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

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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
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
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.


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**Figure 2: Drooped aileron**

Boeing engineers determined that a 2-degree aileron droop was optimal for flight performance.

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**Delivering Fuel and Emissions Savings for the 777**

By Ken Thomson, and E. Terry Schulze

http://www.boeing.com/commercial/aeromagazine/articles/qtr_03_09/pdfs/AERO_Q309_article02.pdf
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


“...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

- Ailerons
- Trailing-edge flaps
- Inboard/outboard leading-edge flaps (ganged together)
- Stabilators
Performance Function, $f(x)$ (unknown shape)

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

Performance Function, $f(x)$ (unknown shape)

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

Transition Opportunities
Eco Demonstrator?
Upgrade Existing Aircraft

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

787

FAST (F-18 853)
Multi-Effector Flight Research
(Prototype in Relevant Environment)

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

n-D Performance Function

1D Performance Function
Fuel Flow
Outboard Elevon (deg)

Technology Maturation (TRL)

Time
Connection to production fuel flow meter

Production fuel flow meter

Connection to production fuel flow meter

Production fuel flow meter

Research fuel flow meter

Spare Pickoff (unused)

Input: from fuel controller

Thermocouple
Advanced Research Testbed System (ARTS)

Fuel flow rate
Surface positions

Peak-Seeking Algorithm

Trim deflections

Fuel flow rate
Surface positions

Pilot inputs

Nonlinear Dynamic Inversion

Surface commands

Aircraft states

Aircraft

Inboard/outboard leading edge flaps (ganged together)
Rudders
Ailerons
Trailing edge flaps
Stabilizers

Research Fuel Flow Meters
Full-scale Advanced Systems Testbed (FAST)

- Rate gyros and accelerometers
- Pilot inputs
- Stabilators and trailing edge flaps positions
- Ailerons, rudders, and leading edge flaps positions
- Angle of attack, impact and static pressures
- Euler angles

- Production CPU
- Input signal management
- Production control laws
- Output signal select/fader logic
- Actuator signal management

- Dual port RAM
- Mode logic/envelope checks
- RFCS control laws
- Surface stick commands (1/160 seconds of delay)

- RFCS
- Mode logic/envelope checks
- Simulink/C Control laws

- Stabilators and trailing edge flaps commands
- Ailerons, rudders, and leading edge flaps commands

Fuel Flow via Ethernet
Flight Research Approach

**Performance Function Identification**

**Flight Experiment**

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

**Piloted HIL Simulation**
using ARTS

**Algorithm-Engaged Initial Flight Experiment**

**Notional Flight Test Point**
- Baseline aircraft
- Initial surface biases
- Algorithm engaged

**Fuel Flow**

**Time (approx. 10 minute duration)**

**Fuel Savings**
Flight 132: PFI Flight Data Examples

Resume test from H

Host system error
Flight 132: Estimated Performance Function

- Recognizable shape
- Substantial gradient relative to noise

Estimated minimum fuel flow

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.
Flight results at 200 KCAS flight condition

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