LONGITUDINAL AERODYNAMIC MODELING OF THE ADAPTIVE COMPLIANT TRAILING EDGE FLAPS ON A GIII AIRPLANE AND COMPARISONS TO FLIGHT DATA

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Outline

• Introduction/Background
• Project description
• Aerodynamic modeling approach
• Results
• Conclusion

Purpose of this presentation:
• Discuss ACTE aerodynamic modeling efforts and provide comparisons of predictions to flight results for lift and pitching moment increments.
Introduction / Background

- Adaptive Compliant Trailing Edge (ACTE) flaps
  - Gapless flaps that deflect by bending
  - Potential noise reduction, weight savings, and improved aerodynamic efficiency with respect to traditional flaps
- Flight tested at NASA Armstrong Flight Research Center

- NASA’s Environmentally Responsible Aircraft (ERA) project, partnered with U.S. Air Force Research Laboratory
Test Airplane

Gulfstream GIII modified for flight research:
• Flow angle vanes added to the nose
• Embedded GPS/INS (EGI) for rates, accels, Euler angles
• Control surface position measurements
• Pressure measurements and tufts
• Structural measurements
ACTE Flaps

- Replaced GIII Fowler flaps
- Span of 18 ft
- Roughly 20% chord
- Deflection set before flight
ACTE Flap Deflection Definition

Undeflected flap

Horizontal reference line

ACTE flap deflection
ACTE Aerodynamic Modeling

- Purposes of aerodynamic model
  - Add to 6-DOF GIII simulation for pilot training
  - Safety of flight and design reviews
  - Charts for control room

- Approach
  - Stage the work so that intermediate models could be generated to support project milestones
  - Use lower-order methods for initial models, while more complex analyses are being performed
  - Update models with sets of data from the more complex tools when complete
Terms of Interest

• ACTE aerodynamic model consisted of many terms
  • $\Delta C_L$, $\Delta C_m$, $\Delta C_D$, as well as $\beta$ derivative increments
  • Asymmetric flap deflection effects
  • Missing transition section effects
• For flight comparisons:
  • Focus on lift and pitching moment coefficient increments ($\Delta C_L$ and $\Delta C_m$)
  • Could not get $\Delta C_D$ (no thrust measurements for calculating $C_D$)
  • Lateral-directional ($\beta$ derivative) changes were small and scatter was large
Modeling Tools: Digital Datcom

- Digital Datcom
  - Software version of USAF Datcom report
  - ACTE flaps modeled as plain flaps with transition sections included as part of flap area
  - Flap calculations do not involve the rest of the airplane

Graphical representation of full-GIII Datcom setup (Datcom does not use meshes)
Modeling Tools: AVL

- Athena Vortex Lattice (AVL)
  - Applicability limited to small angles of attack and small flap deflections
  - Compressibility effects through Prandtl-Glauert transformation

Trailing edge incidence angles
Modeling Tools: TRANAIR

- TRANAIR
  - Full potential flow solver – generally want attached flow
  - Requires surface and wake grids
Modeling Tools: STAR-CCM+

- STAR-CCM+
  - Unstructured, Navier-Stokes
  - SST k-omega turbulence model
  - Around 35 million finite volume cells
Flight $\Delta C_L$ & $\Delta C_m$ Calculation

- Use parameter estimation results
- Makes it possible to remove effects of differences in trim angle of attack and elevator position

\[
C_L = C_{L_B} + C_{L_\alpha} \alpha + C_{L_q} \frac{q \bar{c}}{2V_\infty} + C_{L_{de}} de
\]

\[
\Delta C_L = \hat{C}_{L_{B,2}} - \hat{C}_{L_{B,1}} + \alpha_2 \left( \hat{C}_{L_{\alpha,2}} - \hat{C}_{L_{\alpha,1}} \right)
\]

(Same setup was used for $\Delta C_m$)
Definition of $\Delta C_L$

$$\Delta C_L = \hat{C}_{L_{B,2}} - \hat{C}_{L_{B,1}} + \alpha_2 \left( \hat{C}_{L_{\alpha,2}} - \hat{C}_{L_{\alpha,1}} \right)$$

Angle of attack

Average angle of attack during maneuver

Nonzero ACTE flap deflection

Zero ACTE flap deflection

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Flight Results Confidence Regions

- Uncertainties are based on estimated parameter standard errors or Cramér-Rao bounds, corrected for colored residuals.

- Estimates for individual maneuvers are combined into a weighted mean and a weighted standard error.

- Overall uncertainty for the estimated increments:

  \[ U^2 \approx \hat{\sigma}_{CLB,2}^2 + \hat{\sigma}_{CLB,1}^2 + \left( \alpha_2 \hat{\sigma}_{C_{L\alpha},2} \right)^2 + \left( \alpha_2 \hat{\sigma}_{C_{L\alpha},1} \right)^2 \]

- Confidence regions for plots are based on 2*U about the weighted means of the parameter estimates.
Flight Summary

• ACTE flight test series spanned 23 flights
• Parameter estimation info:
  • 153 test points
  • Used 2-1-1 maneuvers, equation error and output error techniques
  • Some unreconciled differences between the two parameter estimation techniques, mostly at ends of Mach range
    • For deflections of 10 deg and greater, $\Delta C_L$ differences were 6% or less and $\Delta C_m$ differences were less than 10%
    • Results to be shown here are from output error
Estimated Linear $C_L$ Models

$$\hat{C}_{L_B} + \alpha \hat{C}_{L_\alpha}$$

ACTE flap deflection
-2 5 20
0 10 25
2 15 30

Mach 0.3
10,000 ft MSL

Average angle of attack
Matching angle of attack
Extrapolation

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All tools overpredicted $\Delta C_L$ at high deflections

Datcom and STAR-CCM+ predicted diminishing effectiveness

AVL matched others through 10 deg

CFD results include different altitudes and AOA

Confidence region is based on 2*U for flight results…

Flight data confidence region

- STAR-CCM+
- TRANAIR
- AVL
- Digital Datcom
\[ \Delta C_m \text{ vs. ACTE Flap Deflection} \]

- STAR-CCM+ matched trend
- TRANAIR matched trend up to around 20 deg
- Datcom predicted a steeper slope

CFD results include different altitudes and angles of attack
\[ \Delta C_L \text{ vs. Mach Number} \]

- STAR-CCM+ and TRANAIR produced similar Mach trends
- AVL matched CFD codes’ Mach trends up to around Mach 0.75

ACTE flap deflection

-2 5
2 10

\[ \Delta C_L \]

Flight confidence region

- \( \Delta C_L \) vs. Mach number

- 20 June 2016
\( \Delta C_m \) vs. Mach Number

- Non-Datcom tools’ trends match each other and flight data well
- Big mismatch between STAR-CCM+ and TRANAIR at Mach 0.3 for 10 deg deflection
Summary of Results

• Digital Datcom
  • Good for $\Delta C_L$; not as good for $\Delta C_m$ and Mach trends
  • Program may be buggy
  • In hindsight, would be better off using regular Datcom for this problem
• AVL
  • Matched CFD codes well up through 10 deg of flap deflection
  • Matched CFD codes’ Mach number trends very well
• TRANAIR
  • Comparable results to Navier-Stokes up to around 20 deg of flap deflection
• STAR-CCM+
  • Didn’t get $\Delta C_L$ completely correct, but is still probably trusted more than other tools
Concluding Remarks

• Parameter estimation approach to computing $\Delta C_L$ and $\Delta C_m$ worked well, uncertainties may be inadequate

• All tools overpredicted $\Delta C_L$ due to flaps at high deflection angles and the quality of $\Delta C_m$ results varied

• Lower-order prediction tools produced reasonable results for small flap deflections

• Results suggest the simpler tools were adequate for modeling ACTE flaps for certain speeds and deflections
  - Navier-Stokes solutions could be targeted to cases where the other tools are not appropriate
  - The results validate the approach used for creating the ACTE aerodynamic model