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

Darin C. Flynn
Nalin A. Ratnayake
Michael Frederick
NASA DFRC Aerodynamics and Propulsion Research Branch

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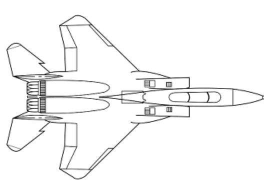
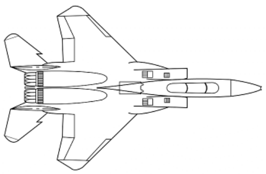


Outline

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



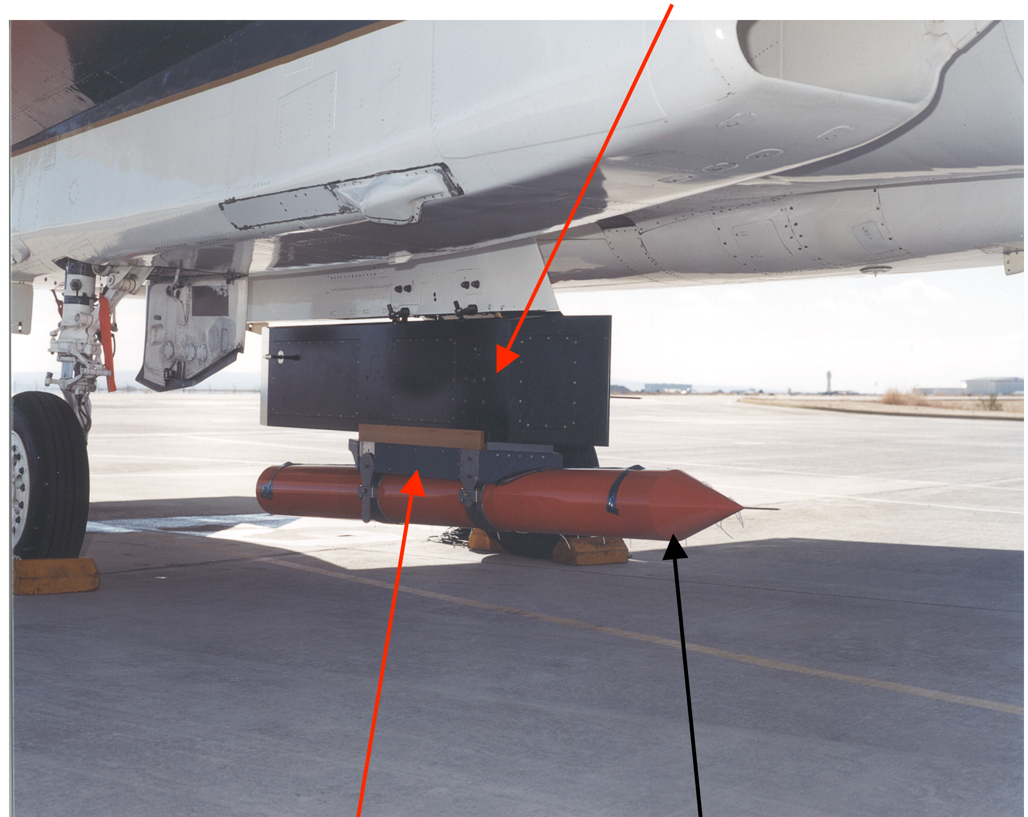
Propulsion Flight Test Fixture

- 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

Force Balance Measurement Limits		
Fx (lbs)	**Fy (lbs)**	**Fz (lbs)**
2000	500	1500
Mx (in-lbs)	**My (in-lbs)**	**Mz (in-lbs)**
8520	55080	10080

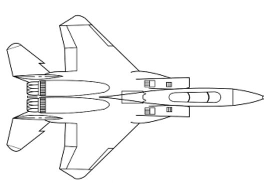
- Highly instrumented
- Large internal space for fuel/pressure tanks, instrumentation, etc

PFTF



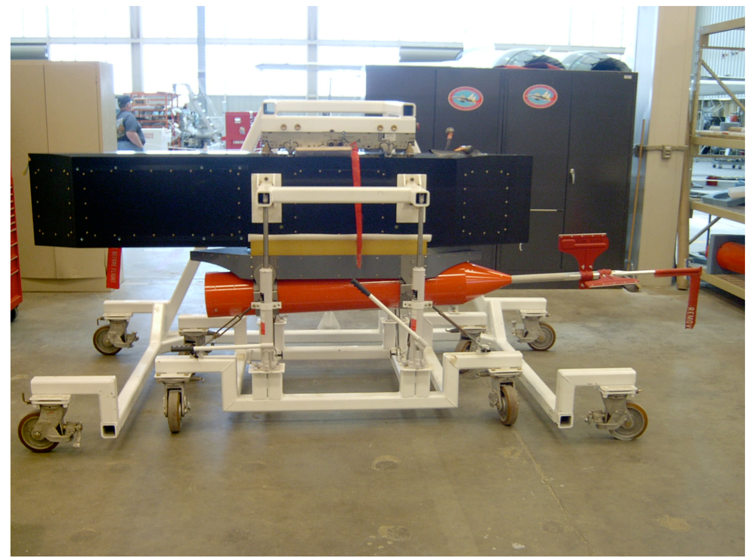
Experiment Adapter
Contains ESP modules and other experiment instrumentation

Experiment

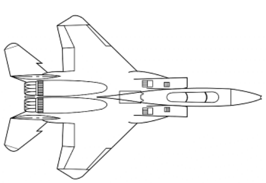


Past PFTF Experiments

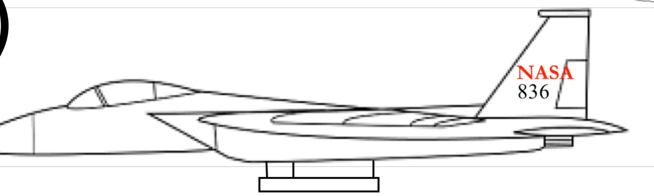
- Previous PFTF Flight Test
  - Cone Drag Experiment (CDE)
    - Envelope expansion of the PFTF with the CDE installed up to Mach 2.0
      - Flutter clearance, handling qualities, force balance checkout



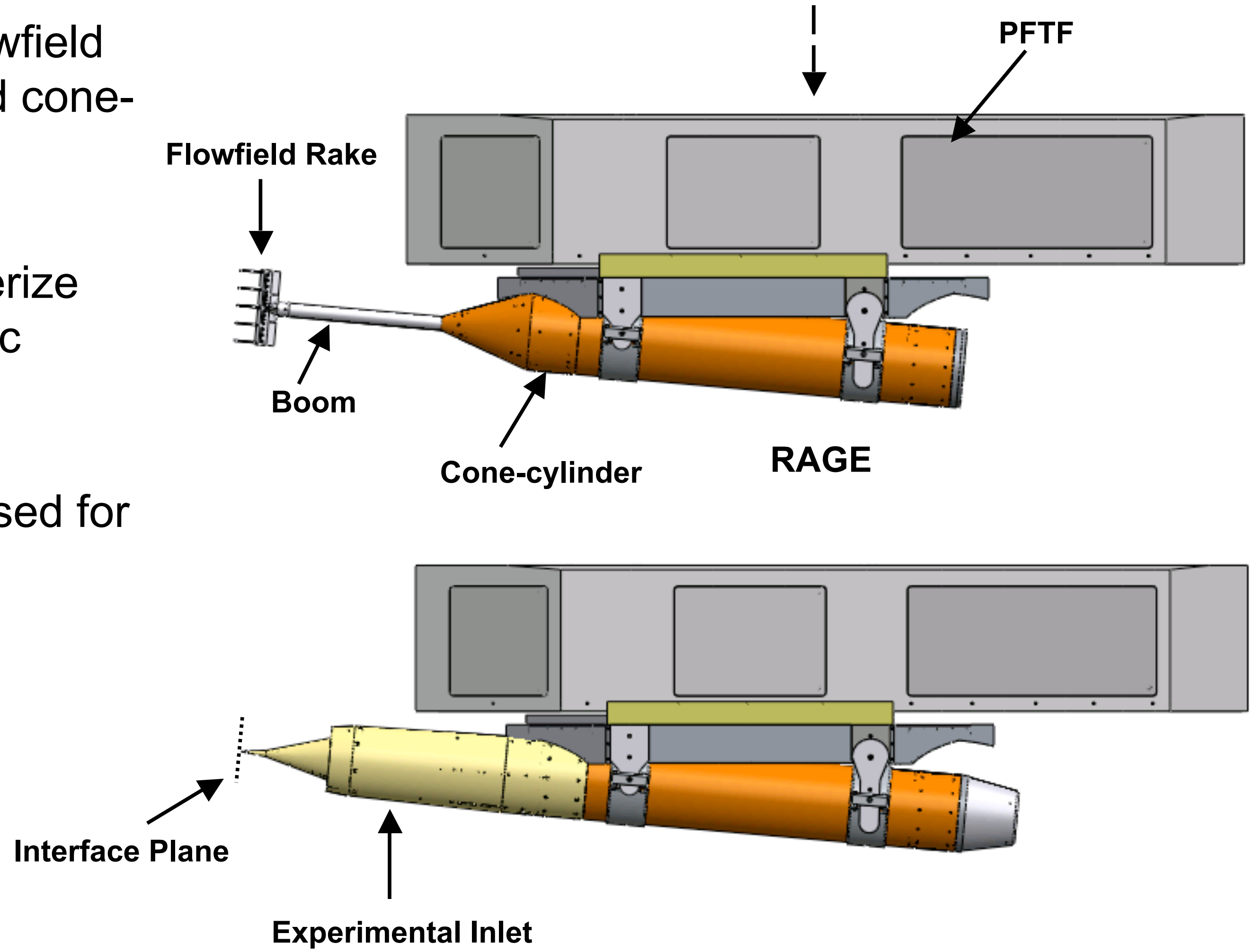
  - Local Mach Investigation (LMI)
    - Utilized NACA air data boom to characterize the flow field (Mach, alpha, and beta) at a single point in front of the PFTF

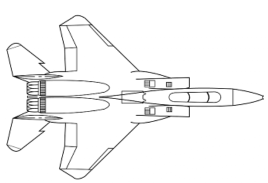


Rake Airflow Gauge Experiment (RAGE)



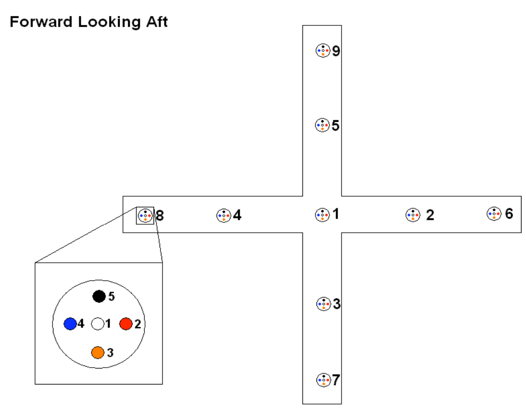
- RAGE consists of a flowfield survey rake, boom, and cone-cylinder
- Attached to PFTF
- Objective is to characterize flowfield at aerodynamic interface plane of experimental inlet
- Flowfield data will be used for CFD and performance modeling of the inlet



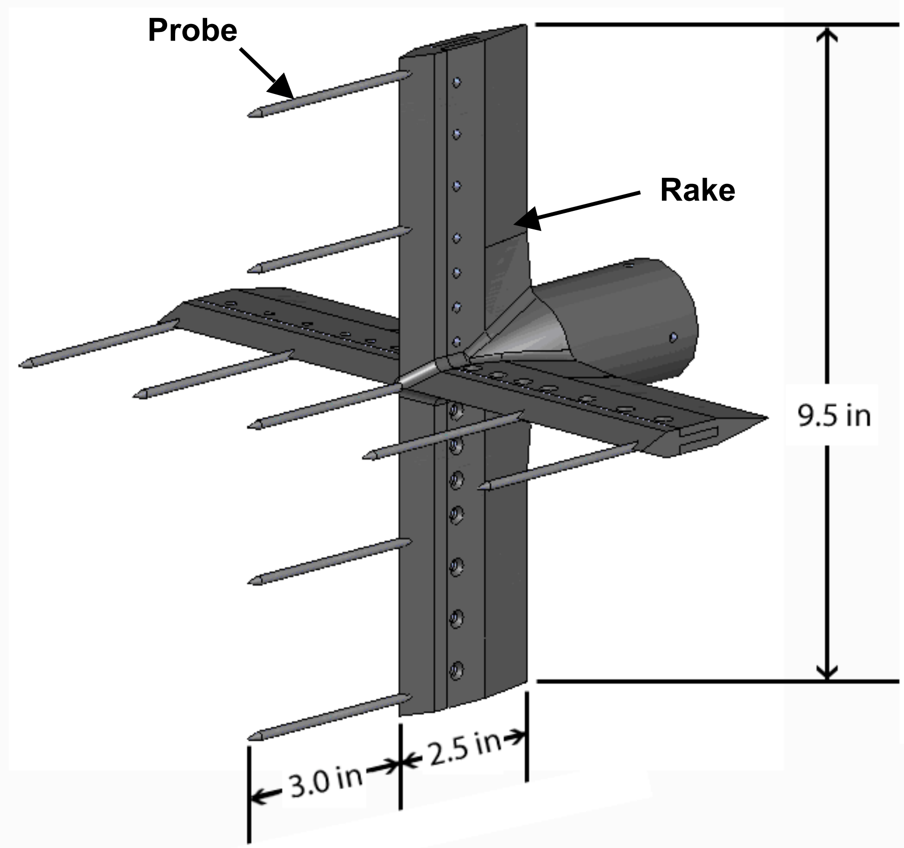


RAGE Flowfield Rake

- 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.
  - 60º included angle
  - 4 static pressure ports, 1 total pressure port per probe



Probe pressure port layout



RAGE flowfield rake

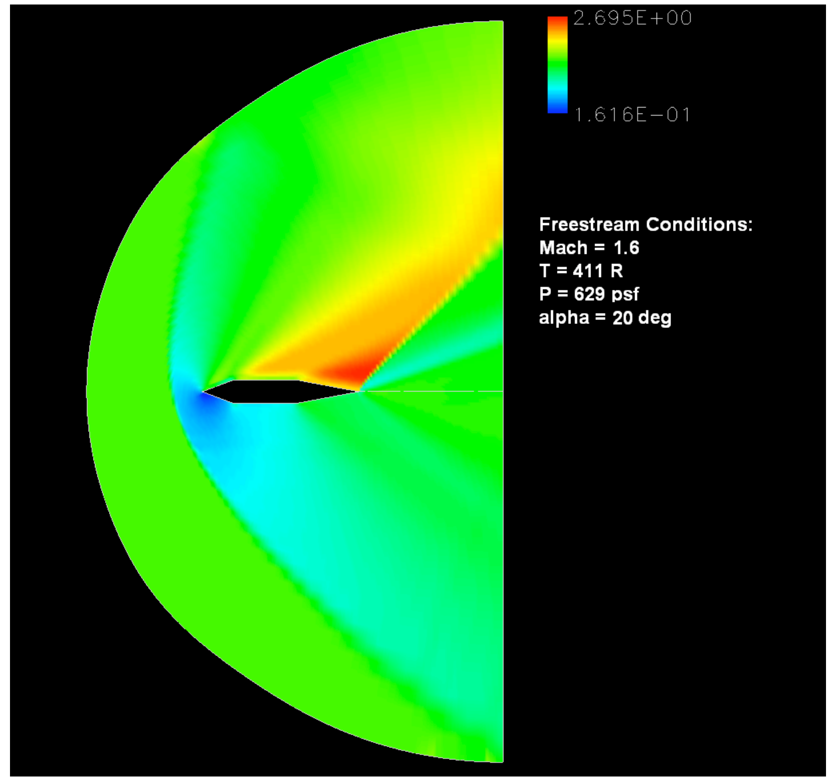
Rake Aerodynamic Loads

- 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 20º is 2x greater than max expected

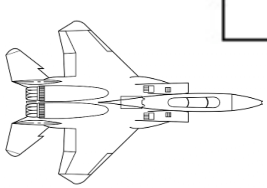
Aerodynamic load predictions

Quantity	NACA	CFD
F_n/l	255 lb/ft	328 lb/ft
F_t/l	13 lb/ft	33 lb/ft
W/l	n.a.	28 lb
c.p.	45%	41%

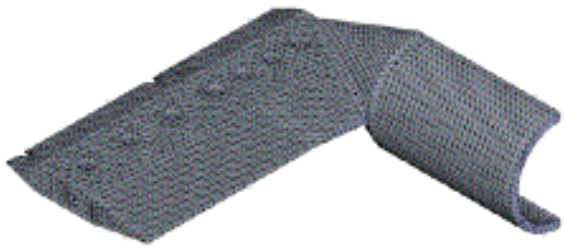
Rake Cross Section



Mach Contours M = 1.6 alpha = 20 deg.

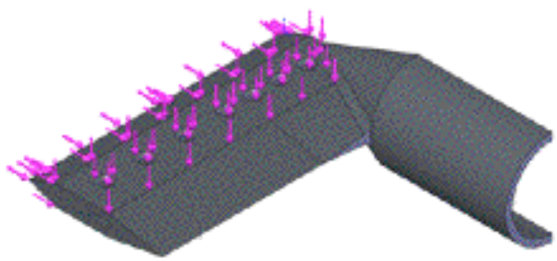


Rake Stress Analysis

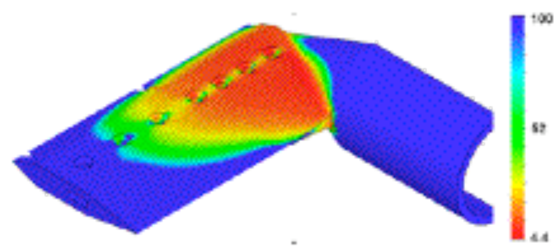


a) COSMOSWorks mesh.

b) Boundary conditions looking from fore to aft.



c) Applied axial and normal loads.

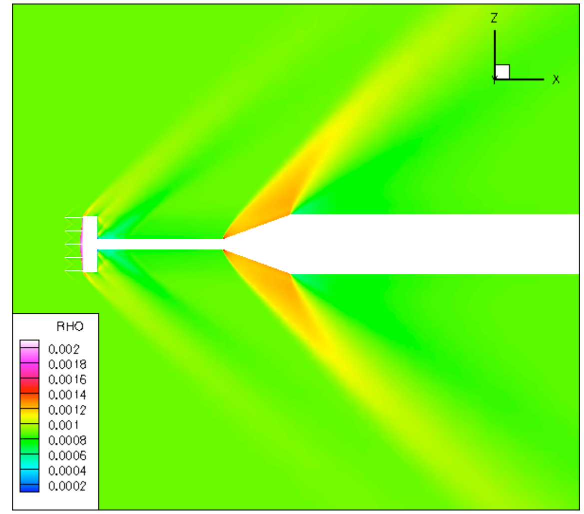


d) Factor of safety contours

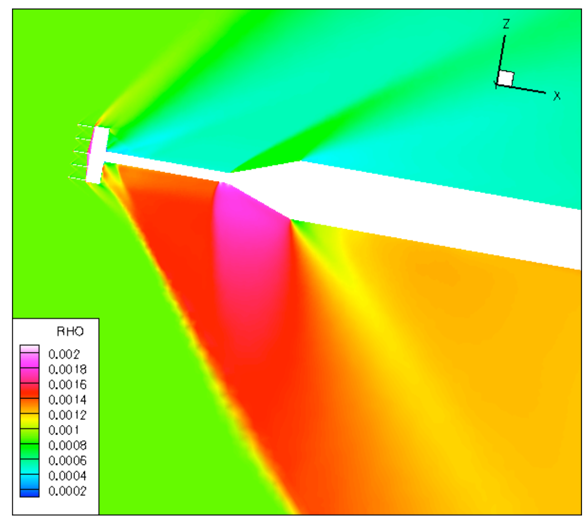
- SolidWorks/COSMOSWORKS finite element solver (95672 nodes)
- CFD estimated aerodynamic loading used for normal and axial forces
- σ_{max} = 13.5 ksi, minimum FOS of 4.4

RAGE Assembly CFD

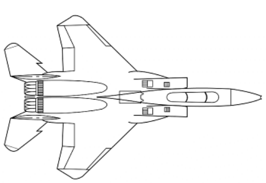
- Aerodynamic loads estimate of entire assembly necessary to ensure PFTF force balance isn't overloaded
- RAGE assembly aerodynamic forces and moments were predicted using CFD
- Air Vehicles Unstructured Solver (AVUS) from AFRL
- 3D unstructured tetrahedron mesh
- 8 zones, 3.36 million points, 17.8 million cells, with 1 plane of symmetry
- Simulated *PFTF local* flight condition: M 1.6 @ 29,500 ft
- Steady-state, inviscid computation



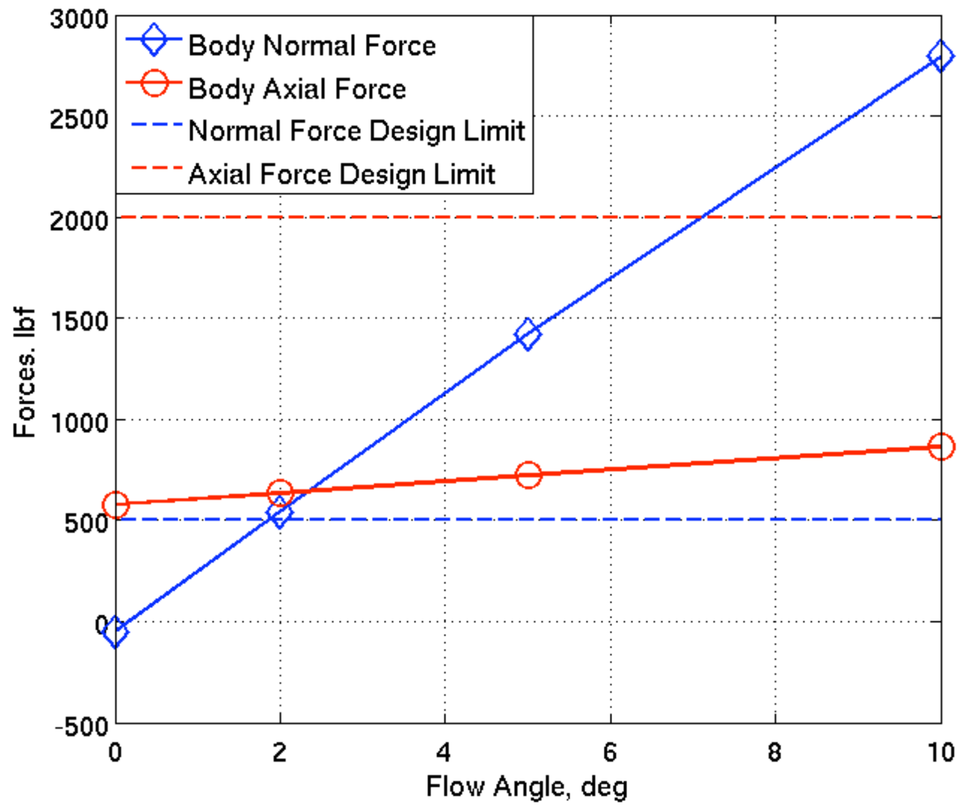
Density Contours 0º AOA



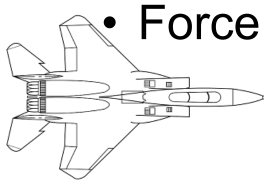
Density Contours 10º AOA



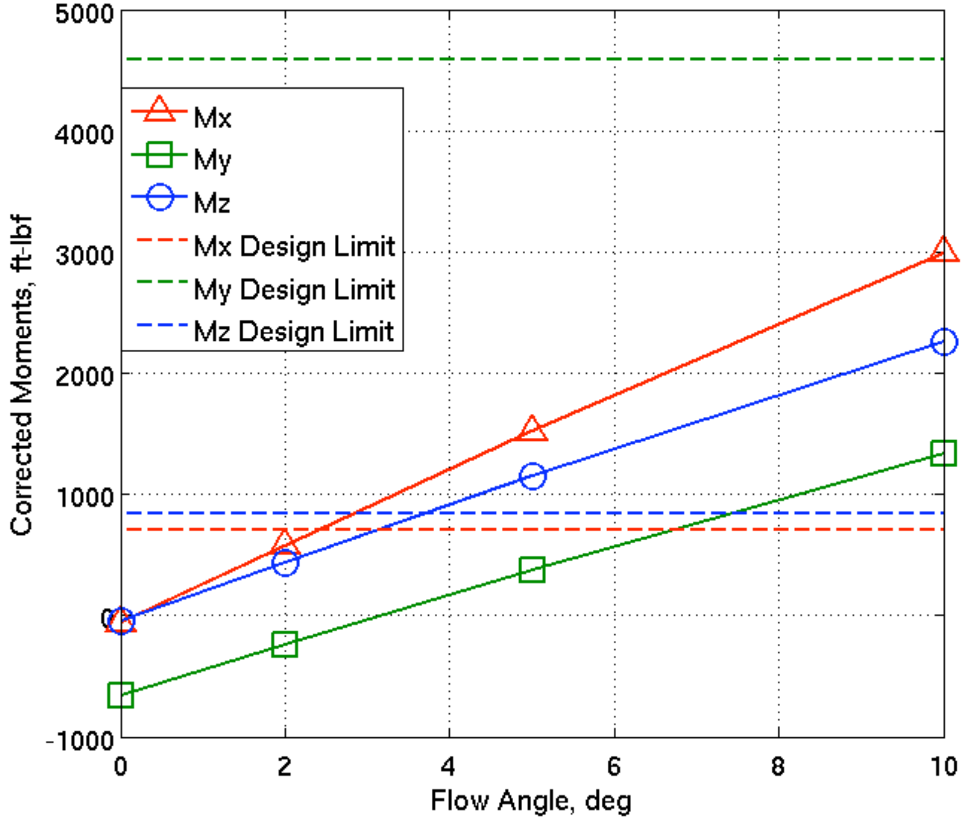
CFD Results: Forces



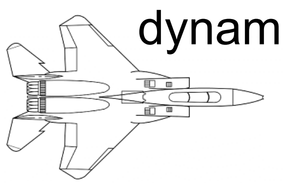
- M = 1.6, hp = 30,000 ft
- Geometry is symmetric in lateral and normal directions
- Axial load significantly less than PFTF force balance limit
- Force balance side load limit hit around 1.8º β at highest dynamic pressure



CFD Results: Moments

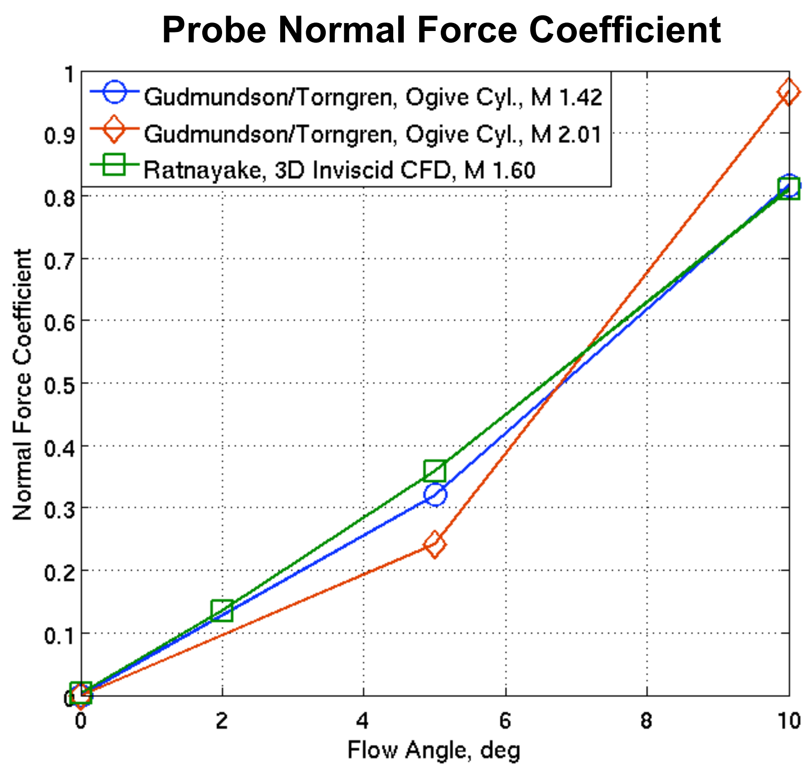


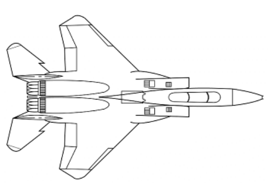
- M = 1.6, hp = 30,000 ft
- Moments corrected to load test reference frame
- Lateral (roll/yaw) moments limits are hit at around 2.5 to 3.5 deg. β at highest dynamic pressure



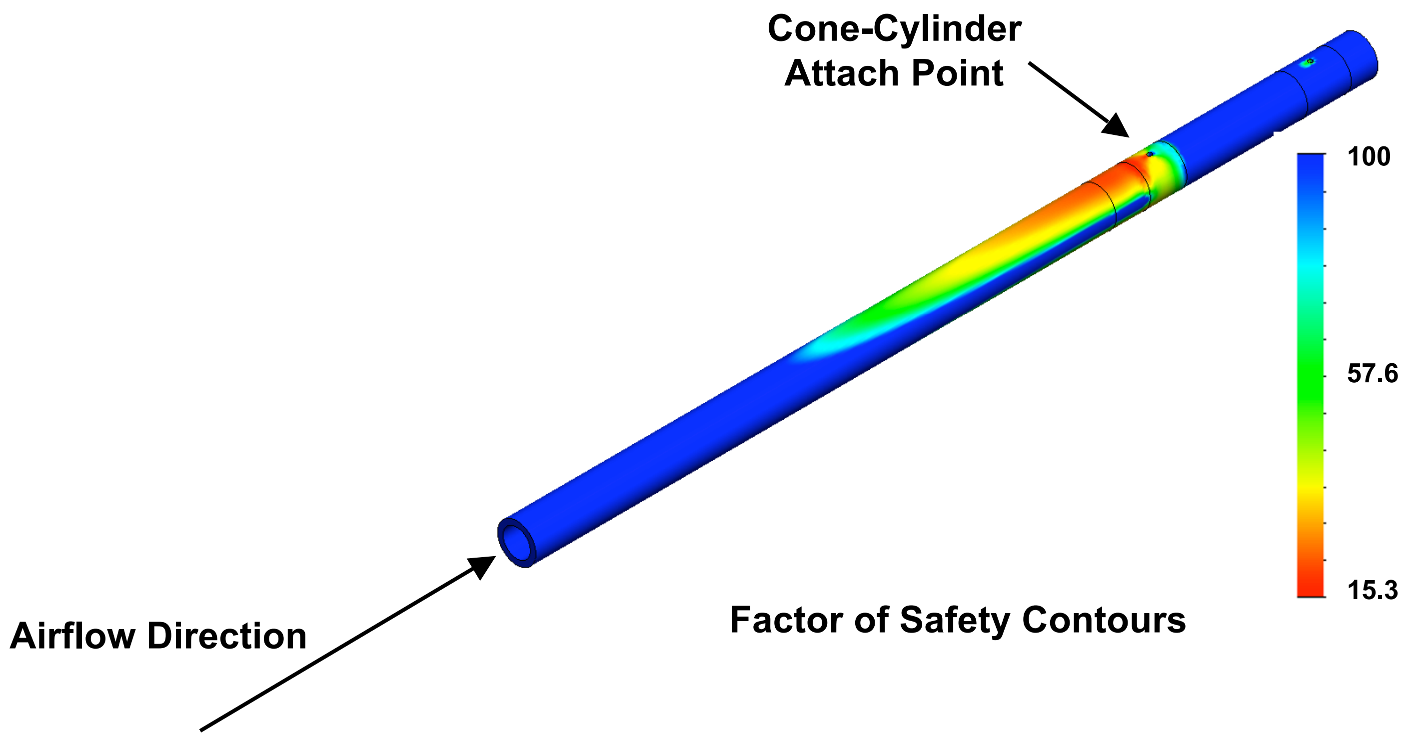
Probe Aerodynamic Loads and Stress

- 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
  - σ_{max} = 9.95 ksi, minimum FOS of 2.59





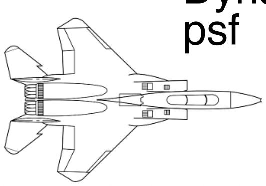
Boom Loads and Stress



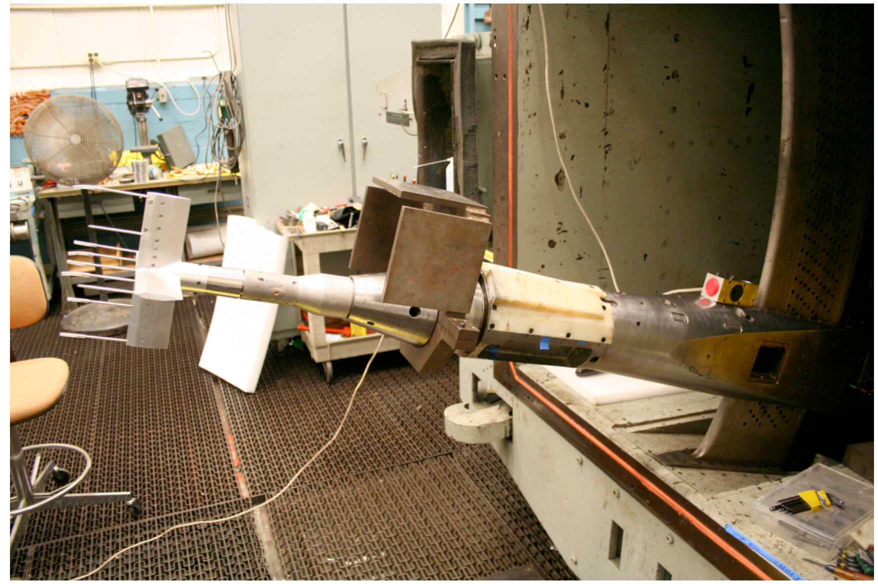
- Rake and boom forces determined from RAGE assembly CFD
  - F_n = 131 lb, F_a = 49.3 lb
- SolidWorks/COSMOSWORKS FEM used for stress analysis (107785 nodes)
- Minimum FOS of 15.3

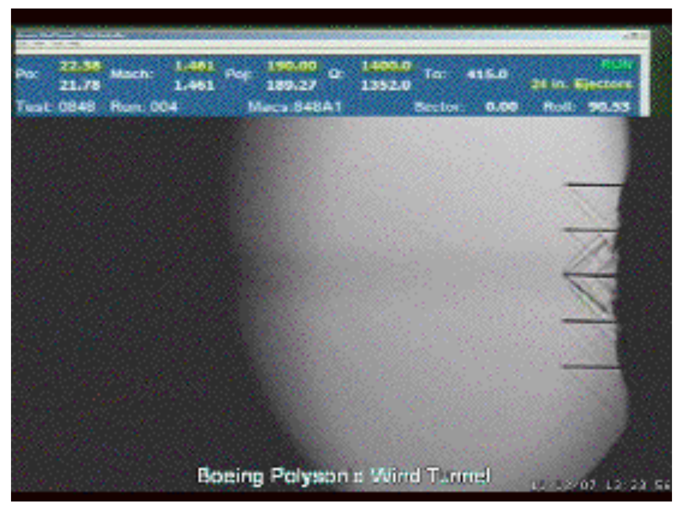
Wind Tunnel Calibration

- 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



Wind Tunnel Setup





Shadowgraph Image M = 1.461

Calibration Data Reduction

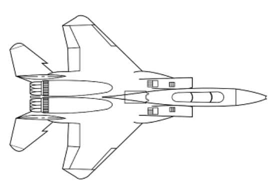
- Wind tunnel data was reduced and calibration algorithm was developed based on the method given in NACA-TN-3967, "Characteristics of a 40 Degree Cone for Measuring Mach Number, Total Pressure, and Flow Angles at Supersonic Speeds"
  - Iterative procedure calculates the local Mach, total pressure, and 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

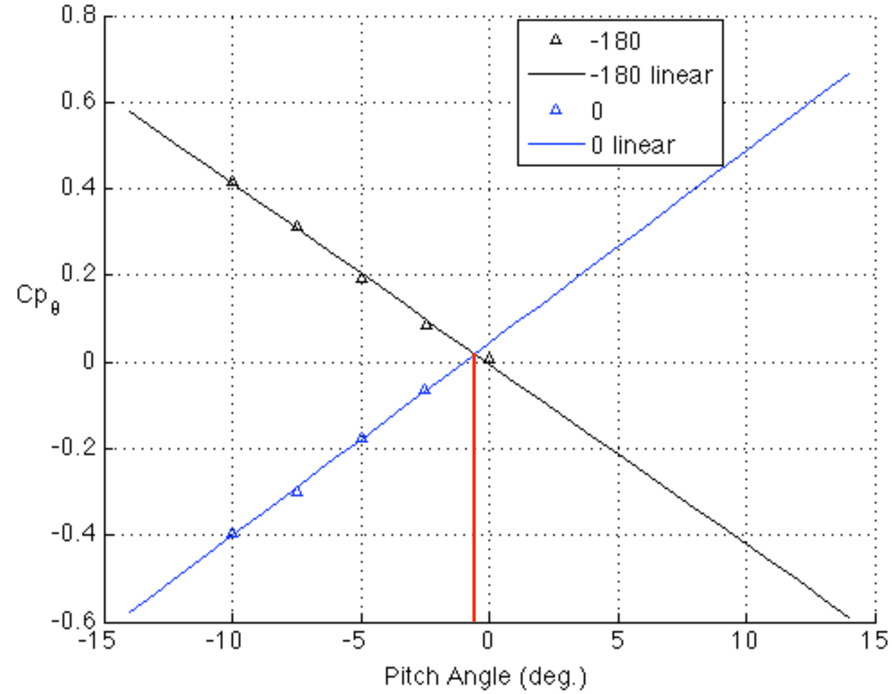
- Wind tunnel data was corrected for misalignment and tunnel stream angularity
- Vertical pressure coefficient defined using vertical pressure ports:

$$Cp_{\theta} = \frac{p_3 - p_5}{q}$$

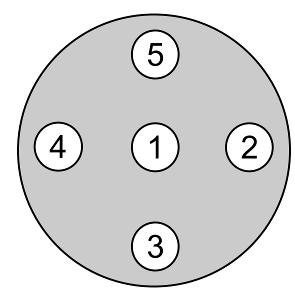
- Vertical pressure coefficient for roll angles of 0° and -180° was plotted versus pitch angle. Intersection of two curves represents the vertical misalignment angle θ_0
- θ_0 = -0.56°, -0.42°, and -0.15° at Mach 1.461, 1.508, and 1.611
- Horizontal misalignment angle couldn't be determined due to absence of data at a roll angle of 90°



Probe 1 misalignment correction (Mach 1.461)

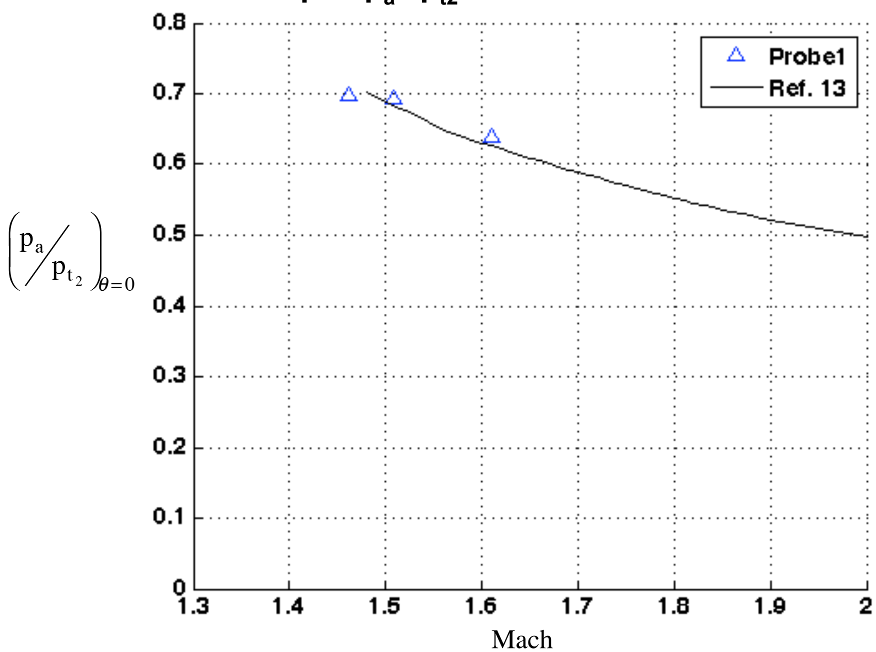


Probe Pressure Port Layout

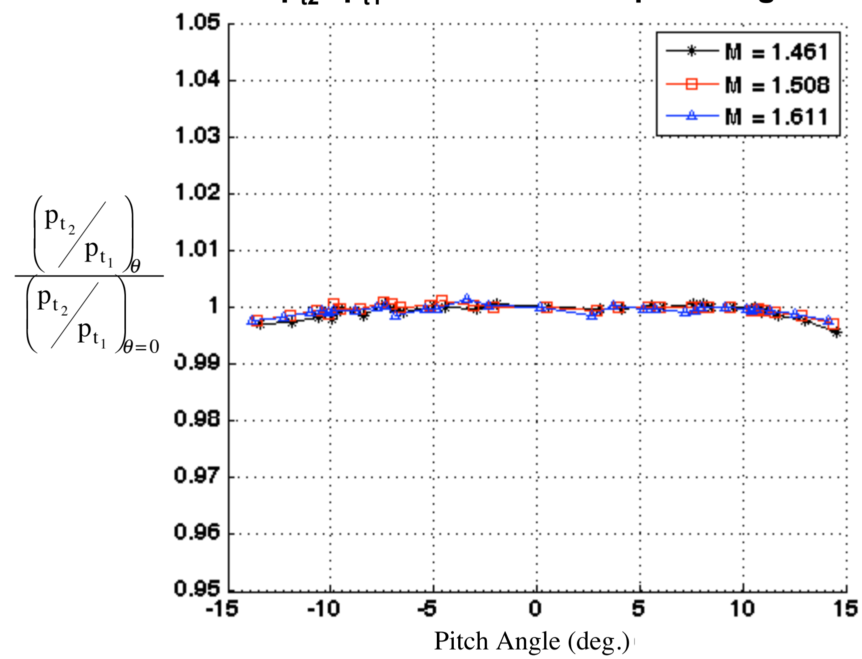


Mach Calibration Maps

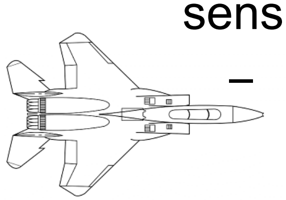
Map1. p_a / p_{t2} as a function of Mach



p_{t2} / p_{t1} as a function of pitch angle

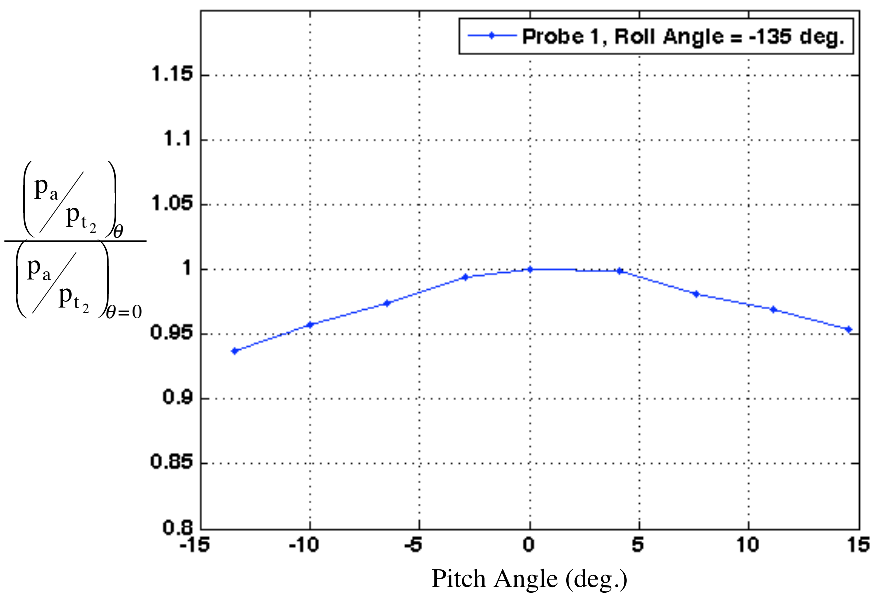


- Mach number is determined from the ratio of the mean of the four static pressures to the pitot pressure (p_a / p_{t2})
- Lookup table created for p_a / p_{t2} at zero flow inclination as a function of Mach
- Ratio of pitot to total pressure in front of shock (p_{t2} / p_{t1}) plotted to check for sensitivity 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

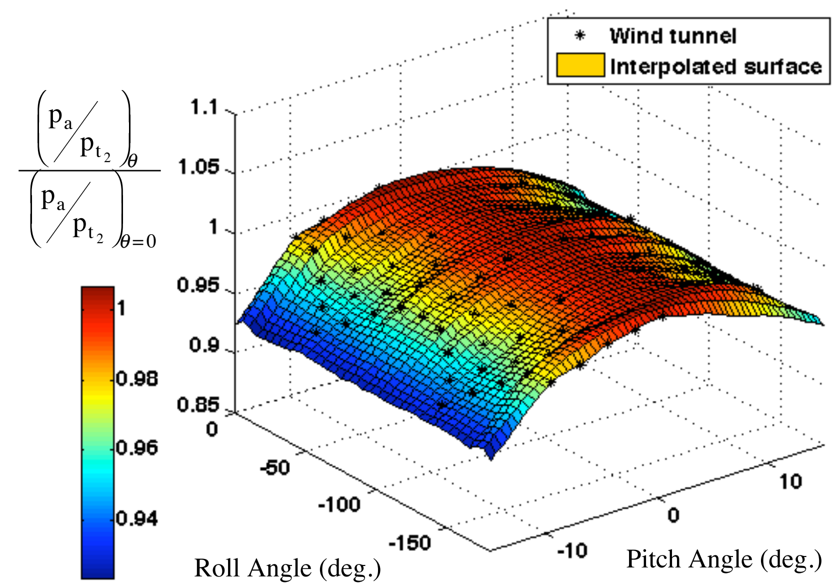


Mach Calibration Maps

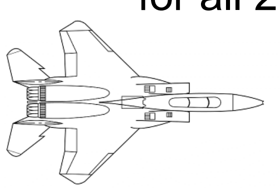
Change in p_a / p_{t2} due to flow inclination (M = 1.461)



Map 2. Correction factor to p_a / p_{t2} due to flow inclination (M = 1.461)



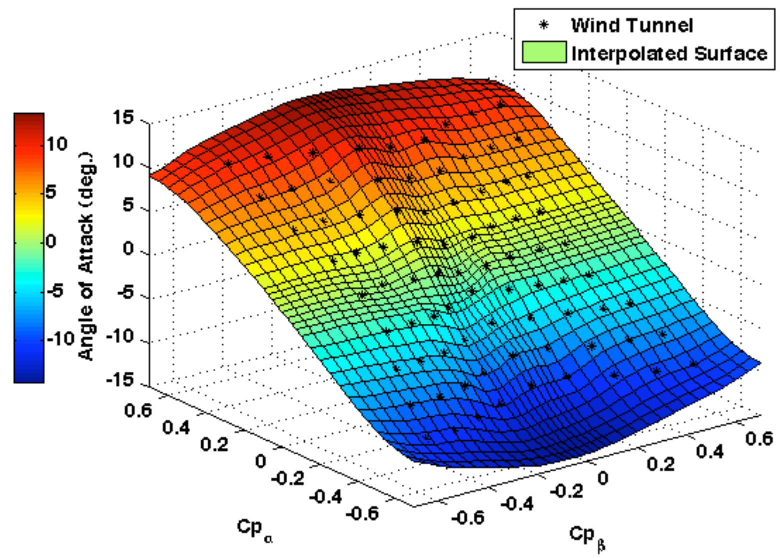
- In general, p_a / p_{t2} must be corrected for flow inclination
- p_a / p_{t2} plotted as a function of pitch angle for all 21 different roll angles
- 3-D calibration maps that provide a correction factor to p_a / p_{t2} were generated from data for all 21 distinct roll angles



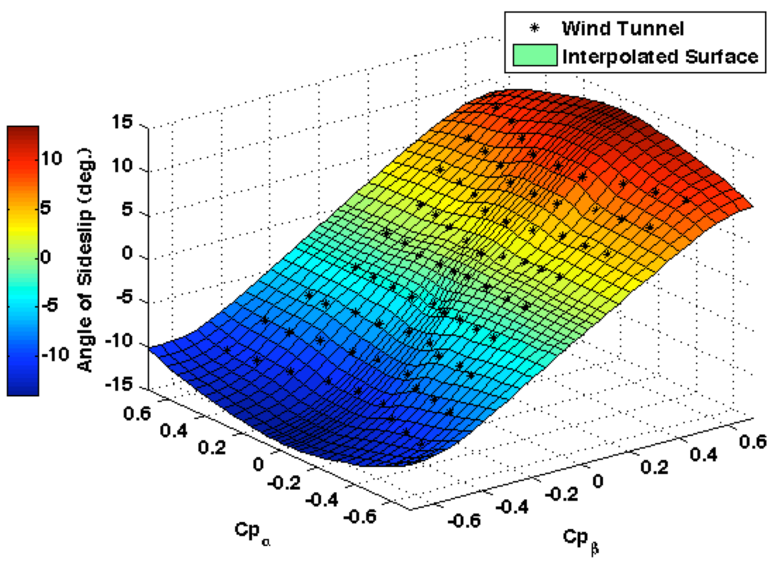
Flow Angle Calibration Maps

- Angle of attack and angle of sideslip pressure coefficients were defined as:

$$Cp_\alpha = \frac{p_3 - p_5}{q} \qquad Cp_\beta = \frac{p_4 - p_2}{q}$$

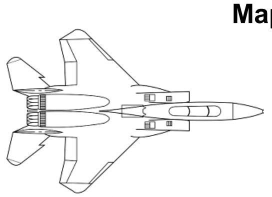


Map 3. Angle of attack calibration map (M = 1.461)

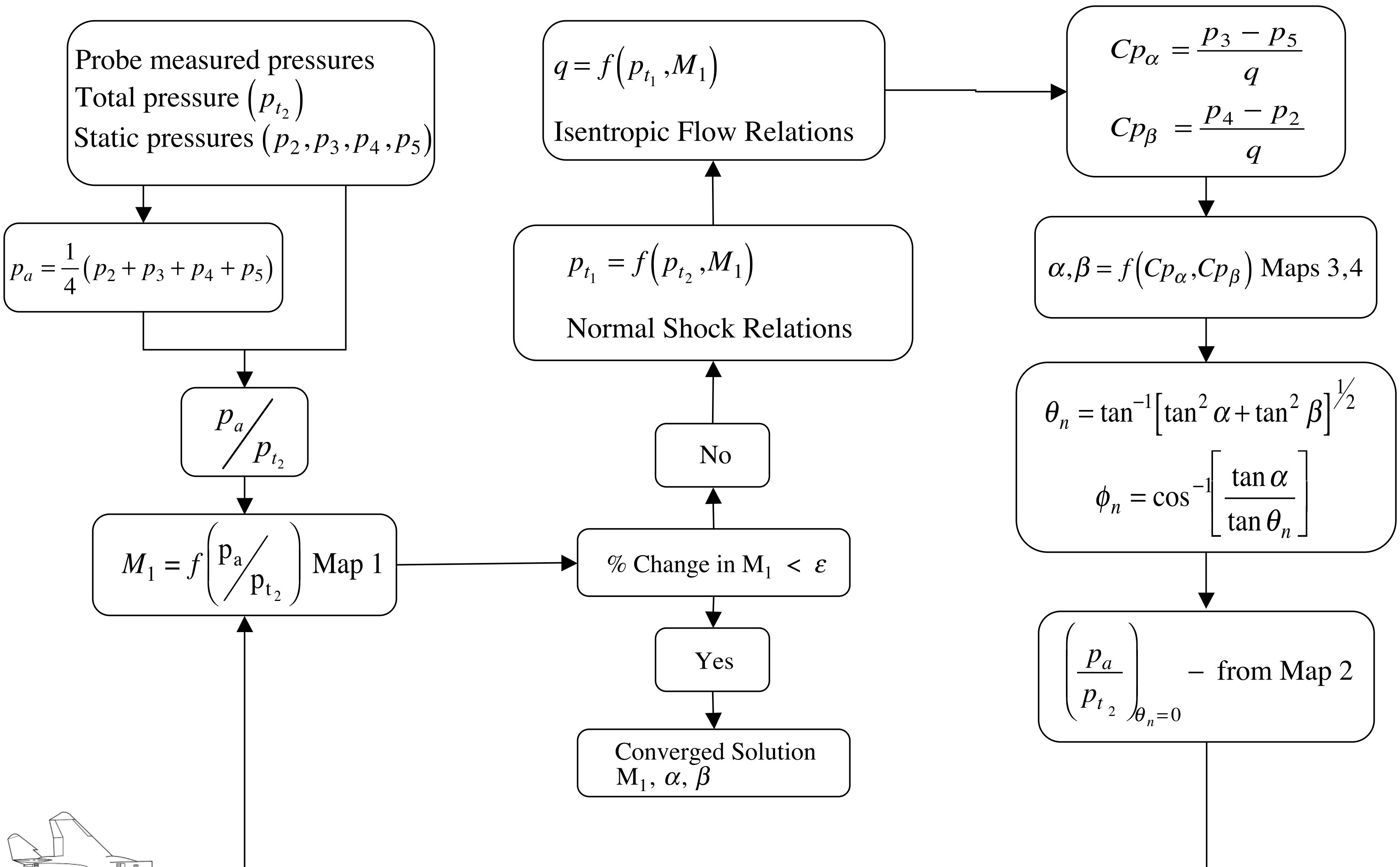


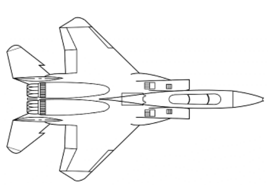
Map 4. Angle of sideslip calibration map (M = 1.461)

- Wind tunnel data was used to create 3-D calibration maps for α and β
  - α and β are looked up using computed Cp_α and Cp_β



Calibration Algorithm





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