Distributed-Flap Layout Trade Study on a Highly Flexible Common Research Model

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VCCTEF Concept

- **Variable Camber Continuous Trailing Edge Flaps**
- Flaps distributed over most of the span of the wing
- Elastomer material between flaps to seal gaps
- Tailors spanwise lift distribution throughout mission
Motivation

- Early application of VCCTEF on GTM on overspeed case indicated wave drag could also be significantly reduced.
- More effective if circular deflection relaxed.

\[ \Delta_2 = 2\Delta_1, \quad \Delta_3 = 3\Delta_1 \]
Goals and Methods

• Determine how complex a distributed flap system must be to be effective for overspeed drag reduction
  • how many spanwise flaps?
  • how many chordwise segments per flap?

• Flap layout trade study
  • Install various layouts with different number of spanwise flaps and chordwise segments
  • Optimize flap deflections on all layouts at overspeed condition
  • Examine results for trends
Platform for Trade Study

• Common Research Model (CRM) fuselage/wing/horizontal tail configuration

• Assume composite wing
  • remove built in deformation from original CRM geometry
  • develop structural model that exhibits greater deformation (about twice original)

• Develop new baseline wing
  • start with original CRM geometry
  • re-optimize twist distribution for cruise using methods that address aeroelastic effects
    • minimize drag
    • constrain lift
    • maintain trim
Static Aeroelastic Analysis Architecture

- Baseline Geometry
  - Aerodynamic Analysis
  - Load Transfer
  - Structural Analysis
  - Deformer
  - Deformed Geometry

- Cart3D
  - No
  - Converged?
  - Yes
  - Stop

- BEAM
  - Aeroelastic Iteration

- Blender
  - Deformed Geometry
Aerodynamic Shape Optimization Architecture

- Baseline Undefomed Geometry
- Aeroelastic Analysis
- Aeroelastic Deformation
- Converged?
- Yes
- No
- Aerodynamic Optimization
- Optimized Undefomed Geometry
Modeling the VCCTEF
Modeling the VCCTEF

- Flap deflections controlled by Blender “armature” (analogous to a skeleton)
- Surface triangulation is bound to “bones”
- Bones can only rotate about hinge lines
- Sequential flaps bones linked to each other
- Blended transition between flaps to mimic elastomer material
Establishing a New Baseline CRM Design

- CRM wing twist distribution re-optimized with more flexible structure
- Minimize drag \( C_D \) at cruise condition \( (M_\infty = 0.85) \)
  - maintain cruise lift \( (C_L = 0.5) \)
  - maintain longitudinal trim \( (C_M = 0) \)
  - cabin deck angle constraint \( (\alpha_{\text{max}} = 3^\circ) \)
- Design variables
  - section incidence at 6 spanwise stations (including root), while linearly vary change in incidence between stations
  - angle of attack (helps satisfy lift constraint)
  - tail incidence (helps satisfy trim)

minimize: \[ C_D (\alpha, \theta_w, i_i) \]
subject to: \[ C_L (\alpha, \theta_w, i_i) = C_{L,\text{cruise}} = 0.5 \]
\[ C_M (\alpha, \theta_w, i_i) = 0 \]
\[ \alpha \leq \alpha_{\text{max}} \]
Convergence of Twist Optimization

![Diagram showing the convergence of twist optimization with iteration. The x-axis represents Aeroelastic Design Iteration, ranging from 0 to 5. The y-axis represents Inviscid Drag Coefficient, ranging from 0.0100 to 0.0120, and Wing Tip Deflection (inches), ranging from 120 to 160. The graph shows a clear decrease in Inviscid Drag Coefficient and a slight increase in Wing Tip Deflection with each iteration.](image-url)
Convergence of Twist Optimization

Design Iteration

Change in Incidence (degrees)

Tail Incidence
Root Incidence
Inboard Incidence
Break Incidence
Outboard 1 Incidence
Outboard 2 Incidence
Tip Incidence
Optimized Twist Distribution

![Graph showing change in incidence (degrees) vs. span fraction]
Optimized Spanwise Lift Distribution

The graph shows the optimized spanwise lift distribution for various sections of an aircraft. The x-axis represents the spanwise fraction, ranging from 0.0 to 1.0, and the y-axis represents the section lift, ranging from -0.2 to 1.0.

Key sections include:
- Entire (original)
- Fuselage (original)
- Wing (original)
- Horizontal tail (original)
- Entire (optimized)
- Fuselage (optimized)
- Wing (optimized)
- Horizontal tail (optimized)

The graph highlights the differences in lift distribution between the original and optimized configurations for each section.
Surface Pressure Distribution

The diagram illustrates the surface pressure distribution on an aircraft model, comparing the original design (red) with an optimized design (blue). The pressure coefficient ($C_p$) is visualized across the wing and body sections, with graphs on the left and right sides depicting $C_p$ as a function of $x/c$. The color scale at the bottom ranges from -1.2 to 1.2, indicating the pressure coefficient values, with darker colors representing lower pressures.
Flap Layout Trade Study

- Install systems with varying numbers of spanwise flaps (4, 8, 12) and chordwise segments (1, 2, 3)
- Increase cruise speed
  - $M_\infty = 0.85 \Rightarrow M_\infty = 0.88$
  - Would save 10 minutes on a 5 hour flight
- Optimize the flap deflections
  - Minimize drag
  - Maintain cruise lift
  - Maintain trim

minimize: $C_D (\alpha, \Delta_{\text{flaps}}, i_t) \ @ \ M_\infty = 0.88$

subject to:

$C_L (\alpha, \Delta_{\text{flaps}}, i_t) = C_L = 0.4665$

$C_M (\alpha, \Delta_{\text{flaps}}, i_t) = 0$

$\alpha \leq \alpha_{\text{max}} = 3^\circ$
Performance of Optimized 4-Flap Layouts

<table>
<thead>
<tr>
<th>Flap Layout</th>
<th>Tip Deflection</th>
<th>Drag</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Flaps</td>
<td>150.06</td>
<td>0.012620</td>
</tr>
<tr>
<td>4 x 1</td>
<td>142.84</td>
<td>0.012024</td>
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<tr>
<td>4 x 2</td>
<td>140.71</td>
<td>0.011123</td>
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<tr>
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<td>141.26</td>
<td>0.011068</td>
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<tr>
<td>8 x 1</td>
<td>143.52</td>
<td>0.012032</td>
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<tr>
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<td>0.01095</td>
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<tr>
<td>12 x 2</td>
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Inviscid Drag Coefficient:

- No Flaps: 0.01245
- 4 x 1: 0.01207
- 4 x 2: 0.01113
- 4 x 3: 0.01107

4 counts down
13 counts down
14 counts down
Lift Distribution on 4-Flap Systems

![Graph showing lift distribution on 4-flap systems with spanwise fraction and section lift on the y-axis and spanwise fraction on the x-axis. Different lines represent the lift distribution for 'no flaps', '4 x 1', '4 x 2', and '4 x 3'.]
Pressure Distributions on 4-Flap Layouts

![Graphs showing pressure distributions at 48% and 83% span for different flap configurations.](image)
Optimized 4-Flap Geometry

- 3-segment deflected flap profile very similar to 2-segment
- 1-segment deflected flap somewhere in between undeflected geometry and deflected 2-segment flap
- Deflecting flaps moves reflex backward (consistent with supercritical airfoil theory)

vertical scale is 4 times greater than horizontal for clarity
Performance of All Optimized Flap Layouts

Inviscid Drag Coefficient

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Inviscid Drag Coefficient: 0.0100, 0.0105, 0.0110, 0.0115, 0.0120, 0.0125, 0.0130
Spanwise Lift Distribution on 2-Segment Systems

- no flaps
- 4 x 2
- 8 x 2
- 12 x 2

Section Lift

Spanwise Fraction
Pressure Distributions on 2-Segment Layouts

- $C_p$ vs $x/c$
- Two graphs showing pressure distributions:
  - 48% span
  - 83% span

Legend:
- no flaps
- 4 x 2
- 8 x 2
- 12 x 2

Color bar:
- -1 to 1
- Colors range from blue to red
Optimized 4 x 2 Flap Layout Deflections

Flap 1
- $\Delta = -0.5^\circ$
- $\Delta = 1.2^\circ$

Flap 2
- $\Delta = -1.5^\circ$
- $\Delta = 2.0^\circ$

Flap 3
- $\Delta = -1.5^\circ$

Flap 4
- $\Delta = -1.7^\circ$
- $\Delta = 1.0^\circ$
- $\Delta = 1.1^\circ$
Conclusions and Future Work

• Flap layout trade study on highly flexible CRM conducted for overspeed off-design case

• 2-segment flaps found to be much more effective than 1-segment flaps, but 3-segment flaps provided only incremental improvement

• 4 spanwise flaps are almost as effective as 12, suggesting induced drag is either already near optimal or wave drag reduction dominates

• Verification with viscous analysis

• Consider other off-design conditions (e.g. maneuver condition)
Acknowledgements

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