Performance Improvements in Boeing/AFOSR Mach 6 Quiet Wind Tunnel Based on CFD Predictions

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3rd International Symposium on Integrating CFD and Experiments in Aerodynamics
US Air Force Academy
Colorado Springs, CO
June 20-21, 2007
Motivation

- Importance of quiet tunnels for hypersonic research
  Understanding the nature of laminar-to-turbulent transition is crucial for:
  - Reusable launch vehicles
  - Hypersonic reconnaissance aircraft
  - Hypersonic cruise vehicles
  - Ballistic reentry vehicles

- Current Programs
  - DARPA FALCON glide vehicle
  - X-51
  - Orion
- Transition location affects data
  - Aerodynamic Heating
  - Skin Friction Drag
  - Heat Shield Weight, Materials

- Conventional wind tunnel
  Contaminated by high noise levels
  - Location of transition
  - Parametric trends for transition
- **Quiet Flow Wind Tunnel**
  - Simulate hypersonic flight where the noise levels are very low
  - Laminar boundary layers in the test section

- **Quiet Facilities**
  - NASA Langley -- $M=3.5$
  - NASA Langley -- $M=6$
    - Reassembled at Texas A&M
  - NASA Langley -- $M=8$
    - Abandoned, 2001
  - Boeing/AFOSR Mach-6 Quiet Tunnel (BAM6QT)
    - 145 psia, $Re \sim 13 \times 10^6$

*The Development of Hypersonic Quiet Tunnels, S. P. Schneider
37th AIAA Fluid Dynamics Conference, June 2007*
Ludwieg Tube

All Clean Stainless Steel from Second-Throat Section Upstream Unique Low-Noise Flow due to Laminar Nozzle-Wall Boundary Layer

(Slow) Gate Valve

17.5-in. Driver Tube, 122.5-ft. long

Bleed-Slot Suction Plumbed Both Through Fast Valve to Tank and to Diffuser

Max. 300 psig (21.7 bar, abs.) and 392F (200C). One 10-s. run per hour. About $10/run operating cost.
During many cycles of expansion-wave reflection, the pressure drops in stair-step fashion.
Quiet flow region in test section is determined by:
- Characteristics marking onset of uniform flow
- Characteristics marking beginning of acoustic radiation from onset of turbulence
Bleed slot before the throat removes contraction-wall boundary layer

Purpose: reduces noise by delaying boundary layer transition
Test Section Expansion

- Shocks emanating from a model interact with nozzle wall boundary layer, causing separation for blunter models
- Expand the test section diameter and determine the largest model that can be started in the tunnel
Objectives

Two cases that used CFD to improve performance of the BAM6QT:

- The effect of bleed lip geometry on nozzle wall boundary layer transition
- The effect of a test section expansion on the ability to test larger blunt models
Bleed Lip Redesign

As of 2005, the tunnel was not yet quiet for the desired range of pressures up to 150 psi.

Cause of test section noise:
• Early transition of the nozzle wall boundary layer.

Cause of early transition:
• Separation bubbles on the bleed lip and associated fluctuations induced near the bleed lip.
Bleed Lip Redesign

- Use CFD to
  - Investigate numerically the existence of steady and unsteady separation bubbles on the main flow and/or the bleed flow side of the original nozzle lip
  - Design a new geometry to eliminate or reduce the size of the separation bubbles
Analysis of Existing Bleed Lip

The geometry is represented by two surfaces.
Analysis of Existing Bleed Lip

- Separation bubbles exist on both the main flow and bleed flow sides for all the stagnation pressures tested.

Mach number contours and streamlines for 150 psi.
Analysis of Existing Bleed Lip

- Separation bubbles exist on both the main flow and bleed flow sides for all the stagnation pressures tested.

\[ \Gamma_w = \mu_w \frac{\bar{s} \cdot \bar{V}}{\Delta n} \]

Mach number contours and streamlines for 150 psi.
Results of Original Bleed Lip

14 psi

Separation bubbles:
- Unsteady on bleed flow side (upper surface)
- Steady on main flow side (lower surface)
Redesign of Bleed Slot

- The bleed lip was cut less than 0.1 in (2.54 mm)
- An adverse pressure gradient is present just aft of the blunt nose on a flat plate in uniform flow. As a semi-elliptical nose becomes more slender, this gradient reduces. (Hess and Smith, 1967)
- The basic idea in the modifications of the bleed lip is to make the lip more slender to eliminate the separation bubbles.
Mach Contours for Modified Geometry

There is no separation bubble on both the main flow and bleed flow sides of the bleed lip with the modified geometry up to a stagnation pressure of 300 psi.
Redesign of Bleed Slot

- No separation bubble on either the upper or the lower surface
- Wall shear stress is always positive around the bleed lip
Goal: Expand Diameter to fit larger, blunter models
Separation of the upstream boundary layer is often induced when strong bow shocks from blunt models interact with the nozzle wall boundary layer.

If the bow shock impinges on a shear layer before reaching the wall separation might be avoided (Skoch, Schneider & Borg, 2005)
Results
Unstart
Results

- U Velocity contours of 75° cone unstarting the tunnel
- Separation bubble forms at expansion corner and grows until inflow boundary
- Separation bubble moves slightly upstream and remains in place
- tunnel is not unstarted
- may cause noise and interfere with quiet flow measurements
Summary

Two examples of design modification based on CFD analysis:

- **Bleed slot modification**
  - Separation bubbles were shown to exist on both the main flow and the bleed flow sides of the bleed lip
  - Separation bubbles are eliminated up to 300 psi (operational limit of the tunnel)
  - BAM6QT was remachined in 2006 and quiet flow was subsequently achieved at 150 psi

- **Test Section Expansion**
  - Bow shocks from large models cause the flow upstream to separate
  - 15° cone fit into modified section without causing unstart – an improvement over the 7° cone currently used