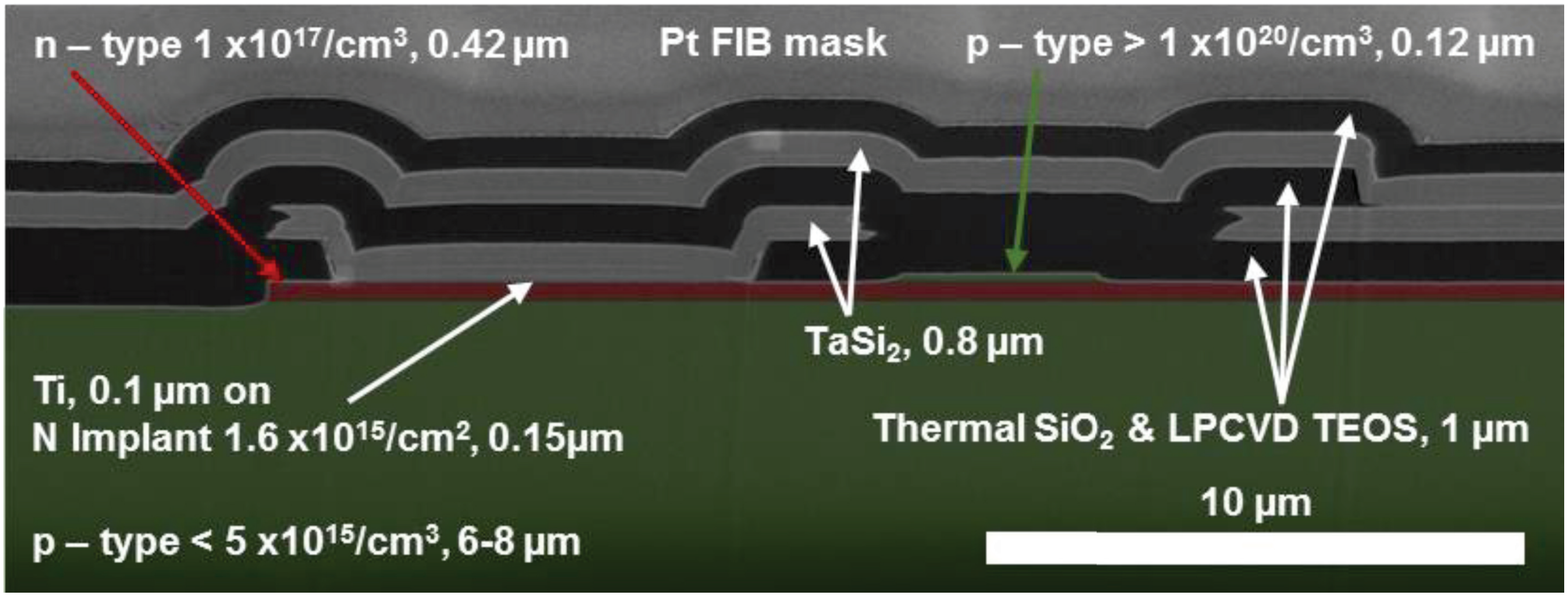
SiC IC Multilayer Interconnect

Multilayer interconnect enables ICs with 10 to 100 s of transistors

Processing enhancements for conformal coverage of high aspect ratio topography:

- Proximity sputtering of $TaSi_2$ (21mm target to substrate spacing)
- LPCVD SiO_2 using TEOS precursor deposited at 720 °C
- Design rules for thick dielectrics and metal traces

Enables crisscrossing traces and on chip capacitors



SiC JFET IC (version 8.2) cross-sectional SEM (color shows SiC dopant type)

Version 9.2 IC Functional Yield at 25 °C

Integrated Circuit Designation	# FETs	# Good	# Tested	% Yield
MF Gate 3-Stage Ring Oscillator	10	36	39	92%
HF Gate 3-Stage Ring Oscillator	10	66	78	85%
Op Amp Design A	10	19	20	95%
Op Amp Design B	10	18	20	90%
LF Gate 3-Stage Ring Oscillator	12	35	41	85%
LF Gate 11-Stage Ring Oscillator	24	37	41	92%

LF, MF and HF = low, medium, and high frequency

9.2 is first wafer fabricated after implementing new Na minimization protocols. First working GRC IC op amps at 500 °C.

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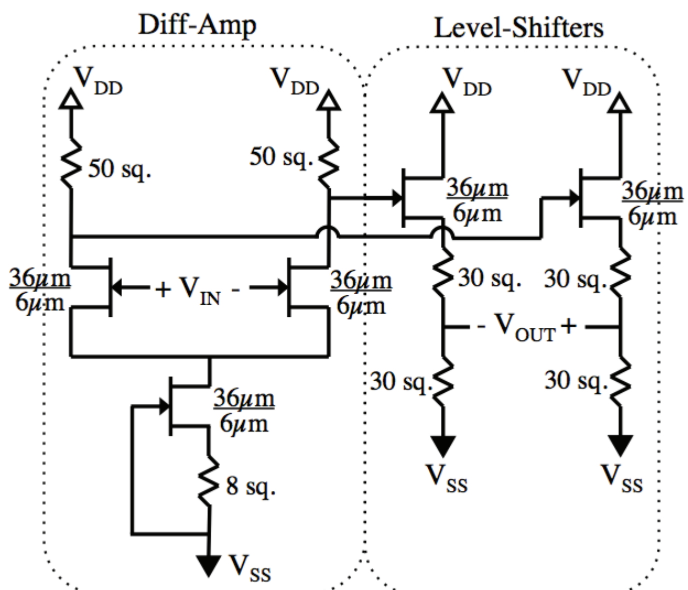
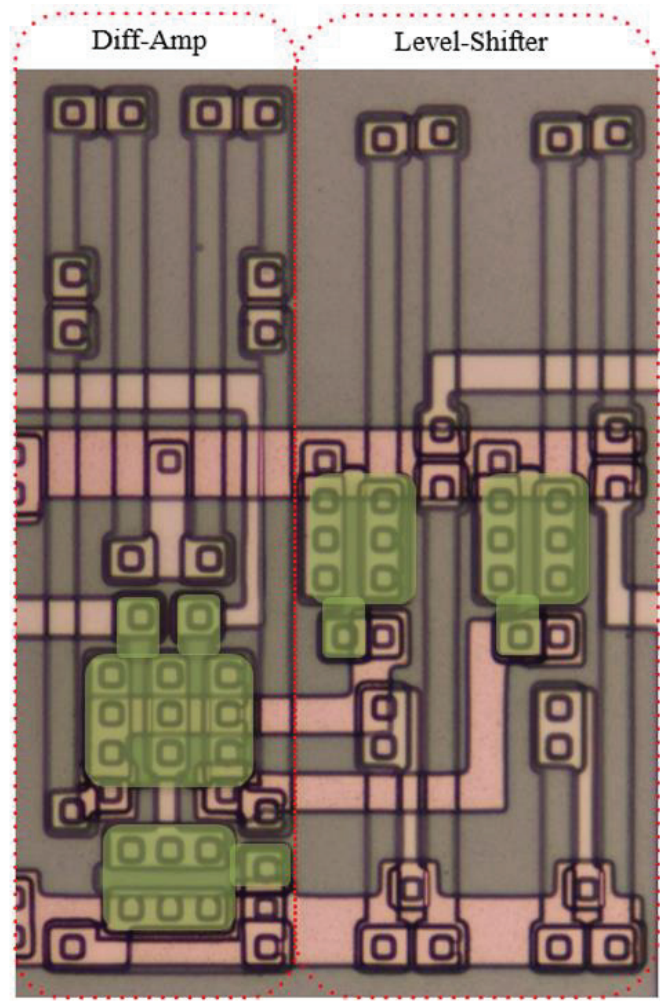
Version 9.2 Amplifiers

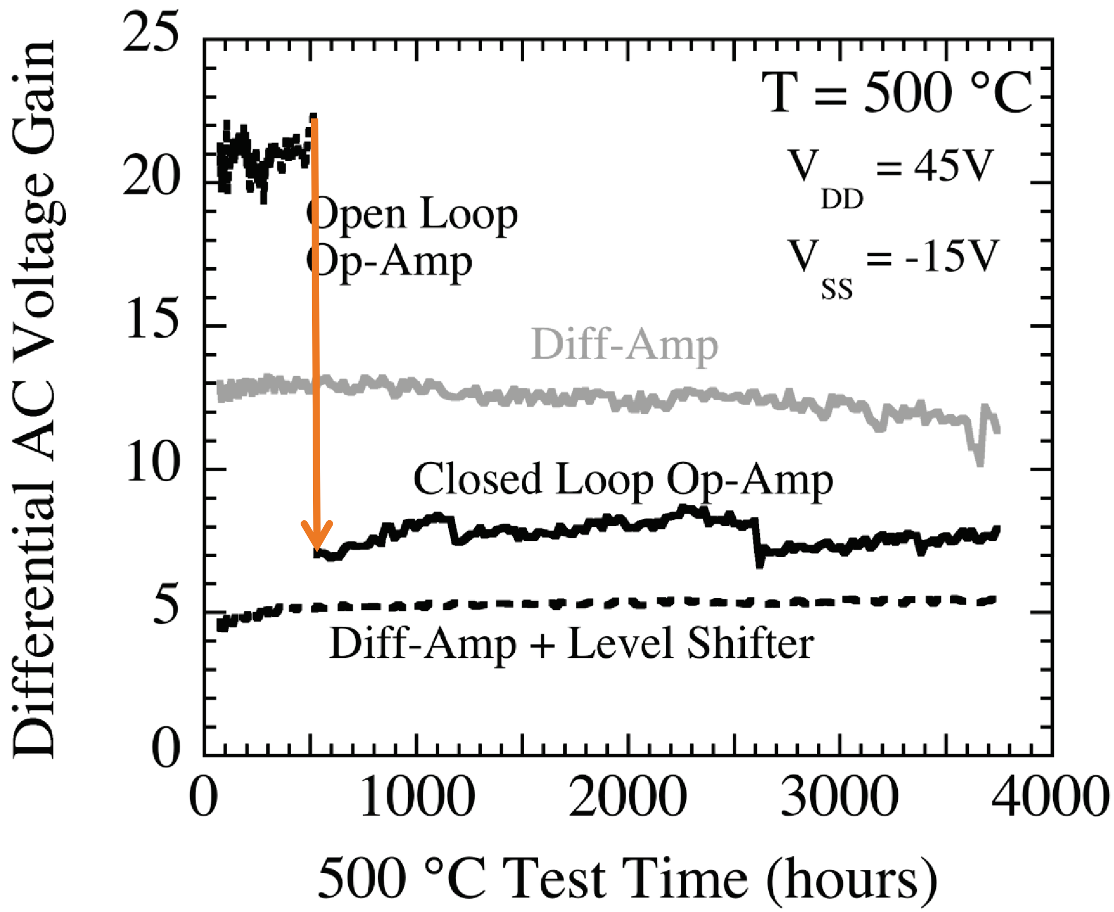


(Above) Schematic diagram of diff-amp and level shifters.



(Right) Optical image of diff-amp and level shifter. JFETs are highlighted in green.

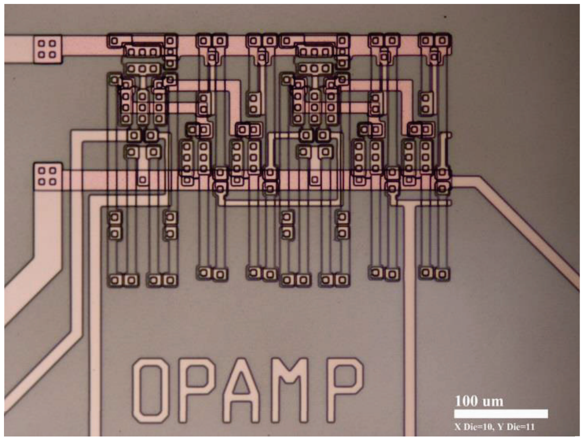
9.2 Amplifiers Durability at 500 °C

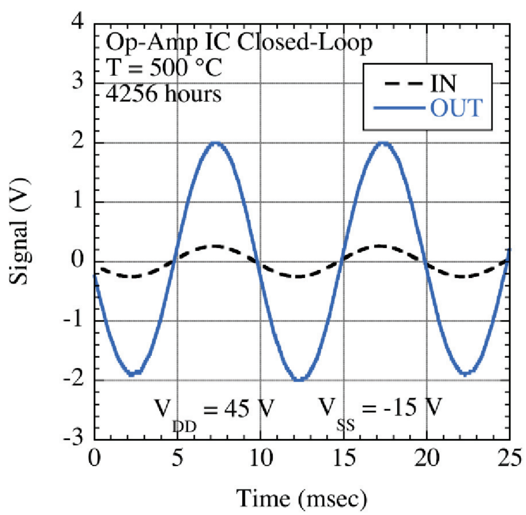


Measured differential small-signal voltage gain vs. time of operation at 500 °C.

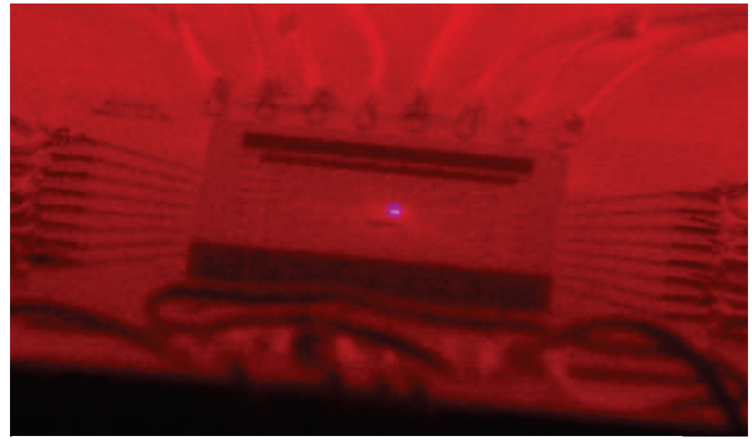
Version 9.2 High Temperature Durability

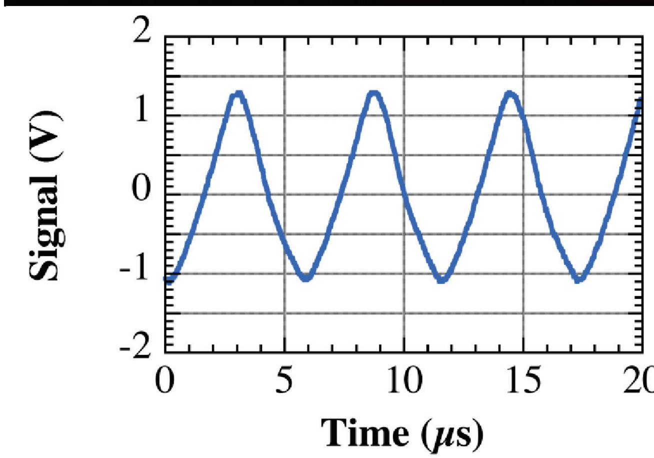
6-Month 500 °C Op-Amp IC





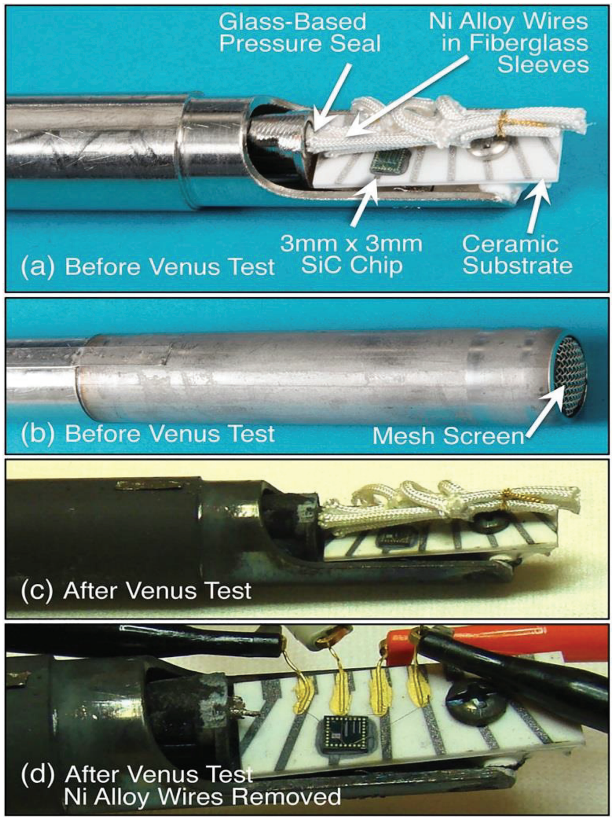
650 °C Ring Oscillator IC



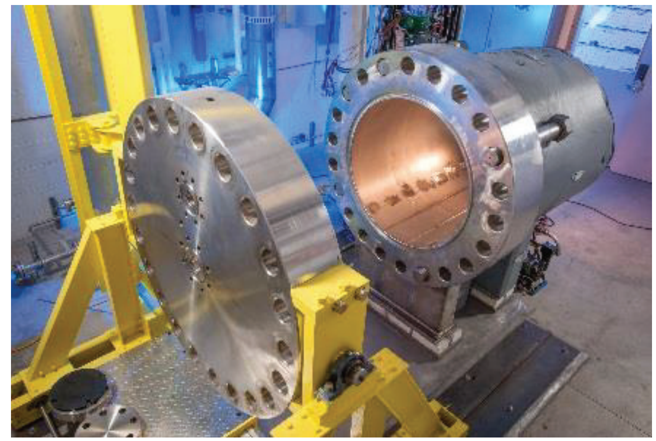


Ring oscillator IC still operating after 150 hrs at 650 °C

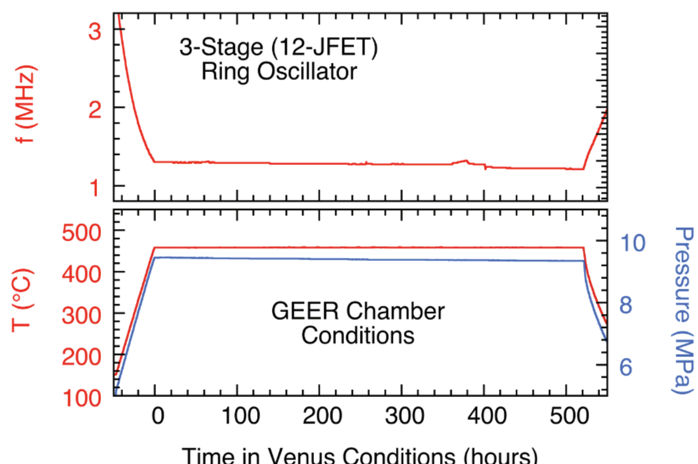
SiC IC Durability Test in Simulated Venus Environment



SiC ICs mounted in Venus chamber feed throughs

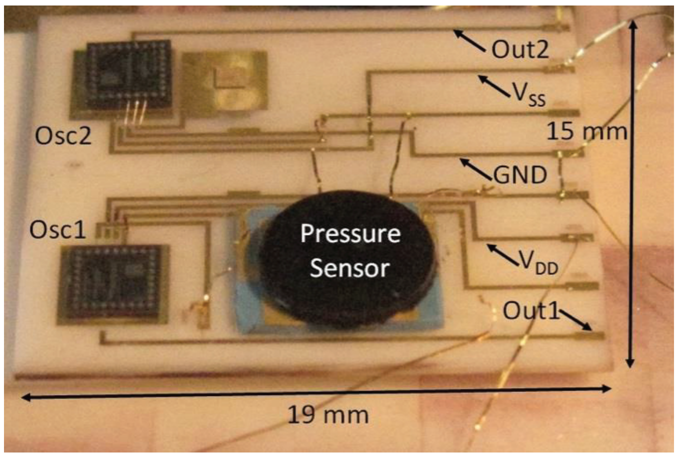


Glenn Extreme Environments Rig (GEER)



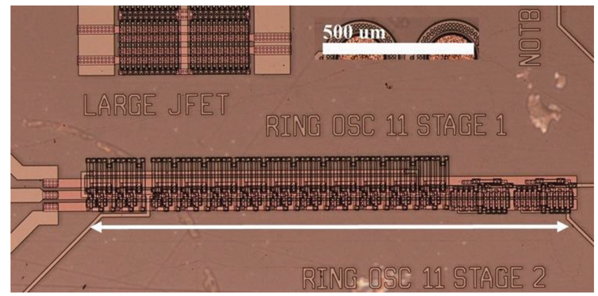
High Temperature Capacitive Pressure Sensor Using SiC IC Signal Conditioning Electronics

Dual SiC ring oscillator ICs provide temperature compensated pressure measurements

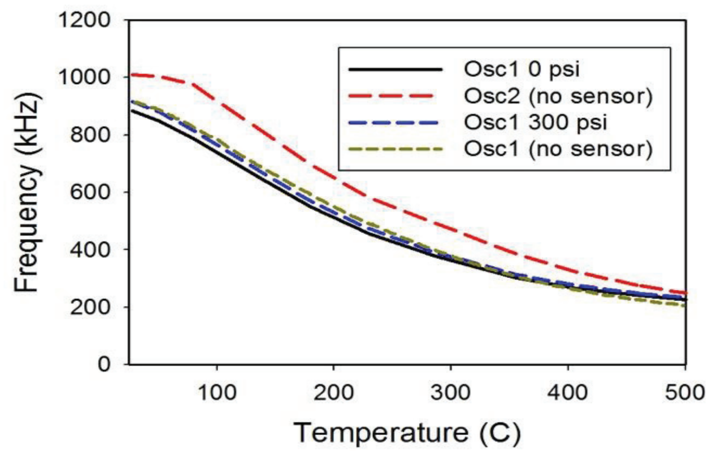


Circuit board with Sporian SiCN capacitive pressure sensor and two ring oscillator ICs: Only Osc1 is connected to the pressure sensor, Osc 2 provides a temperature reference.

Credit: M. Scardelletti

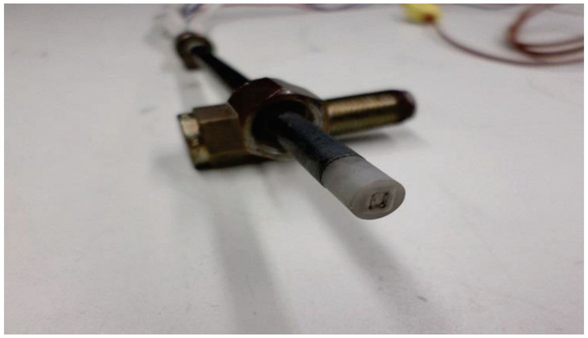


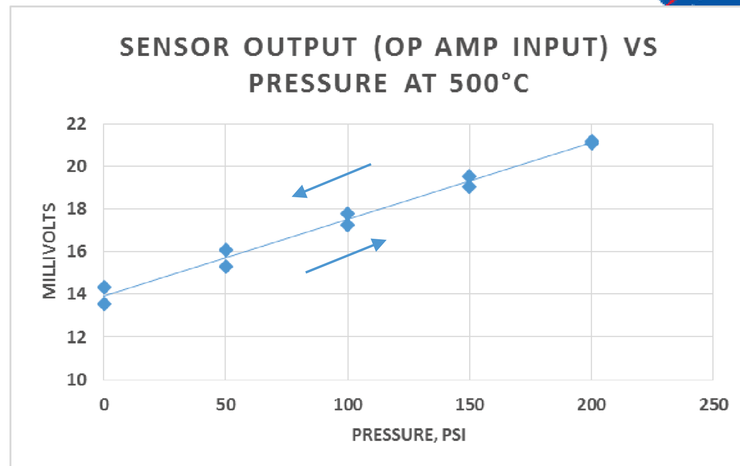
GRC 11 stage ring oscillator IC



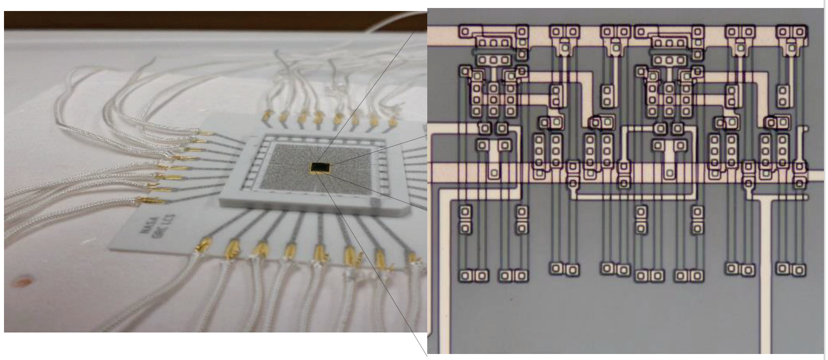
Responses of Osc 1 (T and P sensing) and Osc 2 (T sensing only)

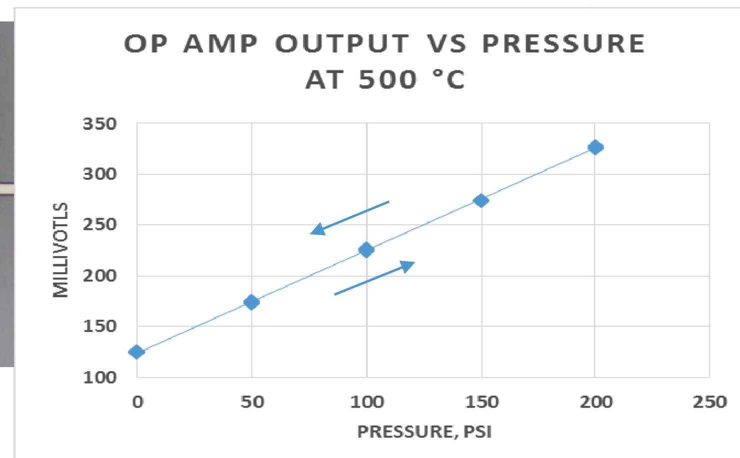
High Temperature Piezoresistive Pressure Sensor & Amplifier





High temperature SiC piezoresistive pressure sensor which was tested with SiC integrated circuit amplifiers to 500 °C.





SiC amplifier chip in high temperature package (lid removed), on circuit board.

Credit: R. Okojie

Version 10.1 Integrated Circuits Fabricated

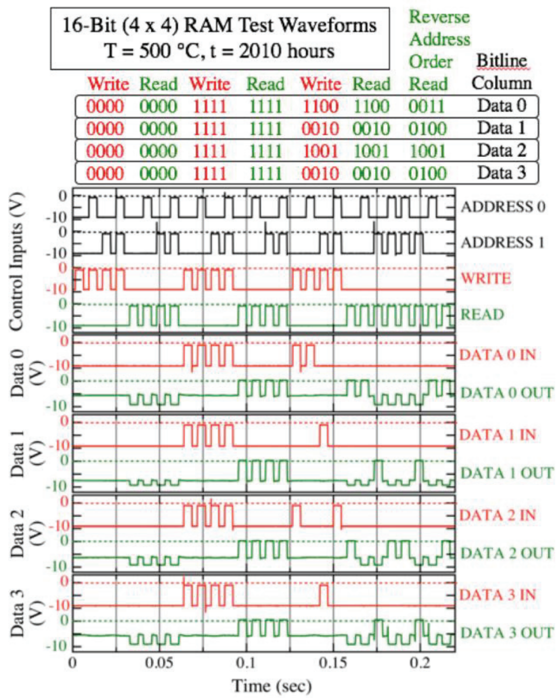
Circuit	Inputs	Outputs	Transistors, I/O Pads	Comments
4-Bit A/D	Analog voltage signal, optional external clock, output type select	4 bit parallel digital latch, pulse width modulated (PWM)	203 JFETs, 23 I/Os	Internal ring-oscillator clock circuit
4X4 Bit Static RAM	Read, Write, Data Lines, Address Lines	4 bit parallel digital latch, pulse width modulated (PWM)	220 JFETs, 30 I/Os	Address decoder, sense amplifiers
Source Separation Sensor Signal Transmitter	Capacitive sensor	Frequency modulated with address code	301 JFETs, 20 I/Os	Each sensor signal is tagged with unique address code
Ring Oscillators	Capacitive sensors	Frequency modulated signals (up to 500 MHz)	10-12 JFETs, 6 I/Os	On-chip large transistors for power amplification
Binary Amplitude Modulation RF Transmitter	Low power binary signal	High-Power RF signal to antenna		Could connect with PWM from A/D
Op Amp, 2-Stage	Differential	Voltage gains to 50 w/ on-chip resistors	10 JFETs	For piezoelectric SiC pressure sensors
4-Bit D/A	4 digital	1 analog	20 JFETs	

National Aeronautics & Space Administration

Version 10 SiC JFET IC Test Results

Version 10 ICs continue to set high temperature durability world records in T ≥ 500 °C Earth-atmosphere oven testing.

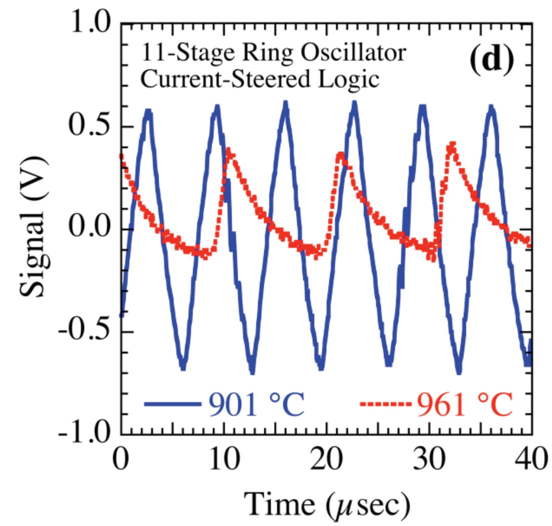
Complex ICs Operating 4000+ hours at 500 °C[1]



IC Version 10 Experimental Timeline:

- Mask design complete: August 2015
- Wafer fabrication complete: March 2016
- Wafer dicing complete: June 2016

ICs Operating at World Record 961 °C[2]



[1] Submitted to ICSCRM 2017
[2] To appear in IEEE Electron Device Lett.

More complicated (by 7-10X) Version 10 ICs are averaging longer 500 °C durability than Version 9 ICs.

High Temperature SiC Electronics Status: Version 11 Designed

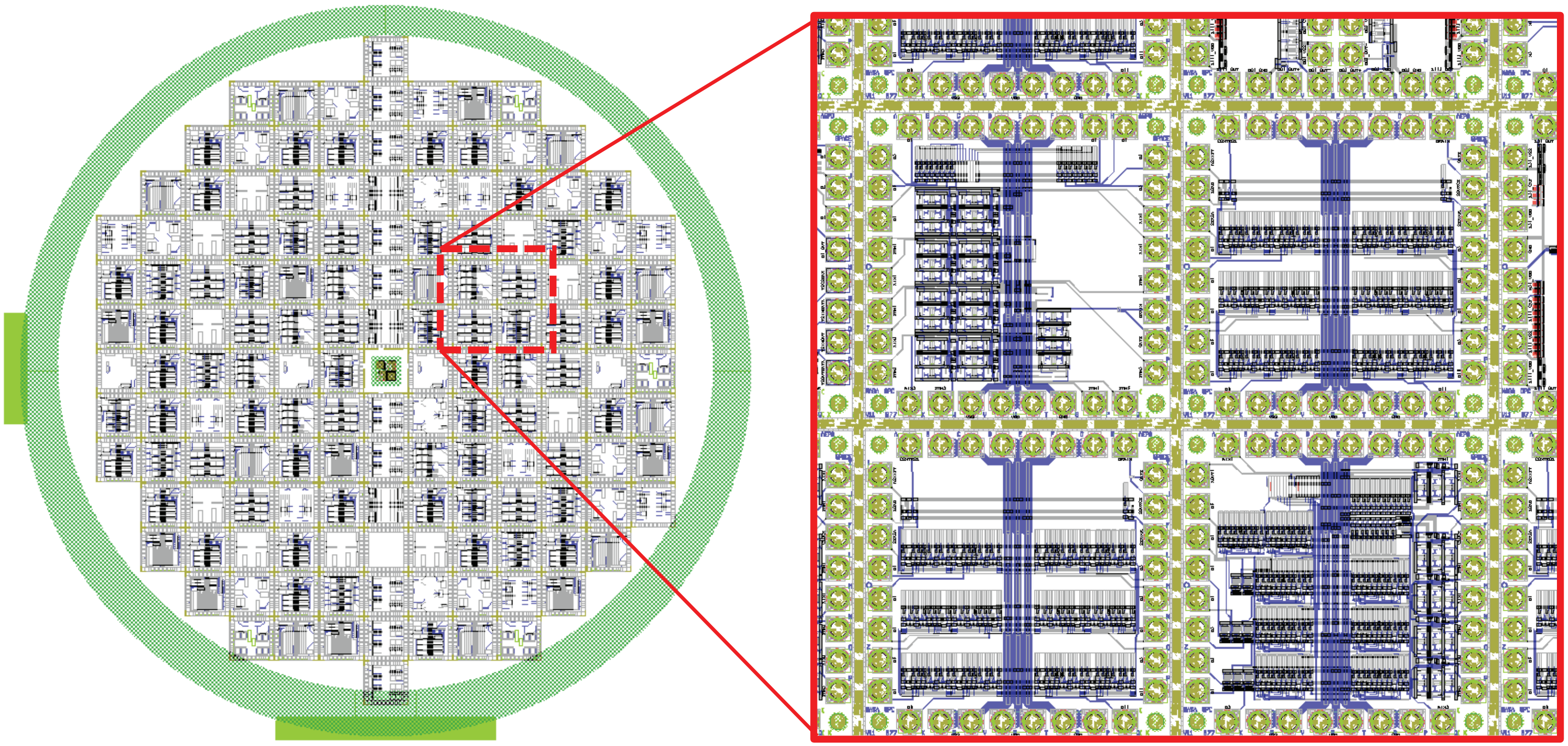
Major Technology Advancements **Designed** into Version 11 IC Run

500 °C IC Capability Metric	Present 2017 "State of Art" (Version 10)	Advancement Attempt (Version 11)	Gain Factor	Mission Impact (**IF** Version 11 wafer run is FULLY successful)
IC Complexity	**~200 Transistors/chip**	**~1000 Transistors/chip**	**~5X**	**Enables smart sensors and nodes**
Logic Gate Power	**~2 mW/gate**	**~ 0.4 mW/gate**	**~5X**	**Power reduction for smart sensors and nodes**
Analog to Digital Converter	None durably demonstrated	8 Bits	∞	First digitization of analog sensor data durable at 500 °C
RS-485 Serial Communications	None durably demonstrated	? kbits/sec	∞	Digital data to/from 500 °C over longer wires (Ozark IC Space Act Agreement)
Random Access Memory (RAM)	16 bits (4 x 4 bits)	120 bits (15 x 8 bits)	~ 7.5X	Read/write memory for smart sensors and nodes
Read Only Memory (ROM)	None durably demonstrated	992 bits (128 x 8 bits)	∞	Read only memory for smart sensors and nodes
Bit Stream RF Modulator	None durably demonstrated	Few MHz Carrier Frequency	∞	Wireless 500 °C digital communications for smart sensors and nodes

NASA/CP—2018-219891

High Temperature SiC Electronics Status: Version 11 Designed

Version 11 Wafer Mask Drawings



76 mm diameter wafer arrayed with
4.65 by 4.65 mm integrated circuit chips

Poster Session

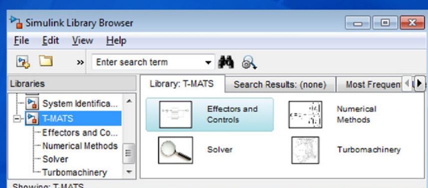
Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)

NASA Glenn Research Center

National Aeronautics and Space Administration

T-MATS Description

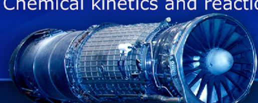
- Simulation system designed for custom thermodynamic Component Level Model (CLM) creation
- Plug-in to MATLAB/Simulink
- Library structure allows user maximum flexibility
- Open source format encourages collaboration



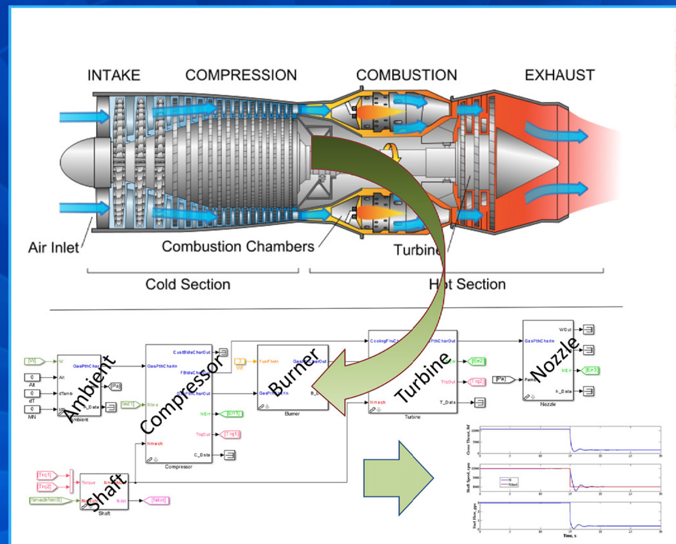
Simulation System Architecture

The T-MATS simulation framework uses iterative solvers for the creation of multi-loop systems in Simulink. It includes:

- Components for building complex thermodynamic model architecture
- Iterative Solver blocks that are both general and flexible
- Advanced turbomachinery modeling
- Control system (hardware and software) modeling block sets
- Chemical kinetics and reactions



Create Custom Turbomachinery Systems in the MATLAB/Simulink Environment



Automated Iterative Solver Algorithms

Converge the System: T-MATS contains the blocks necessary to ensure flow continuity

- Solver Blocks, using numerical methods
  - Automated Jacobian calculation and Newton-Raphson iterative solving

$$x(n+1) = x(n) - \frac{f(x(n))}{f'(x(n))} \quad \text{where, } f'x(n) = J$$

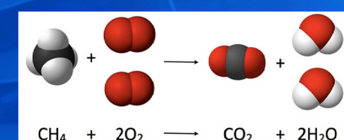
Thermodynamic System Modeling

Supports creation of thermodynamic systems with custom Simulink blocks:

- Turbomachinery blocks
  - gas turbine building components
- Control System blocks
  - actuators
  - sensors
  - PI controllers

Chemical Kinetics and Transport

Integration with Cantera brings chemical kinetics, thermodynamics, and/or transport processes to MATLAB/Simulink.



Major new T-MATS features

- T-MATS auto plotting scripts
- Code building and generation
- Automated NPSS to T-MATS model creator scripts
- Health parameters for engine components
- Engine heat soak
- Volumetric capability (1-D flows!)
- Piecewise linear model generation

Download the Software

Free download available at:
https://github.com/nasa/T-MATS/releases

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NASA/CP—2018-219891

Advanced Geared Turbofan Engine 30,000 lbf AGTF30

NASA Glenn Research Center

National Aeronautics and Space Administration

Description

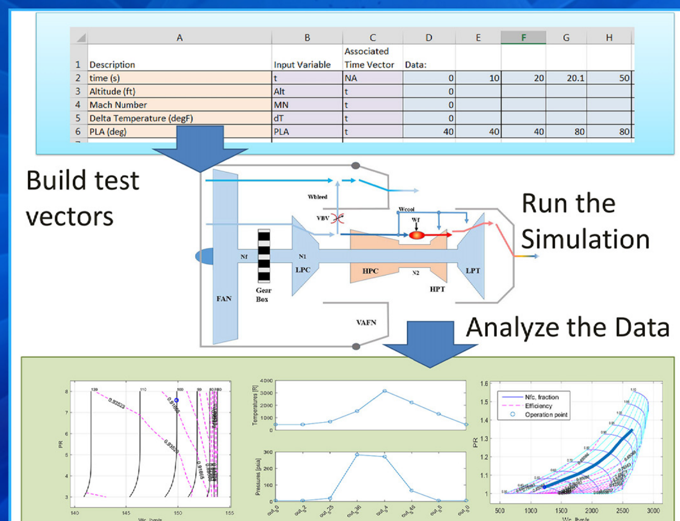
The Advanced Geared Turbofan Engine 30,000lbf (AGTF30) is a simulation built with the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS), which is based in MATLAB/Simulink (The MathWorks Inc., Natick, MA). It represents in-flight engine dynamics. It provides easy access to internal variables, and to control and health information. The user can specify throttle input commands, altitude and Mach number trajectories, and component health condition.
The AGTF30 is a versatile testbed for control system research on an advanced engine concept.

Technical Approach

- The AGTF30 was built with the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS). This tool facilitates the creation of 0-D component level turbomachinery models that utilize an energy approach, where compressor and turbine components rely on empirical map data.
- This model represents a futuristic engine where component performance is based on a 30 year expectation.
- A baseline controller representative of typical industry architecture was developed and tuned to meet all relevant FAA and airframe manufacturers' specifications.

Features of the AGTF30

- Transient and steady state performance is representative of engines in the 30k thrust class
- Capable of executing arbitrarily complex flight profiles
- Can develop linear models at fixed operating points
- Detailed surge margin calculation for steady state and transient operation
- Executes faster than real-time on typical PC
- The controller is representative of typical architecture found on commercial turbofan engines
- Requires no extra MATLAB/Simulink toolboxes
- Can simulate typical engine deterioration as well as engine component faults



Next Generation Research Platform

- Engine system includes advanced engine design features:
  - Ultra-high bypass
  - Small engine core design
  - Variable area fan nozzle (VAFN)
  - Fan gear box

Current NASA Uses of AGTF30

- Turbine tip clearance research, including performance effects and active tip clearance control research.
- Core component of a Distributed Engine Control hardware testbed
- Variable area fan nozzle research, control algorithm and actuator studies.

Public Release Pending

More Information

- Jones, S.M., Haller, W.J., Tong, M.T., "An N+3 Technology Level Reference Propulsion System", NASA/TM-2017-219501, 2017.
- Chapman, J.W., Litt, J.S., "Control Design for an Advanced Geared Turbofan Engine", 2017 AIAA Joint Propulsion Conference, Atlanta, GA, Jul 10-12, 2017.

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NASA/CP—2018-219891

High Bandwidth Liquid Fuel Modulators for Active Combustion Control

George Kopasakis, Joseph Saus, Randy Thomas
NASA Glenn Research

National Aeronautics and Space Administration

Description

Active Combustion Control (ACC) is a control strategy for mitigating thermo-acoustic combustion instabilities by modulating fuel into the combustor that is at the frequency of the instability, but with opposing phase. These instabilities are self-sustaining due to the development of a favorable phase condition between unsteady heat release and the acoustic pressure maintained over the whole oscillation cycle. If ignored, they can cause vibrations which lead to premature mechanical failures, and they can adversely affect emission levels. The intention of the ACC project is to develop a technology-enabling tool for lean burning combustors since they are susceptible to this type of instability.

Benefits

The benefits of ACC are realized by enabling another technology: Lean-Burning Combustion (LBC). LBC provides lowered emission benefits, but they are susceptible to thermo-acoustic instabilities. A single passive corrective design solution is unlikely to remedy the problem especially when considering transient operating conditions such as those experienced during an aircraft's flight profile. To effectively mitigate the instabilities over the entire operating envelope, active control is required.

Relative to Rich-Burn, Quick-Mix, Lean-Burn (RQL) combustion, the benefits of LBC include:

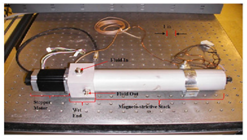
- **Somewhat lower Landing Take-Off (LTO) NOx (~25%)**
- **~50% lower NOx at subsonic cruise**
- **Particulate levels lower by 1 to 2 orders of magnitude**

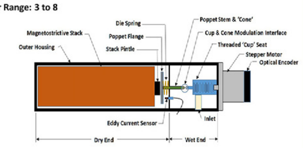
Approach

Initially, NASA GRC teamed with United Technologies Research Center and Pratt & Whitney to demonstrate ACC on a single nozzle combustion rig designed to emulate a real-world prototype aircraft engine known to exhibit instabilities. The demonstration was successful. For that demonstration the main fuel supply was being modulated (flow number approximately 110 $lbm \cdot hr^{-1} \cdot psi^{-0.5}$) to bolster the chances of success. The modulator used for this application was magnetostrictive-based and could cover a flow number range of 13 to 110 $lbm \cdot hr^{-1} \cdot psi^{-0.5}$.

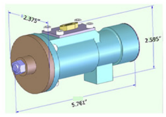
The NASA GRC in-house ACC research is now focused on demonstrating the control concept using modulated pilot flow into the combustor. The flow number range for this application is 1 to 8 $lbm \cdot hr^{-1} \cdot psi^{-0.5}$ and requires modulators capable of accommodating that range. The modulators are not commercial-off-the-shelf items primarily because they require a 1kHz bandwidth. Using the NASA Small Business Innovative Research program three candidate modulators were developed. They are the Active Signal Modulator (ASM), the JASC Modulator, and the WASK Modulator.

The Active Signal Modulator
-- Magnetostrictive-based
-- Flow Number Range: 3 to 8

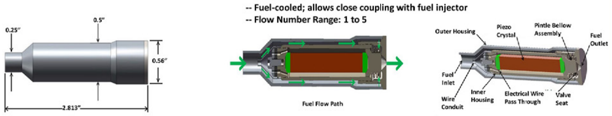




The JASC Modulator
-- Electric Motor/Solenoid-based
-- Flutes on end of rotating/translating shaft move relative to stator window
-- Fluid dispensed through variable flow area
-- Flow Number Range: 3 to 8



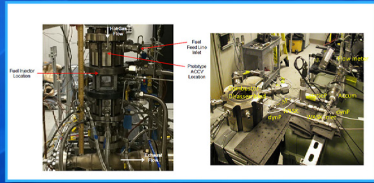
The WASK Modulator
-- Piezoelectric-based
-- Fuel-cooled; allows close coupling with fuel injector
-- Flow Number Range: 1 to 5

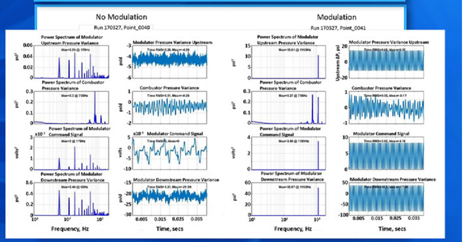


Recent Results

Open loop performance evaluation of the WASK modulator during hot testing with the CE13C combustor.

* Data indicates that the modulator has the ability to influence the combustion process.





Future Work

Individual open loop evaluations of the fuel modulators for their effectiveness in modulating the pilot flow and influencing unsteady heat release for:

- various injector designs
- modulation at a remote distance from the injector
- modulation as closely-coupled to the injector as possible

Closed loop ACC evaluation using best performing modulator candidate.

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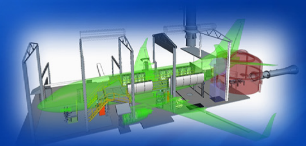


NASA Electric Aircraft Testbed (NEAT)

Rodger Dyson
Hybrid Gas Electric Propulsion

National Aeronautics and Space Administration

Description

As large airline companies compete to reduce emissions, fuel burn, noise, and maintenance costs, it is expected that more of their aircraft systems will shift from using turbofan propulsion, pneumatic bleed power, and hydraulic actuation, to instead using electrical motor propulsion, generator power, and electrical actuation.

Benefits

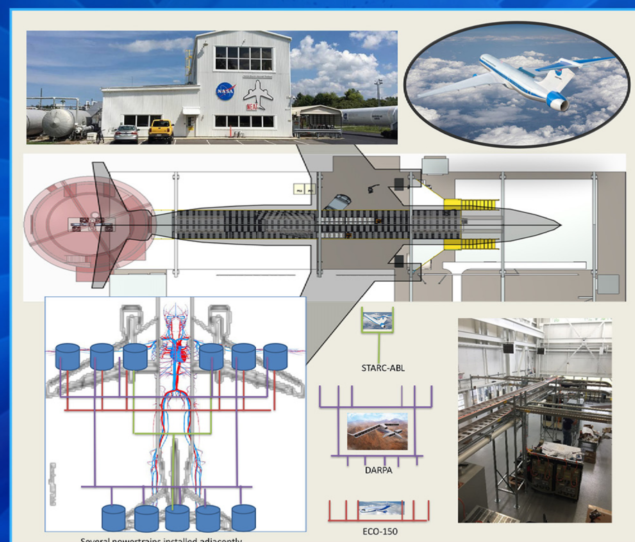
- GRC is now uniquely positioned to develop and test full-scale electrified propulsion systems that leverages our core competencies in power and propulsion.
- The NEAT full-scale testbed has infrastructure for up 48 MW if regenerated, remote control of operations, support for cryogenic fuels, multi-MW cooling capacity, and up to 50,000 feet altitude flight environment capability.

Approach

This new electric aircraft propulsion paradigm requires new flight-weight and flight-efficient powertrain components, fault tolerant power management, and electromagnetic interference mitigation technologies.

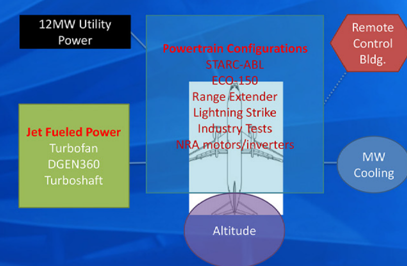
NEAT is the first reconfigurable hybrid gas-electric propulsion testbed capable of supporting full-scale single-aisle electrified aircraft powertrain technology including turbo-generation and thermal management integration.

It leverages an existing infrastructure originally intended to support nuclear thermal rocket propulsion to form a complete full-scale ground testing environment,



Recent Results

- The facility successfully completed its first aircraft engine emulation and X-57 DC bus radiated EMI baseline tests
- NPSS control was integrated and demonstrated to provide simulated dynamic turbo-generation at 125kW level
- Industry/ULI partnerships and infrastructure established
- STARC-ABL 500kW Design and Acquisition Completed
  - 80% of equipment installed for Sept. Test



Future Work

- Finish build-up and demonstrate 500kW STARC-ABL powertrain by Sept. 2017
- Incorporate fault management and power quality features
- Ground test research motors and inverters under flight altitude conditions at full power levels
- Support industrial and ULI powertrain development

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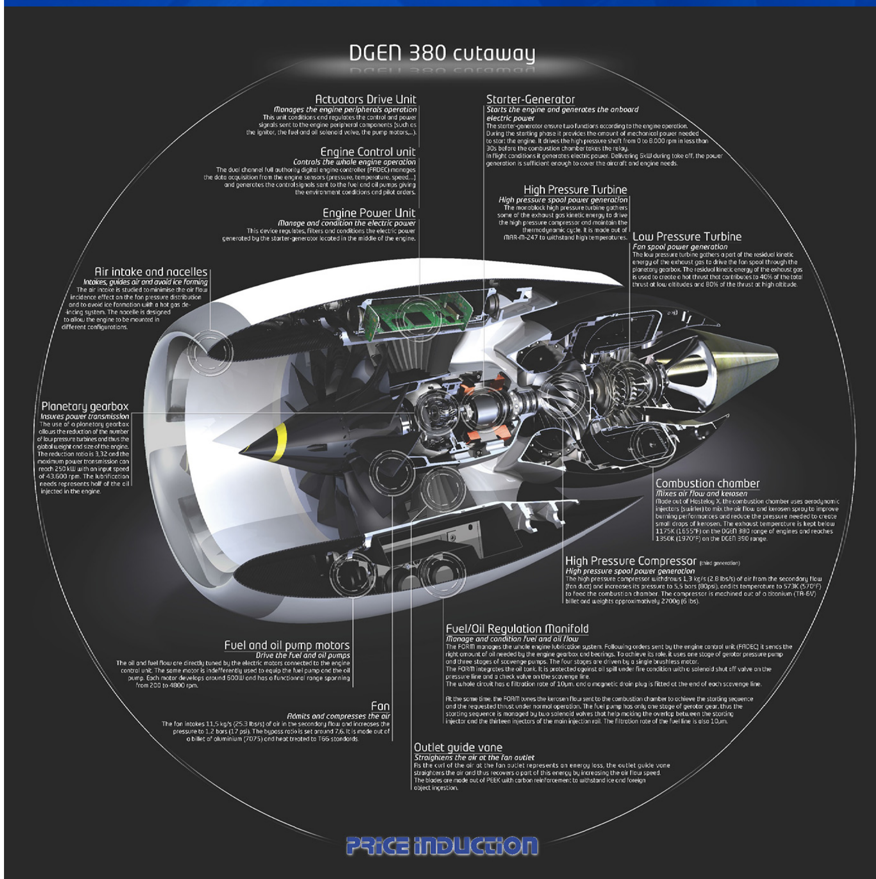
DART Facility
DGEN Aero-propulsion Research Turbofan
NASA Glenn Research Center

National Aeronautics and Space Administration



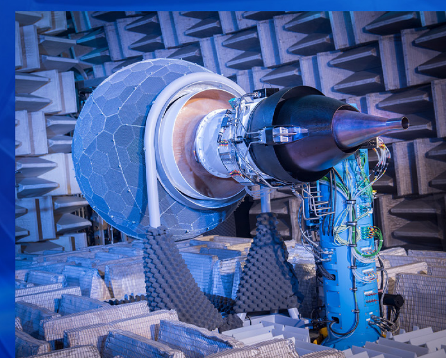
Description

The DART Facility is a small engine testbed for performing multidisciplinary low-TRL research on a relevant, yet affordable engine platform. The facility is designed in a stand-alone, modular format that enables it to be set up in several possible venues, increasing its utility as well as opportunities for test.

The heart of the facility is the Price Induction DGEN 380 engine; a two-spool, high bypass ratio, geared, unmixed flow turbofan engine acquired by NASA Glenn Research Center. Its initial targeted use is for research in acoustics, advanced controls, and high temperature instrumentation.

Future Planned Work

- Acoustics noise measurement of core, near, and far field
- Model based engine control algorithms
- Distributed engine control concepts and hardware
- High temperature sensors and silicon carbide electronics



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Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)

George Thomas, Jeffrey Csank, and Dennis Culley
NASA Glenn Research Center

National Aeronautics and Space Administration

Description

The tool for turbine engine closed-loop transient analysis (TTECTrA) is a semi-automated tool to assess the dynamic capability of subsonic aircraft engine models. At a specific flight condition, TTECTrA produces a controller designed to meet user-defined constraints consisting only of the fundamental limiters that affect the transient performance of the engine. The purpose of this tool is to assess dynamic issues associated with the performance and operability of subsonic turbofan engines early in the conceptual design stage.

Technical Approach

- Open source software developed in the MATLAB®/Simulink® environment(The MathWorks, Inc., Natick MA)
- Designed to easily integrate with engine models capable of executing in Simulink (S-function, .mex files, etc.)
- Custom MATLAB files which design controllers to given specifications
- Software can be executed from the MATLAB command prompt or a GUI.

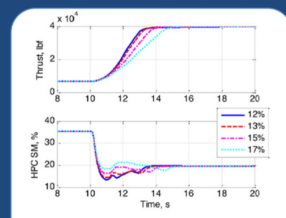
Download TTECTrA

From NASA Github page:

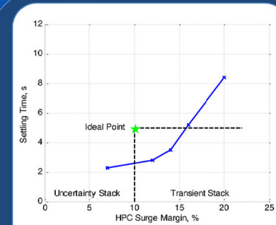
https://github.com/nasa/TTECTrA/releases

Approach

The TTECTrA software will design a closed-loop controller to ensure specific operability constraints, such as high pressure compressor surge margin, are met and provide an estimate of the expected transient performance of the system. With TTECTrA, the user can vary the transient operability margins, redesign the controller, and observe the transient performance to further identify the relationship between the performance and operability.



Performance and operability outputs from TTECTrA for varying HPC surge margin (HPC SM) constraints.



Collect data to better analyze the relationship between performance and operability

TTECTrA allows determining whether engine design can meet dynamic performance and operability requirements, and if so, what is the tradeoff between these two variables (blue line with markers). The closed loop system must be capable of accelerating from idle to 95% thrust in under 5 seconds (FAA Requirement) while maintaining design specific surge margin constraints.

An ideal closed-loop design responds just fast enough to meet the FAA requirement and does not exceed the uncertainty stack up, reserved for engine degradation, engine to engine variations, etc.

TTECTrA allows the assessing how much operability constraints may be safely reduced to open up the engine design space and potentially allow more efficient designs

Applications

- Analysis of NASA N+3 concept engines
- Engine degradation uncertainty analysis
- Assessing minimum necessary transient operability constraints to meet performance requirement

Future Work

Future TTECTrA Plans

- Fully automate TTECTrA and allow the software to design the controller without any user interaction.
- Incorporate TTECTrA into systems design and analysis workflow to reduce the need for overly conservative design constraints that penalize efficiency

References

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- Csank, J.T, and Zinnecker, A.M., "Application of the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) for Dynamic Systems Analysis," AIAA-2014-3975, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014.
- Zinnecker, A.M., and Csank, J.T., "A Methodology to Assess the Capability of Engine Designs to Meet Closed-loop Performance and Operability Requirements," AIAA Propulsion and Energy 2015, Orlando FL, July 27-29, 2015
- Csank, J.T., and Thomas, G.L., "Dynamic Analysis for a Geared Turbofan Engine with Variable Area Fan Nozzle," AIAA Propulsion and Energy 2017, Atlanta, GA, July 10-12, 2017

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High Temperature Smart P3 Sensors and Electronics for Distributed Engine Control

Alex Brand, Laurel Frediani, Michael Usrey
Sporian Microsystems, Inc.

National Aeronautics and Space Administration

Description

Compressor discharge pressure measurement has long been a key to achieving advanced engine performance. Given that, there is a need for a high-temperature, dynamic smart P3 sensor as a key building block for advanced engine controls. To address this need, Sporian is developing an in-situ pressure sensor and dedicated signal conditioning electronics to provide dynamic compressor data to facilitate smart control elements and monitor the stall margin.

Benefits

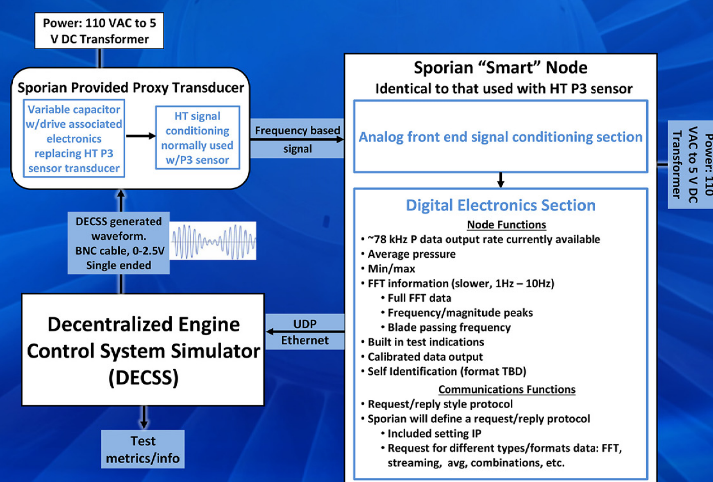
Smart, high-temperature sensors and electronics not only specifically facilitate distributed engine control architectures, but also improve overall costs, safety, and capabilities of engine systems through active monitoring.

Top: NASA HT electronics and Sporian P3 sensor
Bottom: Sporian Smart Node (left), Proxy sensor (right)

Approach

Through ongoing collaboration with the Air Force, initial smart sensor features (including digital bus communication and engineering unit output) and high temperature semiconductor electronics components have been added to piezoresistive high-temperature (HT) sensor hardware to ultimately support distributed engine control architectures. Similarly, through ongoing collaboration with NASA Glenn Research Center, Sporian has developed capacitive HT pressure sensors with smart, high-temperature signal conditioning.

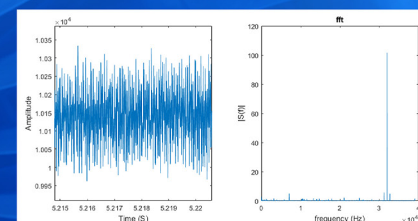
The technology directly supports multiple Aeronautics Research Mission Directorate thrusts including: fixed wing, rotorcraft and supersonic vehicle safety; vehicle efficiency; and vehicle carbon emission reduction by taking advantage of the convergence of emerging materials science, electronics, packaging, manufacturing, and software technologies.



Recent Results

Through development, laboratory validation, and stakeholder participation, the smart P3 and electronics has:

- Successfully demonstrated in NASA's Hardware-in-the-Loop testing facility
- Validated hardware testing in the Vehicle Integration Propulsion Research program
- Achieved data sampling bandwidth of 78kHz to see frequency content up to 39kHz



32kHz Amplitude Modulated signal using SP3CTS

Future Work

Sporian is continuing to work with engine OEMs and control systems providers to guide development and assist in technology transition. Sporian also has several upcoming tests to validate the technology including testing with Aerodyn Engineering, Notre Dame Turbomachinery Laboratory, and the Southwest Research Institute.

Propulsion Control and Diagnostics
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