Measurements of Boundary-Layer Instability and Transition in the Mach-6 Quiet Tunnel

Steven P. Schneider, Brandon Chynoweth, Gregory McKiernan, Joshua Edelman, J. Adam McKenzie, Cameron Sweeney, Chris Ward and Ryan Henderson

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Why Study Laminar-Turbulent Transition?

• Laminar flow results in 2-8 times less aeroheating than turbulent flow. Major issue for many hypersonic systems, including scramjet-powered and boost-glide vehicles for time-critical strike.

• These changes in viscous heating affect signatures.

• Transition affects separation and is affected by separation. Separation and reattachment are important for drag, heating, moments, and other properties. Likewise, transition affects shock/b.l. interaction and shock/shock interaction.

• Laminar flow has much lower skin-friction drag. This affects high L/D vehicles like gliding RV’s and scramjet vehicles. Asymmetric skin-friction drag can also be a critical issue for vehicle moments.
Challenging to Estimate Transition in Flight Using Computations and Ground Experiments

• No single ground-test facility can simultaneously simulate the Mach number, Reynolds number, model scale, roughness scale, enthalpy & chemistry, ablation, wall temperature, and freestream fluctuations in flight.

• There is no reliable theory to predict hypersonic transition. All computations must make many assumptions. However, the first approximate mechanism-based theories are now becoming available and affordable.

• Transition is like structural failure – there are several different mechanisms that can cause it to occur, and all must be considered and approximated.

• Ground-test results must be extrapolated to flight using mechanism-based computational approximations or crude algebraic correlations. These extrapolations are only as good as the data that supports them.

• Measurements in various ground-test facilities should be compared using state-of-the-art theory and computation.

• Six decades of scientific research has led towards a better understanding of the mechanisms, and better methods for computing and measuring them. This science must be advanced and used to improve system designs.
Boeing/AFOSR Mach-6 Quiet Tunnel (BAM6QT)

- Largest of three operational hypersonic quiet tunnels in the world
- Ludwieg tube design provides low operating costs, 3-10 sec. run
- Good optical access, last nozzle section permits various inserts
- Capable of running quiet or noisy
Overall Strategy: Reliable Predictions are Needed and Must Be Based on the Mechanisms

- Develop comparisons between theory, computation, and experiments to work toward reliable prediction methods
  - **Bridge the Gap between Users and Researchers**
- Semi-empirical methods like $e^N$ theory can be improved. What are the critical limitations? How can they be overcome?
- Dominant mechanisms on reentry vehicles and airbreather forebodies remain to be determined; limited data at present
- Prioritize those mechanisms most likely to be important to the DoD
1) **AFOSR**: **Chris Ward**, Crossflow on cone at 6-deg. AoA. Grad. Dec. 2014
^^^^ Students working on Projects 1-5 all left Purdue in 2014 (!) ------^  
6) **AFOSR**: **Brandon Chynoweth**. Second-mode wave growth and breakdown to turbulence on a flared cone under fully quiet flow.
7) LM-AFRL/AFOSR: **Greg McKiernan** continues joint project.
8) Dr. **Matt Borg** from AFRL. HIFiRE-5 in Mach-6 quiet tunnel.
9) USAF 2LT **J. Adam McKenzie**. 2D strips for second-mode control.
10) **Joshua Edelman**, Crossflow on the 7-deg. cone at AoA
11) **Cameron Sweeney**, Further characterization of the Mach-6 quiet tunnel
12) Collaboration with ONERA+CNRS for generic scramjet forebody

FY15 Quiet-Flow Tunnel Performance

• Since Sept. 2010, max quiet pressure has remained higher than before, about 170 psia or $3.8 \times 10^6$/ft. Have not opened throat. Still!

• Nozzle-wall boundary layer is laminar well past the nozzle exit at these pressures, so model sees fully quiet flow (although this still needs to be confirmed with direct model-mounted pitot measurements)

• 7x14-inch window cracked in fatigue, was replaced.

• Mostly running 45-50 weeks per year, ~20 runs/week depending on the experiment. Summer and Fall 2014, tunnel was often idle due to lack of staff to run it. Mostly busy since.

• Tunnel continues to run well except for summer 2014, unplanned maintenance on fast valve for bleed air. This took a long time due to illness of critical staff at vendor. Repairs can now be done in house with spare parts now stockpiled.
Secondary Instability of Stationary Crossflow Waves

- 3D mean flows on lifting vehicles generate secondary flow within the boundary layer, perpendicular to the edge velocity, known as crossflow.
- The associated inflection point creates crossflow instability in two forms:
  - Stationary waves, which are body fixed vortices. Induced from roughness
  - Travelling waves, which travel with respect to the surface.
- A high frequency secondary instability seems to appear when the stationary crossflow instability reaches saturation.
- Can we verify this? When? Etc.
- Can we do $e^{**N}$ with the secondary instability to predict stationary-crossflow transition, as at low speed? (Malik et al. JFM 1999)
- Use a canonical 7-deg. cone, usually at 6-deg. AoA, to study the science.

Schematic of a three dimensional boundary layer with crossflow (J. Adams 1973)
New 7° Half-Angle Cone with More Sensors

Controlled Roughness ala Corke to Induce Stationary Waves. Still Needs improvement.

- 7° half-angle cone, 16 in. long, 4 in. base diameter, sharp nose tip, multiple roughness inserts.
- Often 6° angle of attack, also lower AoA.
- 1 Schmidt-Boelter (SB) gauge.
- 8 PCB pressure transducers
- The two PCB arrays are separated by 0.5 in, with 6° azimuthal angle between the sensors in each array
- Temperature sensitive paint.
Sample Measurement of Probable Secondary Instability

- Apparent secondary instability sometimes observed, when a large stationary crossflow wave passes over a PCB-132 sensor upstream of transition. Only in small region where stationary wave is large but not yet transitional. Further downstream, pressure fluctuation spectra look turbulent.

- Not a second mode wave – small changes in location, upstream roughness or unit Reynolds number cause dramatic effects unlike for second mode.

Roughness insert with 30 dimples of depth 0.006 in and diameter 0.008 in. 6 deg. AoA.
Effect of Small Reynolds Number Changes on Possible Secondary Instability of Stationary Crossflow Wave

Data included for PCBs 1 and 5, shown above with streak passing through.

- Show data for 5 runs at close stagnation pressures of 168, 160, 150, 140 and 133 psia
- PCB 1&5 are at 132° from windward ray
- 6° AoA
- Roughness insert, 50 dimples, 0.004” depth
PCBs 1 (Upstream) and 5 (Downstream)

Secondary Instability Near 250-300kHz?
Smooth Consistent Dependence on Reynolds No.

Travelling crossflow wave

PCB 1 - Runs 20-24
PCB 5 - Runs 20-24

Red solid and dash from two different runs

Normalised by edge pressure for cone at zero angle of attack (Taylor-Maccoll).

PSDs from Welch’s method, frequency resolution of 2 kHz.
Magnitude Squared Coherence, PCBs 1 & 5

Coherence PCBs 1 & 5 - Runs 20-24

Good coherence for cases without much broad-band turbulence

- Travelling crossflow wave
- Potential secondary instability
Summary of Crossflow Instability Results

• Three different graduate students studying the crossflow instability all noticed an apparent secondary instability of the stationary crossflow wave using a 7° cone at angle of attack.

• Further experiments in process:
  - Using more sensors to better map out the development of surface pressure fluctuations, and aligning the sensors with the typical angle of the stationary waves
  - Achieving better control of the stationary waves using improved patterns of surface roughness to introduce them

• Seek computational comparisons, and also predictions of transition onset ala Malik et al. JFM 1999.

• Success could deliver a preliminary method for predicting crossflow transition on DoD flight vehicles.
Overall Summary

1. Continuing study of nonlinear breakdown of second-mode waves on flared cone using small roughness arrays upstream. Improving control. 3-deg. straight cone looks promising as an alternate without Görtler.

2. Small surface roughness affects crossflow-induced transition on a round cone at AoA. Can move transition upstream and downstream, can affect traveling waves. More observations of apparent secondary instability of stationary crossflow. Still need better control and measurement

3. Large effect of tunnel noise on generic scramjet forebody for French. Transition induced using jet trips with good comparisons to their LES computations.


5. 2D roughness can damp 2nd-mode waves on flared cone, looking at effect of strip locations, etc.
Next Steps

- Procuring new throat to improve quiet Reynolds number
- Improve our ability to manipulate the crossflow waves using controlled roughness. Add more instrumentation to better capture the apparent secondary instability, which is very sensitive to small changes in conditions.
- Manipulate nonlinear breakdown streaks on the flared cone and perhaps straight cone, using controlled roughness. Compare to computations. Look at effect of roughness and configuration on second-mode amplitude at breakdown, improve the Marineau correlation.
BACKUP
Shadowgraph of Transition on Sharp Cone at Mach 4

5-deg. half-angle cone in NOL Ballistics Range at Mach 4.31. Shot 6728, Dan Reda, AIAA Journal v. 17, number 8, pp. 803-810, 1979. \( \text{Re}_\infty = 2.66 \times 10^6/\text{inch} \), cone length is 9.144 inches. From Ken Stetson. Cropped

Published as Fig. 1 in Schneider, Prog. Aero. Sci., v. 40, Jan.-Feb. 2004, pp. 1-50
Uncertainty in Empirical Correlations can be a Major Issue for Some Designs

Ballistic Reentry-Vehicle Flight Data, Blunt Sphere-Cones Near Zero AoA

Transition becomes an issue when the uncertainty in transition affects performance!

Sure Turbulent

uncertainty is large!

teflon frusta
phenolic frusta
metallic frusta
graphitic frusta
lower bound?
upper bound?

$\frac{Re_e}{M_e} = 150$

Berkowicz et al. AIAA 77-125 Table 2
This file set transmitted 27 June, to make sure it arrives in time for the meeting, since Schneider is on vacation 29 June to 6 July, and files to be uploaded by 8 July.

Publications, Technical Challenges Remaining, and Business Update to be sent later. Also, further improved figures with even better labels to be sent later.