Peak-Seeking Control For Reduced Fuel Consumption: Flight-Test Results For The Full-Scale Advanced Systems Testbed F/A-18 Airplane

Nelson Brown
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nelson.brown@nasa.gov
Abstract

A peak-seeking control algorithm for real-time trim optimization for reduced fuel consumption has been developed by researchers at the National Aeronautics and Space Administration (NASA) Dryden Flight Research Center to address the goals of the NASA Environmentally Responsible Aviation project to reduce fuel burn and emissions. The peak-seeking control algorithm is based on a steepest-descent algorithm using a time-varying Kalman filter to estimate the gradient of a performance function of fuel flow versus control surface positions. In real-time operation, deflections of symmetric ailerons, trailing-edge flaps, and leading-edge flaps of an F/A-18 airplane are used for optimization of fuel flow. Results from six research flights are presented herein. The optimization algorithm found a trim configuration that required approximately 3 percent less fuel flow than the baseline trim at the same flight condition. This presentation also focuses on the design of the flight experiment and the practical challenges of conducting the experiment.
Peak-seeking control: Typical flight results

Fuel Flow

Ailerons (+TED)

Flaps (+TED)

LE-Flaps (+LED)

Stabs (+TED)

AoA

~20 minutes
Previous Research

Adaptive Performance Optimization
Patent 5,908,176

Gilyard’s L-1011 flight test results in 1999:

“Optimizing the symmetric outboard aileron position realizes a drag reduction of 2-3 drag counts (approximately 1 percent).”

Flight Test of an Adaptive Configuration Optimization System for Transport Aircraft
Gilyard, Glenn B.; Georgie, Jennifer; Barnicki, Joseph S.

http://hdl.handle.net/2060/19990019435

Figure 5. Variation of incremental drag with symmetric outboard aileron deflection for a two-sided raised-cosine maneuver (data filtered, period = 150 sec, \( \sigma = 0.000125 \)).
Boeing, United Teaming To Improve Fuel Efficiency. The International Business Times (3/23, Francheska) reports, "Boeing and United Continental Holdings, Inc. has entered into an agreement to modify United Airlines' 777 fleet with a Performance Improvement Package with the aim of achieving greater fuel efficiency and reduced emissions." The upgrade "improves the airplane's aerodynamics through a software change to enable a drooped aileron, a ram air system improvement and the installation of improved wing vortex generators." If gas costs $100 per barrel, the program is expected to save each plane $200,000 a year in gas costs.

Boeing Trailing Edge Variable Camber (TEVC) System

TEVC System on 787:

“The TEVC cleverly articulates the trailing edge of the flaps in various cruise conditions to help reduce drag.”

guy norris, aviation week in 2010

http://www.aviationweek.com/aw/blogs/commercial_aviation/ThingsWithWings/index.jsp?plckController=Blog&plckScript=blog&plckElementId=blogDest&plckBlogPage=BlogViewPost&plckPostId=Blog%3A7a78f54e-b3dd-4fa6-ae6e-dff2ffd7bdbbPost%3A57b52637-d0a0-4589-bb7a-7a77cc6

“...the flight tests also included simulation of the 787’s drooped ailerons as well as a drag-reducing feature called the trailing edge variable camber (TEVC) function. Boeing expected that the TEVC could cut cruise drag and save the equivalent of 750 to 1,000 pounds in weight, and took advantage of the all-new wing and flight control surface design. The fully automatic system, which was the first practical commercial application of in-flight variable camber, operated by deflecting the trailing edge flaps in 0.5-degree increments while in cruise. The system could be moved through a 3-degree arc, with the trailing edge being set up and down by as much as 1.5 degrees on either side of a neutral position.”

Motivation

- Multiple longitudinal effectors for trim
  - Traditionally horizontal tail incidence angle or elevator.
  - But also: Symmetric ailerons, flaps, leading-edge devices, thrust vectoring, pump fuel fore/aft for c.g. control, etc.
- Is there an alternative, lower-drag trim solution?
- Can we adjust to variations between:
  - Aircraft?
  - Configurations?
  - Flight conditions?
F/A-18 Effectors

- Allerons
- Trailing-edge flaps
- Inboard/outboard leading-edge flaps (ganged together)
- Stabilators
**Effector Position**, \( x \)

(Commanded by Peak-Seeking Controller)

**Performance Function**, \( f(x) \) (unknown shape)
Performance Measurements

Effector Position, \( x \)
(Commanded by Peak-Seeking Controller)

Initial Excitation
Estimated Gradient
Command (\( K \times \text{gradient} \))
Command (\( K \times \text{gradient} \))
And so on…
Performance Function, $f(x)$ (unknown shape)

Effector Position, $x$
(Commanded by Peak-Seeking Controller)

And so on...
Peak-Seeking Control

• Given:
  – A performance measurement, fuel flow, that is a function of surface positions
    • The minimum-cost (blue) combination of surface positions (x,y,z) is **unknown**
    • This is called the **Performance Function**
  – Measurements of surface positions and fuel flow are **noisy**.

• Find:
  – Minimum of the performance function, in flight

• Assumptions:
  – Performance function has a single minimum
  – Measureable surface positions and fuel flow
  – Gaussian distributed noise
  – Plant is stable and controllable (inner loop control design treated as separate problem)
Approach based on work by Ryan and Speyer:

Ryan, J.J. and Speyer, J.L., “Peak-Seeking Control Using Gradient and Hessian Estimates”

http://hdl.handle.net/2060/20100024511

Technology Transition Map

State of the Art:
Static / Pre-scheduled Trim Configurations

Single Effector Sim Study on X-48B
http://hdl.handle.net/2060/20110015999

Multi-Effector Flight Research
(Prototype in Relevant Environment)

Transition Opportunities
Eco Demonstrator?
Upgrade Existing Aircraft

Technology Maturation (TRL)

1D Performance Function

Outboard Elevon (deg)
Fuel Flow

X-48B

FAST (F-18 853)

Single Effector Sim Study on X-48B
http://hdl.handle.net/2060/20110015999

787

C-17
State of the Art:
Static / Pre-scheduled Trim Configurations

Time
Connection to production fuel flow meter

Production fuel flow meter

Inlet

New research fuel flow meter

Afterburner

Input: from fuel controller

Research fuel flow meter

Spare Pickoff (unused)

Thermocouple
Full-scale Advanced Systems Testbed (FAST)

Fuel Flow via Ethernet
Flight Research Approach

Batch Simulation using Simulink Autocode Interface (SAI) in f18sim

Notional Flight Test Point

- Baseline aircraft
- Initial surface biases
- Algorithm engaged

Performance Function Identification

Flight Experiment

Batch Simulation (SAI) Using PFI Surface Fit & Noise for Tuning and V&V

Fuel Flow

Time (approx. 10 minute duration)

Fuel Savings

Piloted HIL Simulation using ARTS

Algorithm-Engaged Initial Flight Experiment
Test Plan

ARTS Engaged
(Autopilot & Autothrottle)

ARTS Disengaged

Select Mode → Arm → Engage

Initial Surface Biases

Algorithm Running (iterative)

Disengage

Wait for FF sliding-window variance to converge (30-120 s)

Algorithm converged?

yes → Return to IC

no → Reasonable progress?

yes → Gain related?

no → Low on fuel?

yes → End tests

no → Wait for FF sliding-window variance to converge (30-120 s)

no → Disengage
Flight 132: PFI Flight Data Examples

Test 1

Test 2

Resume test from H

Host system error
Flight 132: Estimated Performance Function

- Recognizable shape
- Substantial gradient relative to noise

Delta Fuel Flow due to Aileron and TEF Deflections (LEF at 5 deg)

Slice at LEF 5 deg

Delta Fuel Flow due to Aileron, TEF, and LEF Deflections (for simulation)
Flight 132: Summary of PFI Flight Results

Questions Before PFI Flight

Is the approach feasible?
• The algorithm detects small changes in fuel flow. Noise and disturbances may be too large.
• PFI experiment will quantify the signal/noise ratio.

Minimum duration dwell-time interval?
• Short intervals are desired for faster convergence, better use of flight time.
• Short intervals increase the impact of disturbances.
• PFI experiment will inform the designers’ choice of dwell time for the algorithm.

Can autopilot transients be reduced?
• Short settling times & minimal overshoots are desired for faster convergence, better use of flight time.
• Autopilot evaluation will include 3 autopilot gain sets.

What is the shape of the performance function?
• PFI data will be used to choose initial conditions
• Surface fit to PFI data will be used in control room to verify algorithm is ‘on course’.
• PFI data will be used in post-flight analysis & technical reports.

Answers from Post-PFI Analysis

The approach is feasible.
• Substantial gradients were seen between trim configurations despite standard deviations of around 50 lbs/hr.

Dwell time intervals should not be fixed.
• Lesson learned: Manual advance allows flexibility for maneuvering. (Pilot’s suggestion.)
• 30 sec is a good minimum dwell time.

Autopilot performance is good.
• Nominal gainset was selected.
• Good sim prediction of autopilot dynamics.
• Pilot A: “These autopilots are rock-solid on condition.”

Second-order polynomial (paraboloid) fits the PFI data well.
• Six initial conditions selected.
• Performance function added to sim for algorithm tuning.
2d, IC:C, M:5, gain:-0.068

Raw Sensors
20 sec Rolling Average

Time (sec)
Delta Fuel Flow (percent)

2d, IC:B, M:3, gain:-0.068

Raw Sensors
20 sec Rolling Average

Time (sec)
Delta Fuel Flow (percent)

2d, IC:D, M:5, gain:-0.101

Raw Sensors
20 sec Rolling Average

Time (sec)
Delta Fuel Flow (percent)

3d, IC:F, M:5, gain:-0.068

Raw Sensors
20 sec Rolling Average

Time (sec)
Delta Fuel Flow (percent)
Flight results at 200 KCAS flight condition

- Fuel Flow
- Ailerons (+TED)
- Flaps (+TED)
- LE-Flaps (+LED)
- Stabs (+TED)
- AoA