Fundamentals of Jet Engine Control

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Outline

– The Engine Control Problem
– Safety and Operational Limits
– Historical Engine Control Perspective
– Modeling and Simulation
– Basic Control Architecture
– Advanced Concepts
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
Since Thrust (T) cannot be measured, use Fuel Flow WF to Control shaft speed N

\[ T = F(N) \]
Environment within a gas turbine

Aerodynamic Buffeting
120 dB/Hz to 10kHz

2000+°C
Flame temperature
- 40°C ambient

Cooling air at 650+°C

20000+ hours
Between service

40+ Bar
Gas pressures

8mm+
Shaft movement

1100+°C
Metal temperatures

50 000g centrifugal acceleration
>100g casing vibration to beyond 20kHz

10 000rpm
0.75m diameter

2.8m Diameter

Foreign objects
Birds, Ice, stones
Air mass flow
~2 tonne/sec

1000 rpm
0.75m diameter

2000+ºC
Flame temperature
- 40ºC ambient

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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

LPC - Low Pressure Compressor
HPC - High Pressure Compressor
HPT - High Pressure Turbine
LPT - Low Pressure Turbine
N1 - Fan Speed
N2 - Core Speed
Historical Engine Control

- 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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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 a minimum rise time for thrust
Engine Modeling

- Steady State performance obtained from cycle calculations derived from component maps obtained through detailed component modeling and component tests
  - Corrected parameter techniques used to reduce the number of points that need to be evaluated to estimate engine performance throughout the operating envelope
- Dynamics modeled through inertia (the rotor speeds), combustion delays, heat soak and sink modeling etc.
  - Computationally intensive process since it is important to maintain mass/momentum/energy balance through each component
- Detailed thermo-dynamic cycle decks developed and parameters adjusted to match engine test results
- Simplified models generated to develop and evaluate control design
Engine Component Modeling – Modern Turbofan Engine

Aero-Thermodynamics
- Compressor/Fan Maps: PR, Corr. Flow & Efficiency as functions of Shaft Speed & R-line
- Turbines: Corr. Flow and Efficiency as functions of Shaft Speed & PR

Dynamics
- Two physical states: fan speed, core speed
- Actuator/sensor dynamics: first-order lags
- Combustion delay

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Engine Dynamic Modeling – Historical Perspective

- 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: \( \frac{N(s)}{WF(s)} = \frac{K}{(as+1)} \) with \( a = f(N) \)
Limits are implemented by limiting fuel flow based on rotor speed.
- Maximum fuel limit protects against surge/stall, over-temp, over-speed and over-pressure.
- Minimum fuel limit protects against combustor blowout.
- Actual limit values are generated through simulation and analytical studies.

Implementing Limits for Engine Control

\[
\frac{Wf}{P_{S_{30}}}
\]

\[
N_{2}^R
\]
Typical Sensors Used for Engine Control

- N1
- N2
- EGT – Exhaust Gas Temp
- P2
- T2
- P25
- T25
- Ps3
- T3
- WF36
Typical Modern FADEC Control Architecture

All regulators produce incremental fuel flow commands

- **Structural limit regulators**
  - $T_{48}$
  - $P_{S3}$
  - $N2$

- **Fan speed regulator**
  - $T_{20}$
  - $N1_{dndr}$

- **Thrust command**
  - Throttle
  - Power Management

- **Combustion blowout regulator**
  - $P_{S3}$

- **High Limits**
  - $K_{T48}(s)$
  - $K_{P33}(s)$
  - $K_{N2}(s)$

- **Low Limit**
  - $K_{P33}(s)$

- **Burnout limit regulators**
  - $P_{S3}$
  - $N2_{c}$

- **Acceleration/Deceleration schedule**
  - $rac{dW_{f}}{dt}$

- **Fuel flow command**
  - $W_{f}$

- **Min**

- **Max**

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Control Law Design Procedure

- The various control gains $K$ are determined using linear engine models and linear control theory
  - Proportional + Integral control provides good fan speed tracking
  - Control gains are scheduled based on PLA and Mach number
- Control design evaluated throughout the envelope using a nonlinear engine simulation and implemented via software on FADEC processor
- Control gains are adjusted to provide desired performance based on engine ground and altitude tests and finally flight tests

![Control Law Design Procedure Diagram]

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Burst-Chop Example – Inputs/Outputs

- TRA (deg)
- Nf (rpm)
- VSV pos. (deg)
- VBV pos. (% open)
- Wf (pph)
- Wf/Ps30 (pph/psi)
- Nc (rpm)
- T48 (°R)
- Ps30 (psia)
Burst-Chop Example - Stall Margins

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Model-Based Controls and Diagnostics

Actuator Commands
- Fuel Flow
- Variable Geometry
- Bleeds

Adaptive Engine Control

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

Ground Based Diagnostics
- Fault Codes
- Maintenance/Inspection Advisories

Ground Level

Selected Sensors

Sensor Validation & Fault Detection

Sensor Estimates

Sensor Measurements

Component Performance Estimates

Actuator Positions

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

Actuator Commands
- Fuel Flow
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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

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Engine Performance Deterioration Mitigation Control (EPDMC)

- The proposed retrofit architecture:
  - Adds the following “logic” elements to existing FADEC:
    - A model of the nominal throttle to desired thrust response
    - An estimator for engine thrust based on available measurements
    - A modifier to the Fan Speed Command based on the error between desired and estimated thrust
      - Since the modifier appears prior to the limit logic, the operational safety and life remains unchanged

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EPDMC Evaluation
Thrust response for Typical Mission

With EPDMC

- Throttle to thrust response is maintained – no “uncommanded” thrust asymmetry

Without EPDMC

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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

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Summary

• Provided an overview and historical perspective of engine control design
• The control design enables smooth and safe operation of the engine from one steady-state to another through implementation of various limits
• There are tremendous opportunities to improve and revolutionize aircraft engine performance through “proper” use of advanced control techniques
References


NASA TMs are available for free download at: http://gltrs.grc.nasa.gov/