Application of Structural Load Feedback in Flight Control

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NASA Subsonic Fixed Wing Project, Fundamental Aeronautics Program
Subsonic Fixed Wing Project

WHAT

- Reduce environmental impact of aviation
- Increase aircraft efficiency
- Improve mobility of aircraft in airspace

WHY?

- Unacceptable community noise and other environmental emissions
- Need to reduce fossil fuel consumption
- Demands from NextGen airspace
- Air transportation plays key role in our economy and quality of life

HOW!

- Create prediction and analysis tools for design
- Develop concepts and technologies for significant improvements in noise, emissions and performance
- Partner with academia, industry, and government
Historical Perspective: Reducing Impact

Information provided by Joe Totah, NASA Ames

May 1965

2-Segment Approach
Noise levels reduced by 10PNdB
[ref. NASA/SP-2002-4526]

April 1973

3D Area Navigation
Noise Abatement
Noise levels reduced by 8-18 EPNdB. [J. of Aircraft, 10(4), April 1973, pp. 226-231]

Oct. 1976

Delayed-Flap Concept
Reduced fuel use and approach noise [ref. NASA/SP 1998-3300]

Dec. 1979

Fuel Optimal Trajectories
Fuel savings ranging from 5% to over 25%. [IEEE CDC Conf, Dec. 1979, Ft, Lauderdale, FL]
1985-1988

**Mission Adaptive Wing**
Drag reduction ranging from 7% at the wing design cruise point to over 20% at an off-design condition, [ref. NASA TM-4415, AIAA-1983-1057]

June 1992

**Performance Seeking Control**
Minimize thrust specific fuel consumption by 16% by optimizing engine inlet, vane, and nozzle control (NASA TM 4394)

Jan. 1999

**Adaptive Performance Optimization**
L1011 testbed aircraft using symmetric outboard aileron provided 2-3 drag count reduction (approximately 1%). [NASA/TM-1999-206569]

Dec. 2001

**Autonomous Formation Flight**
F/A-18 flying in the wingtip vortex behind another F/A-18 exhibited a 14% fuel savings. [NASA/TM-2003-210734]
Active CG Control
The use of a tail-trim tank for CG control was pioneered on the Concorde (the Trident and Super VC10 also had fuel in the fin). On the A310 the use of this system reduces fuel burn by up to 3% as well as giving extra fuel capacity. [ref. The Putnam Aeronautical Review ©, Vol. 2, pp. 158] [ref. Flight operations and Support Line Assistance, “Getting to Grips with Fuel Economy”, Airbus Customer Service, Issue 3, July 2004]

Spiral Approach
C-17 noise contours for 5 deg spiral approach pulls high noise levels back within the typical airport landing zone. [ref. AIAA 2007-1398]
## Expected Benefits

<table>
<thead>
<tr>
<th>ERA Goals</th>
<th>Demonstrated Flight Control Benefits</th>
<th>Capability</th>
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<tbody>
<tr>
<td>Noise</td>
<td>8-18 EPNdB reduction&lt;br&gt;High-noise footprint within Airport threshold</td>
<td>2-Segment Approach&lt;br&gt;Spiral Approach</td>
</tr>
<tr>
<td>Fuel Burn</td>
<td>3% reduction (system-wide)&lt;br&gt;16% reduction&lt;br&gt;14% reduction&lt;br&gt;7% reduction&lt;br&gt;3% reduction&lt;br&gt;1% reduction</td>
<td>Trajectory Optimization¹&lt;br&gt;Performance Seeking&lt;br&gt;Formation Flying&lt;br&gt;Drag Minimization&lt;br&gt;Mission Adaptive Wing&lt;br&gt;Active CG Control&lt;br&gt;Surface Optimization</td>
</tr>
<tr>
<td>Emissions</td>
<td>$\text{Emissions} = f(\text{Fuel Burn})$</td>
<td>3% Addt’l Fuel Weight per A/C per Yr&lt;br&gt;Produces Addt’l 235,000 kg CO$_2$ due to higher fuel burn (example)$^2$</td>
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¹ Assumes 621M gal/yr saved from continuous climbs/descents, direct routing/improved re-routing and no-stop taxi [ERO Planning Guidance, Nov. 25, 2008]. Current estimates of fuel consumption range between 17B and 20B gal. [ref. http://www.airlines.org/economics/energy/MonthlyJetFuel.htm], thus the expected fuel savings range from 3% to 4% per year.

Weight Reduction for Increased Efficiency

- Create new fabrication processes for lightweight materials, esp. large structures
- Design lightweight wing structures with aeroelastic tailoring to eliminate heavy control surfaces
- Use aerogels for super-lightweight insulation
- Increase temperature capability of composites for greater use in engines

Electron Beam Freeform Fabrication (EBF3)

Polymer-enforced aerogel

Fan containment system with high temperature capability
Drag Reduction for Increased Efficiency

- Increase laminar boundary layer by delaying transition to turbulent flow
  - Design surfaces with favorable pressure gradients (natural laminar flow)
  - Include active or passive local suction surfaces (hybrid laminar flow)
- Use active aeroelastic tailoring of wing to reduce drag during cruise
- Advanced CONOPS – formation flight
- Develop & validate CFD codes for design & analysis of advanced drag reduction concepts

Formation flight for drag reduction

D-8 (double bubble) has natural laminar flow on wing bottom, design by MIT team
- Noise damping materials & technologies
- Morphing chevrons
- Distortion-tolerant fans with active noise control
- Integrated propulsion-airframe designs
- Investigate noise generation in turbine
- Improved engine & noise modeling tools
Airframe Strategies for Noise Reduction

- Airframe shielding of engines
- Continuous mold-line wing structures
- Drooped leading edge
- Active flow control
- Adaptive, flexible wing structure
- Landing gear fairings

SUGAR Ray design by NASA sponsored team led by The Boeing Company

Landing gear noise simulation
Reduce Emissions Due to Aviation

Increase engine efficiency
- Improve propulsive efficiency
  - Ultra high bypass (UBH) engine designs
  - Alternative combustor concepts
  - Advanced fuel-air mixers
- Improve thermal efficiency
  - Improve cooling effectiveness to reduce cooling flow
  - Develop materials for high temperature operation
- Develop high-fidelity, CFD-based computational tools

Design fuel-flexible combustors that maintain performance with alternative fuels

NASA – GE open rotor test
Variable Camber Continuous Trailing Edge Flap

Shape wing to minimize drag

Collaboration with Boeing under SMAAART contract NNL11AD25T
NextGen N+2 Research Configurations

Cruise-efficient Short Take-off and Landing (CESTOL)

- Extended flight envelope
- High lift and drag devices
- Integrated Flight-Propulsion Control

Hybrid Wing-Body (HWB)

- High lift, low drag
- Engines above wings

Increases Mobility

NASA's Zuk Flyer Conceptual Aircraft
Boeing’s X-48B Blended Wing-Body
NextGen N+3 Concept Aircraft

MIT Double Bubble

SUGAR Ray

Truss-braced Wing
Traditional Flight Control System

Control Allocation: Determine surface deflections needed to achieve desired rates
Example: Use ailerons on wing to achieve roll

Traditional Approaches for Control Allocation
- Ganging of Actuators: use elevator for pitch, ailerons for roll, rudder for yaw
- Mixers: fixed combination of surfaces to achieve commands
Given a control effectiveness matrix $B$, a vector of desired surface deflections $u_p$ and $\epsilon > 0$, find $u$ such that

$$J = \left\| Bu - a_d \right\| \minerr + \epsilon \left\| u - u_p \right\| \minctrl$$

is minimized subject to $u_{\min} \leq u \leq u_{\max}$, $\left\| \dot{u} \right\| \leq \dot{u}_{\max}$

**Structural Limits**
- Design engineers determine critical load paths in aircraft
- Mostly concerned with bending, torsion, and shear loads
- Load limits are determined through ground tests and flight tests
- Load limits imposed by restricting flight envelope; position & rate limiting actuators
New Challenges for Flight Control Systems

- Many redundant effectors
- Surfaces affecting multiple axes
- Actuator rate & position saturation
- Low control authority
- Lighter more flexible structures

Optimal Control Allocation

Given $B$, a desired vector $u_p$ and $\varepsilon > 0$, find $u$ such that

$$J = \left\| Bu - a_d \right\| + \varepsilon \left\| u - u_p \right\|$$

is minimized subject to $u_{\min} \leq u \leq u_{\max}$, $|\dot{u}| \leq \dot{u}_{\max}$

No Structural Constraints!!
Objective:
Use multiple control surfaces in most effective way, while remaining within structural load limits

Approach:
Replace traditional control allocation with optimal control allocation with load constraints and real-time load feedback
- Measure internal (structural) loads along critical load paths
- Use aircraft aerodynamic and structural models to determine incremental loads due to incremental surface deflection
- Include structural load constraints and measured loads in optimal control allocation problem

Significance:
This approach enables fuel efficient aircraft with many multi-purpose control surfaces to achieve acceptable performance & safety
Study Assumptions

- Only considering static loads due to lift and rolling forces
- Structural model is finite element model (FEM) of aircraft wings and tail
- Loads due to lift and roll are applied to nodes in FEM model
- Only bending moments are considered
- A restricted number of load points are monitored and included in the optimal control allocation constraints
Proposed Framework

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$a_d$</td>
<td>desired accelerations</td>
</tr>
<tr>
<td>$u_p$</td>
<td>preferred delta surface positions</td>
</tr>
<tr>
<td>$B$</td>
<td>control effectiveness matrix</td>
</tr>
<tr>
<td>$T$</td>
<td>incremental loads matrix, where $Tu$ gives the incremental loads at critical points</td>
</tr>
<tr>
<td>$y_s$</td>
<td>structural loads from sensors (or model in sim)</td>
</tr>
<tr>
<td>$F_I$</td>
<td>internal structural loads at critical points</td>
</tr>
</tbody>
</table>
Formulation & Solution Approaches

Mixed Optimization Formulation

Find $u$ that minimizes $J = \|(CB)u - a_d\| + \varepsilon \|u - u_p\|$

subject to $u_{\min} \leq u \leq u_{\max}$, $|\dot{u}| \leq \dot{u}_{\max}$

Solution Approaches Using Different Norms

- **$l_1$ norm:** $\|u\|_1 = \sum_i |u_i|$
  - Convert to linear programming problem
    - Simplex algorithms (Bodson)
    - Interior-point algorithms (Peterson, Bodson)

- **$l_2$ norm:** $\|u\|_2 = \sqrt{\sum_i u_i^2}$
  - Active Set Method with norms squared (Härkegård)
  - Interior-point algorithms

- **$l_\infty$ norm:** $\|u\|_\infty = \max_i (u_i)$
  - Simplex algorithm (Bodson, Frost)
Optimal Control Allocation Problem:
Given $B$, a desired vector $u_d$ and $\varepsilon > 0$, find $u$ such that

$$J = \underbrace{\|Bu - a_d\|_1}_{\text{error min}} + \underbrace{\varepsilon \|u - u_d\|_\infty}_{\text{control min}}$$

is minimized subject to:

$$u_{\text{min}} \leq u \leq u_{\text{max}} , \quad F_I + Tu \leq F_{I,\text{max}}$$

where $F_{I,\text{max}}$ are critical point load limits

Can also be formulated with load minimization, using constraints given above and cost function:

$$J = \|Bu - a_d\| + \varepsilon \|u - u_d\| + \gamma \left\| F_{I,\text{max}} - F_I + T(u - u_p) \right\|$$

under load min
Up-scale GTM Simulation

- Simulink model based on 5.5% dynamically scaled aircraft derived from wind tunnel & flight test data
- Up-scaled by incorporating Reynolds adjusted aero tables
- Actuator models sized for up-scale GTM
- NASA Glenn’s Simp2 engine (simplified version of C-MAPSS40k)
- GTM bare airframe
- 6 ailerons, 4 elevons, 2 rudders, 2 stabs, 2 flaps
- Vehicle Management System
  - sensor processing module
  - mission manager
  - guidance/control
- Vehicle Control Augmentation System
  - reference model dynamic inverse controller
  - optimal control allocator
Wings/tails modeled as cantilever beams with fixed ends at roots
Beam mesh for each wing has 20 nodes and 19 beams
Constant thickness hollow aluminum shells following outer mold line give beam cross section properties
Beam nodes located at centroids of wing cross sections
Each beam has 6 degrees of freedom – 3 translation & 3 rotation
FEM Global Coordinates

- Positive x-direction points nose to tail
- Positive y-direction points out right wing
- Positive z-direction points up

FEM of GTM aircraft

FEM of wings and empennage
Assume static loads and static response, $F = Kx$

- Stiffness matrix $K$ is derived from FEM
- $K^{-1}$ is computed off-line
- Static loads applied during simulation to FEA nodes
- Measured loads are calculated from deflections using $K^{-1}$

Nodes of wings
- Elliptically distributed lift load applied to nodes along wings and horizontal tail.
- Loads arising from roll moments applied as concentrated forces in z-direction on each aileron in proportion to aileron deflection.
- Flap-wise bending moment at critical points are calculated & passed to control allocator
- $K^{-1}$ and $B$ are used during simulation to determine incremental loads matrix $T$
- Aileron forces are assumed to be proportional to surface deflections for calculation of $T$
Flight conditions:
- Altitude 30,000 ft
- Mach 0.85

Test cases:
- Normal case
  Load limits set to values determined for safe flight
- Case I
  Right aileron load limit set to 55,000 ft-lb
- Case II
  Left outboard aileron deflection limits set to ±0.01 deg
Roll Doublet Case I

Normal Load Constraints

Reduced Load Constraints

IEEE CSS SV 5/23/12
Case I: Outboard aileron critical point limit set to 55,000 ft-lb
Aileron Deflections Case 1

Right aileron 3 deflection reduced
Aileron Deflections Case II

IEEE CSS SV 5/23/12

Left aileron 3 deflection 0

Normal limits
Restricted position limit
Normal Case with $l_\infty$ versus $l_1$ Norm on Control

- $l_\infty$ Norm on Control
- $l_1$ Norm on Control

Outboard aileron is most effective
All surfaces are used
Thank you!