# Analysis of Asymmetric Aircraft Aerodynamics Due to an Experimental Wing Glove


**Fletcher Hartshorn**
Tybrin Corporation
Aerodynamics and Propulsion Branch
NASA Dryden Flight Research Center



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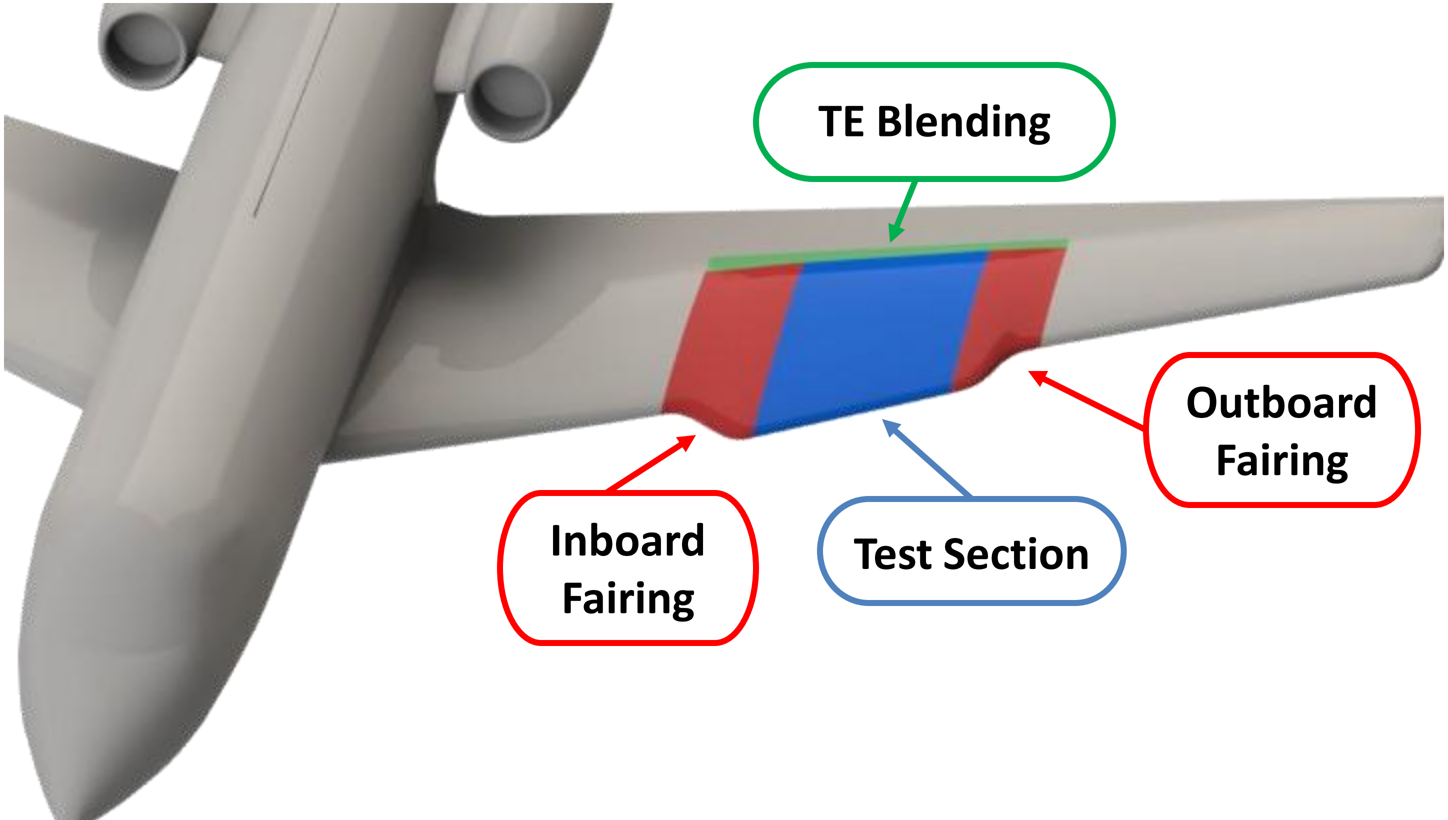
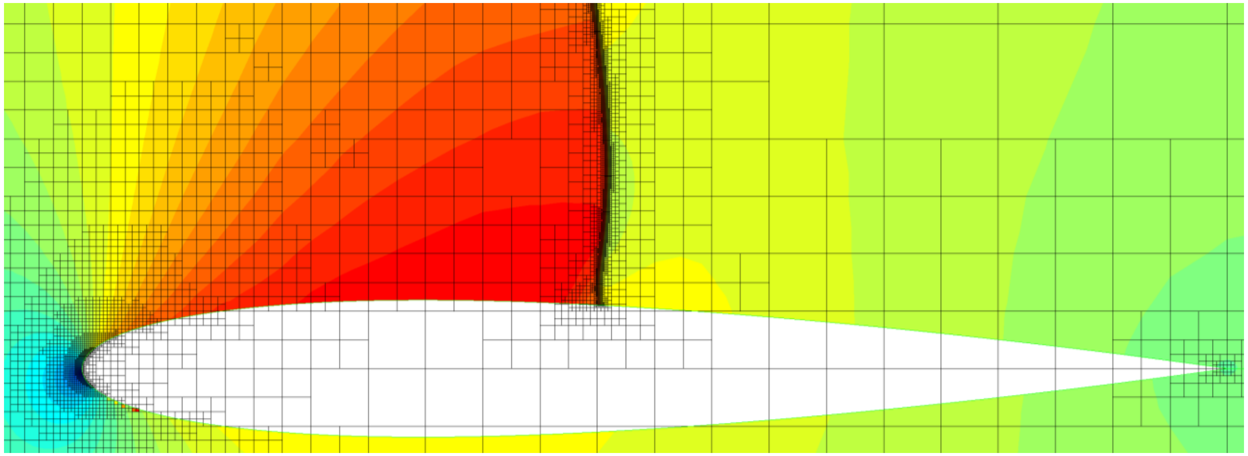
# DRE LFGE Project Background

- A natural laminar flow wing glove will be placed on a Gulfstream G-III business jet.
- The project is under the Environmentally Responsible Aviation (ERA) sub-project and is called Discrete Roughness Elements Laminar Flow Glove Experiment (DRE LFGE)
- Texas A&M University is the main partner and is credited with the design of the glove
- The glove is a large modification to the outer mold line of one aircraft wing, and the changes need to be analyzed using CFD to ensure pilot, aircraft, and mission safety



# Code Descriptions

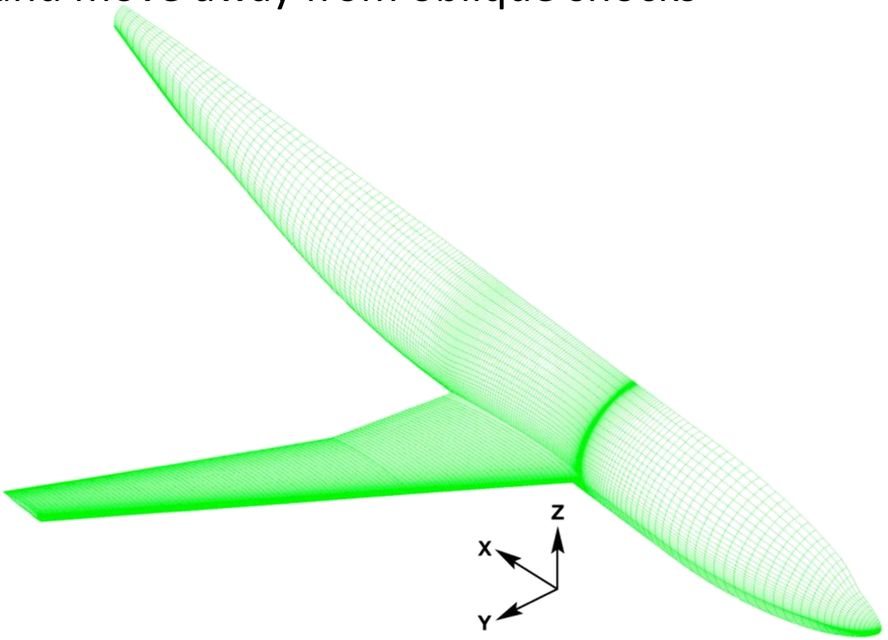
- TRANAIR
  - Well-validated non-linear full-potential flow aircraft aerodynamics code
  - Implicit direct coupling with a boundary layer code for viscous effects
  - Underlying surface grid is fully structured
  - Automatically generated solution adaptive Cartesian unstructured grid
  - Refines the grid where the error estimates from the velocity gradients are high
  - **Used for most of the GIII full aircraft analysis.**
- Star-CCM+
  - Unstructured, full Reynolds Averaged Navier-Stokes commercial CFD code.
  - Steady state, compressible capability, Menter SST Turbulence model
  - Used to confirm Tranair results as well as for complex aircraft flows outside the applicability of Tranair, such high flap deflections, high aircraft angles of attack, etc...



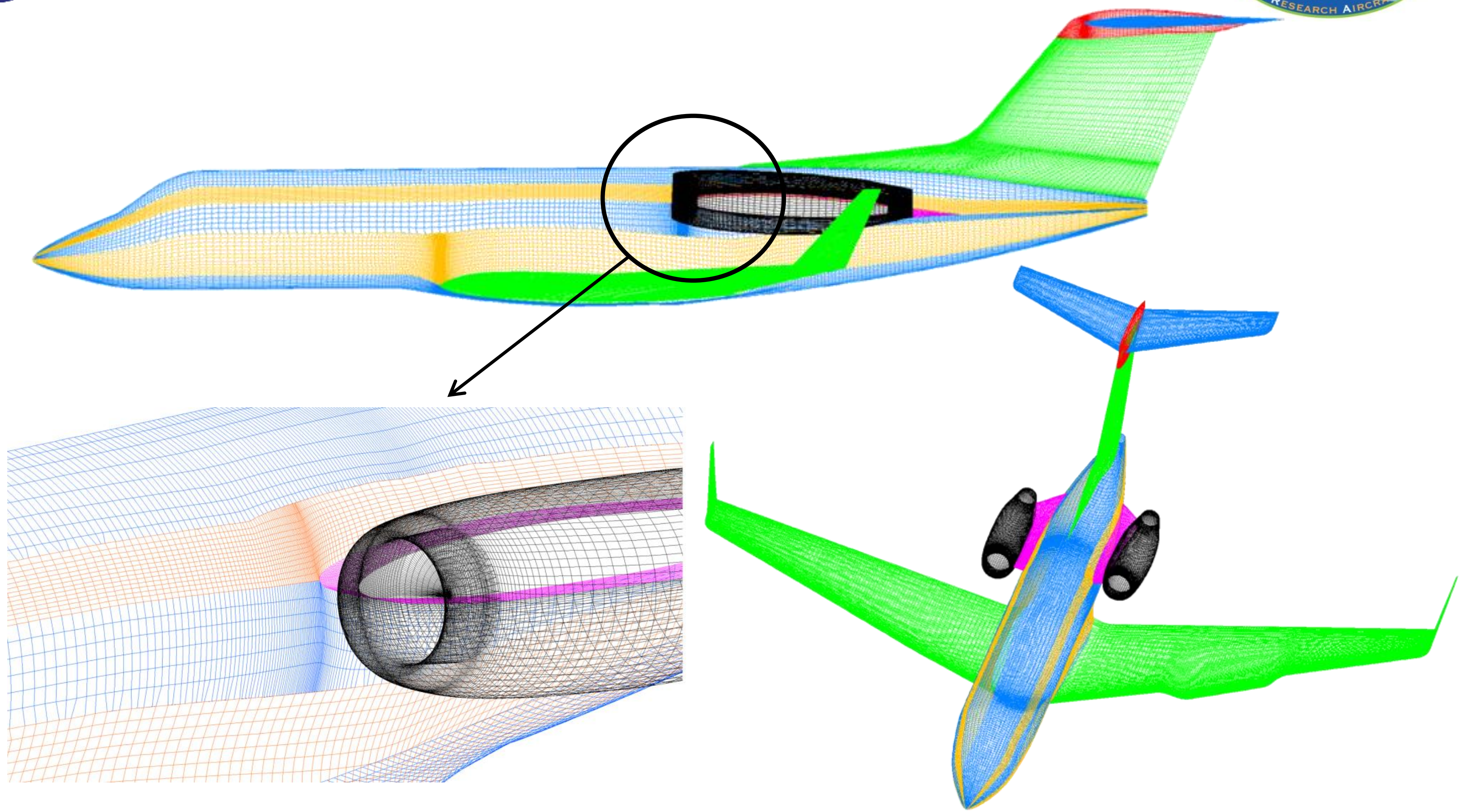
Mach Contours of a NACA 0012 airfoil

# Grid Independence

- Grid Independence studies were performed mostly for TRANAIR using the DLR-F6 aircraft
- Surface cell count and sizes are varied
- Volume cell count and maximum/minimum sizes analyzed
  - Care taken when decreasing minimum adaptive cell size
  - E.g. decreasing cell size while maintaining cell count will allow for more cells to cluster around suction peaks, and move away from oblique shocks
- Domain size needs only to be a couple aircraft lengths away from aircraft grid
  - Much less sensitive then full RANS computational domains
- Lessons learned and grid sizes from independence study are applied to the GIII surface grid

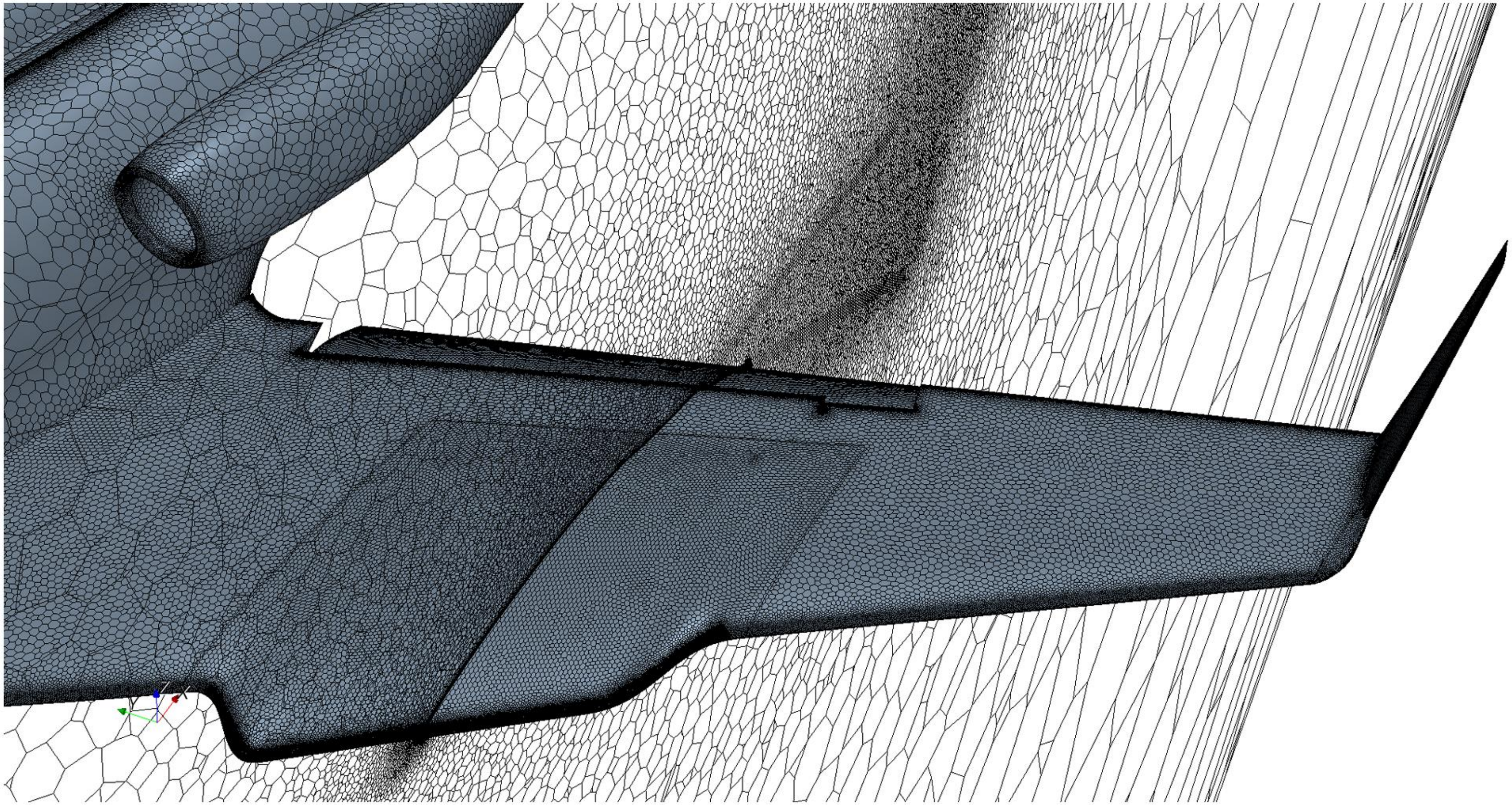


# TRANAIR Surface Grid



High quality surface mesh is lofted using AGPS and forms the foundation for Tranair's automatic volume grid generation

# Star-CCM+ Aircraft Grid



- 26 Million Volume Cells, 16 Prism Layers, Y+ 100
- Refinement of glove LE and TE wakes to help ensure accuracy of the solution

# CFD Analysis Matrix

- Seven main flight conditions were chosen at which to perform the analysis:
- Common Cruise Points – Close to proposed flight test conditions
  - Mach($M_\infty$) 0.75, Altitude(H) 45k ft
  - $M_\infty$ 0.75, H 40k ft
  - $M_\infty$ 0.7, H 25k ft
- Near Highest Mach and Dynamic Pressure limits of the aircraft
  - $M_\infty$ 0.85, H 25k ft
- Low speed landing configuration (No flaps)
  - $M_\infty$ 0.26, H 0 ft
  - $M_\infty$ 0.26, H 35 ft, Ground Effects
- Worst case takeoff configuration at takeoff safety speed
  - $M_\infty$ 0.22, H 100 ft, 20° Flaps, One Engine Inoperable (OEI)
- Multiple aircraft angles of attack and sideslip were analyzed at each flight condition
- Takeoff configuration analyzed using Star-CCM+ because of the prominence of complex flow, separation and recirculation.

# Aircraft Aerodynamic Results

- Differences in forces and moment between the baseline and gloved aircraft are quantified using deltas and control surface deflections
- Deltas are defined as the force or moment of the gloved aircraft subtracted from that of the baseline aircraft
  - Note at each analysis point the inflow is constant with no transients modeled
- Control surface deflection required to trim out the delta force and moments are calculated
- The glove produces only small changes in overall aircraft aerodynamics in all cases.
- The glove is not a problem for the aircraft high-speed, maximum dynamic pressure flight; as well as the low-speed, one-engine out, 20-deg. flap, low-altitude flight
- The glove does not change the aircraft’s ground effects aerodynamics
- Coordinate system is defined X positive forward, Y positive out right wing, Z positive down
  - Rolling moment positive rolling into right wing
  - Pitching moment positive pitch up
  - Yawing moment positive yawing into right wing

# Aircraft Aero Results

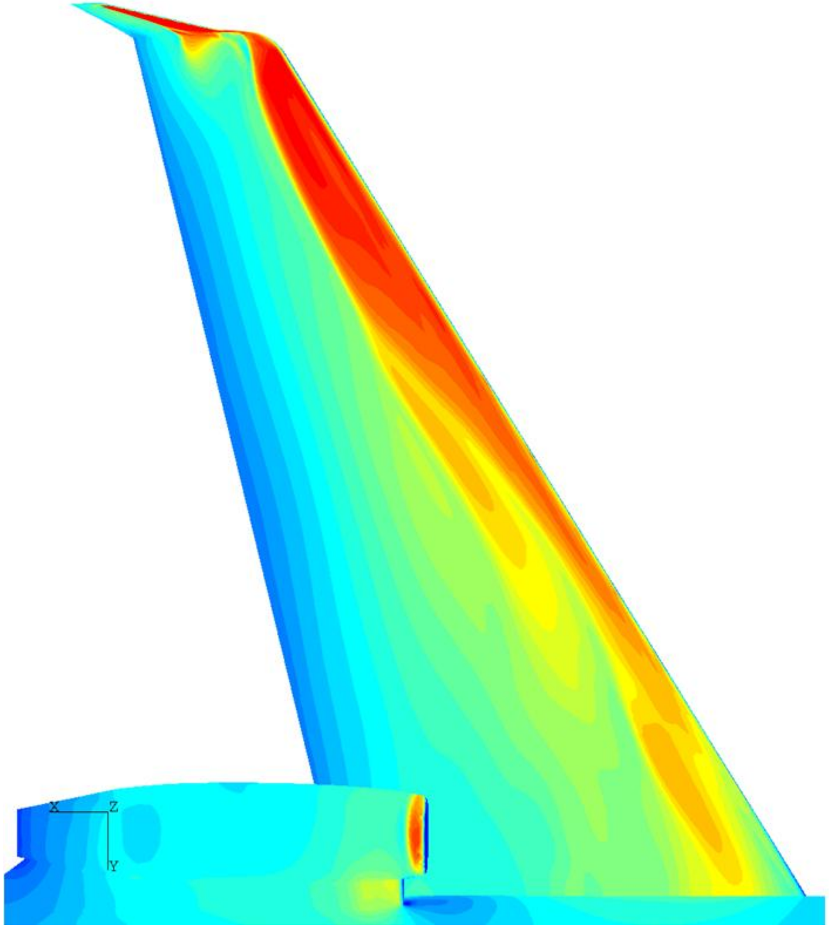
| Flight Condition | $M_\infty$ | H (ft) | Alpha (°) | Beta (°) | $\Delta C_L$ | $\Delta C_D$ | $\Delta C_Y$ | $\Delta C_l$ | $\Delta C_m$ | $\Delta C_n$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.75 | 45 K | 4.24 | 0 | -0.0106 | -0.0015 | 0.0017 | -0.0012 | -0.0037 | -0.0003 |
| 1 | 0.75 | 45 K | -0.76 | 0 | -0.0039 | 0.0002 | 0.0008 | -0.0008 | 0.0019 | -0.0002 |
| 1 | 0.75 | 45 K | 4.24 | 5 | -0.0120 | 0.0012 | 0.0024 | -0.0007 | -0.0031 | -0.0005 |
| 1 | 0.75 | 45 K | 4.24 | -5 | -0.0081 | -0.0044 | 0.0031 | -0.0006 | -0.0046 | -0.0005 |
| 2 | 0.75 | 40 K | 4.24 | 0 | -0.0089 | -0.0015 | 0.0016 | -0.0010 | -0.0041 | -0.0003 |
| 2 | 0.75 | 40 K | -0.76 | 0 | -0.0041 | -0.0003 | 0.0009 | -0.0008 | 0.0021 | -0.0003 |
| 2 | 0.75 | 40 K | 4.24 | 5 | -0.0102 | -0.0015 | 0.0011 | -0.0012 | -0.0036 | -0.0003 |
| 2 | 0.75 | 40 K | 4.24 | -5 | -0.0096 | -0.0008 | 0.0002 | -0.0016 | -0.0042 | 0.0000 |
| 3 | 0.7 | 25 K | 2.30 | 0 | -0.0071 | -0.0004 | 0.0012 | -0.0011 | -0.0026 | -0.0003 |
| 3 | 0.7 | 25 K | -2.70 | 0 | 0.0005 | -0.0021 | 0.0000 | -0.0005 | 0.0053 | 0.0000 |
| 3 | 0.7 | 25 K | 6.00 | 0 | -0.0121 | -0.0003 | 0.0023 | -0.0016 | -0.0066 | -0.0006 |
| 3 | 0.7 | 25 K | 2.30 | 5 | -0.0073 | -0.0004 | 0.0014 | -0.0009 | -0.0017 | -0.0004 |
| 3 | 0.7 | 25 K | 2.30 | -5 | -0.0069 | -0.0004 | 0.0012 | -0.0013 | -0.0030 | -0.0003 |
| 4 | 0.85 | 25 K | 1.59 | 0 | 0.0059 | -0.0013 | 0.0007 | 0.0034 | -0.0038 | 0.0002 |
| 4 | 0.85 | 25 K | 1.09 | 0 | 0.0023 | -0.0016 | 0.0001 | 0.0020 | -0.0005 | 0.0004 |
| 4 | 0.85 | 25 K | 0.59 | 0 | -0.0055 | -0.0021 | -0.0003 | -0.0005 | 0.0051 | 0.0004 |
| 5 | 0.26 | 0 | 2.67 | 0 | -0.0060 | -0.0003 | 0.0011 | -0.0011 | -0.0027 | -0.0003 |
| 5 | 0.26 | 0 | 7.67 | 0 | -0.0103 | -0.0009 | 0.0023 | -0.0018 | -0.0092 | -0.0007 |
| 5 | 0.26 | 0 | 10.67 | 0 | -0.0130 | -0.0018 | 0.0028 | -0.0020 | -0.0129 | -0.0009 |
| 5 | 0.26 | 0 | 7.67 | 5 | -0.0110 | -0.0011 | 0.0024 | -0.0016 | -0.0080 | -0.0007 |
| 5 | 0.26 | 0 | 7.67 | -5 | -0.0099 | -0.0009 | 0.0022 | -0.0022 | -0.0105 | -0.0006 |
| 6 | 0.26 | 35 | 7.67 | 0 | -0.0081 | -0.0008 | 0.0014 | -0.0020 | -0.0032 | -0.0001 |
| 7 | 0.22 | 100 | 6.75 | 15 | -0.0112 | -0.0038 | -0.0019 | -0.0011 | -0.0056 | 0.0000 |
| 7 | 0.22 | 100 | 6.75 | -15 | -0.0075 | -0.0085 | 0.0002 | -0.0026 | -0.0129 | 0.0000 |

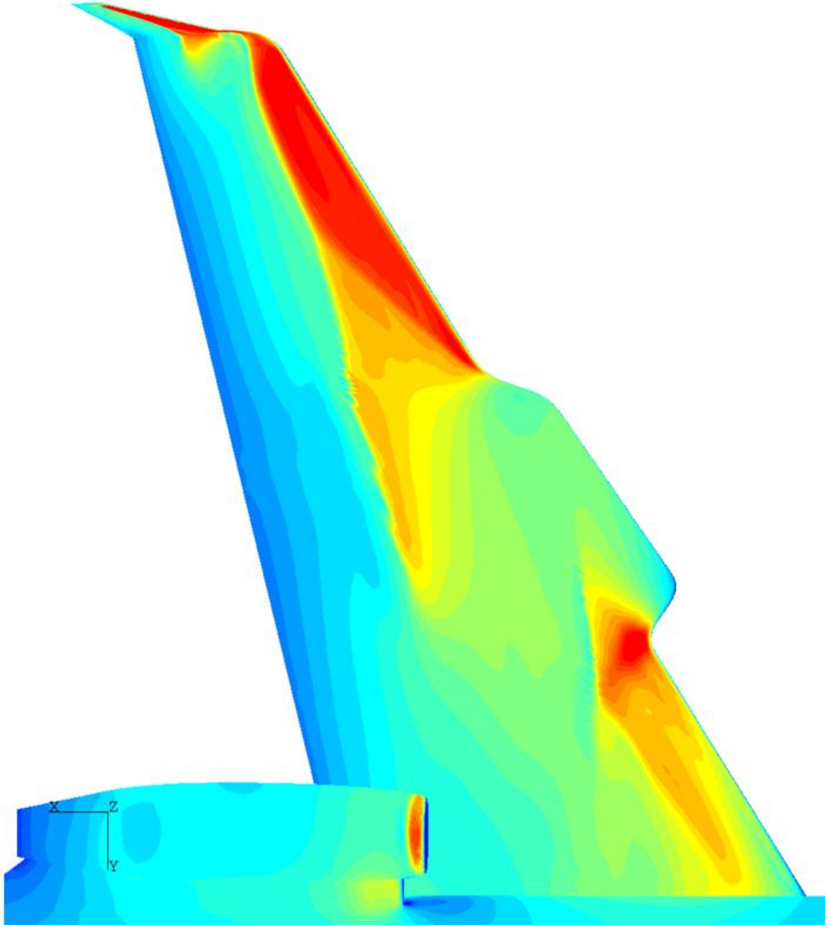
# Control Surface Deflections

| Flight Condition | $M_\infty$ | H (ft) | Alpha (º) | Beta (º) | $\Delta C_l$ | $\Delta C_m$ | $\Delta C_n$ |
|---|---|---|---|---|---|---|---|
| | | | | | **Aileron (º)** | **Elevator (º)** | **Rudder (º)** |
| **1** | 0.75 | 45 K | 4.24 | 0 | 1.0 | 0.2 | 0.2 |
| **1** | 0.75 | 45 K | -0.76 | 0 | 0.6 | -0.1 | 0.2 |
| **1** | 0.75 | 45 K | 4.24 | 5 | 0.5 | 0.2 | 0.4 |
| **1** | 0.75 | 45 K | 4.24 | -5 | 0.5 | 0.3 | 0.4 |
| **2** | 0.75 | 40 K | 4.24 | 0 | 0.8 | 0.3 | 0.2 |
| **2** | 0.75 | 40 K | -0.76 | 0 | 0.6 | -0.1 | 0.2 |
| **2** | 0.75 | 40 K | 4.24 | 5 | 0.9 | 0.2 | 0.2 |
| **2** | 0.75 | 40 K | 4.24 | -5 | 1.2 | 0.3 | 0.0 |
| **3** | 0.7 | 25 K | 2.30 | 0 | 0.9 | 0.2 | 0.2 |
| **3** | 0.7 | 25 K | -2.70 | 0 | 0.4 | -0.4 | 0.0 |
| **3** | 0.7 | 25 K | 6.00 | 0 | 1.3 | 0.5 | 0.5 |
| **3** | 0.7 | 25 K | 2.30 | 5 | 0.7 | 0.1 | 0.3 |
| **3** | 0.7 | 25 K | 2.30 | -5 | 1.1 | 0.2 | 0.2 |
| **4** | 0.85 | 25 K | 1.59 | 0 | **-2.9** | 0.4 | -0.2 |
| **4** | 0.85 | 25 K | 1.09 | 0 | -1.7 | 0.1 | -0.3 |
| **4** | 0.85 | 25 K | 0.59 | 0 | 0.4 | -0.6 | -0.3 |
| **5** | 0.26 | 0 | 2.67 | 0 | 0.9 | 0.1 | 0.3 |
| **5** | 0.26 | 0 | 7.67 | 0 | 1.4 | 0.5 | 0.6 |
| **5** | 0.26 | 0 | 10.67 | 0 | 1.6 | **0.7** | **0.8** |
| **5** | 0.26 | 0 | 7.67 | 5 | 1.2 | 0.4 | 0.6 |
| **5** | 0.26 | 0 | 7.67 | -5 | 1.8 | 0.6 | 0.5 |
| **6** | 0.26 | 35 | 7.67 | 0 | 1.5 | 0.2 | 0.1 |
| **7** | 0.22 | 100 | 6.75 | 15 | 0.8 | 0.3 | 0.0 |
| **7** | 0.22 | 100 | 6.75 | -15 | 1.9 | 0.7 | 0.0 |

# Cruise Condition Mach Contours

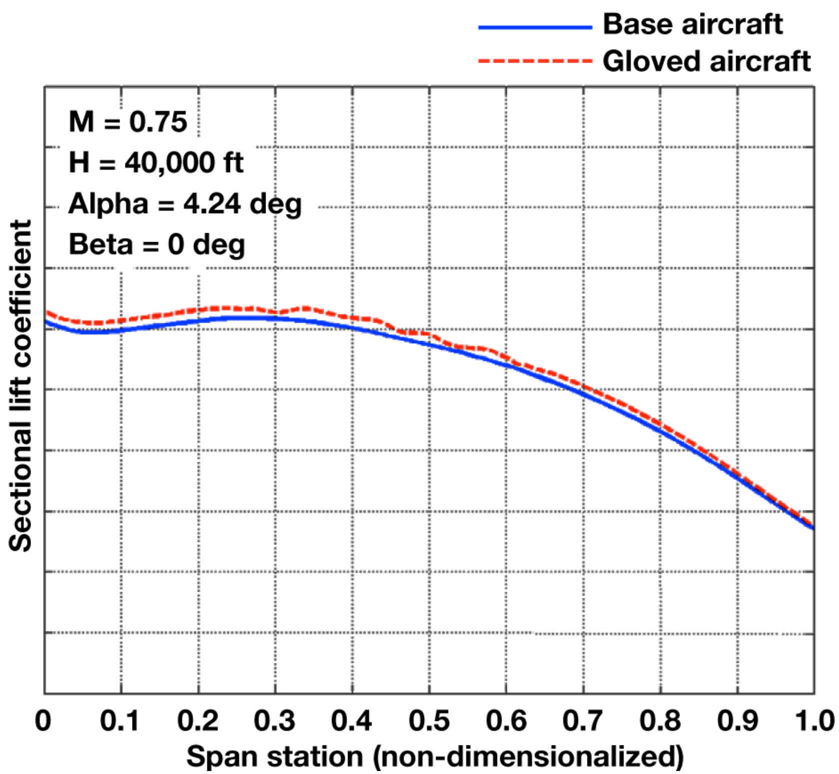
- Mach 0.75, 40,000 ft, 4.24 deg. AoA
- The glove modifies the shock structure on the upper surface of the wing.
- The glove produces a pocket of supersonic flow at the inboard fairing.

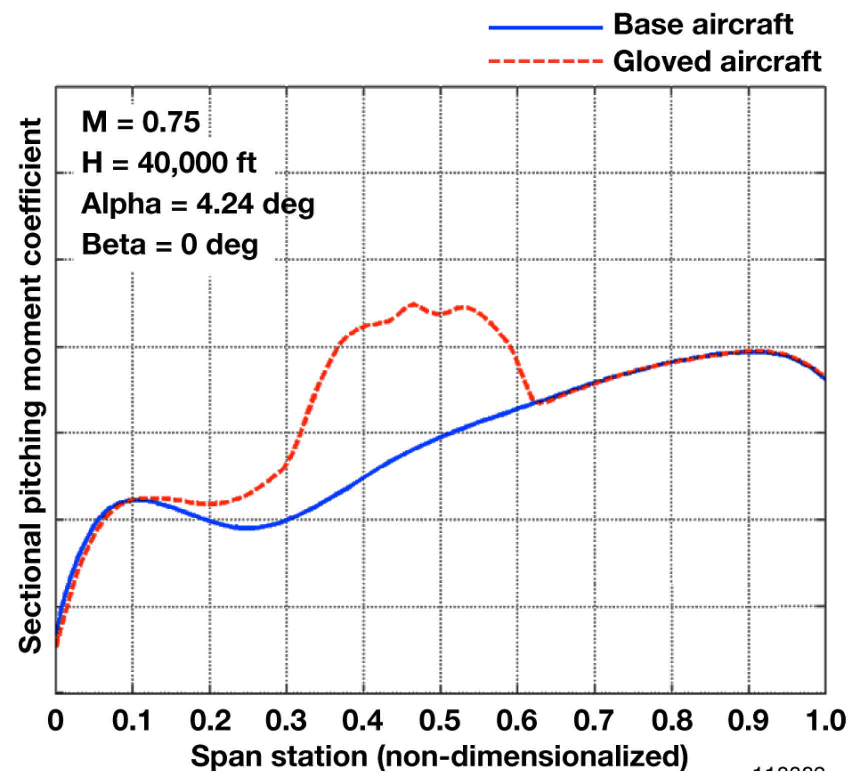




# Cruise Condition Span Loads

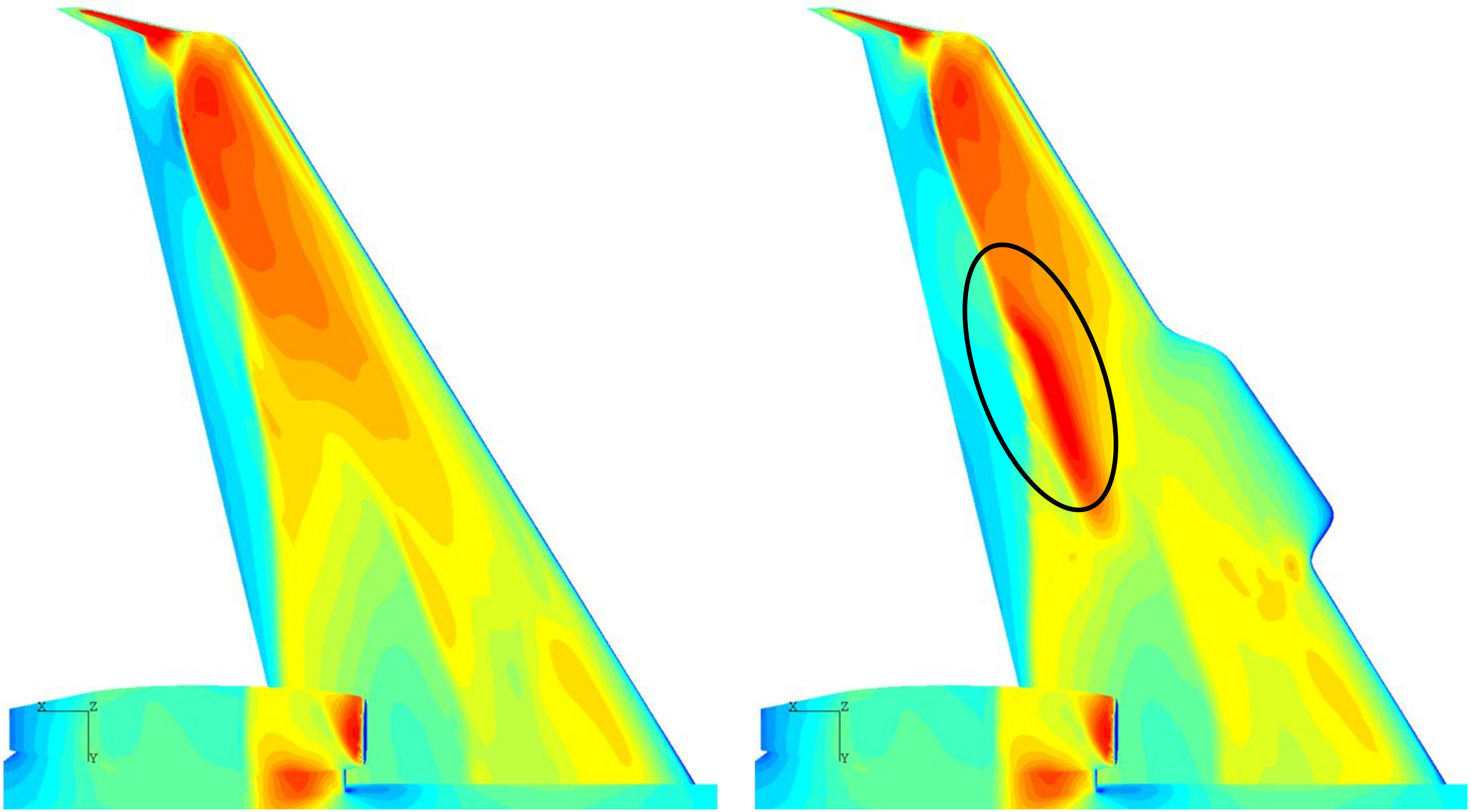
- Lift and moment coefficient are non-dimensionalized by one reference chord.
- The glove does not have a significant effect on span-wise lift distribution.
- The glove significantly modifies the local span-wise pitching moment distribution in the glove area



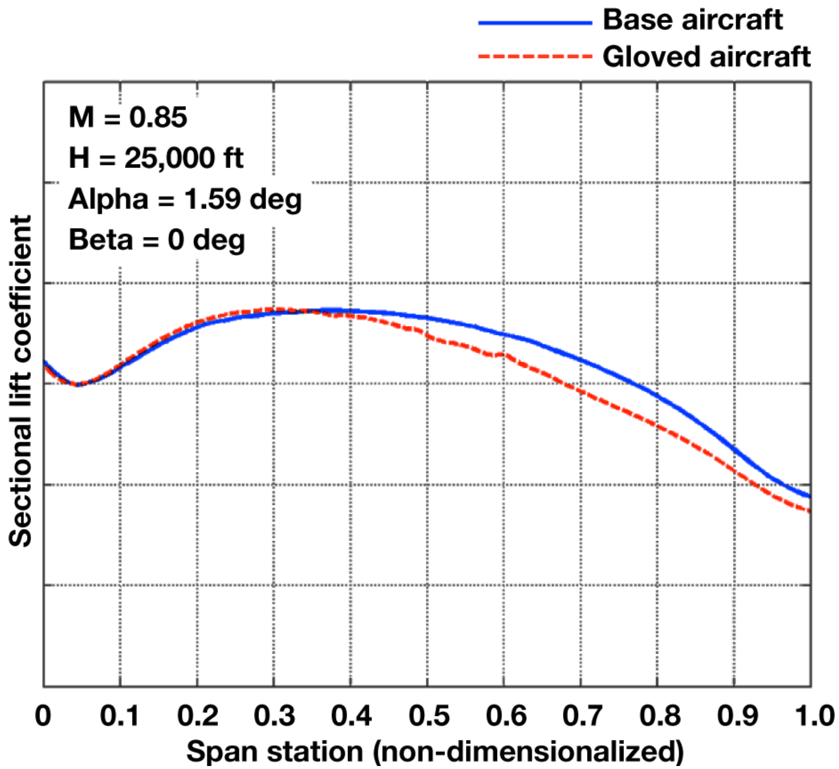
# Max $q_\infty$ Mach Contours

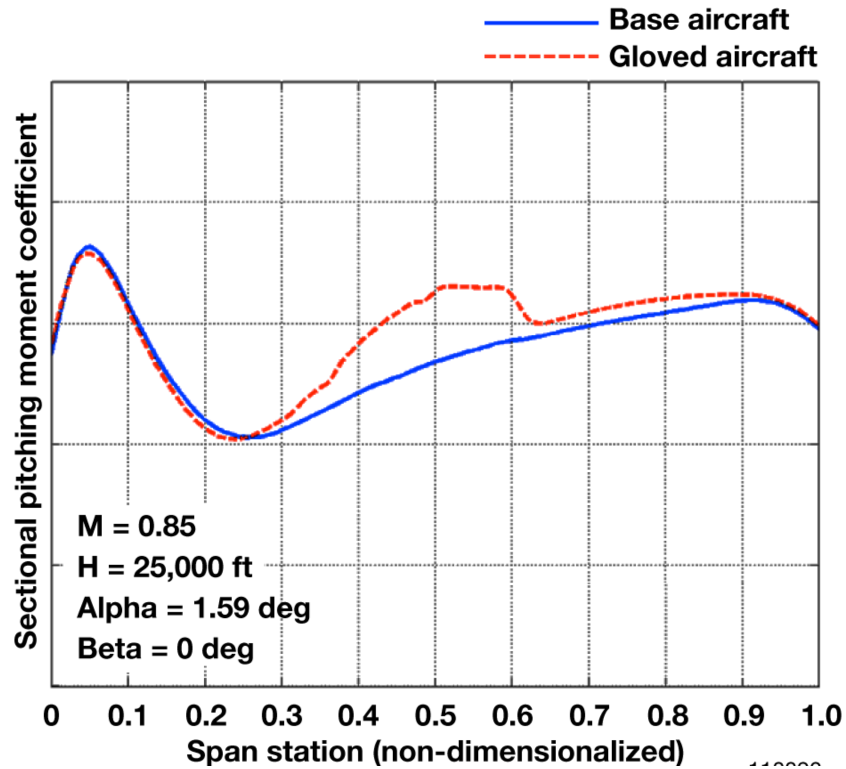
- Mach 0.85, 25,000 ft, 1.59 deg. AoA
- Glove adds a strong shock near the glove blending region.
- The aircraft engine's zone of influence extends into the glove area.



# Cruise Condition Span Loads

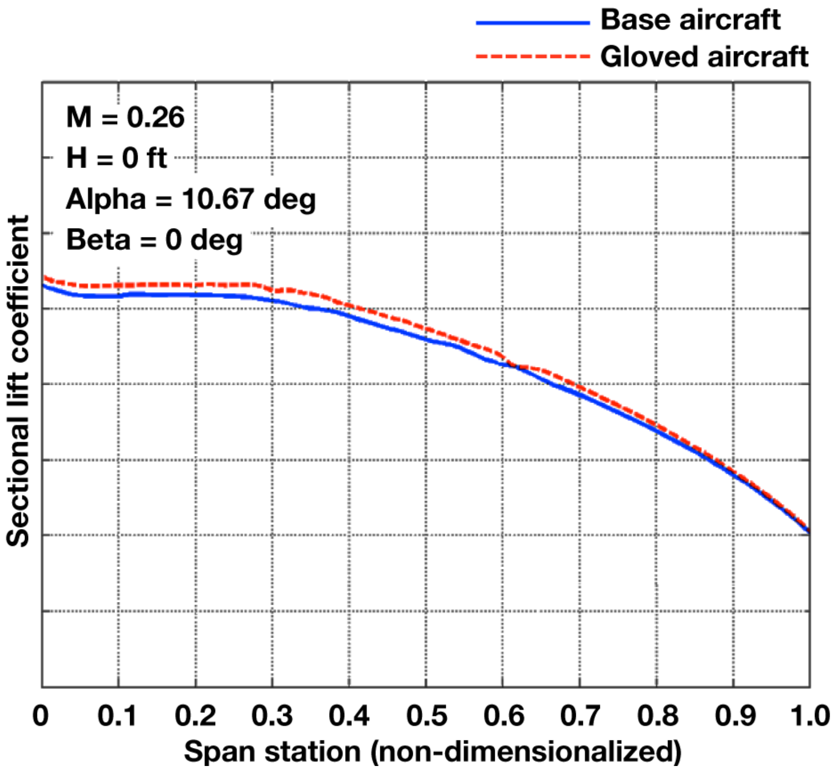
- The glove has a slightly more significant effect on span-wise lift distribution.
- Lift decreases because the glove changes the chord wise extent of the shocks
- The added lift at the front of the glove, is partially balanced out by the added lift caused by the shock near the blending region of the glove

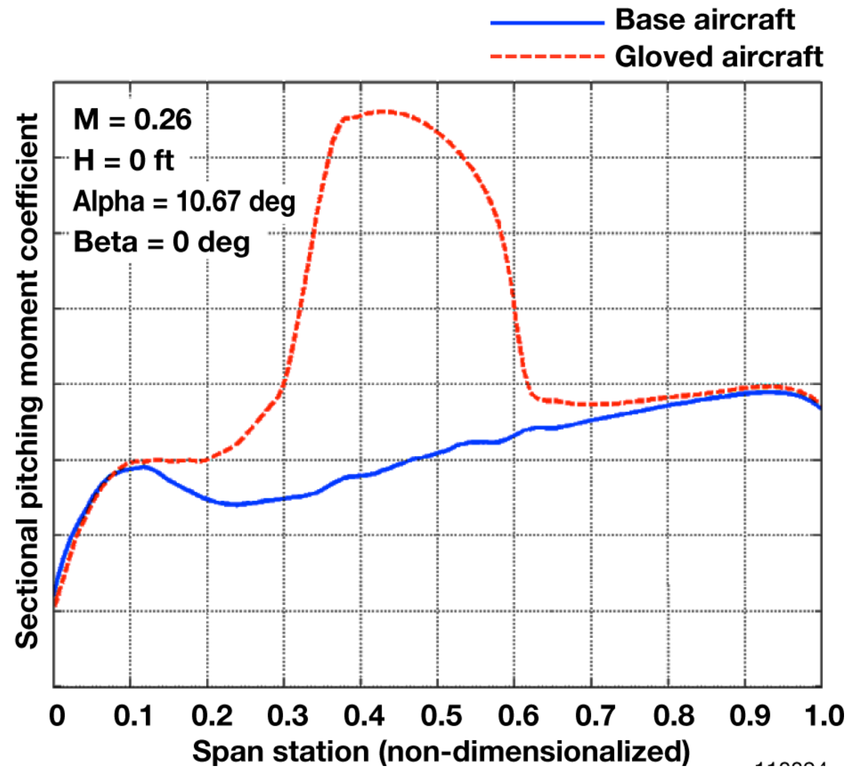


# Landing Config. Span Loads

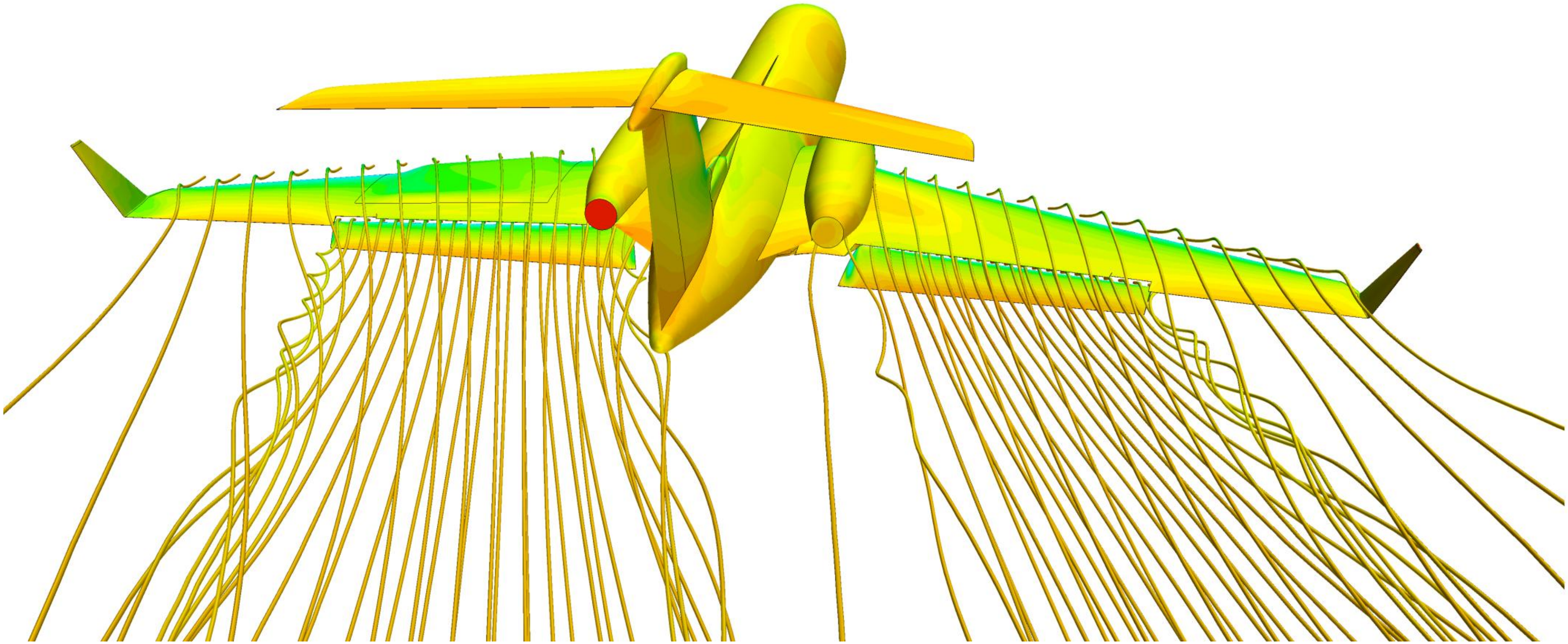
- The glove has a very minimal effect on span-wise lift distribution.
- The glove significantly modifies the local span-wise pitching moment distribution in the glove area
- Structural studies need to be performed to determine if the wing can handle the added torsional load



# Takeoff Config. $C_P$ Contours

Mach 0.22, 100 ft alt., 6.75-deg. $\alpha$, -15-deg. $\beta$



The glove has no significant effects on aircraft aerodynamics

# Conclusions

- The delta aerodynamic forces and moments produced by the glove are fairly small
- Only Small control surface deflections are needed to trim out the asymmetries
- The spanwise lift distribution of the gloved wing matches very well with the clean wing
- TRANAIR and Star-CCM+ worked very well in generating the necessary results for these studies
- Flight data will be gathered that will include aircraft PID parameters, wing pressure distributions, surface temperatures, and much more and used to help validate the CFD models