Introduction to Advanced Engine Control Concepts

Abstract
With the increased emphasis on aircraft safety, enhanced performance and affordability, and the need to reduce the environmental impact of aircraft, there are many new challenges being faced by the designers of aircraft propulsion systems. The Controls and Dynamics Branch at NASA (National Aeronautics and Space Administration) Glenn Research Center (GRC) in Cleveland, Ohio, is leading and participating in various projects in partnership with other organizations within GRC and across NASA, the U.S. aerospace industry, and academia to develop advanced controls and health management technologies that will help meet these challenges through the concept of Intelligent Propulsion Systems. The key enabling technologies for an Intelligent Propulsion System are the increased efficiencies of components through active control, advanced diagnostics and prognostics integrated with intelligent engine control to enhance operational reliability and component life, and distributed control with smart sensors and actuators in an adaptive fault tolerant architecture. This presentation describes the current activities of the Controls and Dynamics Branch in the areas of active component control and propulsion system intelligent control, and presents some recent analytical and experimental results in these areas.
Lesson 16: Advanced Control Concepts

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Lesson 16: Introduction to Advanced Engine Control Concepts

Agenda:
- Intelligent Engine Concept – from a controls perspective
- Intelligent Engine Control
- Model-Based Controls and Diagnostics
- Life Extending Control
- Performance Deterioration Mitigating Control
- Active Component Control
  - Flow Control to improve compressor efficiency
  - Combustion Control for enabling reduced emissions
  - Higher bandwidth turbine tip Clearance Control
- Distributed Engine Control
- Lesson summary
Advanced Health Management technologies for self diagnostic and prognostic propulsion system - Life usage monitoring and prediction - Data fusion from multiple sensors and model based information

Active Control Technologies for enhanced performance and reliability, and reduced emissions - active control of combustor, compressor, vibration etc. - MEMS based control applications

Distributed, Fault-Tolerant Engine Control for enhanced reliability, reduced weight and optimal performance with system deterioration - Smart sensors and actuators - Robust, adaptive control

Advanced Health Management technologies for self diagnostic and prognostic propulsion system - Life usage monitoring and prediction - Data fusion from multiple sensors and model based information

INTELLIGENT ENGINES Control System perspective Multifold increase in propulsion system Affordability, Reliability, Performance, Capability and Safety
NASA GRC Controls and Dynamics Branch (CDB) 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
  ▪ 20+ engineers and scientists - 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
Components such as actuators, sensors, control logic, & diagnostic systems have to be designed with overall system requirements in mind.

Simplified models are essential for controller design. Understanding the physics of the phenomena is required to capture critical system dynamics in these models.
Autonomous Propulsion System Technology

Reduce/Eliminate human dependency in the control and operation of the propulsion system

Vehicle Management System

- Performance Requirement
- Engine Condition/Capability

Self-Diagnostic Adaptive Engine Control System
- Performs autonomous propulsion system monitoring, diagnosing, and adapting functions
- Combines information from multiple disparate sources using state-of-the-art data fusion technology
- Communicates with vehicle management system and flight control to optimize overall system performance

Model-Based Fault Detection

Diagnostics/Prognostics Algorithms Are Being Developed

Fuzzy Belief Network

Data Fusion

Demonstrate Technology in a relevant environment
Model-Based Controls and Diagnostics

Actuator Commands
- Fuel Flow
- Variable Geometry
- Bleeds

Engine Instrumentation
- Pressures
- Fuel flow
- Temperatures
- Rotor Speeds

Selected Sensors
- Component Performance Estimates
- Sensor Estimates
- Sensor Measurements

On-Board Model & Tracking Filter
- Efficiencies
- Flow capacities
- Stability margin
- Thrust

Sensor Validation & Fault Detection

Adaptive Engine Control

Actuator Positions

Ground-Based Diagnostics
- Fault Codes
- Maintenance/Inspection Advisories

Ground Level

On Board
A general influence coefficient matrix may be derived for any particular gas turbine cycle, defining the set of differential equations which interrelate the various dependent and independent engine performance parameters.

Physical Problems
- Erosion
- Corrosion
- Fouling
- Built up dirt
- FOD
- Worn seals or excessive clearance
- Burned, bowed or missing blades
- Plugged nozzles

Result in

Degraded Component Performance
- Flow capacities
- Efficiencies
- Effective nozzle areas
- Expansion coefficients

Producing

Changes in Measurable Parameters
- Spool speeds
- Fuel flow
- Temperatures
- Pressures
- Power output
High Reliability Engine Control

Neural Network Based Sensor Validation
- Sensor Estimates
- Failed Sensor Detection and Isolation

Sensor Measurements → Validated Sensors → FADEC Closed Loop Control

Actuator Commands

PLA
ALT
XM
P2
T2
HREC - Closed Loop Control of System with Sensor Validation

Diagram showing the flow of signals between the FADEC (Full Authority Digital Engine Control) and PLANT (Plant) systems, with sensors for actuator and controller validation.
Life Extending Control

PLANT

Performance Controller

Structural Model

Damage Estimator

Damage Control

\( J = J_p + q J_D \)

\( \sigma_i, \varepsilon_i, T_i \)

Gain Space

Optimize \( J_p \) Only

Optimize \( J_D \) Only

\( J_{p,\text{min}}, J_{p,\text{opt}} \)

\( J_{D,\text{opt}} \)

\( J_{D,\text{min}} \)
Engine Control Unit adjusts fuel flow to set power management
- Speed Control limits
- Acceleration/Deceleration speed limits
- Fuel Flow limits
- Pressure Control

Typical Engine Control

Designed Limits:
Burner Pressure, Temperatures, Speed Red Line
Effect of Optimizing Core Accel Schedule

Acceleration Schedule Optimized for various Rise Time Constraints
**Smart Life Extending Control**

**Engine Simulation Demonstration Using Stochastic Based Life Models**

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

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

### TMF Damage Accumulation
(Comparison of Original, ILEC, and Optimized Control at hot day conditions)

1. Component damage accumulation is a function of ambient operating condition
2. Engine control logic can be optimized to minimize damage while maintaining desired engine performance
3. Optimized control results in significant component life savings

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

- Typical Operation
- Cold Day Bias
- Hot Day Bias
Engine Performance Deterioration Mitigation Control

- Motivation—Thrust-to-Throttle Relationship Changes with Degradation in Engines Under Fan Speed Control

Throttle  Fan Speed  Thrust

Degradation-induced shift

[Diagram showing engine and control systems]
Control Architecture

- Leverages existing FADEC Control logic based on a Fan Speed Control
- Adds the following logic/software elements:
  - A simplified model of the engine which matches the “nominal” PLA to Thrust response
  - A Thrust estimator
  - A PI control to modify the PLA to Fan Speed command
Parts of the Testbed Architecture

- **Engine Control**
  - Typical Full Authority Digital Engine Control (FADEC) type controller
  - PLA in, fuel flow out
  - Fan speed is controlled

- **Nominal Engine Model**
  - Piecewise linear model
  - Scheduled on percent corrected fan speed

- **Thrust Estimator**
  - Piecewise linear Kalman filter
  - Based on Nominal Engine Model
  - Provides optimal estimation of variables in a least squares sense subject to sensors selected
Steady State Evaluation

Normalized Thrust and Thrust Estimate, PLA=70

Baseline

Outer Loop
Control On

Operating Point
### Transient Evaluation of Architecture

- **Pilot-in-the-loop in a fixed-base simulator**
- Maintain airspeed and heading while following profile
- Three cases: Nominal, 1 engine degraded – OLC Off/On

<table>
<thead>
<tr>
<th>Segment</th>
<th>Fan Speed</th>
<th>Indicated Airspeed</th>
<th>Heading</th>
<th>Altitude</th>
<th>Duration</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>86%</td>
<td>290 knots</td>
<td>270°</td>
<td>32,000 feet</td>
<td>3 minutes</td>
</tr>
<tr>
<td>2</td>
<td>90%</td>
<td>290 knots</td>
<td>270°</td>
<td>33,000 feet</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>82%</td>
<td>290 knots</td>
<td>270°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>88%</td>
<td>290 knots</td>
<td>270°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>86%</td>
<td>290 knots</td>
<td>270°</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Pilot Workload During Transient Flight

Very Clear Increase in Workload With Outer Loop Control Off
Active Stall Control

- Detect stall precursive signals from pressure measurements.
- Develop high frequency actuators and injector designs.
- Actively stabilize rotating stall using high velocity air injection with robust control.

- Demonstrated significant performance improvement with an advanced high speed compressor in a compressor rig with simulated recirculating flow.
Active Flow Control - Compressors

Compressor Stator Suction Surface Separation Control

Multistage Axial Compressor

Installed Smart Vane Stators

Rapid Prototype Flow Control Vane

Flow Delivery System

Sensing Separation from Blade Surface Pressures
Flow Control Actuation Development

**Inlet-Fan-Compressor**
- Stator suction surface injection for separation control
- Rotor tip injection for stability control
- Lightweight, low power hybrid actuation

**Hot Gas Path**
- Active cooling control for mass flow reduction
- Film cooling efficiency enhancement
- Separation control

**FLUIDIC**
- Passive
- Active
  - Variable frequency
  - Variable duty cycle

**VOICE COIL**

**ROTARY**

**Solenoid**

**Hybrid**
- Based on high temperature shape memory alloy

**RAPID PROTOTYPING**
Active Combustion Controls

Pattern Factor Control
**Objective:** actively reduce combustor pattern factor
**Status:** Concept demonstrated in collaboration with Honeywell Engines under the AST program.

Combustion Instability Control
**Objective:** actively suppress thermo-acoustic driven pressure oscillations
**Status:** Continuing research under the Smart Efficient Components project

Emission Minimizing Control
**Objective:** actively reduce NOx production
**Status:** Fuel actuation concept and hardware developed under AST program. Preliminary low order emission models developed under the HSR program.
Active Control of Combustion Instability

High-frequency fuel valve

Fuel delivery system model and hardware

Advanced Control Methods

Combustor Instrumentation (pressures, temp's)

Research combustor rig

Active Control of Combustion Instability
High-frequency fuel valve

Advanced Control Methods

Fuel delivery system model and hardware

Research combustor rig
Active Combustion Control of Instability
Recent Experimental Results

Large amplitude, low-frequency instability suppressed by 90%

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.
Intelligent Turbine Tip Clearance Management

**Time Scales:**
- Flights
- Minutes
- Seconds
- Milliseconds

**Problem:**
- Engine Wear
- Cruise Clearance
- Pinch Points
- Eccentric Shaft Motion

**Approach:**
- Regen. Seals
- Case Cooling
- Case Actuation
- Magnetic Bearings

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**Notional Mission Profile**

- Take-off
- Decel
- Re-Accel
- Cruise
- Pinch Points

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Turbine Tip Clearance

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Time
Intelligent Control of Turbine Tip Clearance

This structure accommodates:
- Simplified Models
- High-order models
- Experiment

- Structural Deformations – Casing & Blades
- Dynamic Material Models
- Active Shape and Vibration Control
- Coupled Thermo-electro-mechanical Response

Engine Model

Smart Structures

Turbine

Interdisciplinary Transient Simulation

- Aerodynamic Loads
- Performance Losses
- Clearance Derivatives
- BCs for Engine Model

Intelligent Controller

Tip Clearance Measurement

- BCs for Component Sims
- Transient Performance Model

Tip Clearance Calculation
First Principles Based Clearance Model

Engine Simulation

Outputs:
- $N_{\text{Shaft}}$
- $P_{\text{Compressor}}$
- $T_{\text{Compressor}}$
- $P_{\text{Turbine}}$
- $T_{\text{Turbine}}$

Results: Deflections & Clearance

Results: Throttle & Shaft Speed

ΔClearance
High-Temperature Shape Memory Alloy Actuator for Active Turbine Tip Clearance Control

**HTSMA Design**

- **SMA actuator consists of wire bundle**
  - Facilitates heat transfer, Provides failure redundancy, Lowers fabrication costs
- **Engine fan bleed air utilized to cool actuator below transition**
- **Design ensures rub-free failsafe operation that improves and preserves performance and extends turbine life**

**Results of System Simulation**

- Generated by incorporating HTSMA actuator model & control with detailed turbofan engine simulation
- Demonstrated clearance control at a 5-mil set point, at takeoff, and other operating points
- Optimized design operates with little fan bleed air
- Shows significant reduction in EGT and SFC

**Rub-free clearance control during a takeoff transient**
Current Engine Control Architecture

- Centralized with each sensor/actuator directly connected to FADEC
Centralized Engine Control

- **Pros:**
  - Works, reliable, well-understood, experience, comfort level

- **Cons:**
  - Expensive, inflexible, in the future will become a limiting factor in engine performance
  - Wire harness weight forces the FADEC to be co-located on the engine structure
  - Co-located FADEC requires environmental hardening (thermal, mechanical) further increasing weight and cost.
  - Complicates fault detection and isolation
Distributed Engine Control

Sensor_1
Sensor_2
Sensor_j
Actuator_n
Actuator_2
Actuator_1

Sensor electronics
Sensor electronics
Sensor electronics
Actuation electronics
Actuation electronics
Actuation electronics

Communication
Communication
CPU/ Memory
Power

BUS

FADEC
Distributed Engine Control

- **Topologies:**
  - Star (point to point), Ring or bus (daisy chain)
  - Wired or wireless

- **Pros:**
  - Known to work well in other industries, much less expensive (initial and overall cost), very flexible

- **Cons:**
  - Communication unknowns and deterministic behavior
  - Overall increased complexity
  - Requires new technologies, i.e., high temperature electronics
Lesson 16 Summary

- There are tremendous opportunities to improve and revolutionize aircraft engine performance through “proper” use of advanced control techniques
  - Intelligent engine control integrated with reliable condition monitoring and fault diagnostics to extend on-wing operating life, maintain performance with aging, safely accommodate faults while maintaining best achievable performance etc.
  - Active control of engine components to provide the desired performance characteristics throughout the flight envelope and enable low emission higher performance components
  - Distributed engine control to reduce “control system” weight, increase operational reliability and flexibility to easily incorporate new and improved capabilities