Integrated Control with Structural Feedback to Enable Lightweight Aircraft

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Agenda

• System Level Metrics
• Benefits of Active Structural Control
• Active Structural Control Research Areas
• Integrated Control for the Prevention of Critical Loads
  – Problem Statement
  – Control System Architecture
  – Simulation Studies
    • Approach
    • Results and Discussion

• Future Research
### NASA Subsonic Transport System Level Metrics

*... technology for dramatically improving noise, emissions, & performance*

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<thead>
<tr>
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<tbody>
<tr>
<td>Noise (cum below Stage 4)</td>
<td>- 32 dB</td>
<td>- 42 dB</td>
<td>- 71 dB</td>
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<tr>
<td>LTO NOx Emissions (below CAEP 6)</td>
<td>-60%</td>
<td>-75%</td>
<td>better than -75%</td>
</tr>
<tr>
<td>Performance Aircraft Fuel Burn</td>
<td>-33%**</td>
<td>-50%**</td>
<td>better than -70%</td>
</tr>
<tr>
<td>Performance Field Length</td>
<td>-33%</td>
<td>-50%</td>
<td>exploit metroplex* concepts</td>
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*** Technology Readiness Level for key technologies = 4-6

** Additional gains may be possible through operational improvements

* Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

### SFW Approach

- Conduct Discipline-based Foundational Research
- Investigate Advanced Multi-Discipline Based Concepts and Technologies
- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes
- Enable Major Changes in Engine Cycle/Airframe Configurations
Benefits of Active Structural Control

• Reduction in aircraft fuel burn due to reduced structural weight
  – Reduced structural margins
    • Gust loads
    • Aeroelastic instabilities

• Gust loads and aeroelastic instabilities inherent in high lift-to-drag, high aspect ratio, low sweep wings (N+3 aircraft)

• One study has shown a 25% reduction in airframe weight through the use of active flutter suppression
  – “System Benefits of Active Flutter Suppression for a SensorCraft-Type Vehicle”, Nicolai, Hunten, Zink, and Flick

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<tr>
<td>Takeoff Gross Weight</td>
<td>96,000 lb</td>
</tr>
<tr>
<td>Empty Weight</td>
<td>36,332 lb</td>
</tr>
<tr>
<td>Wing Area</td>
<td>2445 ft²</td>
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<tr>
<td>Aspect Ratio</td>
<td>14</td>
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Research Areas

Materials and Actuation
- Conformable mold-line
- Effector development

Sensors
- Fiber optics
- Stagnation point sensors

Control Laws
- Unstable rigid body dynamics
- Unsteady aeroelastic effects (limit cycle oscillation, flutter, dynamic gust load response)
- Reduction of peak loads
- Wing shape optimization

Actively Controlled, Lightweight Structure
*Improved fuel burn, noise, and performance*

Test, Evaluation, and System Analysis
- Flight validated models and simulations
- Multi-disciplinary design guidelines
- Uncertainty analysis and propagation
Fiber Optic Sensor Development

- **Objective:** enable a high density of real-time measurements of deflection, rotation, bending moment, torsion, and mode shape
  - Validate method and equations
  - Determine accuracy of measurements
  - Determine optimal fiber placement

- **Approach:** capture data from ground and flight tests on aircraft and simple test articles to investigate fundamental principles and draw comparisons to other sensor technologies

*Ground Test of Global Observer wing*
Fiber Optic Sensor Development

- **Results:** data captured in flight and ground tests
  - Good results for bending deflection of simple test articles and a full scale UAV

- **Remaining Work:** progression to more complicated structures, validate loads measurements, increased sample rate, increased resolution, and multi-core fiber

- **Significance:** enable structural weight reduction
  - Structural feedback to control system (shape and loads)
    - Maneuver and gust load alleviation
    - Active control of aeroelastic instabilities
    - Structural health monitoring

*Swept Plate Undergoing Test*
Aerodynamic Force Sensor Development

- Objective: enable real-time measurement of external forces acting on the aircraft in the presence of flow separation through direct measurement of stagnation point
  - Model generation
  - Parameter identification
  - Stagnation point control
    - Loads, aeroelastic instabilities

- Approach: progression from open-loop observability and validation to closed loop control of stagnation point location

Aerostructures Test Wing
Aerodynamic Force Sensor Development

- Results: validation of stagnation point to sectional forces through wind tunnel tests and open-loop flight test (observability)

- Remaining Work: close the loop around stagnation point sensors to check controllability

- Significance: enables structural weight reduction, optimization of sectional forces to reduce drag, and precise lift control during takeoff and landing
  - Direct measurement of external forces without the associated structural lag
  - Indirect measurement of drag
  - Provides an observable for the state of separated flow around stall conditions
  - Detection and diagnosis of shock/boundary-layer interaction and separation-induced load fluctuations
Integrated Control for the Prevention of Critical Loads

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<tr>
<th>NASA DFRC</th>
<th>NASA ARC</th>
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<tbody>
<tr>
<td>Brian Taylor</td>
<td>Susan Frost</td>
</tr>
<tr>
<td>John Burken</td>
<td>Khanh Trinh</td>
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<td>Christine Jutte</td>
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**Problem Statement**

- Use active structural feedback to determine the optimal control surface positions to:
  - Meet commanded rigid body moments
  - Minimize structural loads
  - Ensure that structural loads do not exceed limits

- Optimal control allocation with structural feedback is a potential solution
Optimal Control Allocation

- Separate the regulation task from the control allocation task
- Mixed optimization to solve multiple objectives simultaneously

Conventional Control Law with Optimal Control Allocation (ref. 2)
Control Allocation Objectives

- Meet commanded rigid body moments ($\nu$)
  - Solve for surface positions ($u$) such that $\nu = Bu$

- Need both structural feedback and predictive portion similar to the rigid body moments and the control effectiveness ($B$) matrix
  - Measured load ($M$) and incremental load due to incremental control surface deflection ($T$)

\[ L = M + Tu \]

- Minimize structural loads

- Ensure that structural loads do not exceed limits
  - Treated like control surface saturation

- Cost function:

\[ J = \|Bu - \nu\| + \gamma\|M + Tu\| \]

Subject to:

\[ u_{\min} \leq u \leq u_{\max} \quad (M + Tu) \leq L_{\max} \]
Control Allocation Diagram

- Feedback of measured load to control allocator
- Inclusion of the $T$ matrix
  - Computed from FEM code
  - Lookup table
  - Parameter estimation

$$T = \frac{\text{Incremental Load}}{\text{Incremental Deflection}}$$

$$B = \frac{\text{Incremental Moment}}{\text{Incremental Deflection}}$$
Simulation Study Approach

- Modified Generic Transport Model (GTM) simulation
  - 6 ailerons, 4 elevators, 2 rudders
  - FEM of wing, horizontal tail, and vertical tail
  - "Critical points" at inboard edge of control surfaces and roots
  - Distributed lift force over entire wing/tail and point forces due to control surfaces

- Roll maneuver
  - Load control on and off with load limits set low enough to require change in allocation
    - Same rigid body motion with reduction in load at critical point

![Diagram of Right Wing with Applied Point Forces and Critical Points]
Simulation Study Results

Outboard Aileron Bending Moment

![Graph showing Outboard Aileron Bending Moment with Time (s) on the x-axis and Bending Moment (ft-lb) on the y-axis. The graph compares different scenarios: Limits Turned Off, Limits Turned On, and Imposed Limit.]
Simulation Study Results

Roll Performance

![Graph showing roll performance with time (s) on the x-axis and roll rate (deg/s) on the y-axis. The graph compares roll performance with limits turned off and limits turned on.](image-url)
Simulation Study Discussion

• Roll moment generation moved from outboard aileron surfaces to inboard surfaces
  – L1 norm optimal control allocation used for study
  – L2 norm would more evenly distribute demand
  – All control surfaces that generate roll moment available (split elevator and rudder)

• Roll performance maintained without violating load limits

• Can be used to:
  – Enable optimal control allocation on existing aircraft
    • Control surface commands constrained not to exceed existing load limits
  – Enable lighter weight structure on future aircraft
    • Reduce future load limits while still meeting performance demands
    • Extension to algorithm for gust load alleviation
Next Steps

• Study $T$ matrix assumptions and accuracy necessary for flight

• Extension of algorithm for gust load alleviation
  – Gust load alleviation literature survey
  – Incremental load per incremental gust
    • “G” matrix
  – Need measurement of gust
  – Addition of gust loads into optimal allocator objectives

• Improved sensor fidelity
  – Delays inherent in each sensor

• Hardware test of algorithm and feedback
Future Research

• Characterize input and response of structure in flight
  – Stagnation point sensors, fiber optics, strain gages, accelerometers, photogrammetry
• Create and release validated models and simulations
• Active load control, gust load alleviation, and flutter suppression
  – Dedicated surfaces
  – Demands spread across all surfaces
• Passive aeroelastic tailoring
• Develop analysis techniques
• Validate design and optimization tools using flight data
# Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$r$</td>
<td>Commanded rates</td>
</tr>
<tr>
<td>$v$</td>
<td>Commanded moments</td>
</tr>
<tr>
<td>$u$</td>
<td>Commanded surface positions</td>
</tr>
<tr>
<td>$y$</td>
<td>Aircraft response</td>
</tr>
<tr>
<td>$x$</td>
<td>Observed aircraft states</td>
</tr>
<tr>
<td>$M$</td>
<td>Measured load</td>
</tr>
<tr>
<td>$L$</td>
<td>Predicted future load</td>
</tr>
<tr>
<td>$T$</td>
<td>Incremental load per incremental surface deflection</td>
</tr>
<tr>
<td>$B$</td>
<td>Incremental moment per incremental surface deflection</td>
</tr>
<tr>
<td>$G$</td>
<td>Incremental load per incremental gust</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Weighting matrix</td>
</tr>
<tr>
<td>$u_{\text{max}}$</td>
<td>Maximum surface position</td>
</tr>
<tr>
<td>$u_{\text{min}}$</td>
<td>Minimum surface position</td>
</tr>
<tr>
<td>$L_{\text{limit}}$</td>
<td>Load limit</td>
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<tr>
<td>$J$</td>
<td>Cost function</td>
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References


Integrated Control for the Prevention of Critical Loads Publications


Acknowledgements

John Bakalayar (DFRC)
Marty Brenner (DFRC)
Christine Jutte (DFRC)
Susan Frost (ARC)
Arun Mangalam (Tao Systems)
Backup Slides

- Elevator outboard
Backup Slides

• Elevator inboard
Backup Slides

- Aileron outboard
Backup Slides

- Aileron middle
• Aileron inboard
Backup Slides

- Rudder upper and lower