Design and Calibration of a Flowfield Survey Rake for Inlet Flight Research

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Outline

• Propulsion Flight Test Fixture (PFTF) Overview
• Rake Airflow Gage Experiment (RAGE) description
• Aerodynamic loads estimates and stress analysis
• Wind tunnel test
• Calibration
• Summary
Propulsion Flight Test Fixture

- Pylon for flight testing of propulsion related experiments, including “cold” (unfueled) and “hot” (fueled) experiments
- Flown on NASA DFRC F-15B testbed
  - PFTF Attaches to F-15B centerline pylon
- Fixture has Mach 2 capability
- Integrated 6-component force balance

<table>
<thead>
<tr>
<th>Force Balance Measurement Limits</th>
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<tbody>
<tr>
<td>Fx (lbs)</td>
<td>2000</td>
<td>500</td>
<td>1500</td>
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<tr>
<td>My (in-lbs)</td>
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<td>Mz (in-lbs)</td>
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- Highly instrumented
- Large internal space for fuel/pressure tanks, instrumentation, etc

Experiment Adapter
Contains ESP modules and other experiment instrumentation
Past PFTF Experiments

• Previous PFTF Flight Test
  – Cone Drag Experiment (CDE)
    • Envelope expansion of the PFTF with the CDE installed up to Mach 2.0
      – Flutter clearance, handling qualities, force balance checkout
  – Local Mach Investigation (LMI)
    • Utilized NACA air data boom to characterize the flow field (Mach, alpha, and beta) at a single point in front of the PFTF
Rake Airflow Gauge Experiment (RAGE)

- RAGE consists of a flowfield survey rake, boom, and cone-cylinder
- Attached to PFTF
- Objective is to characterize flowfield at aerodynamic interface plane of experimental inlet
- Flowfield data will be used for CFD and performance modeling of the inlet
RAGE Flowfield Rake

- Array of nine 5-hole probes
- Two-piece design, with internals designed for sensors and pressure plumbing
- AL 7075-T6
- Probes manufactured by Aeroprobe Corp.
  - 60° included angle
  - 4 static pressure ports, 1 total pressure port per probe
Rake Aerodynamic Loads

- Rake aerodynamic loads were estimated for wind tunnel testing
  - Wind tunnel dynamic pressure 30% greater than flight
- CFD and empirical solutions
  - WIND-US2 code
    - 2D, viscous solver
  - NACA TN 2712 - Lifting wedges in supersonic flow
- Mach 1.6, hp = 30,000 ft
- AOA of 20° is 2x greater than max expected
Rake Stress Analysis

- SolidWorks/COSMOSWORKS finite element solver (95672 nodes)
- CFD estimated aerodynamic loading used for normal and axial forces
- \( \sigma_{\text{max}} = 13.5 \text{ ksi} \), minimum FOS of 4.4
• Aerodynamic loads estimate of entire assembly necessary to ensure PFTF force balance isn’t overloaded
• RAGE assembly aerodynamic forces and moments were predicted using CFD
• Air Vehicles Unstructured Solver (AVUS) from AFRL
• 3D unstructured tetrahedron mesh
• 8 zones, 3.36 million points, 17.8 million cells, with 1 plane of symmetry
• Simulated *PFTF local* flight condition: M 1.6 @ 29,500 ft
• Steady-state, inviscid computation
• M = 1.6, hp = 30,000 ft
• Geometry is symmetric in lateral and normal directions
• Axial load significantly less than PFTF force balance limit
• Force balance side load limit hit around 1.8° β at highest dynamic pressure
CFD Results: Moments

- \( M = 1.6, \) \( hp = 30,000 \) ft
- Moments corrected to load test reference frame
- Lateral (roll/yaw) moments limits are hit at around 2.5 to 3.5 deg. \( \beta \) at highest dynamic pressure
Probe Aerodynamic Loads and Stress

- Probe aerodynamic loads were estimated using CFD and empirical methods
  - CFD estimated loads were extracted from RAGE assembly CFD
  - Gudmundson/Torngren - Supersonic wind tunnel tests of ogive cylinders
- Analytical stress analysis with worst case load predictions
  - $\sigma_{\text{max}} = 9.95$ ksi, minimum FOS of 2.59
Boom Loads and Stress

- Rake and boom forces determined from RAGE assembly CFD
  - $F_n = 131$ lb, $F_a = 49.3$ lb
- SolidWorks/COSMOSWORKS FEM used for stress analysis (107785 nodes)
- Minimum FOS of 15.3
Wind Tunnel Calibration

• Calibration data were generated in the Boeing Polysonic Wind Tunnel (blowdown tunnel)

• Rake was attached to a sting that could be rotated in roll and pitch to achieve specific angles of attack and sideslip
  • Alpha and beta were varied from +/- 10 degrees

• Four different flow conditions were tested
  • Mach = 1.461, 1.508, 1.611 corresponding to Re = 6.2, 6.7, 6.2 million/ft
  • Additional run at Mach = 1.508, Re = 5.7 million/ft to check for Reynolds number effects
  • Dynamic pressure range of 1260 - 1497 psf
Calibration Data Reduction

- Wind tunnel data was reduced and calibration algorithm was developed based on the method given in NACA-TN-3967, “Characteristics of a 40 Degree Cone for Measuring Mach Number, Total Pressure, and Flow Angles at Supersonic Speeds”
  - Iterative procedure calculates the local Mach, total pressure, and flow angles using calibration maps in conjunction with normal shock and isentropic relations
  - Local Mach is calculated using the ratio of the mean of the 4 static ports to the pitot pressure and is corrected based on flow angularity
  - Angles of attack and sideslip are determined using pressure differences across diametrically opposed pressure ports
Misalignment Correction

- Wind tunnel data was corrected for misalignment and tunnel stream angularity
- Vertical pressure coefficient defined using vertical pressure ports:
  \[ C_{p\theta} = \frac{p_3 - p_5}{q} \]
- Vertical pressure coefficient for roll angles of 0° and -180° was plotted versus pitch angle. Intersection of two curves represents the vertical misalignment angle \( \theta_0 \)
  \( \theta_0 = -0.56°, -0.42°, \) and -0.15° at Mach 1.461, 1.508, and 1.611
- Horizontal misalignment angle couldn’t be determined due to absence of data at a roll angle of 90°
Mach Calibration Maps

- Mach number is determined from the ratio of the mean of the four static pressures to the pitot pressure \( \frac{p_a}{p_{t2}} \)
- Lookup table created for \( \frac{p_a}{p_{t2}} \) at zero flow inclination as a function of Mach
- Ratio of pitot to total pressure in front of shock \( \frac{p_{t2}}{p_{t1}} \) plotted to check for sensitivity to flow inclination
  - Pitot pressure decreased by only 0.5% at the maximum pitch angle making it unnecessary to correct measured pitot pressure for flow inclination
Mach Calibration Maps

- In general, $p_a / p_{t2}$ must be corrected for flow inclination.
- $p_a / p_{t2}$ plotted as a function of pitch angle for all 21 different roll angles.
- 3-D calibration maps that provide a correction factor to $p_a / p_{t2}$ were generated from data for all 21 distinct roll angles.
Flow Angle Calibration Maps

- Angle of attack and angle of sideslip pressure coefficients were defined as:
  
  \[ C_{p\alpha} = \frac{p_3 - p_5}{q} \quad C_{p\beta} = \frac{p_4 - p_2}{q} \]

- Wind tunnel data was used to create 3-D calibration maps for \( \alpha \) and \( \beta \)
  - \( \alpha \) and \( \beta \) are looked up using computed \( C_{p\alpha} \) and \( C_{p\beta} \)
Calibration Algorithm

Probe measured pressures
Total pressure \( p_{t_2} \)
Static pressures \( p_2, p_3, p_4, p_5 \)

\[
p_a = \frac{1}{4}(p_2 + p_3 + p_4 + p_5)
\]

\[
M_1 = f\left(\frac{p_a}{p_{t_2}}\right) \quad \text{Map 1}
\]

\[
q = f\left(p_{t_1}, M_1\right)
\]

Isentropic Flow Relations

\[
p_{t_1} = f\left(p_{t_2}, M_1\right)
\]

Normal Shock Relations

\[
\alpha, \beta = f(Cp_\alpha, Cp_\beta) \quad \text{Maps 3, 4}
\]

\[
Cp_\alpha = \frac{p_3 - p_5}{q}
\]

\[
Cp_\beta = \frac{p_4 - p_2}{q}
\]

\[
\theta_n = \tan^{-1}\left[\tan^2\alpha + \tan^2\beta\right]^{1/2}
\]

\[
\phi_n = \cos^{-1}\left[\frac{\tan\alpha}{\tan\theta_n}\right]
\]

\[
\left(\frac{p_a}{p_{t_2}}\right)_{\theta_n=0} \quad \text{from Map 2}
\]

Converged Solution \( M_1, \alpha, \beta \)

\% Change in \( M_1 < \epsilon \)

No

Yes

Converged Solution \( M_1, \alpha, \beta \)
RAGE Flight Test
Summary

• Flowfield rake was designed to quantify the flowfield for inlet research underneath NASA DFRC’s F-15B airplane
• Detailed loads and stress analysis performed using CFD and empirical methods to assure structural integrity
• Calibration data were generated through wind tunnel testing of the rake
• Calibration algorithm was developed to determine the local Mach and flow angularity at each probe
• RAGE was flown November, 2008. Data is currently being analyzed