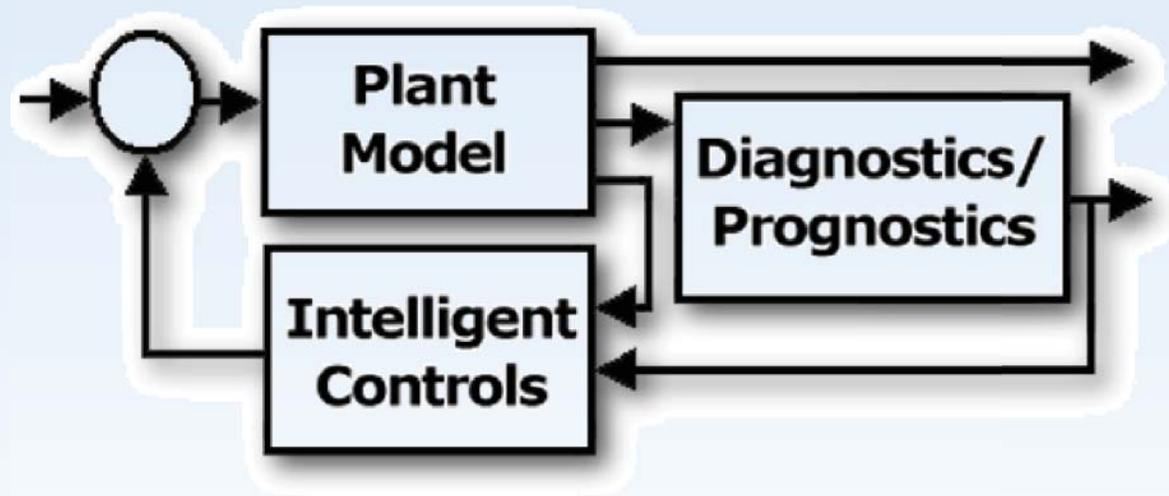


Aircraft Turbine Engine Control Research at NASA Glenn Research Center



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Outline

- The Engine Control Problem
 - Safety and Operational Limits
 - State-of-the-Art Engine Control Logic Architecture
- Historical Glenn Research Center Contributions
 - Early Stages of Turbine Engine Control (1945-1960s)
 - Maturation of Turbine Engine Control (1970-1990)
- Advanced Engine Control Research
 - Recent Significant Accomplishments (1990- 2004)
 - Current Research (2004 onwards)
- Conclusion



Basic Engine Control Concept

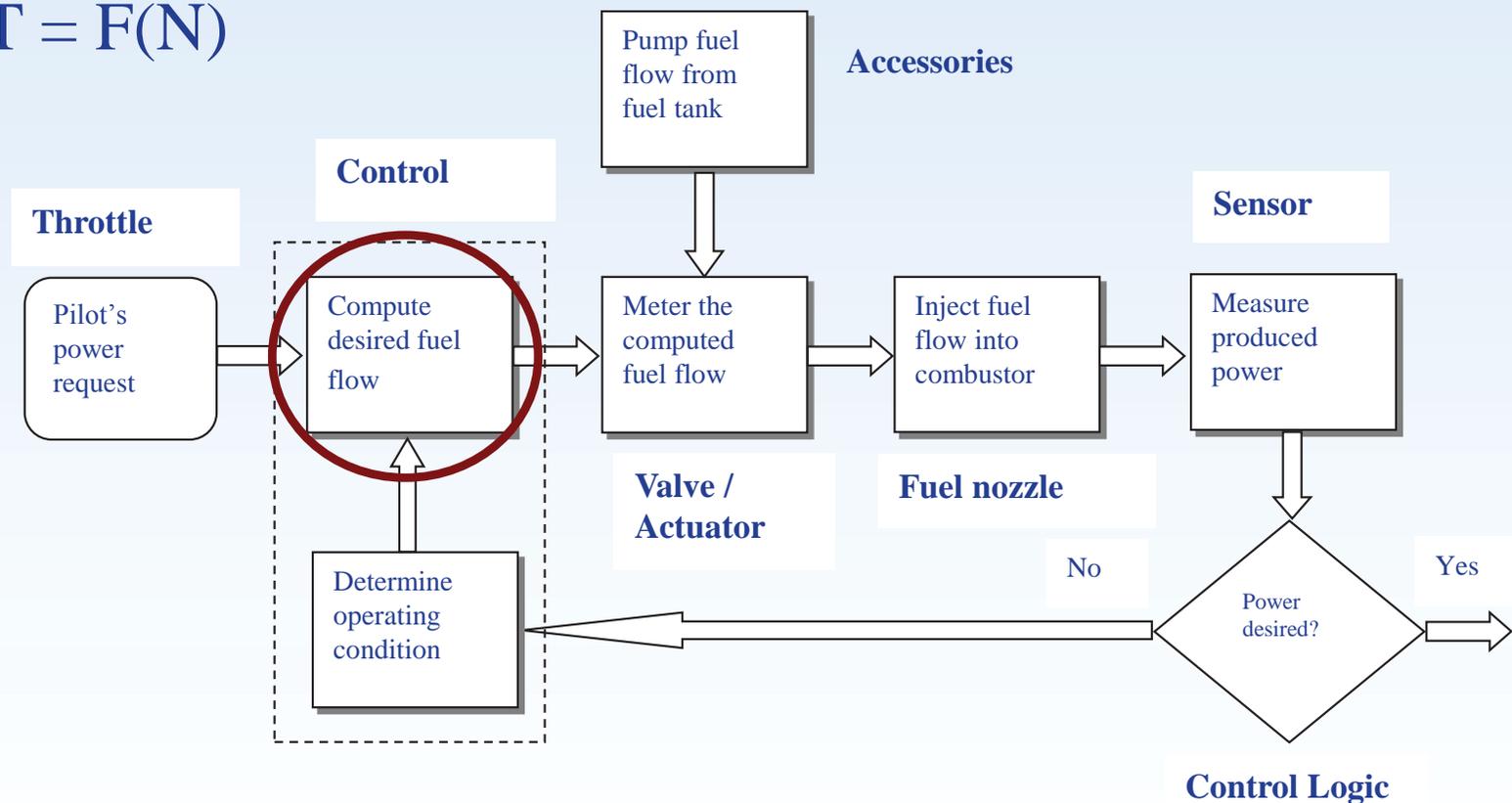
- **Objective:** Provide smooth, stable, and stall free operation of the engine via single input (PLA) with no throttle restrictions
 - Reliable and predictable throttle movement to thrust response
- **Issues:**
 - Thrust cannot be measured
 - Changes in ambient condition and aircraft maneuvers cause distortion into the fan/compressor
 - Harsh operating environment – high temperatures and large vibrations
 - Safe operation – avoid stall, combustor blow out etc.
 - Need to provide long operating life – 20,000 hours
 - Engine components degrade with usage – need to have reliable performance throughout the operating life



Basic Engine Control Concept

- Since Thrust (T) cannot be measured, use Fuel Flow WF to Control shaft speed N (or other measured variable that correlates with Thrust

- $T = F(N)$



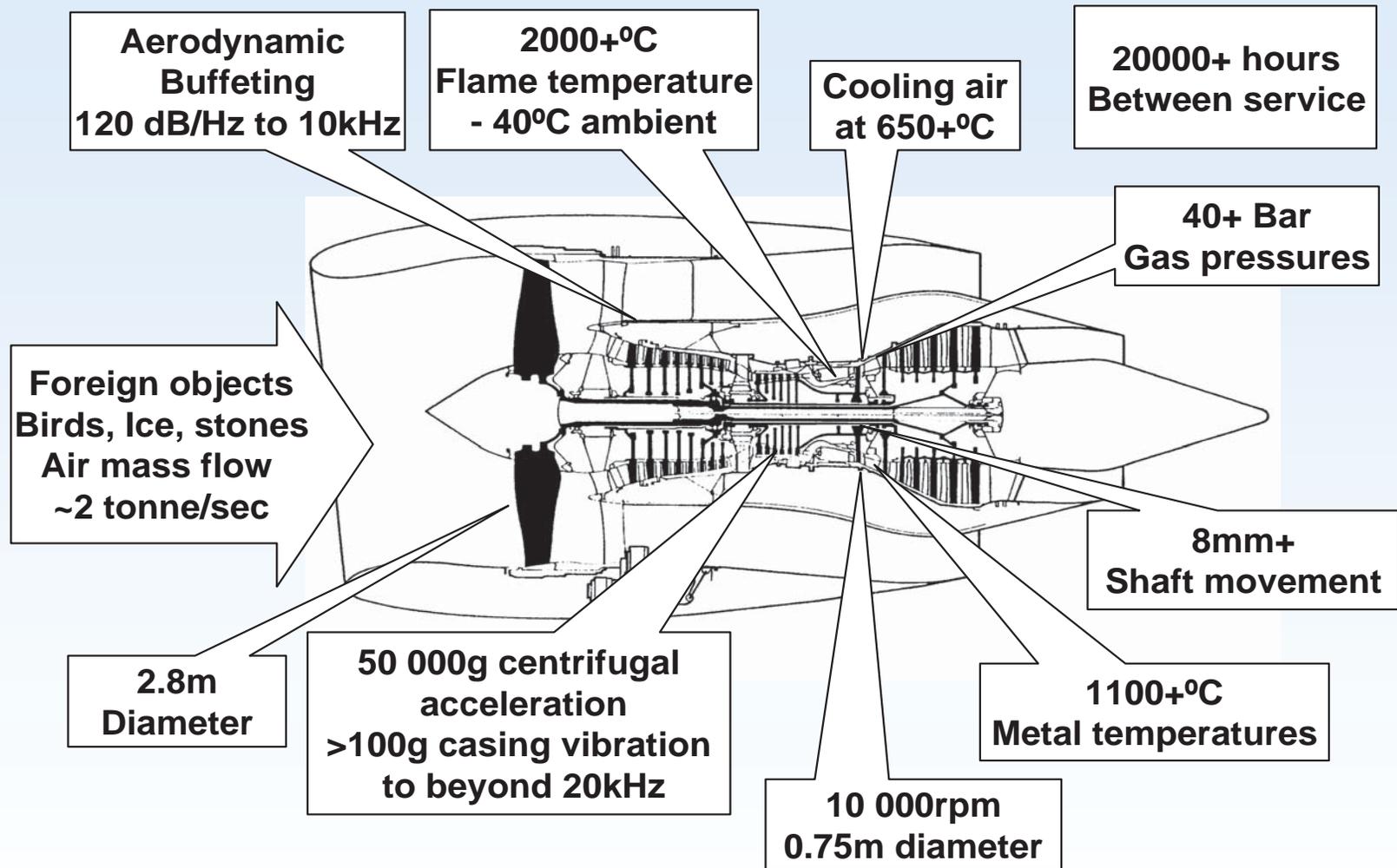
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Environment within a gas turbine



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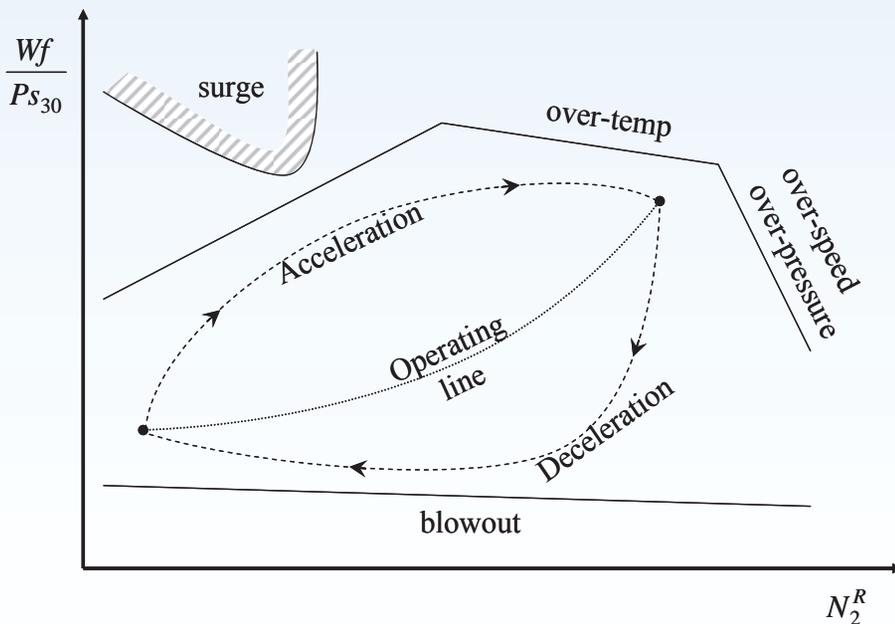
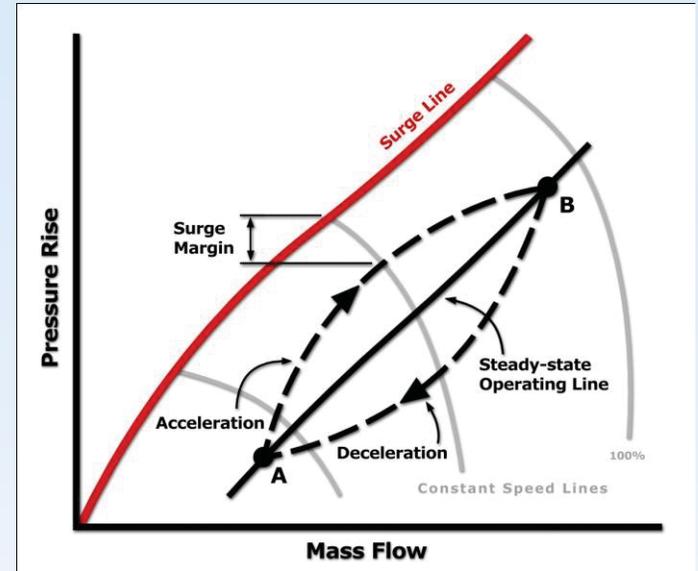
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Operational Limits

- **Structural Limits:**
 - Maximum Fan and Core Speeds – N1, N2
 - Maximum Turbine Blade Temperature
- **Safety Limits:**
 - Adequate Stall Margin – Compressor and Fan
 - Lean Burner Blowout – minimum fuel
- **Operational Limit:**
 - Maximum Turbine Inlet Temperature – long life



Operational Limits Mapped into Limits on allowable fuel flow (ratio of fuel flow to combustor pressure) as a function of Corrected Fan Speed
- Referred to as Accel/Decel Schedule

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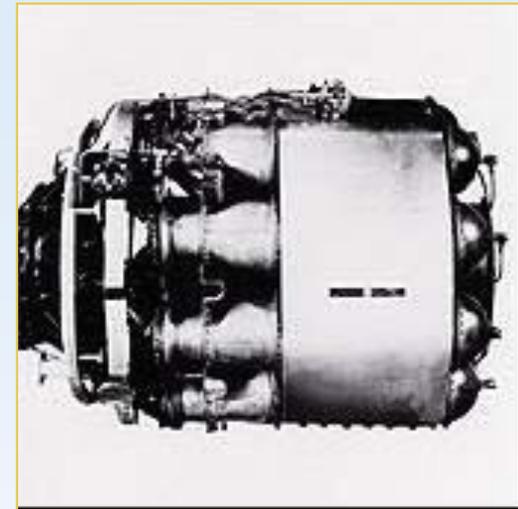
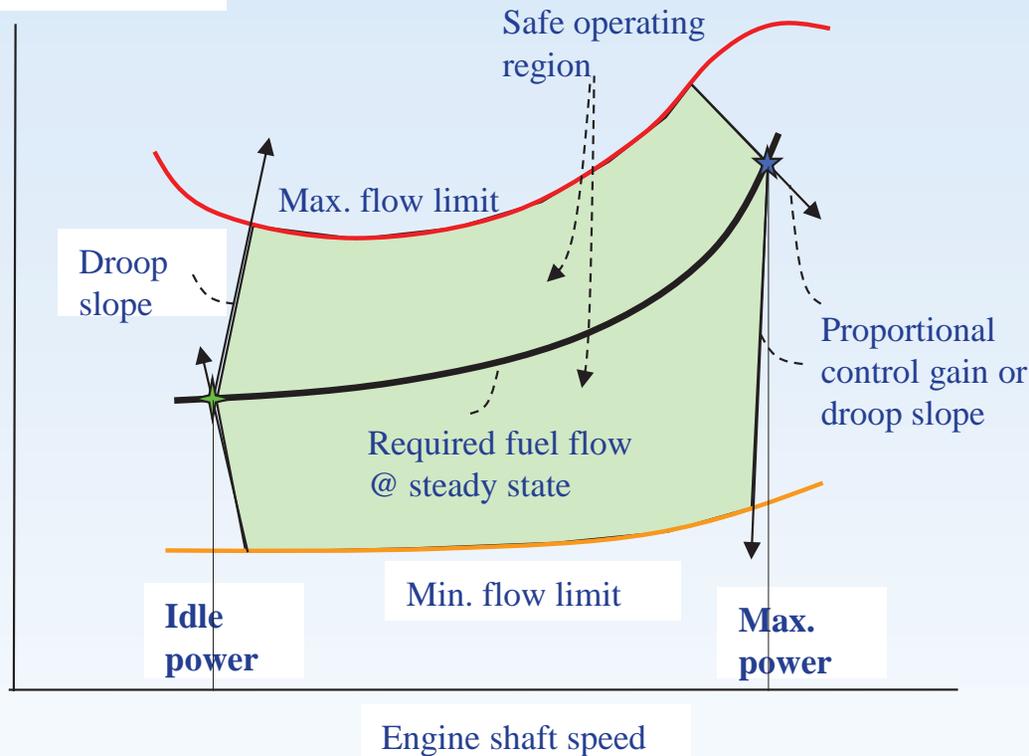
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Historical Engine Control

Fuel flow rate
(Wf) or fuel ratio
unit (Wf/P3)



GE I-A
(1942)

- Fuel flow is the only controlled variable.
 - Hydro-mechanical governor.
 - Minimum-flow stop to prevent flame-out.
 - Maximum-flow schedule to prevent over-temperature
- Stall protection implemented by pilot following cue cards for throttle movement limitations

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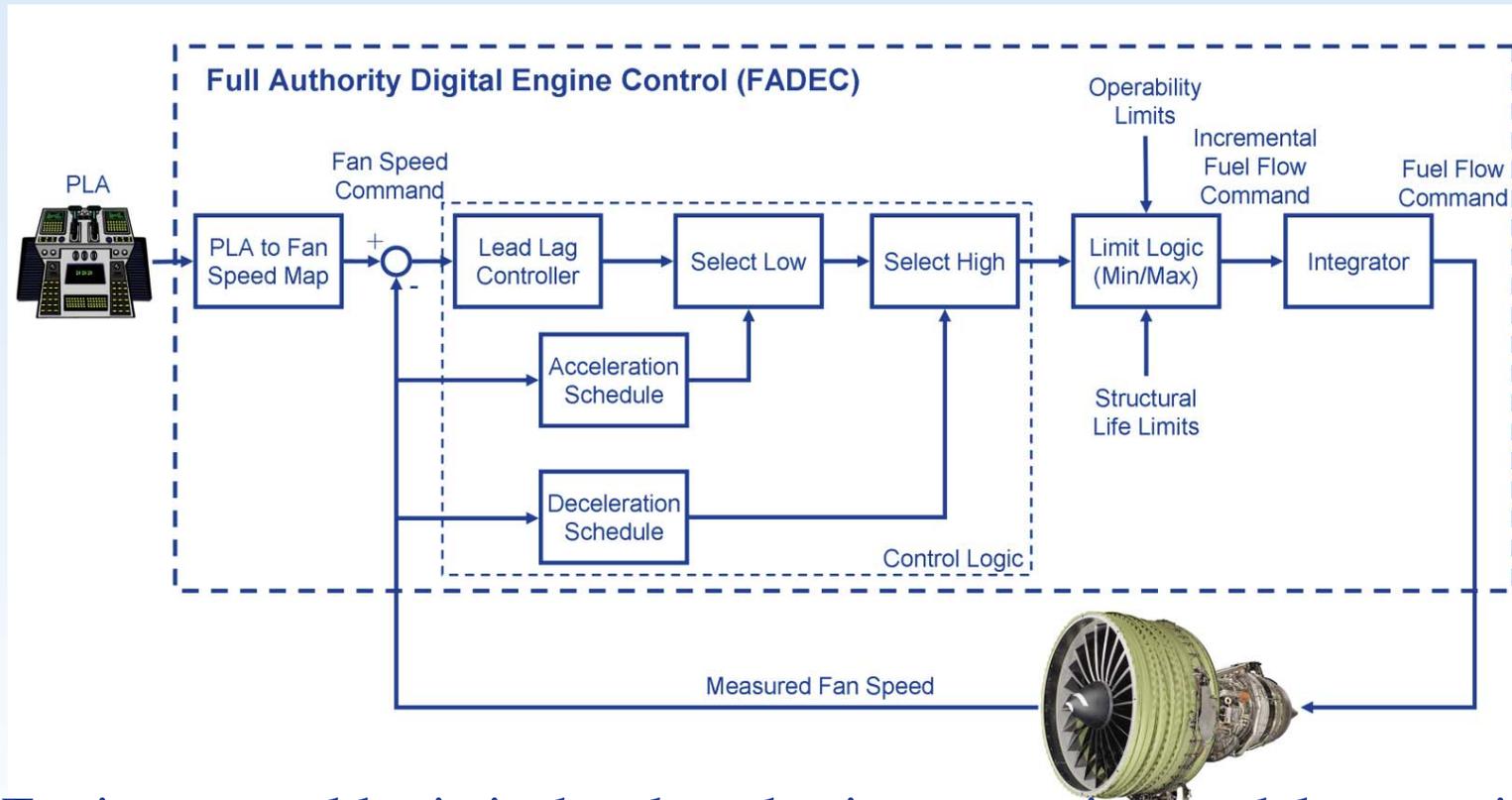
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Typical Current Engine Control

- Allows pilot to have full throttle movement throughout the flight envelope
 - There are many controlled variables – we will focus on fuel flow



- Engine control logic is developed using an engine model to provide guaranteed performance (minimum thrust for a throttle setting) throughout the life of the engine
 - FAA regulations provide an allowable maximum rise time and maximum settling time for thrust from idle to max throttle command

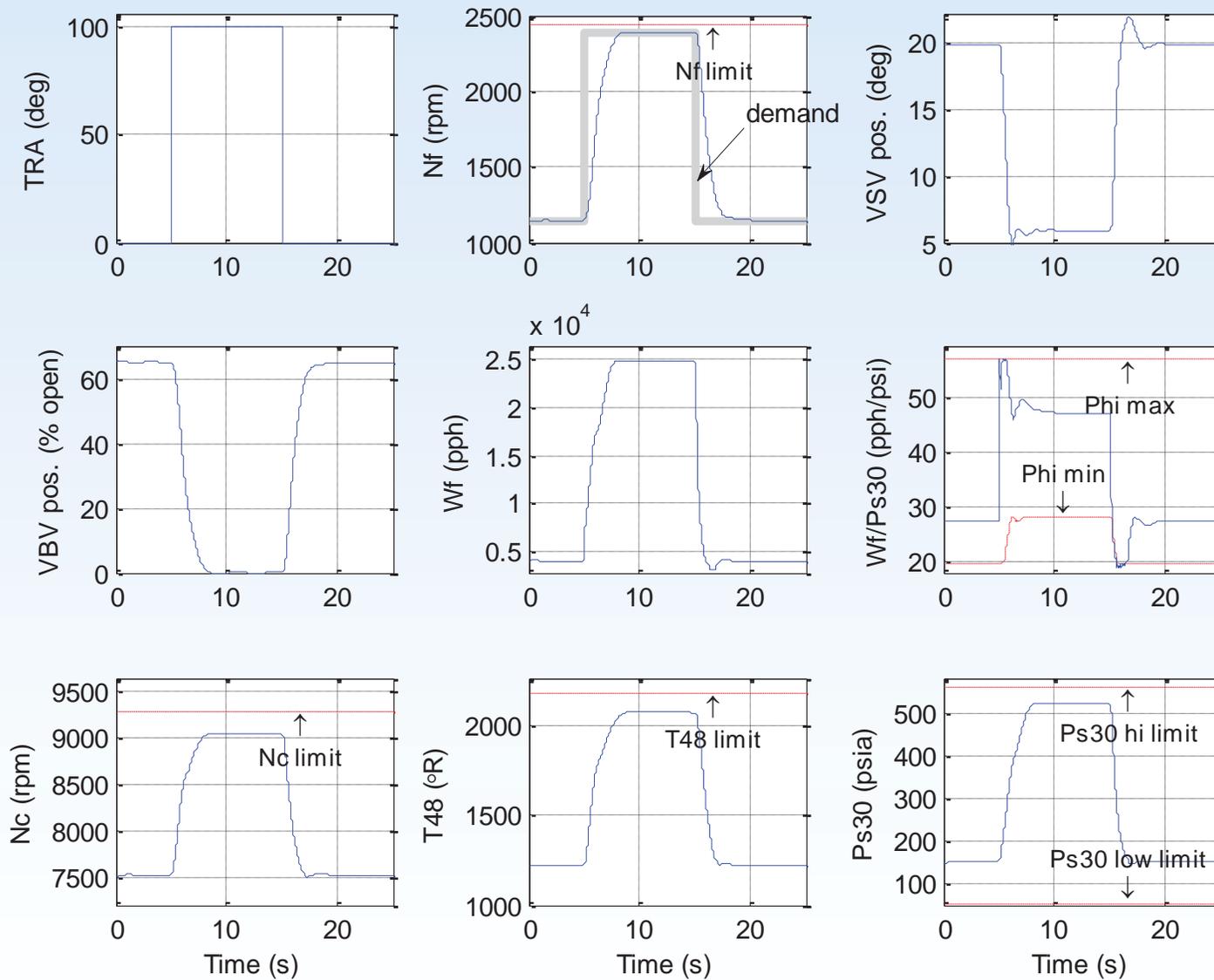
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Burst-Chop Example – Inputs/Outputs



Early Stages of Turbine Engine Control (1945-1960s)

- Time-Domain Closed-loop Engine Analysis
- Corrected Parameters for Model Simplification
- Simplified Dynamic Model of Engine Response
- Real-time Engine Dynamic Modeling Using Computers



Time-Domain Closed-Loop Engine Analysis

1948: GE tests the first afterburning turbojet in the world – J47:

- Hydro-mechanical fuel control for main fuel flow and electronic (vacuum tube) fuel control for afterburner
- Limit cycle observed in altitude testing at GRC – noise from speed sensor feeding into the “high gain” of the speed governor
- GE and NASA engineers worked together to solve the problem – performed time-domain studies to identify the problem and reduce the control gain at altitude

This established the strong industry/government partnership in engine controls development which continues to this day



Corrected Parameters for Model Simplification

- Engine steady-state performance obtained through cycle calculations using slide rule / desk calculators
 - Performance calculations at each operating point took several hours
- NASA engineers developed the concept of “Corrected Parameters” – performance parameters corrected to non-dimensional temperature and pressure w.r.t. sea level static conditions
 - Considerably reduced the amount of time to develop engine steady-state performance model – from months to a few weeks, and also reduced the amount of experimental testing to be done

Corrected Parameters concept is being used to this day for engine simulation and analysis

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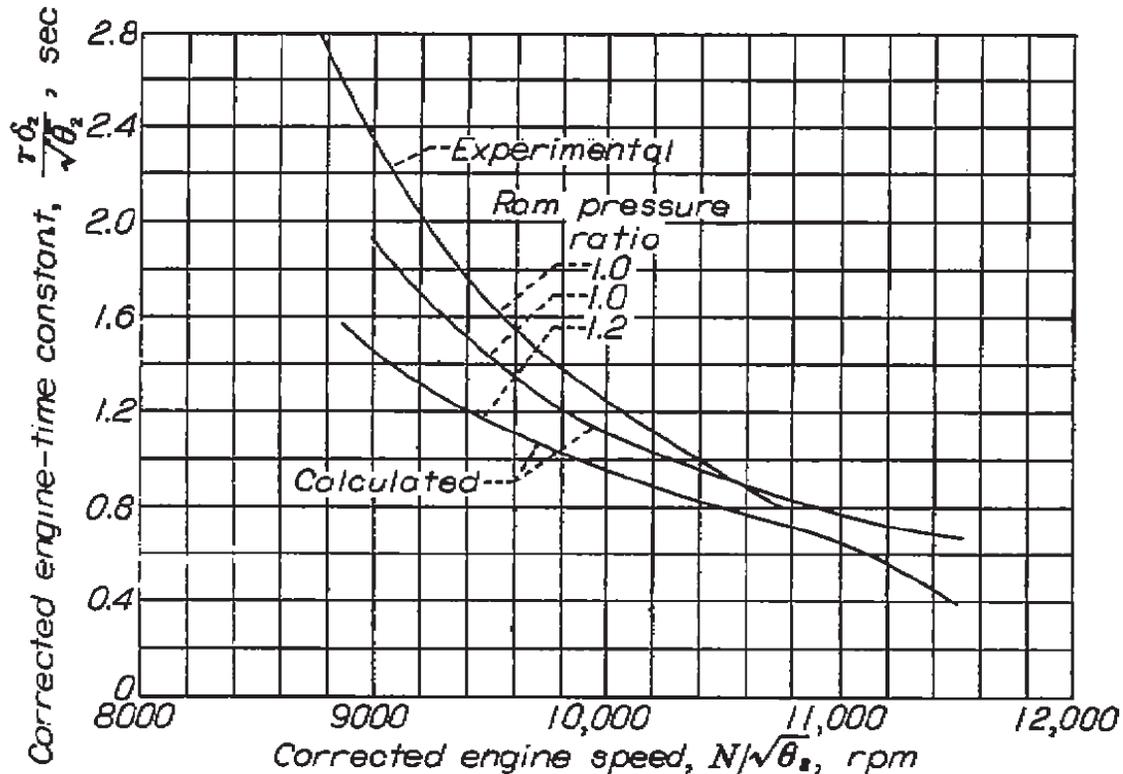
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Simplified Dynamic Model of Engine Response

- Dynamic behavior of single-shaft turbojet first studied at NACA Lewis Laboratory in 1948



The study showed that the transfer function from fuel flow to engine speed can be represented by a first order lag linear system with a time constant which is a function of the corrected fan speed:
$$N(s)/WF(s) = K/(as+1)$$
with $a=f(N)$

This discovery significantly reduced the time required to design and validate the control logic

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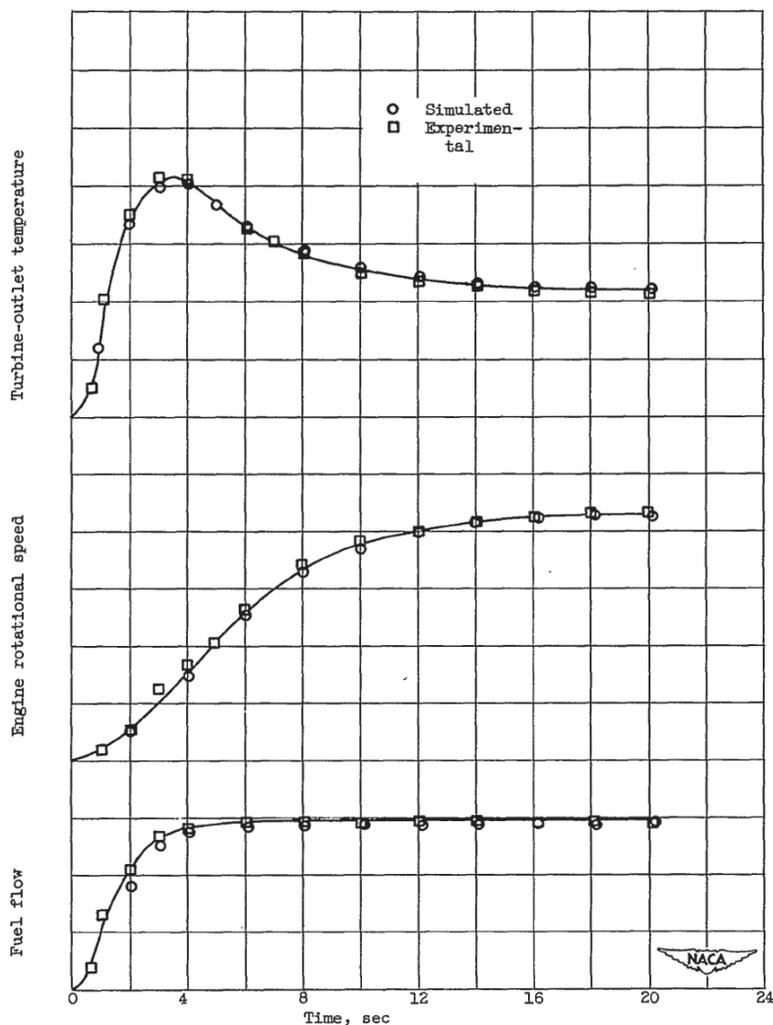
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Real-time Dynamic Engine Modeling using Computers

- With increasing complexity of engines, it became too complicated to design and evaluate control logic primarily through testing.



- GRC pioneered methods to perform closed-loop (integrating control logic with the engine model) dynamic simulation using analog computers
- Simulations using Analog Computers at NACA Lewis in the 1950s
 - Dynamic response of a turbojet to a step fuel input

From J.R. Ketchum, and R.T. Craig, "Simulation of Linearized Dynamics of Gas-turbine Engines," NACA-TN-2826.



Maturation of Turbine Engine Control (1970-1990)

- Digital Electronic Engine Control (DEEC)
- Multivariable Engine Control Development
- Sensor Fault Detection, Isolation and Accommodation

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Digital Electronic Engine Control

- Early 1980s NASA in collaboration with USAF and P&W conducted flight tests of DEEC on an F-100 engine
- Benefits of DEEC:
 - increased thrust, faster response times, improved afterburner operation, improved airstart operation, elimination of ground trimming, fail-operate capability, and **simplified hardware**
- Testing at GRC altitude test facility led to resolution of a nozzle stability and verification of a faster augmentor transient capability
 - Extensive PSL testing done for operation throughout the flight envelope to get clearance for flight tests on the F-15
- Flight testing at DFRC (now AFRC) demonstrated capability of digital control and led to introduction of Electronic Engine Control Units on military and commercial jets.

NASA testing of DEEC was a critical step leading to current FADECs

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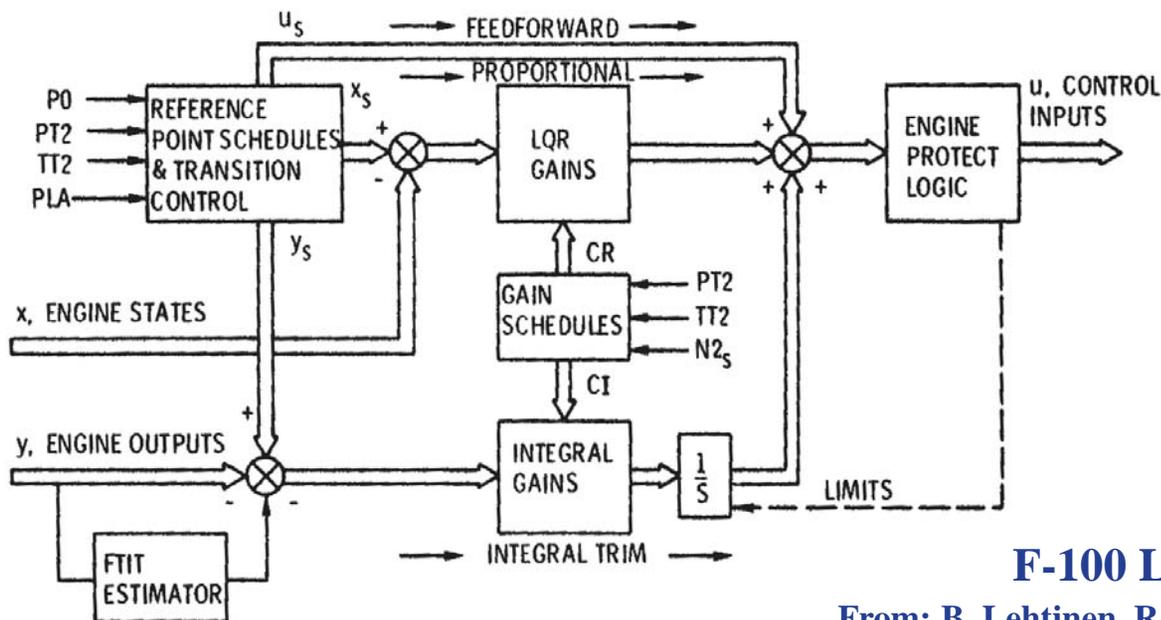
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Multivariable Engine Control Development

- AFWAL and NASA-Lewis jointly sponsored the Multivariable Control Synthesis (MVCS) program from 1975 to 1978 to investigate applicability of emerging optimal control and Linear Quadratic Regulator control theory to jet engines.



F-100 LQR Control Block Diagram

From: B. Lehtinen, R.L. DeHoff., and R.D. Hackney, "Multivariable Control Altitude Demonstration on the F100 Turbofan Engine," paper presented at the 15th Joint Propulsion Conference, 1979, AIAA-79-1204.

- GRC developed a series of LQRs connected with simple transition logic and several operating limits to achieve effective large-transient controls.
- Successful testing on an F100 engine in NASA's altitude test facilities

Studies concluded that performance benefits of MVCS were not commensurate with complexity of control design and implementation

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Sensor Fault Detection, Isolation and Accommodation

- In mid to late 1980s GRC investigated engine sensor failure detection approaches under the Advanced Detection, Isolation and Accommodation (ADIA) program
- ADIA algorithm consisted of 3 elements: i) hard sensor failure detection and isolation logic; ii) soft sensor failure detection & isolation logic; and iii) an accommodation filter
- ADIA algorithm was integrated with a microcomputer implementation of F-110 engine and a real-time evaluation was performed using a hybrid computer simulation
- Transient engine operation over the full power range with a single sensor failure detection and accommodation was demonstrated on the F-100 in the PSL.
- The ADIA development team received the prestigious R&D 100 award

Many elements of the NASA ADIA approach are implemented in current FADECs

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Recent Significant Accomplishments (1990- 2004)

- Integrated Flight Propulsion Control Research (IFPC)
- Practical Application of Multivariable Control Design
- Intelligent Life Extending Control (ILEC)
- High Stability Engine Control (HISTEC)
- Active Stall Control

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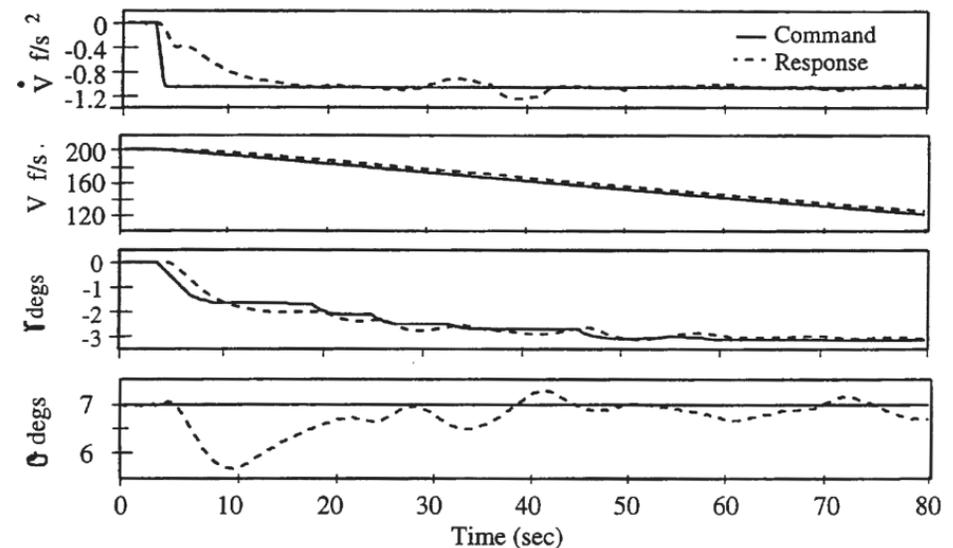
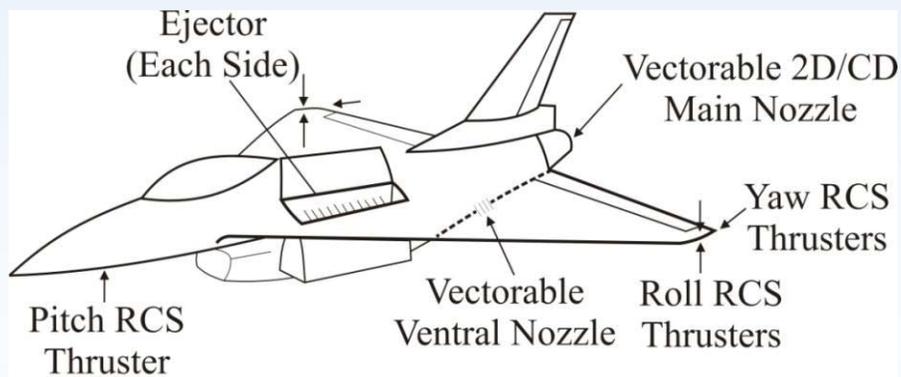
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Integrated Flight Propulsion Control Research (IFPC)

- Emphasis on Advanced Short Take-Off Vertical Landing Aircraft (ASTOVL) led to investigation of IFPC concepts
- GRC developed IMPAC – Integrated Methodology for Propulsion and Airframe Control and applied it to a concept ASTOVL aircraft
- IMPAC based ASTOVL IFPC design was successfully demonstrated in piloted simulations in the transition flight phase



IMPAC and GRC led industry IFPC design studies helped developed various concepts that were later applicable to F-35

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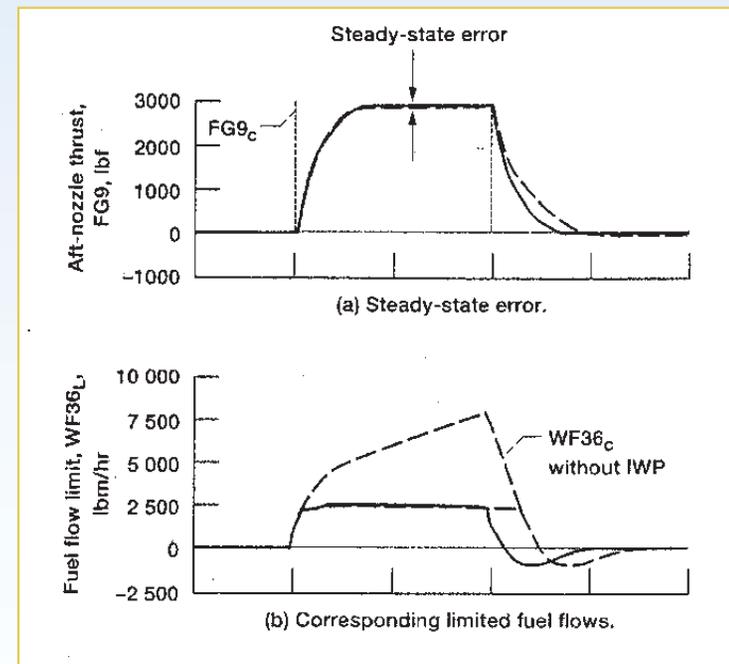
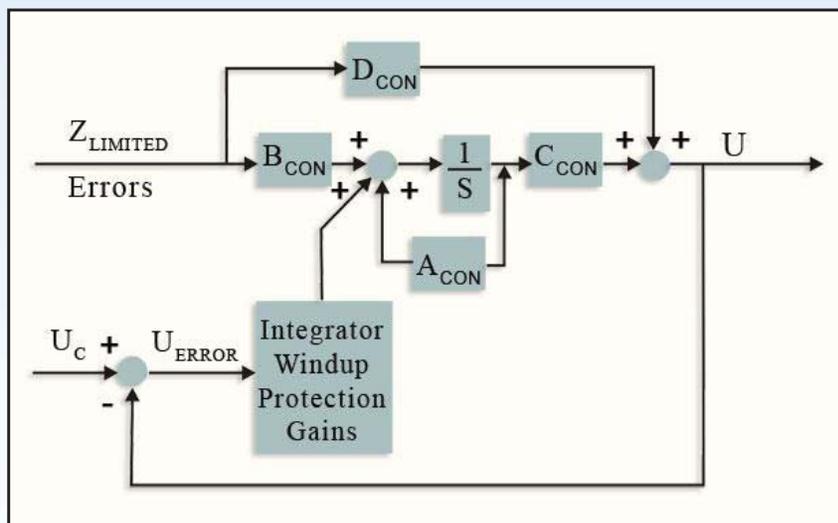
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Practical Application of Multivariable Control Design

- GRC IFPC research led to development of methods for practical application of Multivariable Control Design, including problem formulation using robust control design techniques, addressing controller scheduling and Integrator Wind Up Protection (IWP)

IWP design and application to an engine simulation

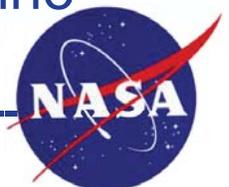


Technologies were transferred to industry through collaborative tasks and contributed to successful application of MVC for F-135 engine

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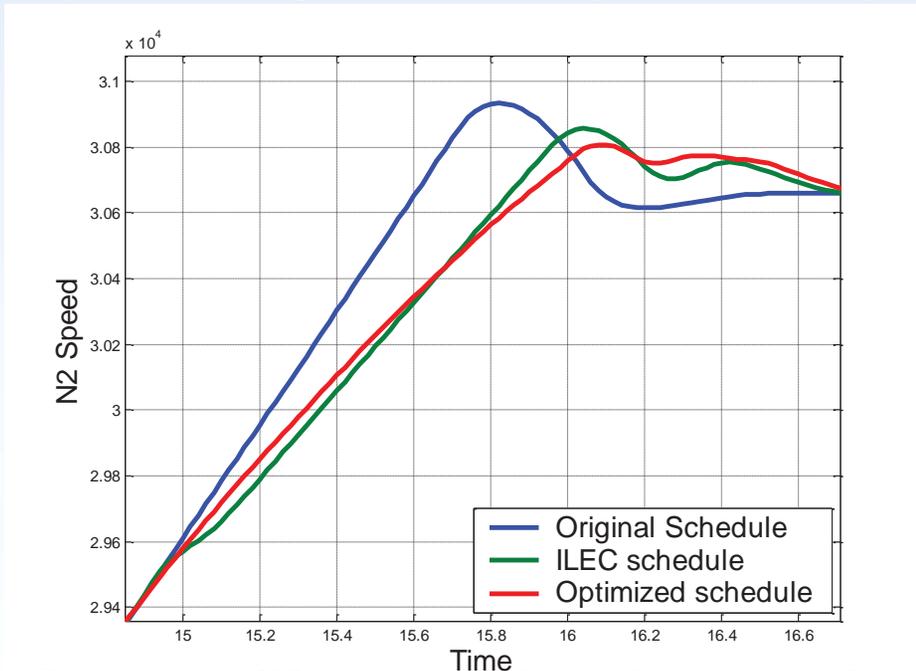
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Intelligent Life Extending Control (ILEC)

- How the engine is controlled during transients has a significant impact on life of the hot gas path components
- GRC research in collaboration with industry demonstrated that optimizing the engine acceleration schedule can result in significant increase in engine on-wing life

Engine Core Speed Acceleration Response
(Comparison of Original, ILEC, and Optimized Control)



Comparison of Average TMF Damage Accumulation
(With Varying Ambient Condition and Control Mode)

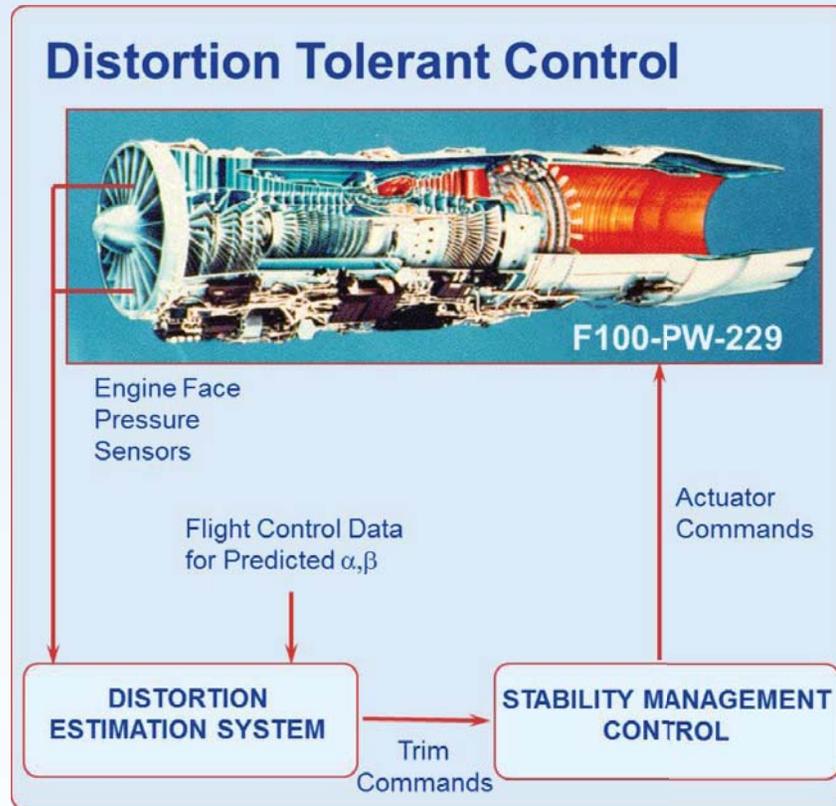
	Original Control Schedule	ILEC Control Schedule	Optimized Control Schedule
Design Condition	1.0	0.725 (-27.5%)	0.628 (-37.2%)
With Typical Operating Conditions	1.132	0.826 (-27.0%)	0.718 (-36.6%)
Hot Day Bias	1.668	1.181 (-29.2%)	0.931 (-44.2%)
Cold Day Bias	0.609	0.500 (-17.9%)	0.481 (-21.0%)

On-wing life extension through “Intelligent Control” continues to be an area of interest in the industry
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High Stability Engine Control (HISTEC)

- In mid to late 1990s, GRC in collaboration with P&W, USAF, and DFRC, developed the HISTEC concept and tested it with the PW-229 engine on a modified F-15 Aircraft



Highly successful flight test program demonstrated the capability to estimate inlet distortion and accommodate it through setting the stall margin requirement online in real time

System studies indicate that up to 2% SFC reduction can be obtained by intelligently managing the operating stall margin – continues to be an area of research

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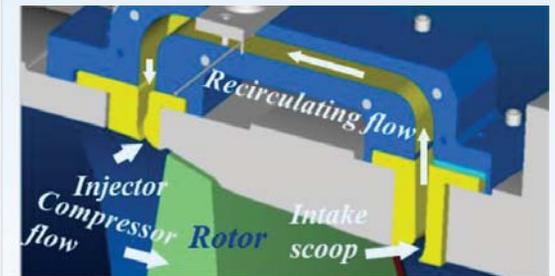
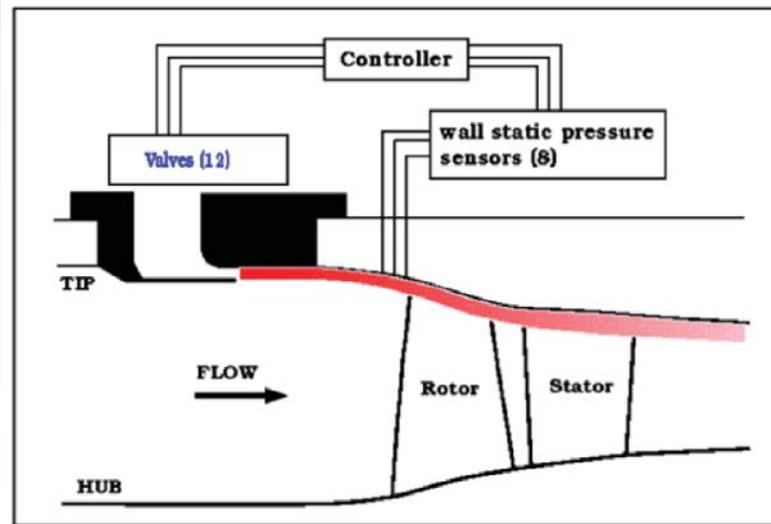
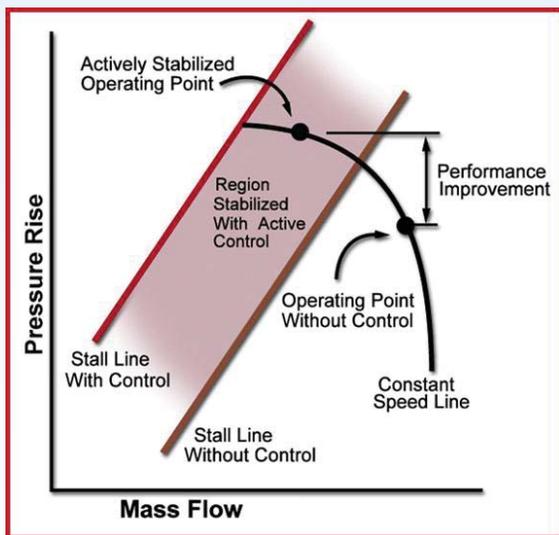
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Active Stall Control

- In mid 1990s to early 2000s, there was a tremendous interest in exploring the feasibility of extending compressor operation into a higher efficiency region by using active flow control
- GRC developed various technologies including stall precursor detection, optimum flow injector design, high frequency actuation. Technologies were demonstrated on a modern multi-stage compressor in collaboration with USAF and industry



Active Stall Control demonstrated with simulated recirculated flow

System level benefits did not appear to be sufficient enough to warrant transition of technology to product

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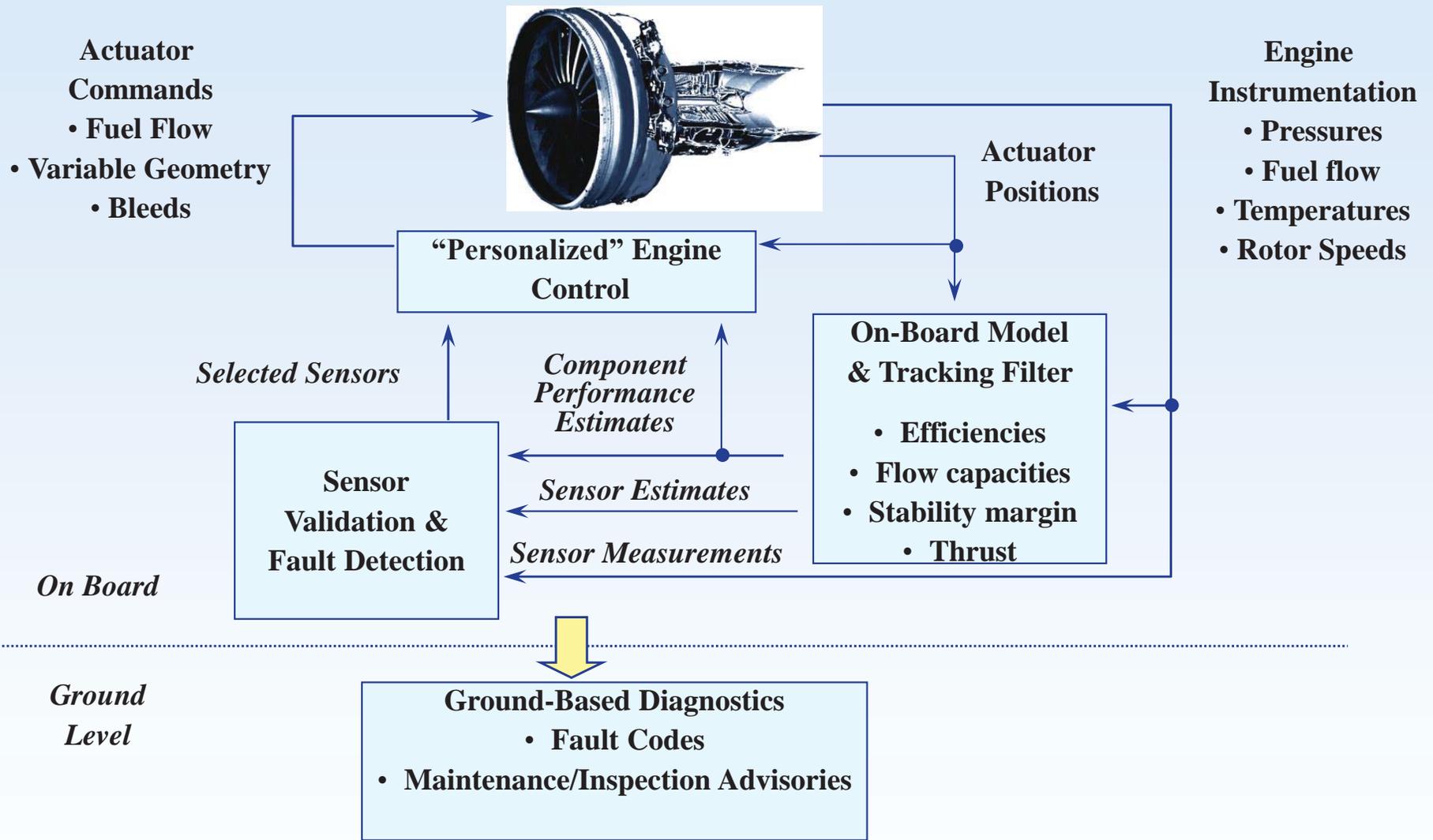


Current Research (2004 Onwards)

- Model-Based Engine Control and Diagnostics
- Engine Dynamic Models for Control and Diagnostics
Technology Development
- Distributed Engine Control (DEC)
- Active Combustion Control
- High Speed Propulsion System Dynamic Modeling and
Control



Model-Based Engine Controls and Diagnostics



- **Real-time performance estimation**
- **Enhanced gas path diagnostics**
- **Performance enhancing engine control**

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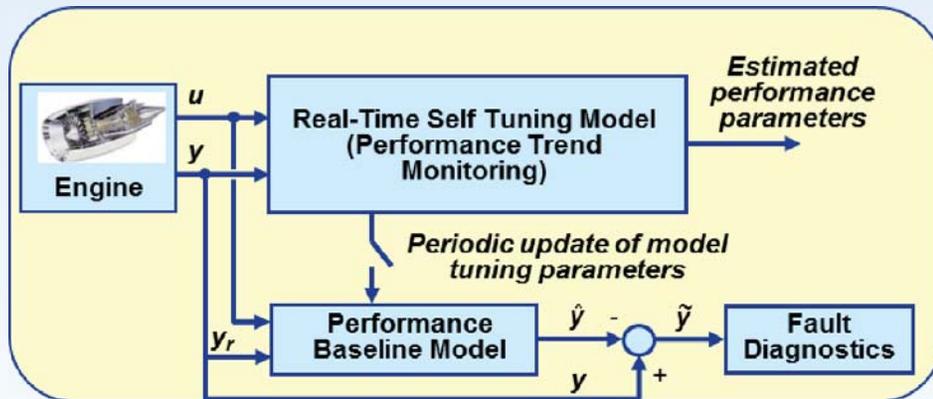
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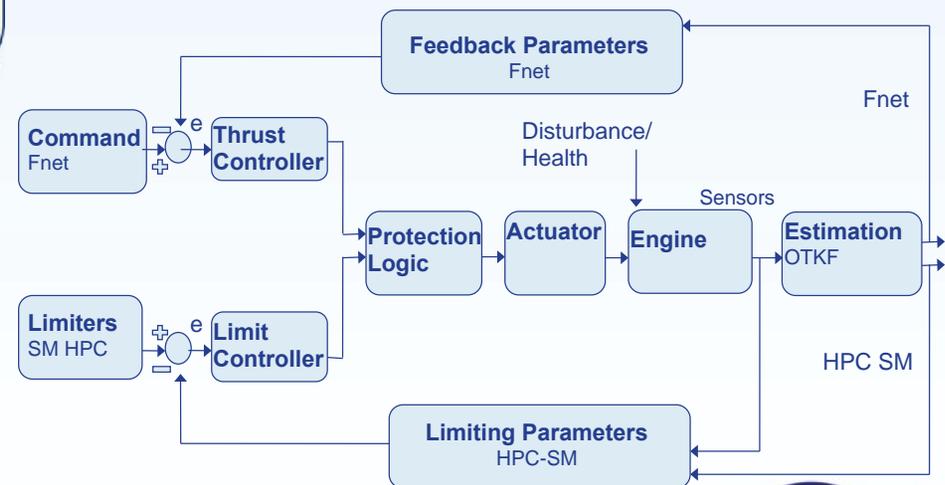
Model-Based Engine Control and Diagnostics

- Challenge is to have an accurate enough on-board model which reflects the true condition of the engine – typically number of sensors is less than the “health parameters” in the model
- GRC has developed a patented approach to determining a set of “tuners” which provide a good estimate of unmeasured engine performance and operability parameters in the presence of degradation with usage



An Integrated Architecture for Aircraft Engine Performance Monitoring and Fault Diagnostics has been developed and validated against engine test data

An architecture for Model-Based Engine Control has been developed and demonstrated on a nonlinear engine simulation to provide a tight control of thrust and stall margin



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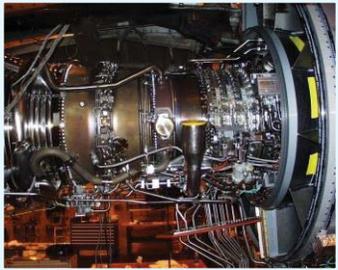
Engine Dynamic Models for Control and Diagnostics Technology Development

The following engine simulation software packages, developed in Matlab/Simulink and useful for propulsion controls and diagnostics research, are available to U.S. citizens from GRC software repository

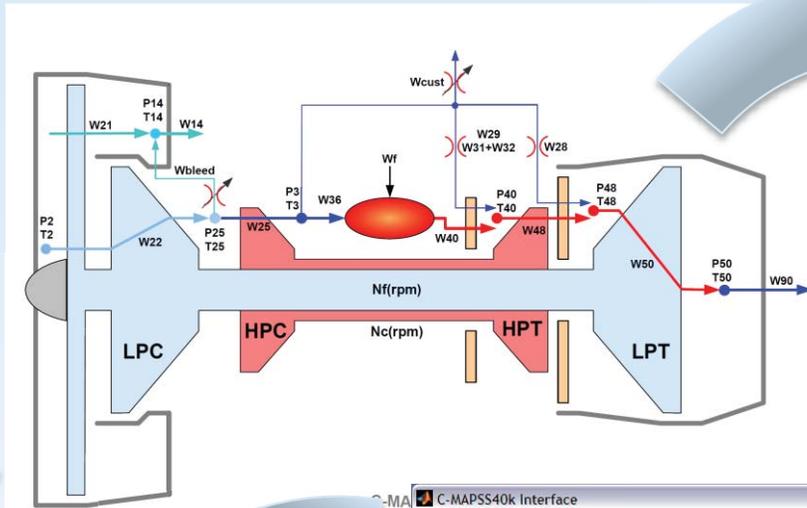
- **MAPSS** – Modular Aero-Propulsion System Simulation (2003)
 - Simulation of a modern fighter aircraft prototype engine with a basic research control law:
<http://sr.grc.nasa.gov/public/project/49/>
- **C-MAPSS** – Commercial Modular Aero-Propulsion Sys Sim (2008)
 - Simulation of a modern commercial 90,000 lb thrust class turbofan engine with representative baseline control logic:
<http://sr.grc.nasa.gov/public/project/54/>
- **C-MAPSS40k** (2010)
 - High fidelity simulation of a modern 40,000 lb thrust class turbofan engine with realistic baseline control logic:
<http://sr.grc.nasa.gov/public/project/77/>
 - This simulation is being used extensively in NASA sponsored propulsion control and diagnostics research, and has been downloaded by over 30 external organizations



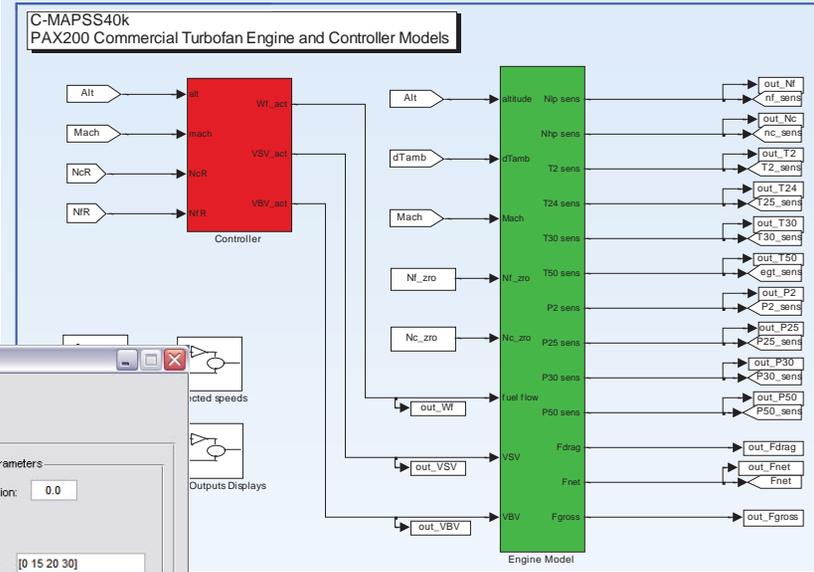
Commercial Modular Aero-Propulsion System Simulation 40k



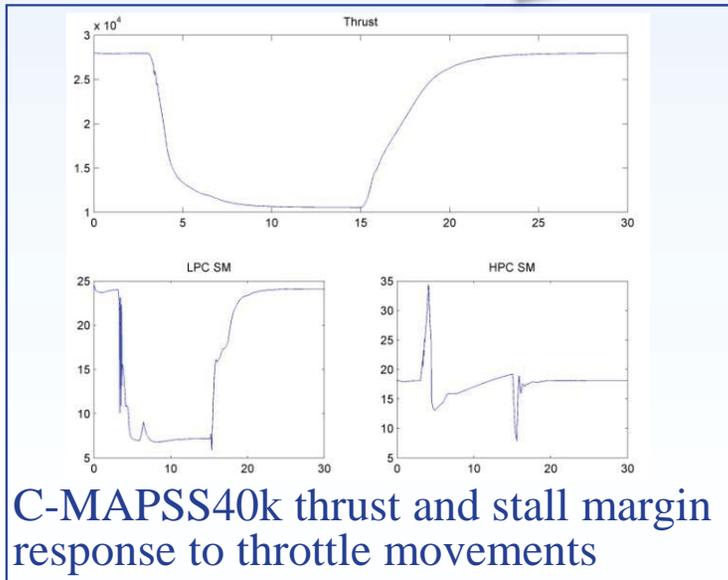
Engine flight data used to tune physics-based model



Simulation programmed in graphical language



Plotting and graphical analysis capability



C-MAPSS40k thrust and stall margin response to throttle movements

GUI driven operation

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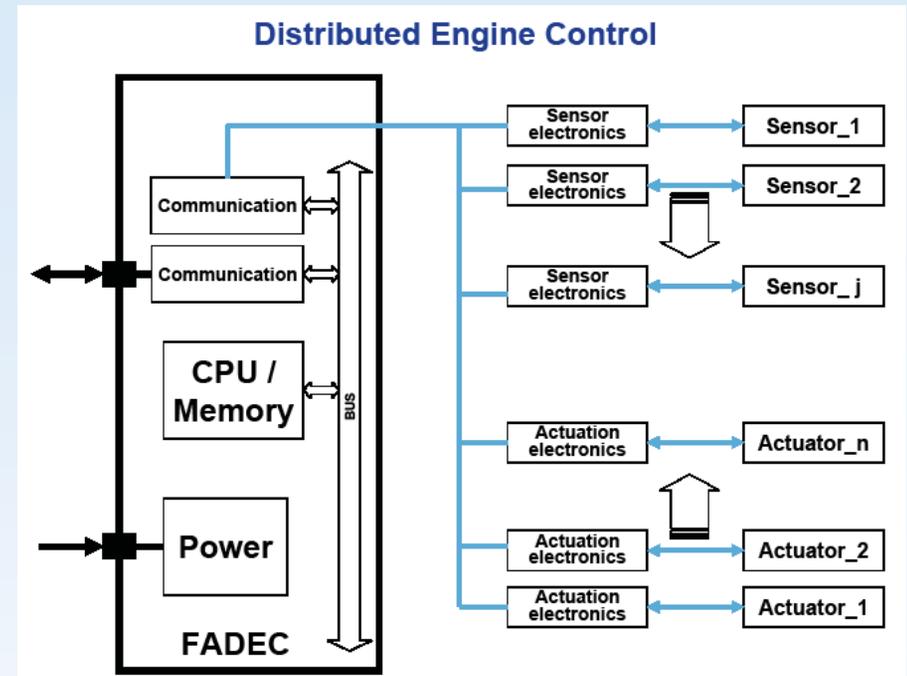
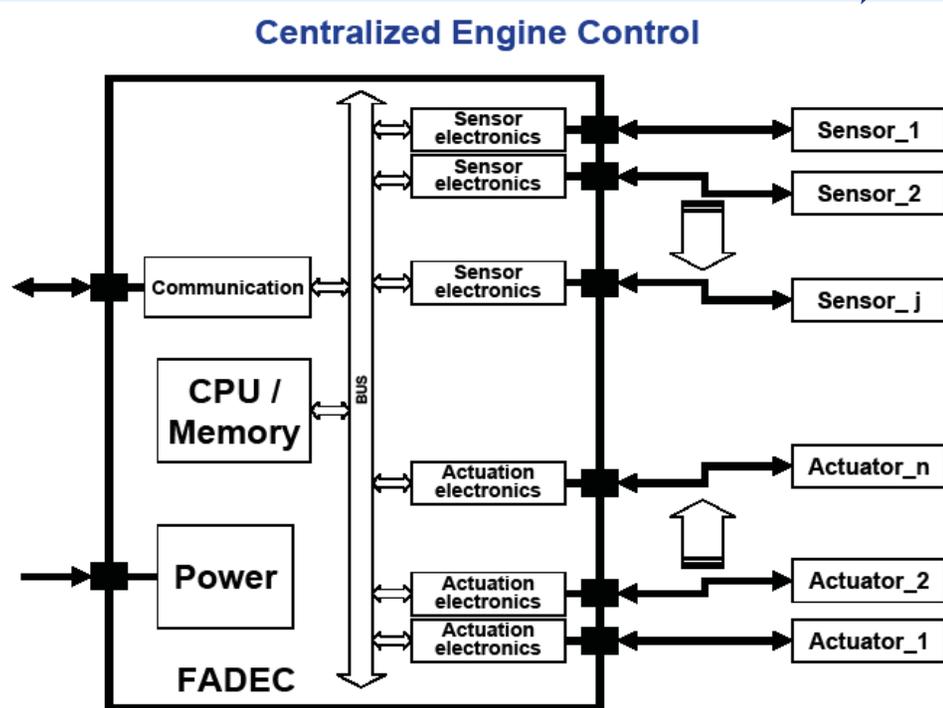
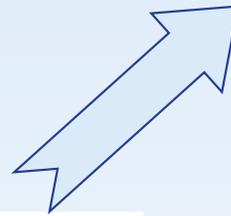
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Distributed Engine Control

Objectives:

- Reduce control system weight
- Enable new engine performance enhancing technologies
- Improve reliability
- Reduce overall cost



Challenges:

- High temperature electronics
- Communications based on open system standards
- Control function distribution

Government – Industry Partnership
Distributed Engine Control Working Group

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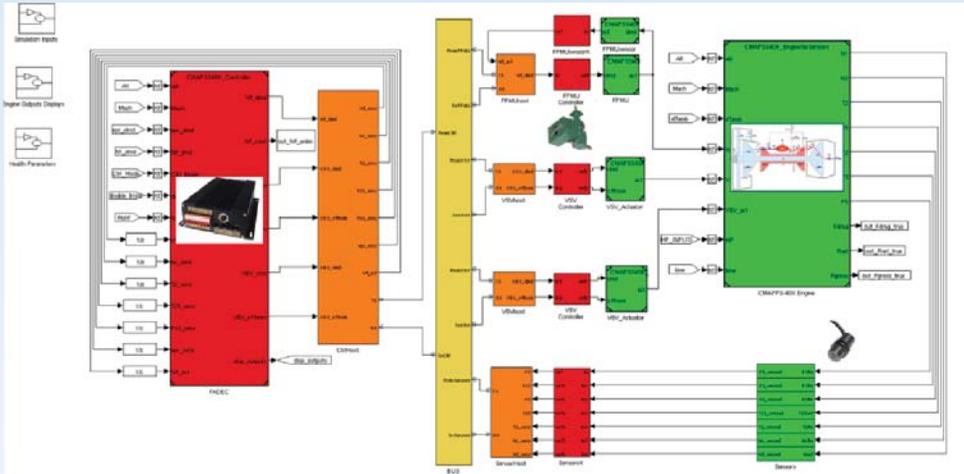
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Distributed Engine Control

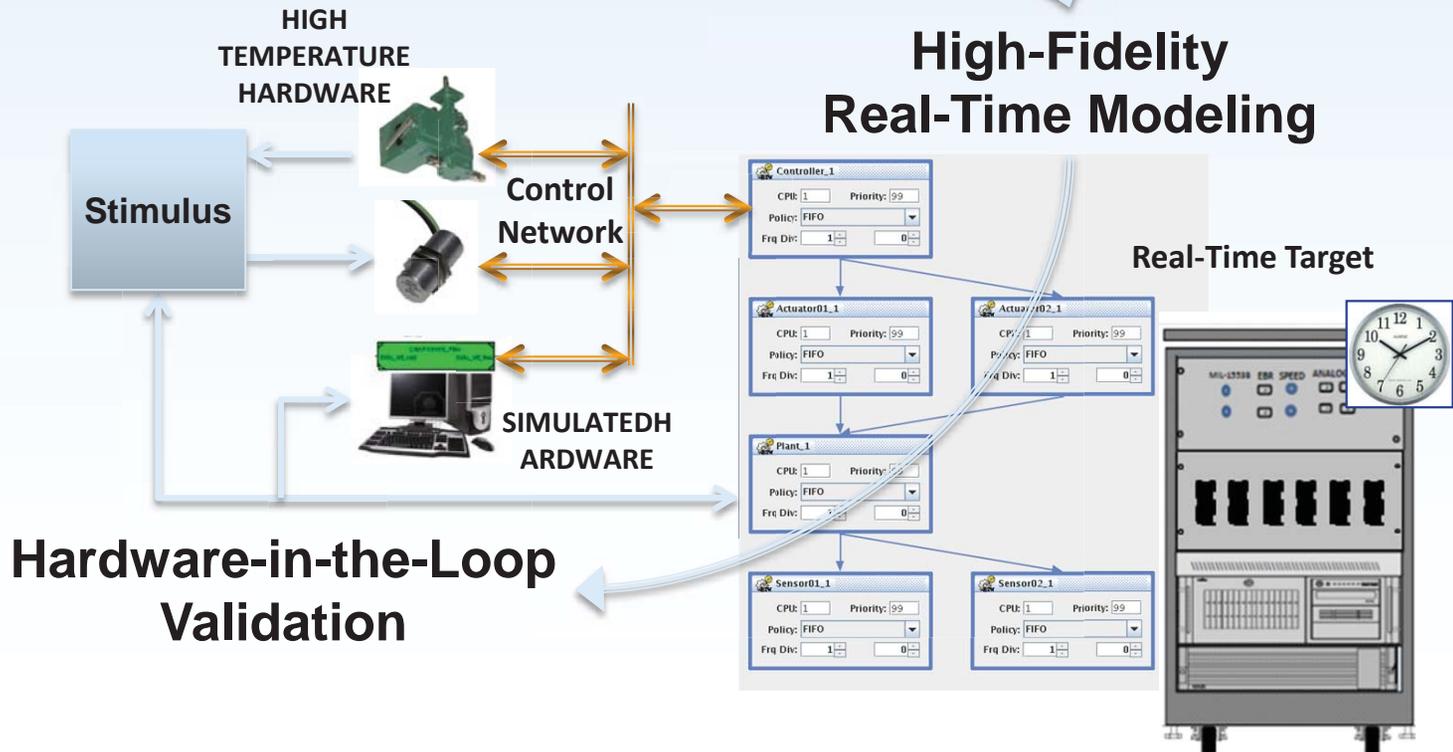
Modeling – Simulation – Hardware-in-the-Loop



Collaborative Environment for Development of Distributed Control Applications on the Turbine Engine

Concept

Revolutionary Controls Technology
Development, Evolution, & Sustainment



Hardware-in-the-Loop Validation

High-Fidelity Real-Time Modeling

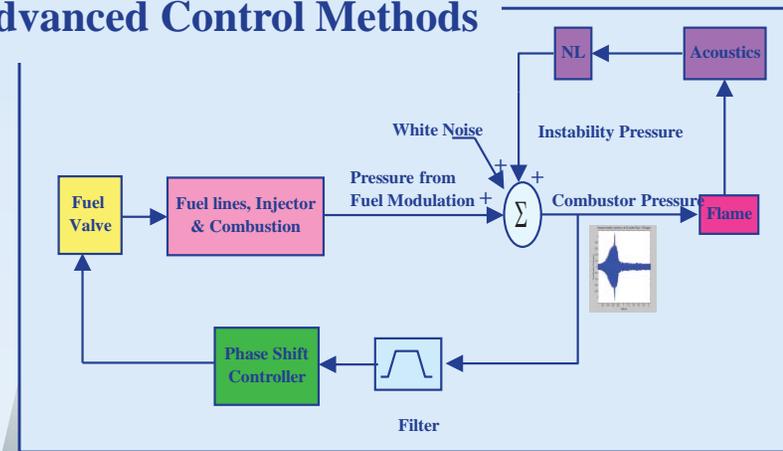
Real-Time Target

Active Combustion Control

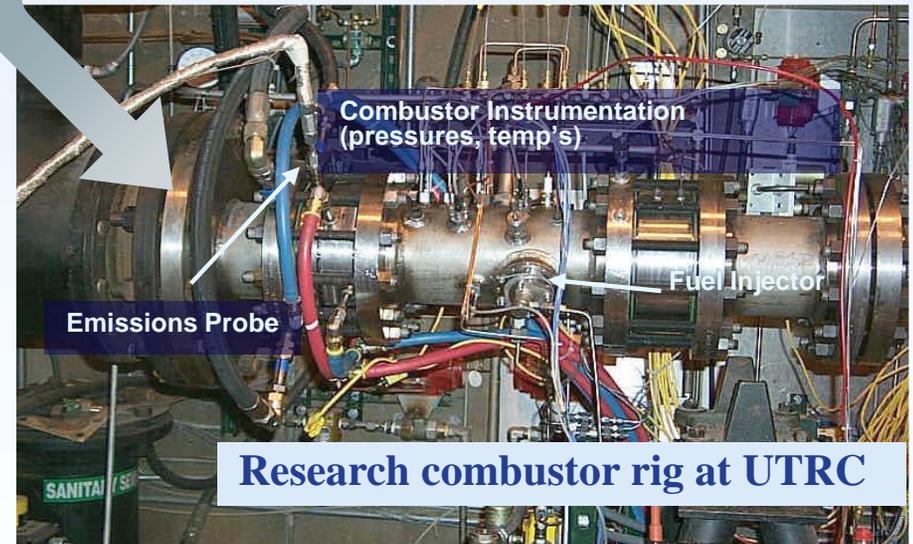
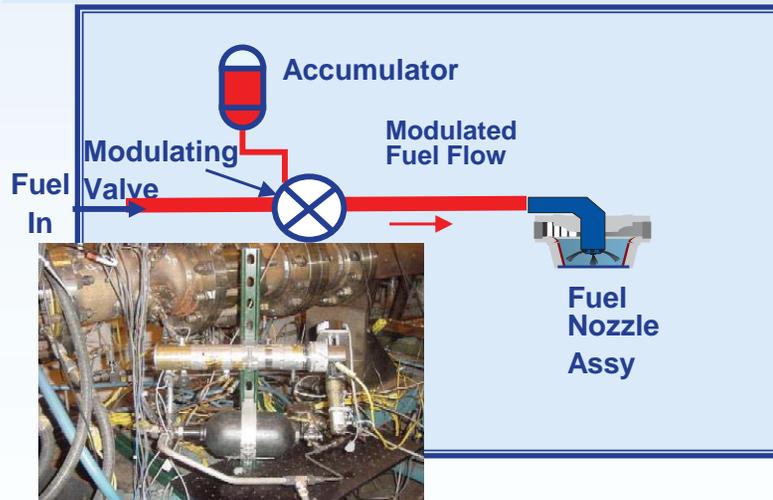
High-frequency fuel valve



Advanced Control Methods



Fuel delivery system model and hardware

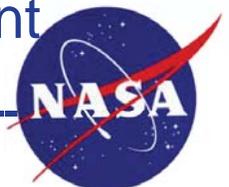


In 2005, GRC demonstrated the feasibility of active suppression of combustion instability in a realistic aero-combustion environment

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Active Combustion Control

Combustion Instability Suppression Demonstrated for Low NOx Combustor Configuration (2012)

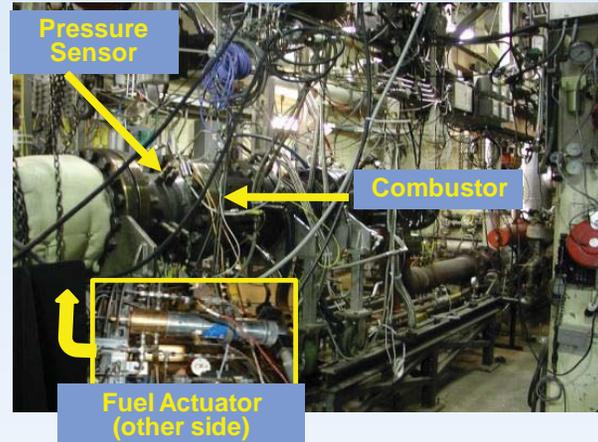
Objective: Utilize Active Combustion Control Techniques to suppress combustion instabilities.

Approach: Instability suppression was demonstrated using a high-frequency fuel valve to modulate the main fuel. Fuel valve dynamic characterization rig utilized to predict actuator authority prior to combustion testing.

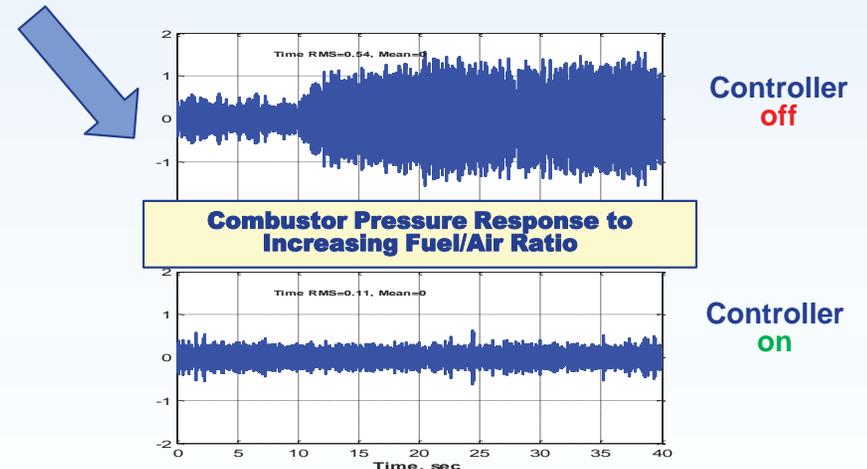
Results: NASA GRC developed Adaptive Sliding Phasor Averaged Control able to prevent growth of combustion instability in a low emissions advanced combustor prototype with a separate pilot and main fuel stage.

Impact: Active combustion control can suppress combustion dynamics and allow operation of a low emissions combustion concept at conditions that would otherwise be precluded due to unacceptably high pressure oscillations.

Low Emissions Advanced Combustor Prototype



Fuel Valve Dynamic Characterization Rig



Adaptive Sliding Phasor Averaged Control algorithm used to prevent growth of combustion instability

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High Speed Propulsion System Dynamic Modeling and Control

- Future Supersonic aircraft are expected to be long slender body fuselage. There is potential for interaction between flexible body modes and propulsion dynamics which can negatively impact performance and ride quality
 - GRC is performing research in Aero-Propulso-Servo-Elasticity (APSE) - developing higher fidelity propulsion system dynamic models to investigate coupling effects with flexible modes
- NASA has interest in developing hypersonic air breathing propulsion systems for low cost access to space. Air Force is interested in systems to provide rapid access to space
 - GRC is conducting research in Combined Cycle Engine (CCE) technologies with an emphasis on inlet design for turbine based CCE. Controls focus is on developing dynamic models and control for safe mode transition

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Aero-Propulso-Servo-Elasticity (APSE)

Goals

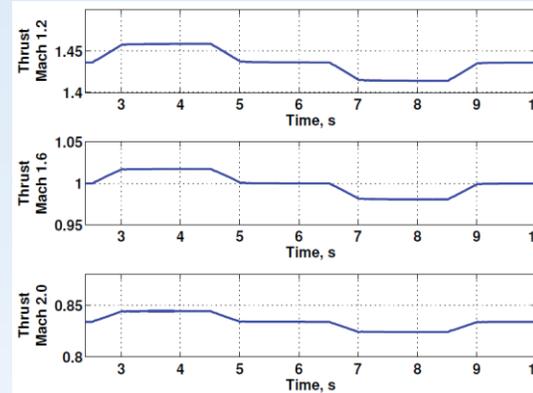
Develop dynamic propulsion system models, aero-servo-elastic & aerodynamic models, and integrate them in closed loop together with atmospheric turbulence to study the dynamic performance of supersonic vehicles for ride quality, vehicle stability, and aerodynamic efficiency.

Approach

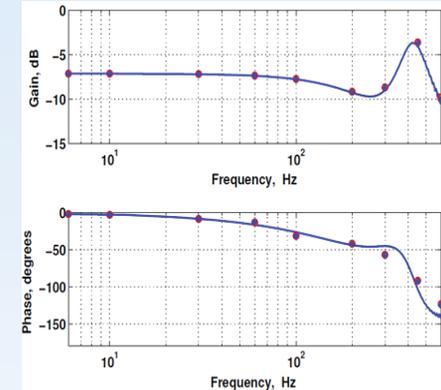
- At NASA GRC the propulsion system models are developed for a Variable Cycle Engine (VCE) based on 1D gas dynamics for engine and quasi-1D CFD for the inlet and nozzle.
- Alternatively, parallel flow path modeling is developed that includes rotational flow to study dynamic performance of flow distortion.

Accomplishments

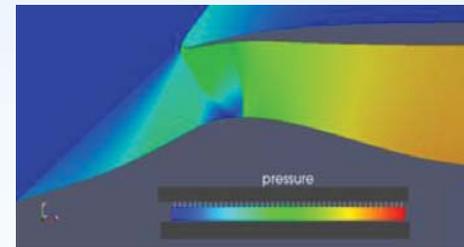
- Developed atmospheric turbulence models, propulsion system 1D gas dynamics models, and quasi 1D inlet and nozzle models.
- Developed first VCE dynamic model with feedback controls and schedules to operate continuously with varying power level.
- Developed first closed loop APSE system.**



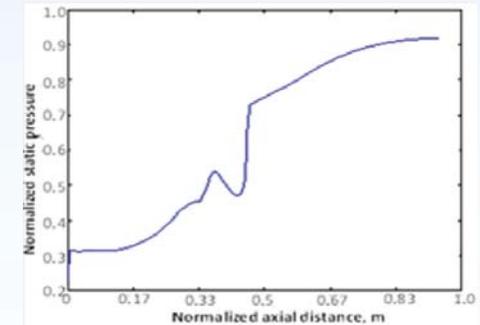
Variable cycle engine thrust response



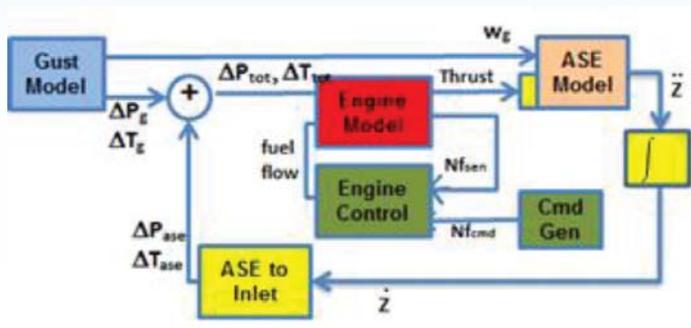
Nozzle frequency domain response



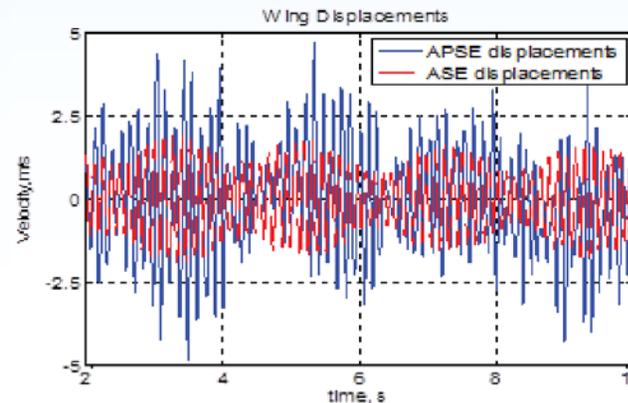
Inlet CFD – 2D flow field



Inlet axial pressure distribution

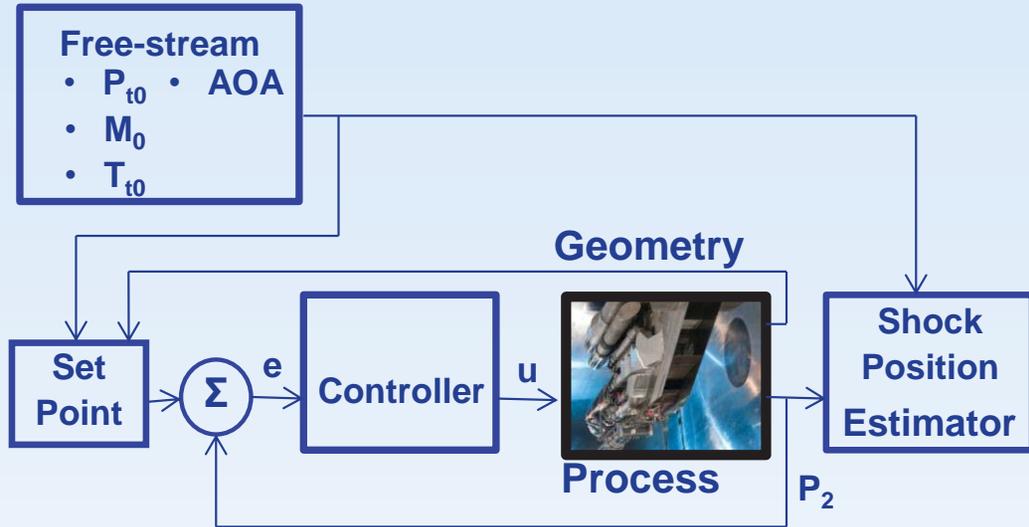


Closed loop APSE Model



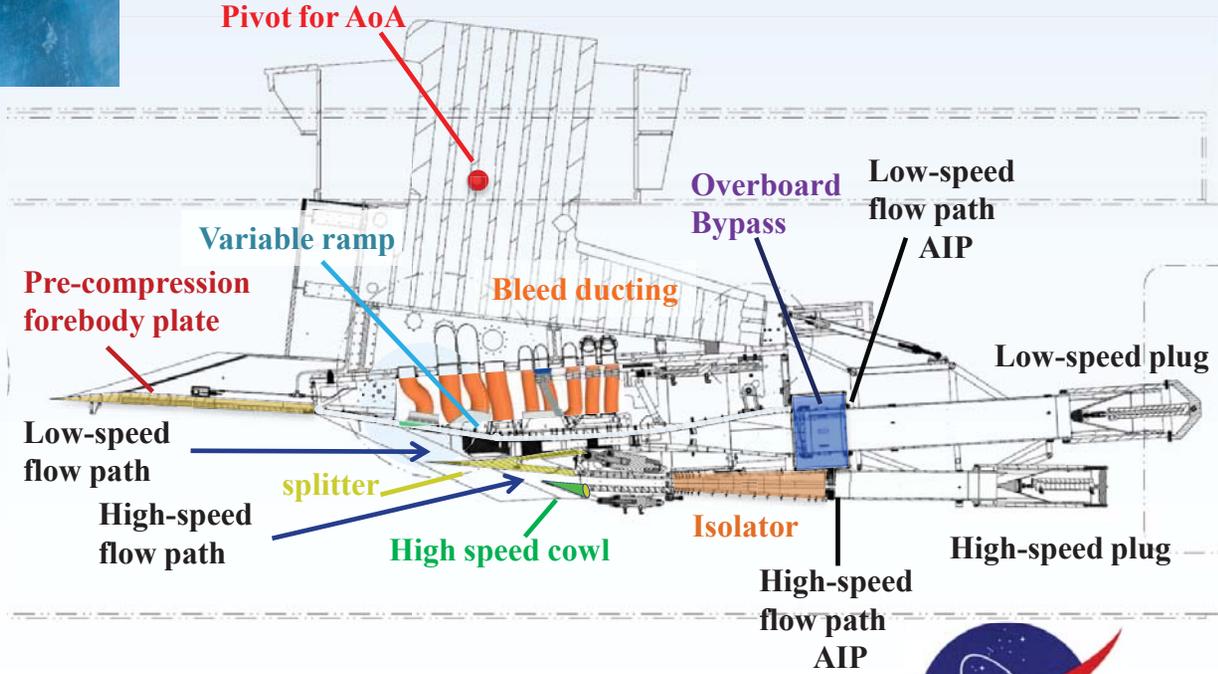
Aero-Servo-Elastic wing displacements w/ and without propulsion system coupling

Hypersonic Propulsion System Control – Overview



GRC 10-foot x 10-foot Combined Cycle Engine (CCE) Testbed

- Low to high speed flowpath transition control
- Shock positioning
- Fuel flow



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Concluding Remarks

- GRC contributions to engine dynamic modeling and control technology development were critical for advancement of turbine engines, and are reflected in the modern Full Authority Digital Engine Control (FADEC) on today's aircraft
- GRC developed engine dynamic model software packages provide an important set of tools for the technical community to develop and demonstrate advanced propulsion control and diagnostics technologies
- Current GRC research will enable revolutionary advances in control logic architecture – Model Based Engine Control, and control hardware architecture – Distributed Engine Control
 - These technologies are critical for achieving the challenging goals of increased aviation efficiency and safety, and reduced environmental impact
- GRC research in high speed propulsion system dynamic modeling and control is critical to enable future supersonic aircraft and hypersonic air-breathing propulsion vehicles

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