Application and Evaluation of Control Modes for Risk-Based Engine Performance Enhancements

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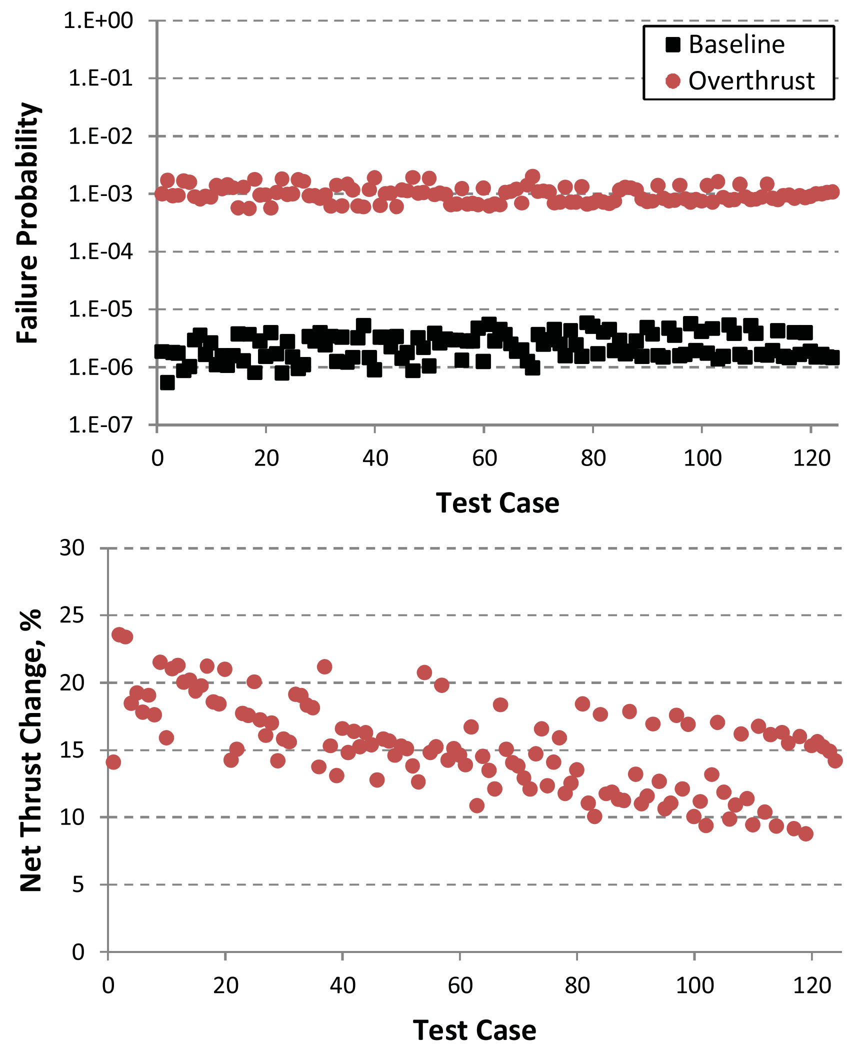
Background

- NASA Aviation Safety Program
- Emergency situations (e.g., runway incursion, airframe damage) may warrant unconventional usage of aircraft engines
- Overthrust (OT): Increase maximum thrust output
- Faster response (FR): More responsive transient thrust response
- Development of risk-based control modes that enhance engine performance for emergency use

- Csank et al., "The Effect of Modified Control Limits on the Performance of a Generic Commercial Aircraft Engine," 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 2011.
- May et al., "Improving Engine Responsiveness during Approach through High Speed Idle Control," 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 2011.
- Liu et al., "Design and Demonstration of Emergency Control Modes for Enhanced Engine Performance," 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2013

Control Mode: Overthrust

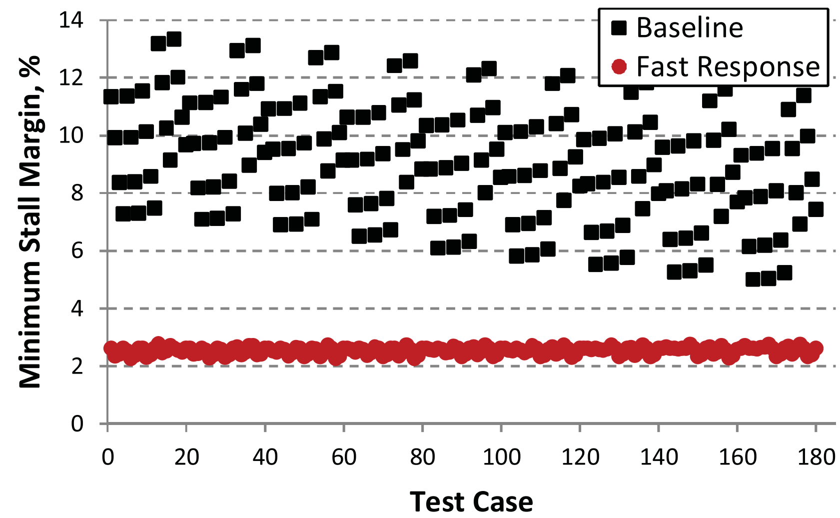
- Control mode relaxes limits on temperature and rotational speeds
- Thrust available is increased
- Maximum overthrust at any operating condition is defined by a predetermined disk/blade failure risk level

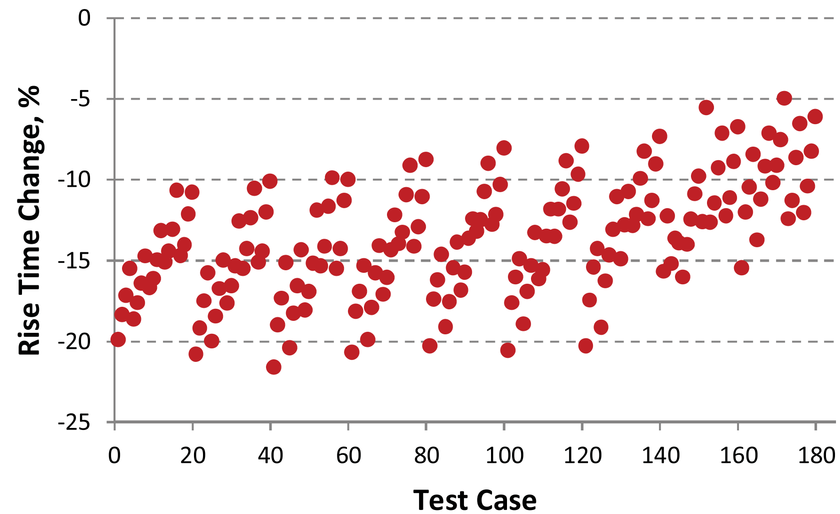


Liu et al., "Design and Demonstration of Emergency Control Modes for Enhanced Engine Performance," 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2013.

Control Mode: Faster Response

- Control mode activation increases thrust responsiveness to throttle changes
- Modification to engine control system gains, schedules, etc.
- Risk of stall related to minimum stall margin attained during transient
- Reduction of minimum stall margin to consistent level

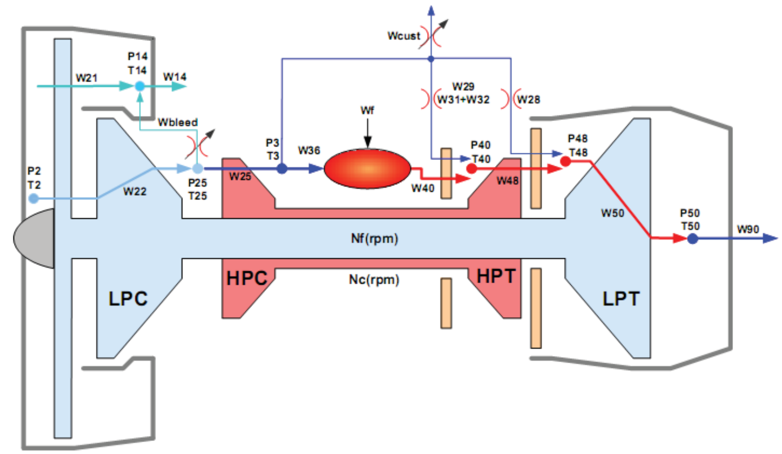




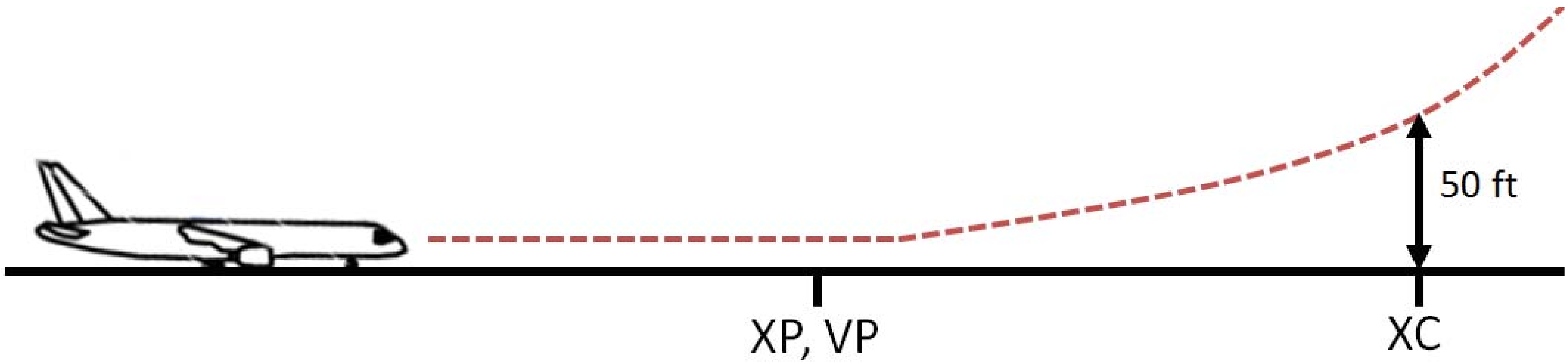
Liu et al., "Design and Demonstration of Emergency Control Modes for Enhanced Engine Performance," 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2013.

Objectives

- Apply control modes to aircraft simulation
  - Propulsion: Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k), NASA Glenn
  - Airframe: Transport Class Model (TCM), NASA Langley
  - Piloted flight simulator: Modular Flight Deck (MFD), Precision Flight Controls, Inc.
- Evaluate effectiveness of control modes through simulations of emergency scenarios
- Runway incursions
  - Computer simulation (i.e., autopilot)
- Flight control surface failure
  - Autopilot and piloted evaluations



Runway Incursion



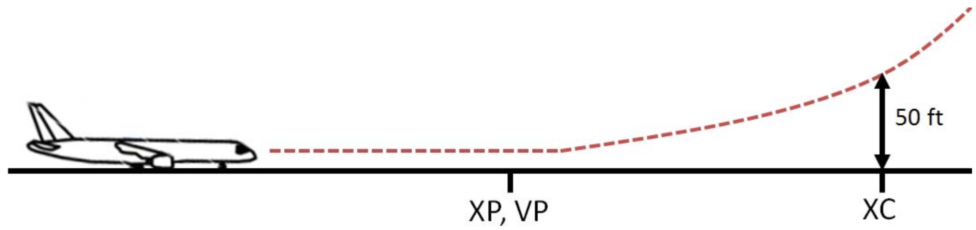
- Aircraft stationary
- Throttles 0 to 90%

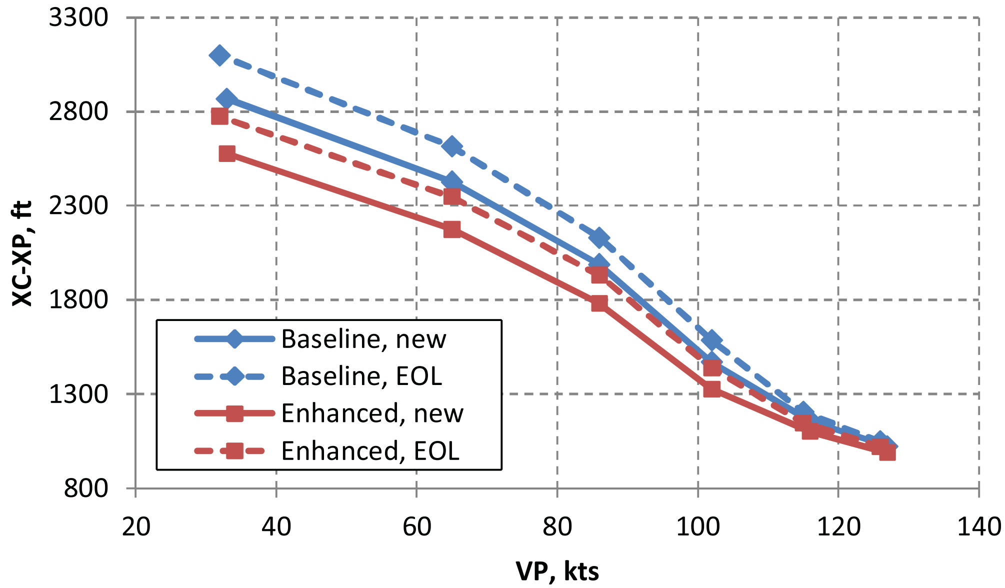
- Incursion detected
- Throttles 90% to 100%
- Pull up to 15º pitch

- Aircraft clears 50 feet above ground level (AGL)

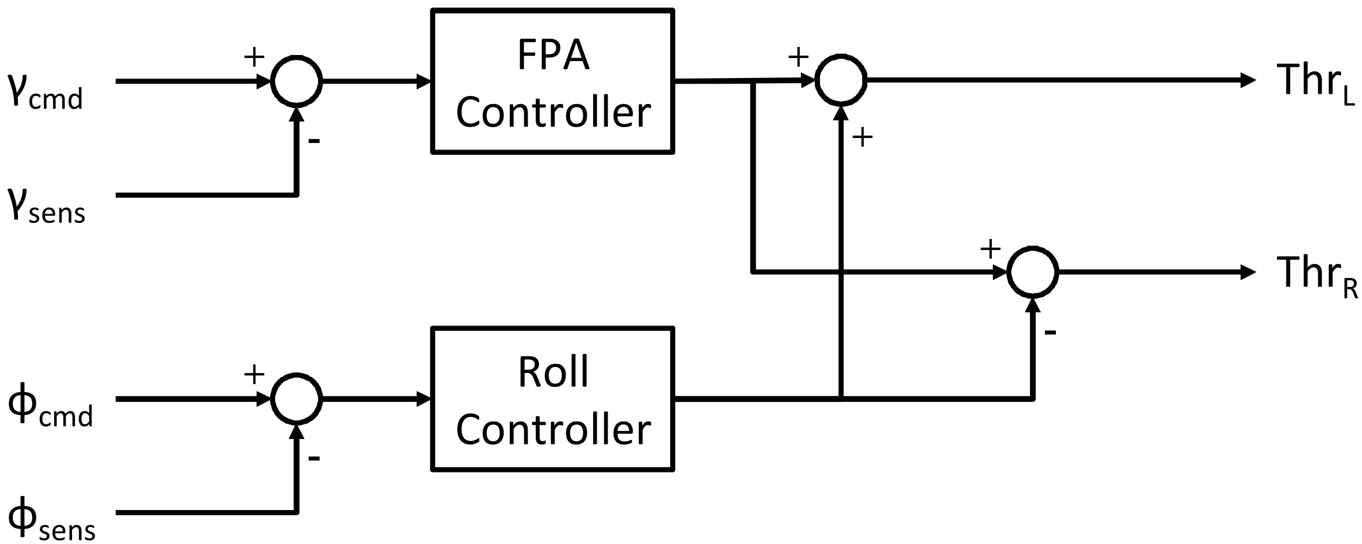
Runway Incursion

- Test cases:
  - Baseline vs. enhanced performance
  - New vs. end-of-life (EOL) engines
  - Vary XP (point where incursion is detected)
- Metric: additional distance required to clear 50 feet AGL (XC-XP)
- Greater improvement with earlier detection (but also less useful)
- OT mode with EOL engines nearly recovers baseline/new performance





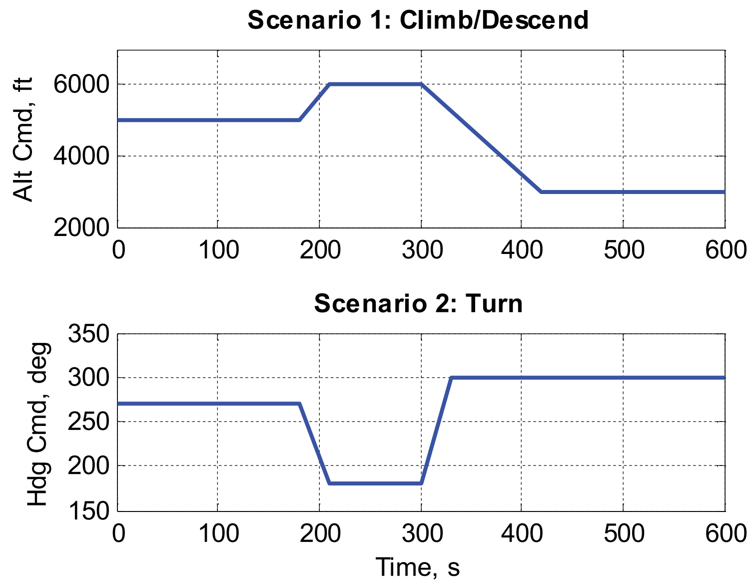
Flight Control Surface Failure



- Failure of all primary flight control surfaces (elevator, aileron, rudder)
- Propulsion Controlled Aircraft (PCA): control system reconfigured to command engine power setting

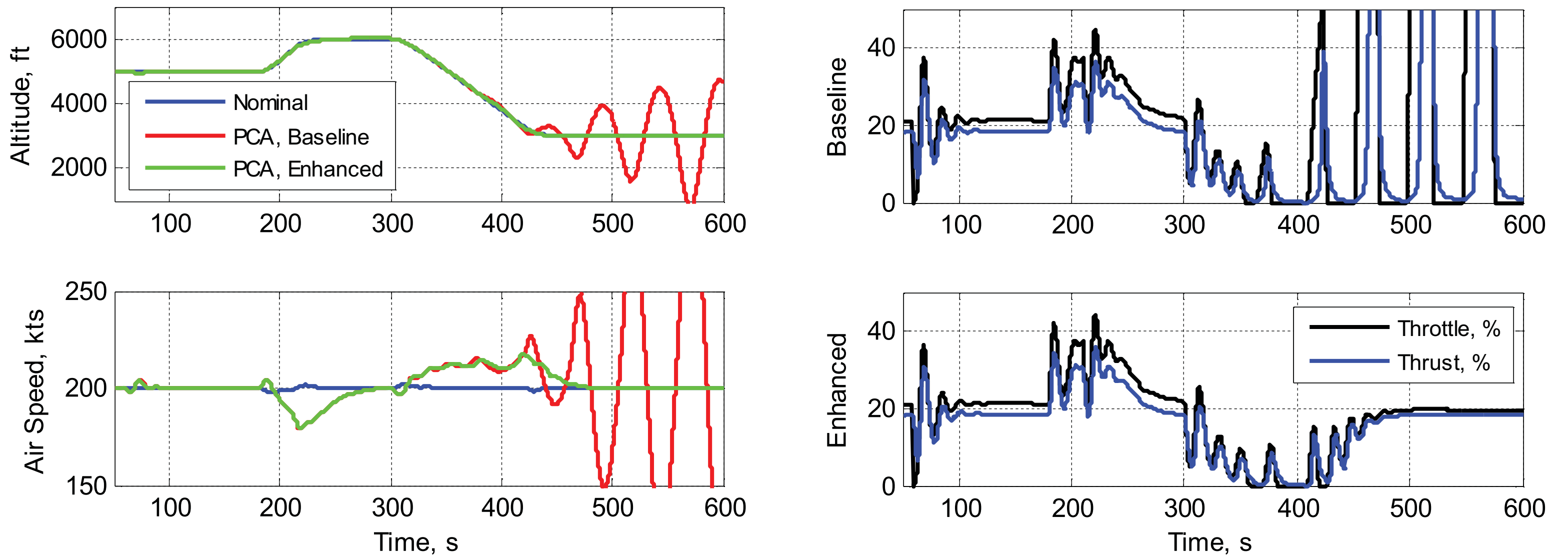
Burcham et al., "Development and Flight Evaluation of an Emergency Digital Flight Control System Using Only Engine Thrust on an F-15 Airplane," NASA Technical Paper, 1996.

Control Surface Failure: Evaluations



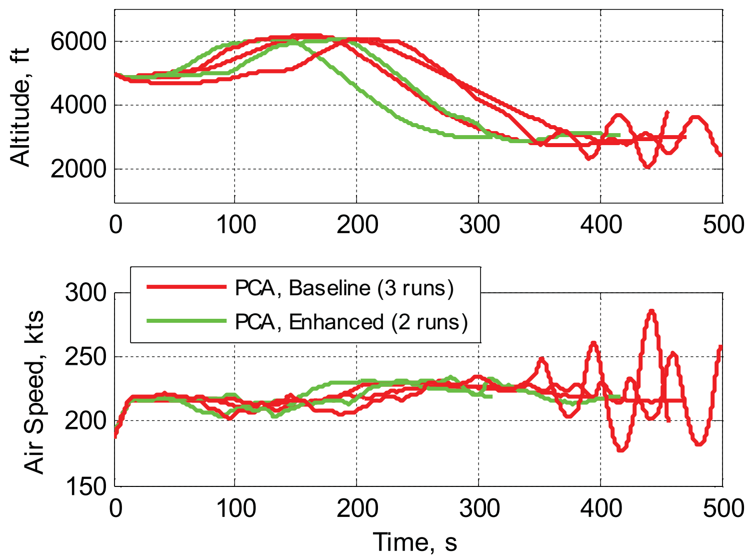
- Evaluations of longitudinal and lateral aircraft maneuverability with baseline and enhanced engines
- Tests conducted by autopilot (“unaware” of control surface failure) and human pilot
- Engine power settings are indirectly controlled through PCA control system

Control Surface Failure
Longitudinal Maneuvers—Autopilot



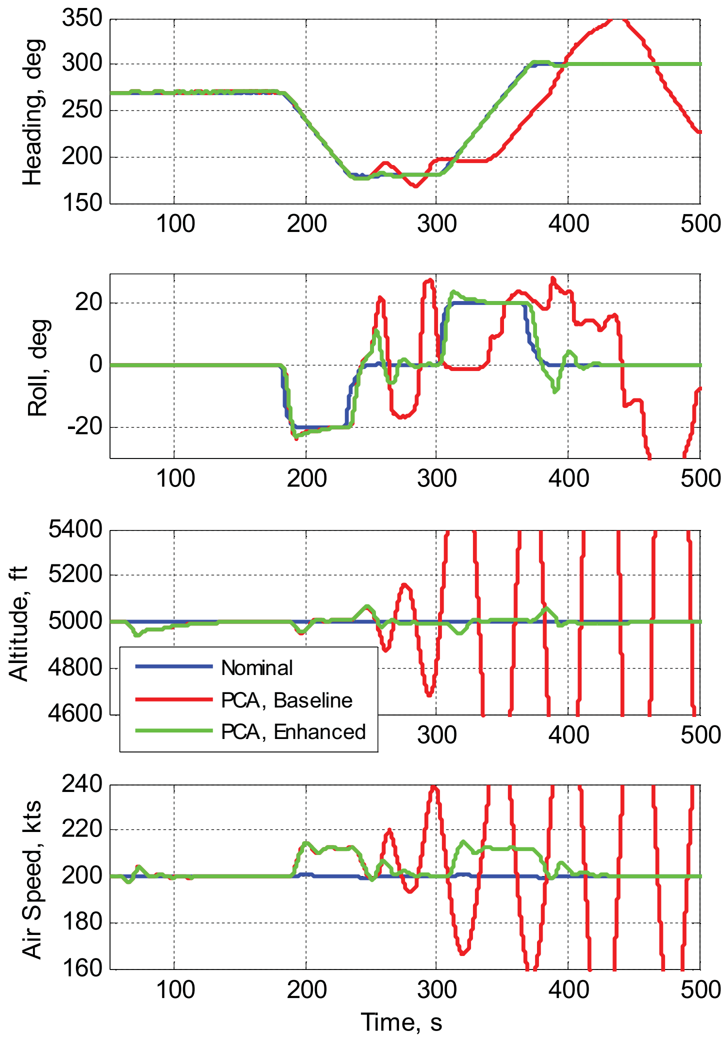
- Altitude profile of PCA with enhanced control modes nearly identical to that of nominal aircraft (fully functional flight controls)
- PCA with baseline engines results in instability
  - Autopilot does not compensate for slow response of baseline engines (commands too aggressive)
  - PCA control gains may not be optimal
- Performance-enhancing control modes provide protection against instabilities

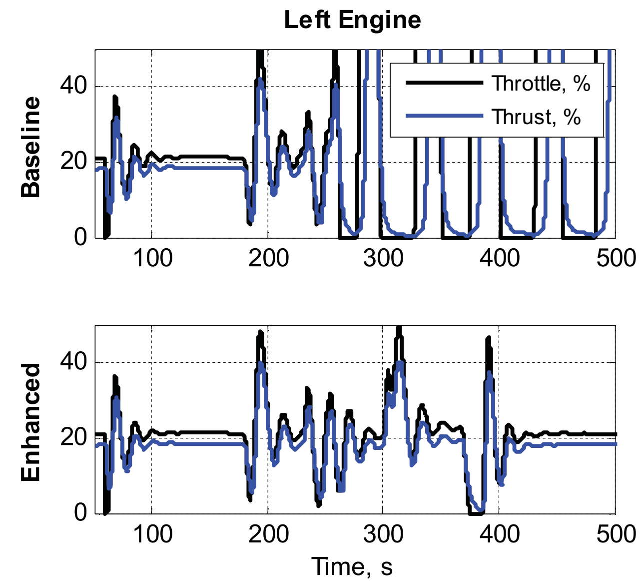
Control Surface Failure
Longitudinal Maneuvers—Piloted



- Maneuver requirements relaxed for piloted evaluations
  - Exact trajectory not required
  - Just hit the altitude waypoints (e.g., 5000 feet, 6000 feet, 3000 feet)
- Pilot was aware of control surface failure, but unaware of engine control mode status
- Aircraft control with baseline engines more difficult, though the pilot was able to prevent instabilities for 1 of 3 baseline PCA runs

Control Surface Failure
Lateral Maneuvers—Autopilot

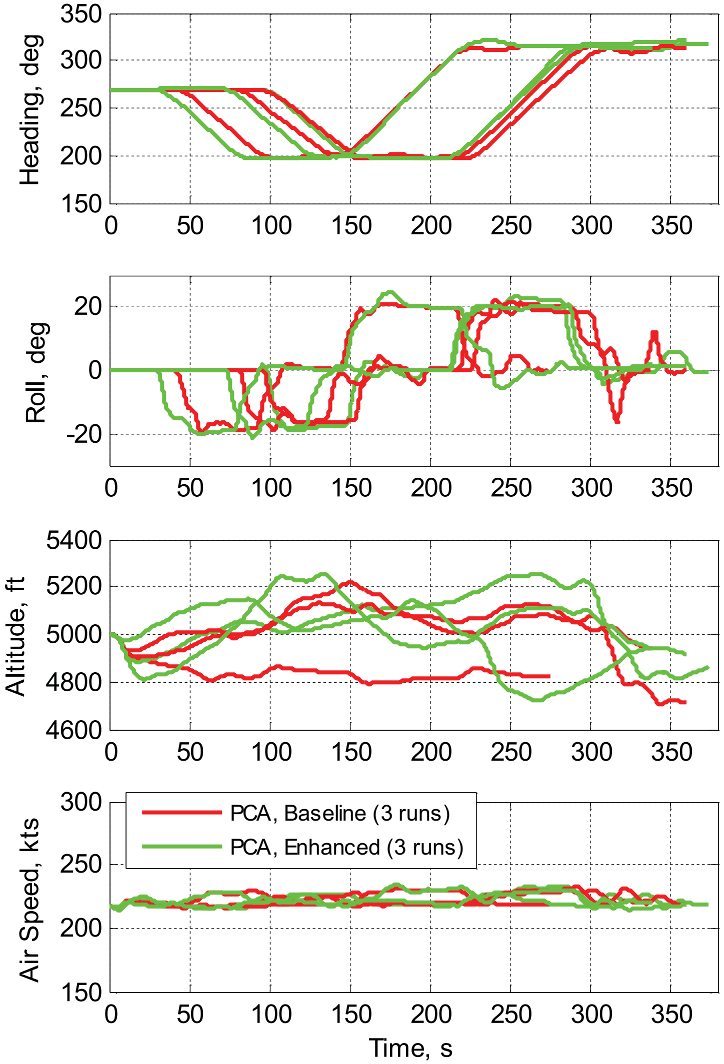




- Roll response not ideal, but faster engines prevent instabilities
- Autopilot too aggressive in trying to maintain altitude during rolling maneuvers

Control Surface Failure
Lateral Maneuvers—Piloted

- Pilot had to hit heading waypoints (no trajectory requirement)
- No instabilities for baseline or enhanced engines
- Pilot tried to maintain altitude, but not at expense of stability
- Autopilot had tighter altitude control, but only successful with faster thrust response



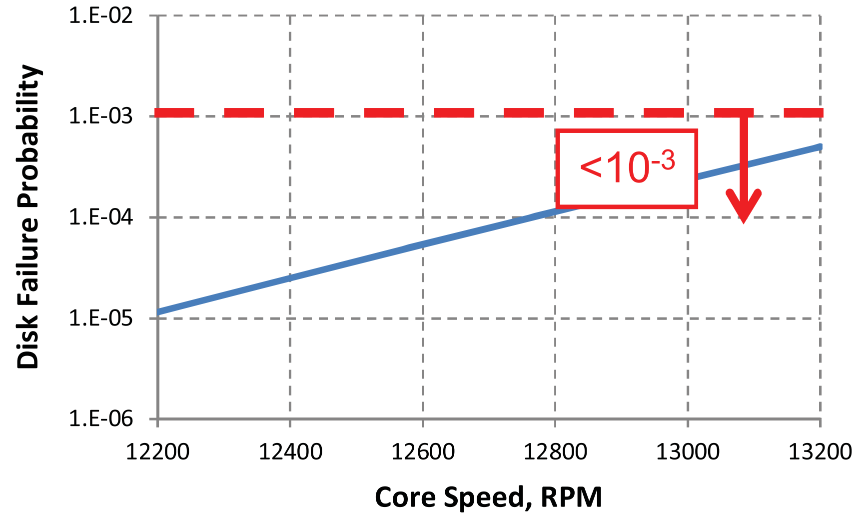
Summary & Conclusions

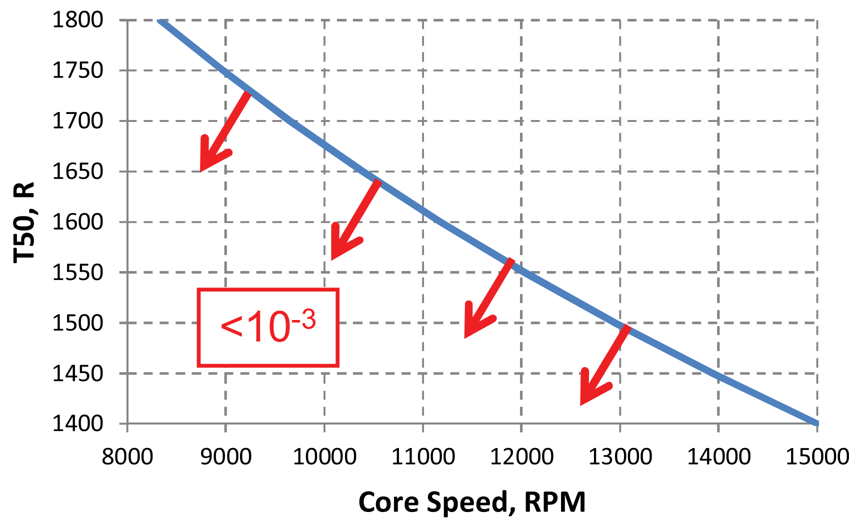
- Control modes: engine performance enhancements based on failure risk elevation
- Control mode implementation on aircraft/propulsion simulation and flight simulator test bed
- Evaluated control modes using example flight emergency scenarios (runway incursion & flight control surface failure)
- Extra thrust reduces takeoff distance
- Faster response protects against instabilities if aircraft must be maneuvered with engines only

Backup Slides

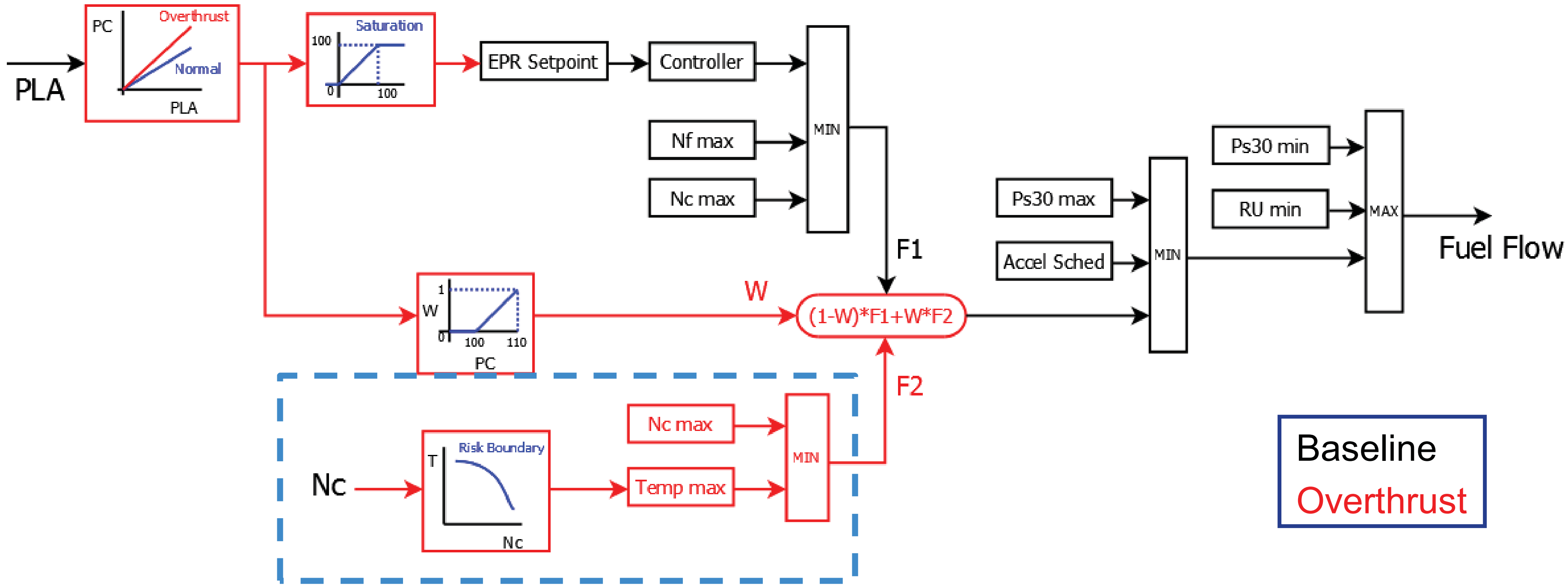
Overthrust: Implementation

- Reduced-order risk function used for control design and implementation (NOT used when evaluating results)
- Disk failure risk as function of core speed
- Blade failure risk as function of core speed and single turbine temperature
- Allowable elevated risk (10^{-3}) manifested as:
  - Core speed limit for disk failure
  - Speed-temperature boundary for blade failure





Overthrust: Implementation

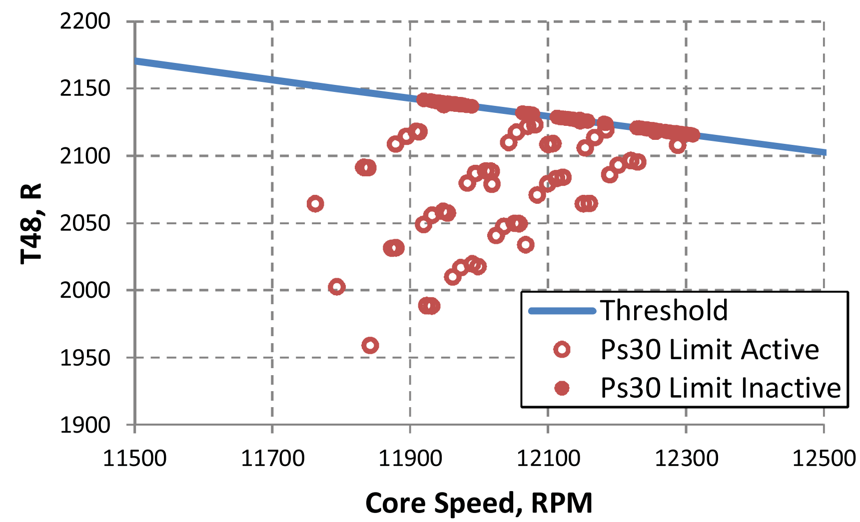


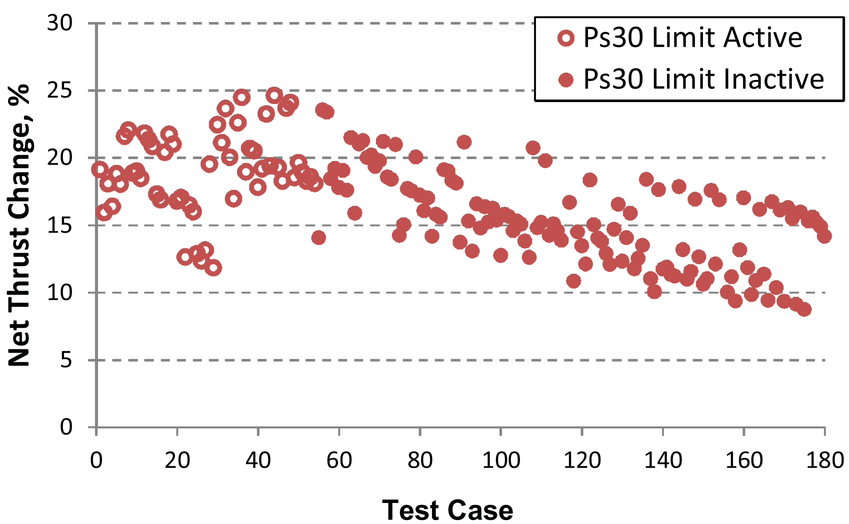
- Core speed and turbine temperature regulators used to maintain engine operating point on risk boundary
- Overthrust activation: PLA mapping switches from idle-to-max to idle-to-overthrust

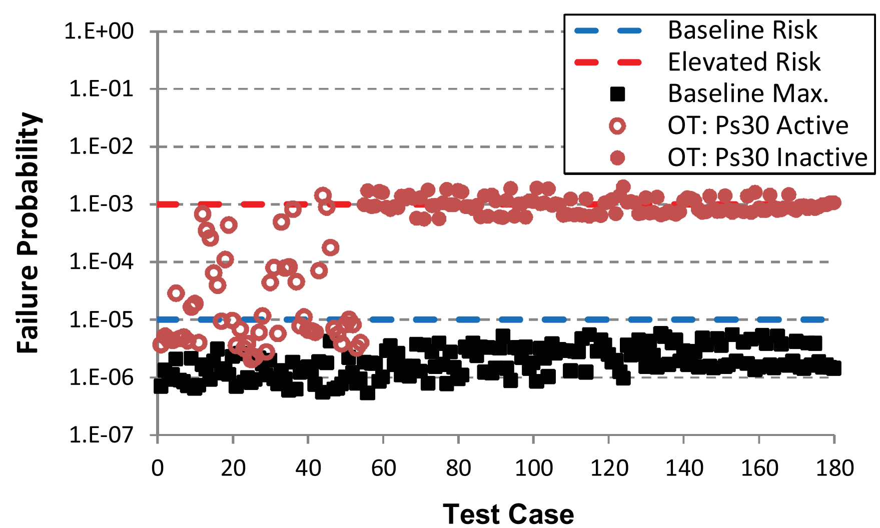
National Aeronautics and Space Administration

Overthrust: Results

- Tested at 180 operating points (0 to 4000 feet, Mach 0 to 0.3, standard to +40°R ambient temp, new to full deterioration)
- Maximum power setting: baseline vs. overthrust
- Nc-T48 reduced-order risk boundary (LPT inlet temperature)



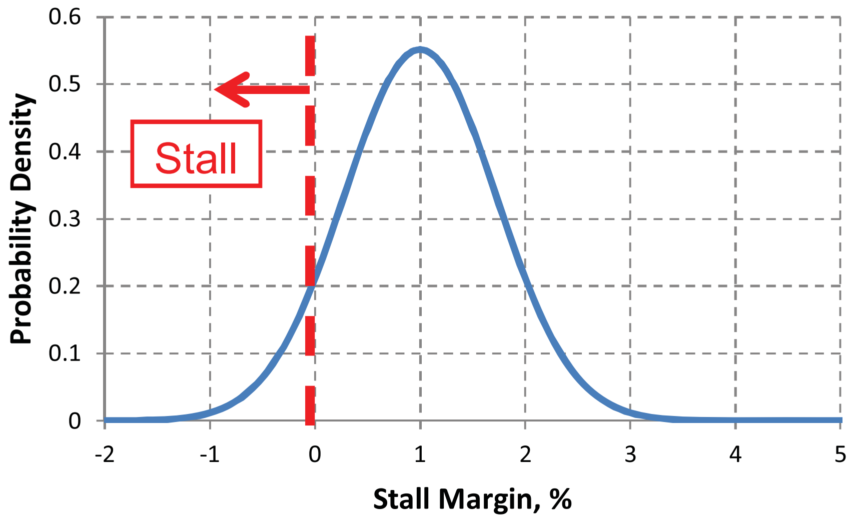


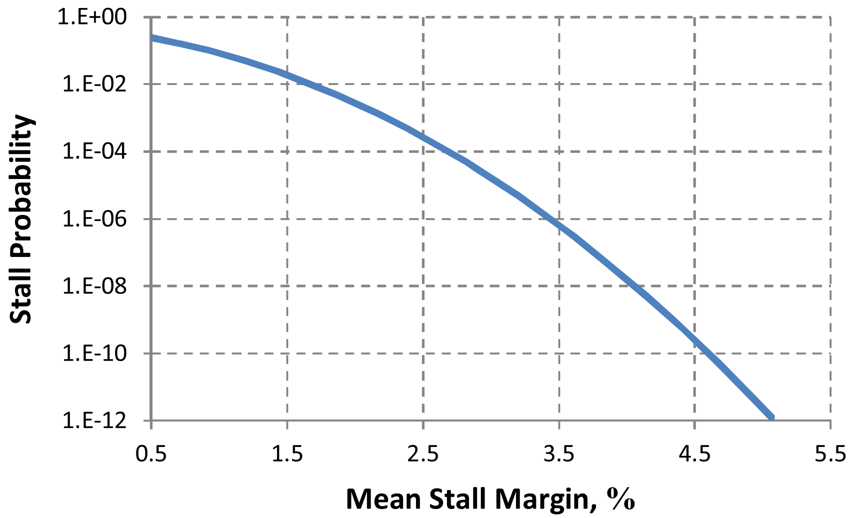


Faster Response: Risk Function

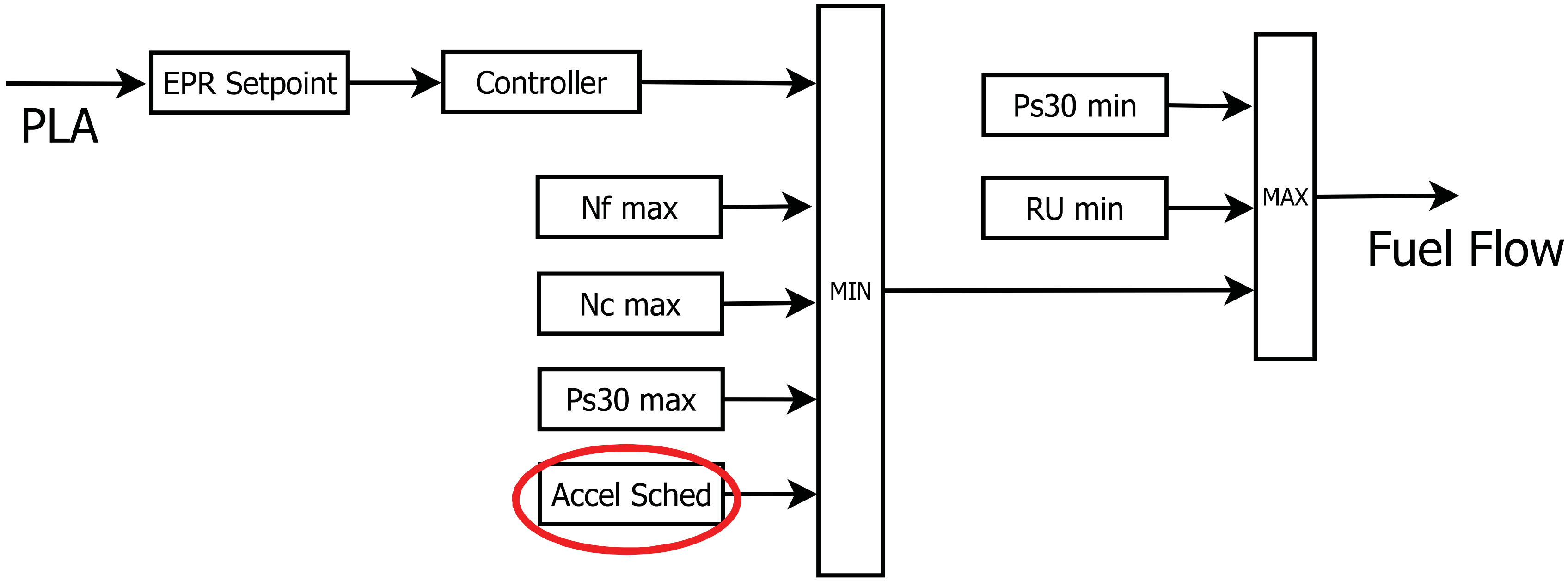
- Statistical stability assessment (SAE AIR1419 Rev. A, 1999)
- Risk of stall modeled as normal distribution
  - Stall margin reported by simulation equals mean
  - Root-sum-square of random effects equals 3 standard deviations
- Stall probability of 10^{-3} corresponds to ~2.3% stall margin

	Destabilizing Effects	Non-random	Random
Operating Line	Inlet Distortion	0.7%	-
	PLA Transient	6.0%	-
	Fuel Control Tolerance	-	±1.15%
	Engine-to-Engine Variation	-	±1.25%
Surge Line	Reynolds Number	0.36%	-
	Inlet Distortion	7.5%	-
	Engine-to-Engine Variation	-	±1.35%
Total		14.56%	2.17%





Faster Response: Implementation



- Shifting acceleration schedule allows for faster dynamic response with lower minimum stall margin
- Iterative search conducted at 60 operating points (0 to 4000 feet, Mach 0 to 0.2, standard to +40°R ambient temperature, new to full deterioration) to determine offset values
- Implementation: 4-D interpolation on operating conditions to determine offset value

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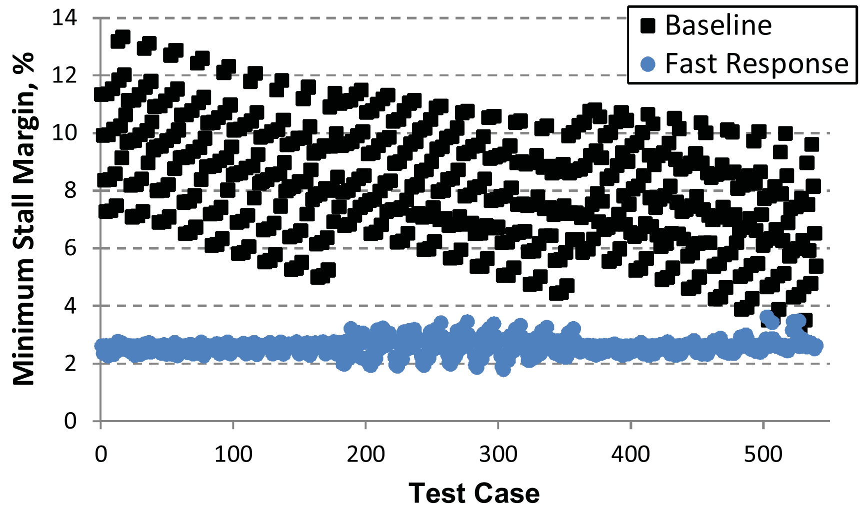
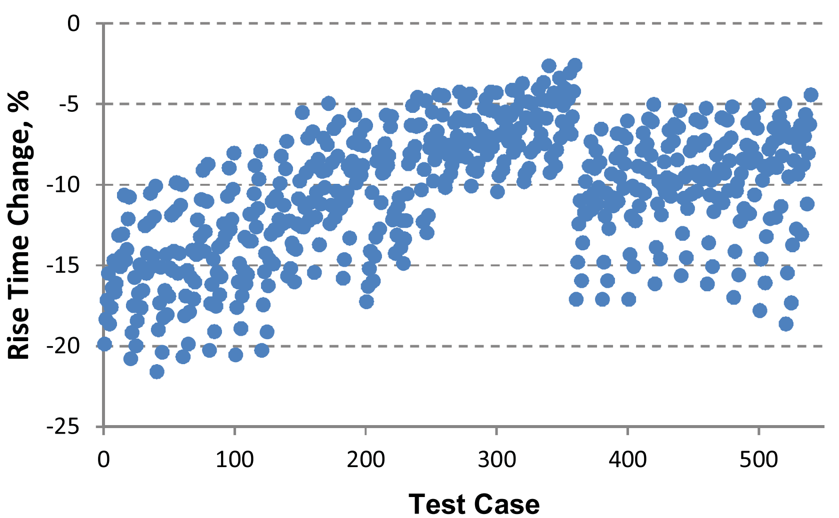
- May et al., "Improving Engine Responsiveness during Approach through High Speed Idle Control," 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 2011.

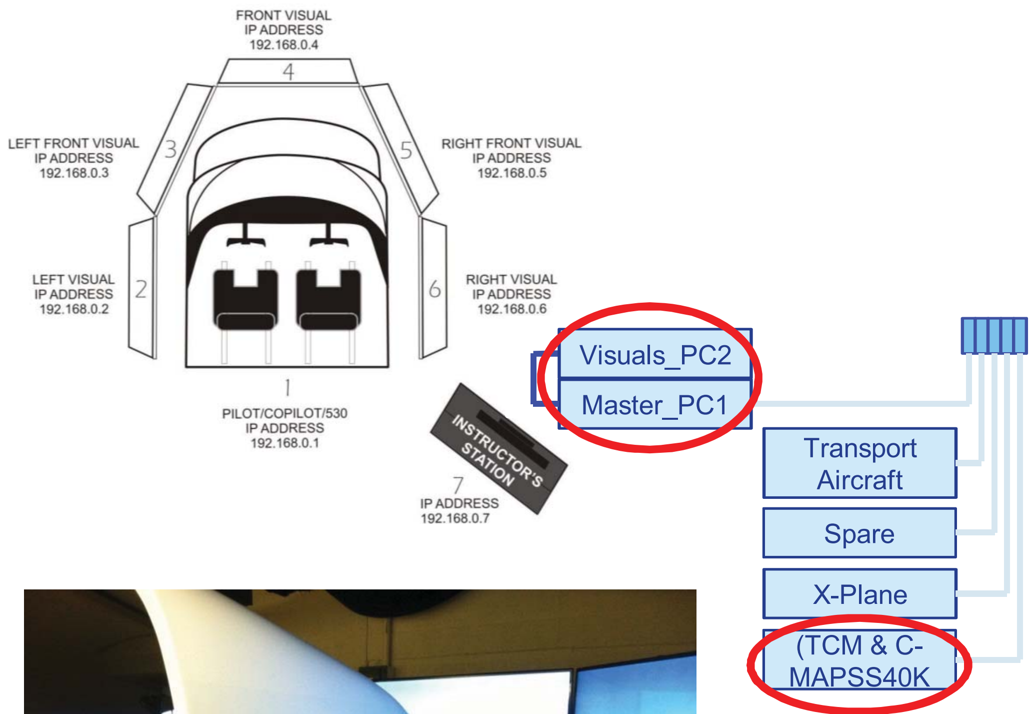
Faster Response: Results

- Tested at 540 operating points (within interpolation range)
- PLA from flight idle to maximum in 0.1 seconds
- Rise time: time to traverse 10% to 90% of difference between initial and final thrust levels





Flight Simulator



- Full cockpit with standard pilot/copilot controls and instrumentation
- PC 1: X-Plane
- PC 2: Displays
- PC 3: Everything else
  - Models and control systems for aircraft and engines (TCM + C-MAPSS40k)
  - Flight path predictor
  - MPARS flight/propulsion control override algorithms

Flight Simulator