Discrete surface roughness effects on a blunt hypersonic cone in a quiet tunnel

AEROSPACE ENGINEERING
TEXAS A&M UNIVERSITY

Nicole Sharp
Edward White

APS DFD, Pittsburgh, PA
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Roughness and transition

- All realistic hypersonic flight vehicles have roughness, which can cause transition to turbulence.
- Turbulent boundary layers exhibit higher skin friction and mixing, causing increased vehicle drag and heating.

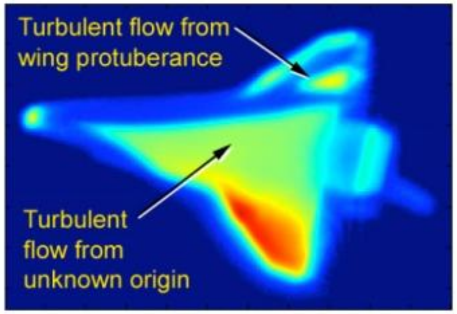


Fig. 8. STS-119 Mach 8.4
Slant Range ~ 28 nautical miles
Alt. ~ 161 kft
Body Flap Deflection = 1.86 deg

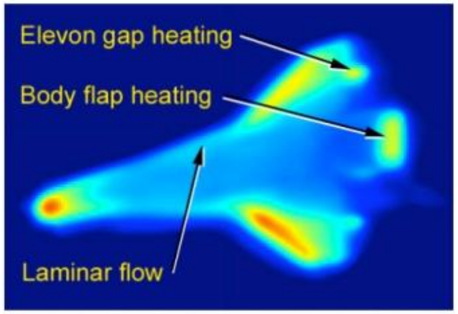


Fig. 9. STS-125 Mach 14.3
Slant Range ~ 38 nautical miles
Alt. ~ 189 kft
Body Flap Deflection = 1.9 deg

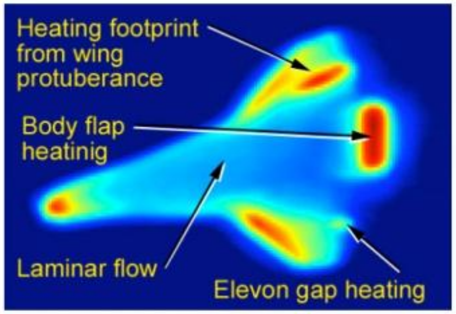
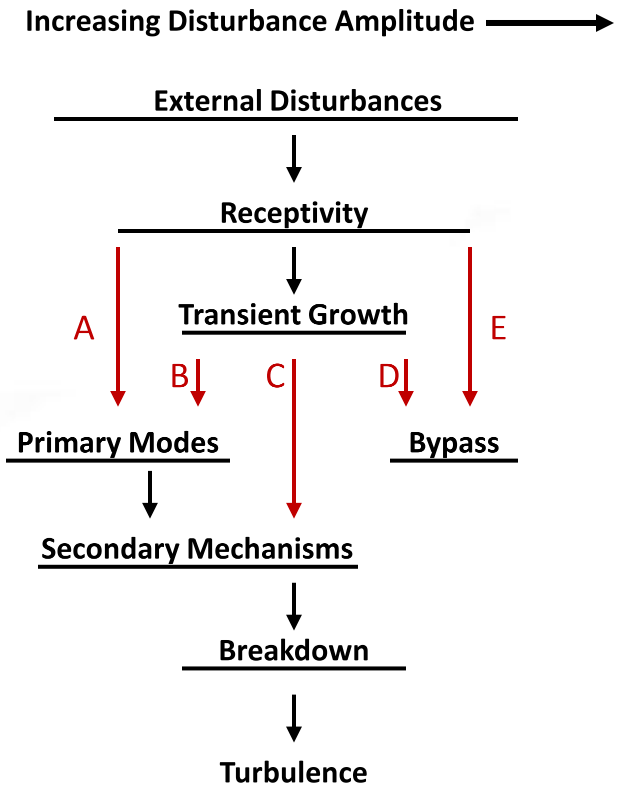
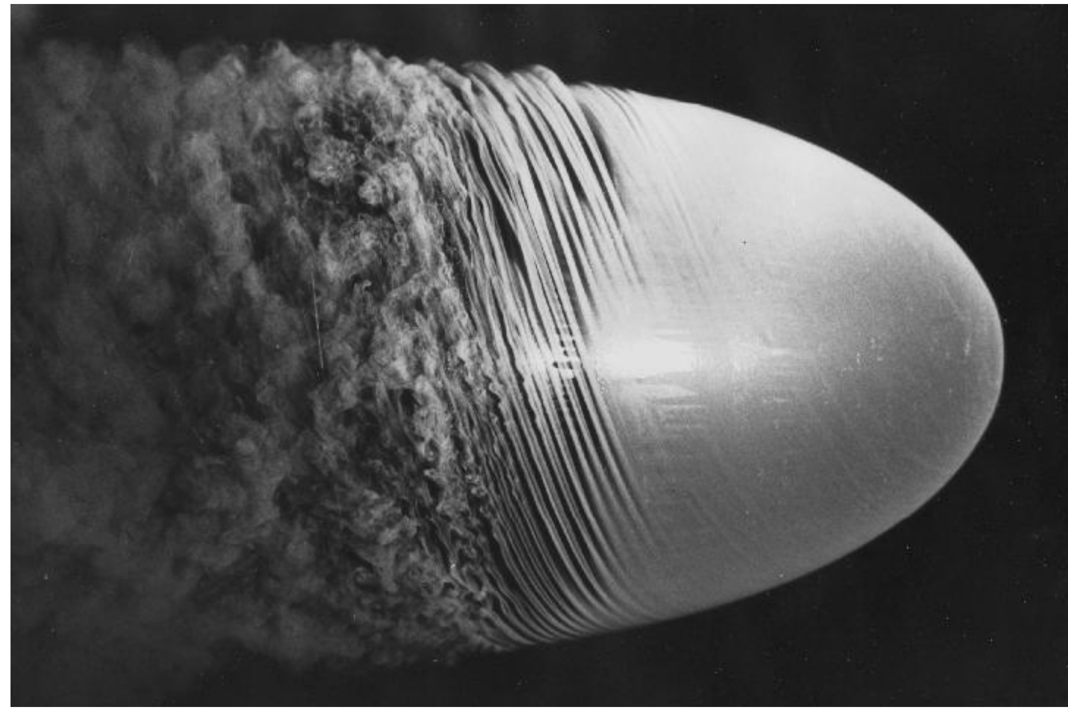


Fig. 10. STS-128 Mach 14.7
Slant Range ~ 43 nautical miles
Alt. ~ 191 kft
Body Flap Deflection = 7.54 deg

Image credits: NASA, Horvath *et al.* AIAA 2010-241.

The transition roadmap



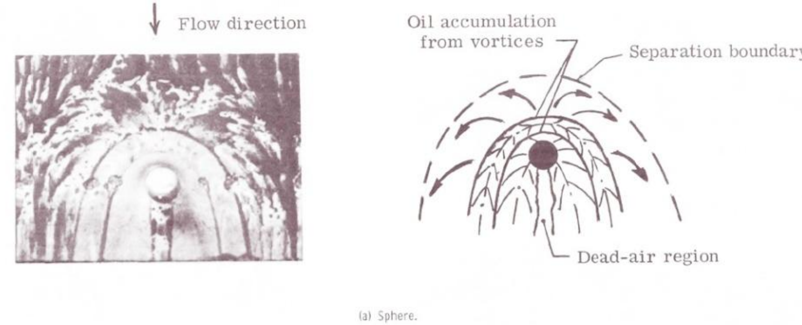


- Disturbances enter the boundary layer through *receptivity*, then grow by one or more mechanisms before causing breakdown and turbulence.
- These disturbances include freestream turbulence or acoustic noise, surface roughness, curvature discontinuities, surface vibration, etc.

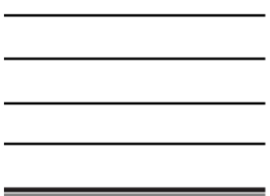
Image credit: Y. Kohama; Transition map adapted from Morkovin *et al.* (1994).

Transient growth: physically

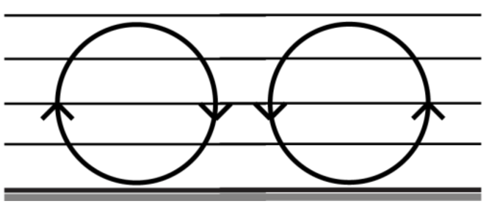
- Transient growth of high and low speed streaks can form as a result of the lift-up mechanism.
- Transient growth is particularly effective for streamwise vortices,[1] such as those produced downstream of roughness.[2]



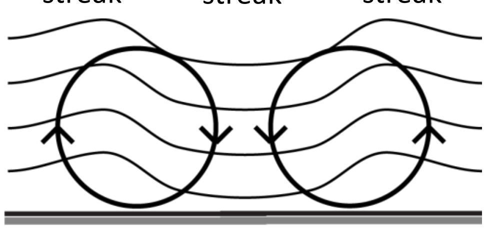
Oil flow visualization of spherical roughness element in Mach 5.5 flow from Whitehead.[2]



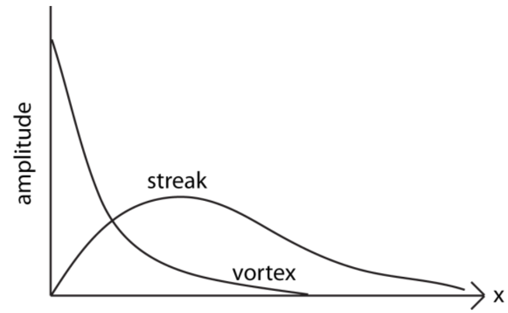
Spanwise view of a boundary layer with contours of constant velocity.



Superpose a streamwise vortex pair onto the uniform boundary layer flow.



The vortex pair lifts up low-momentum fluid on the outside and pulls down high-momentum fluid in between.



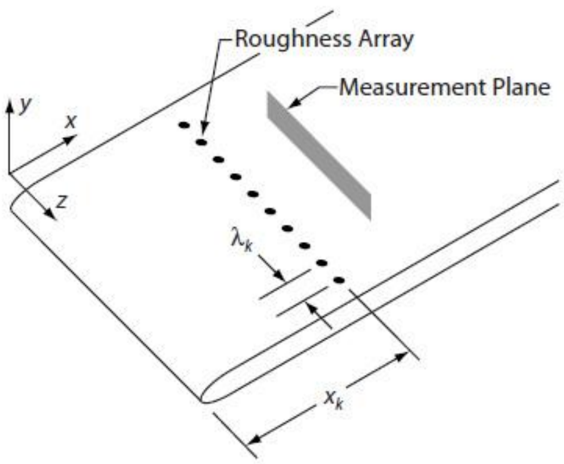
Streak growth is fed by the lift-up mechanism, and the streak decays as the vortex weakens.

1. Tumin, A., and Reshotko, E., *Phys. Fluids*, 13:7, 2001.
2. Whitehead, A. H., NASA TN D-5454, 1969.

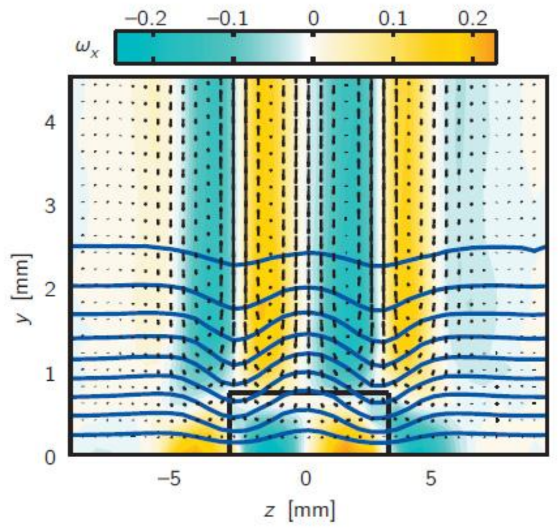
Low-speed experiments

- Subsonic experiments by Ergin and White[1] (and colleagues) have measured transient growth in the wake of an array of isolated roughness elements.

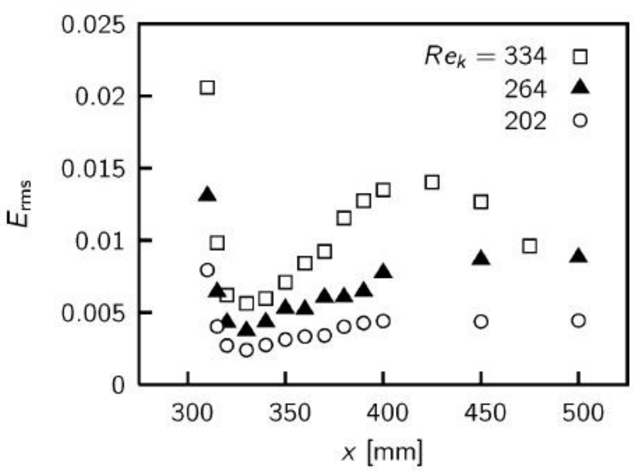
- In doing so, they showed experimentally-realized transient growth is ***suboptimal***, meaning receptivity does not produce a set of initial disturbances that will achieve maximum growth downstream.



Experimental set-up of Ergin and White.[1]



Steady velocity and vorticity contours from Ergin and White.[1]



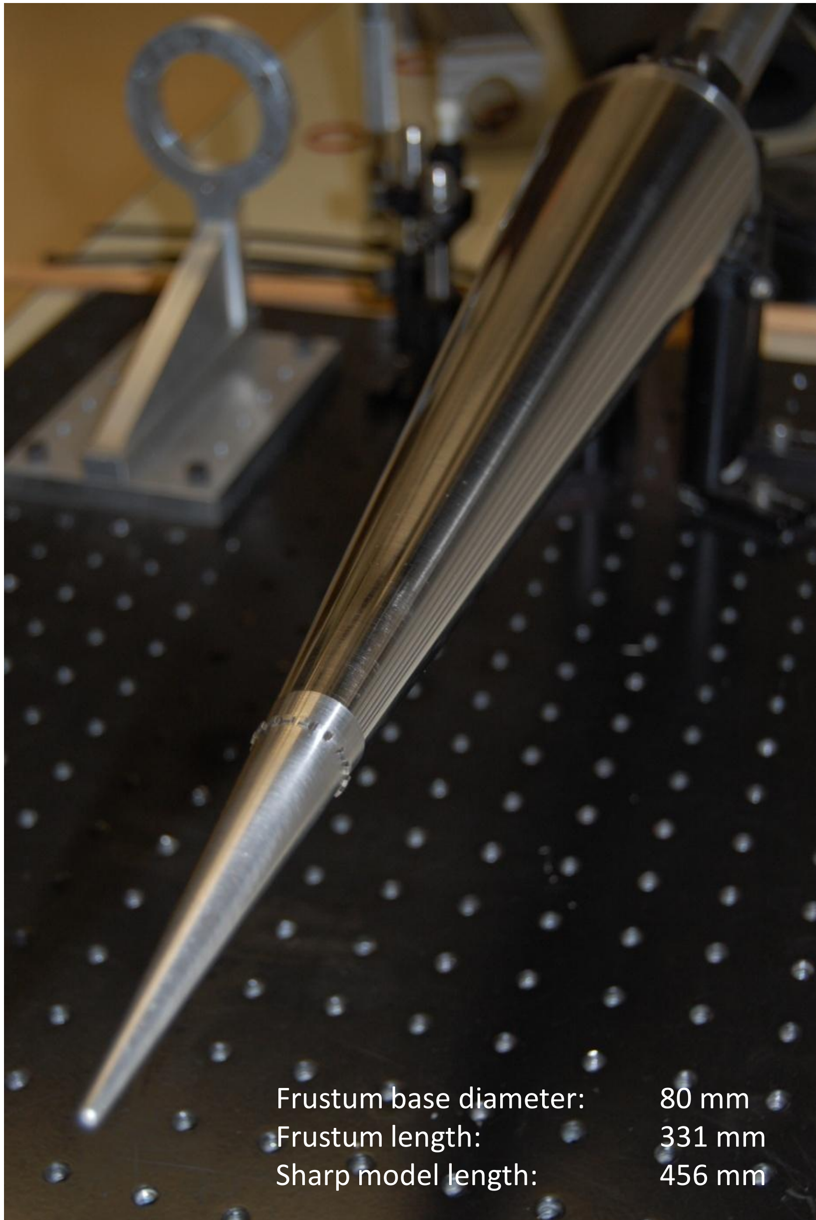
Streamwise evolution of disturbance energy E_{rms} from Ergin and White.[1]

1. Ergin and White, *AIAA Journal*, 44:11, 2006.

Transient Growth Cone (TGCone)

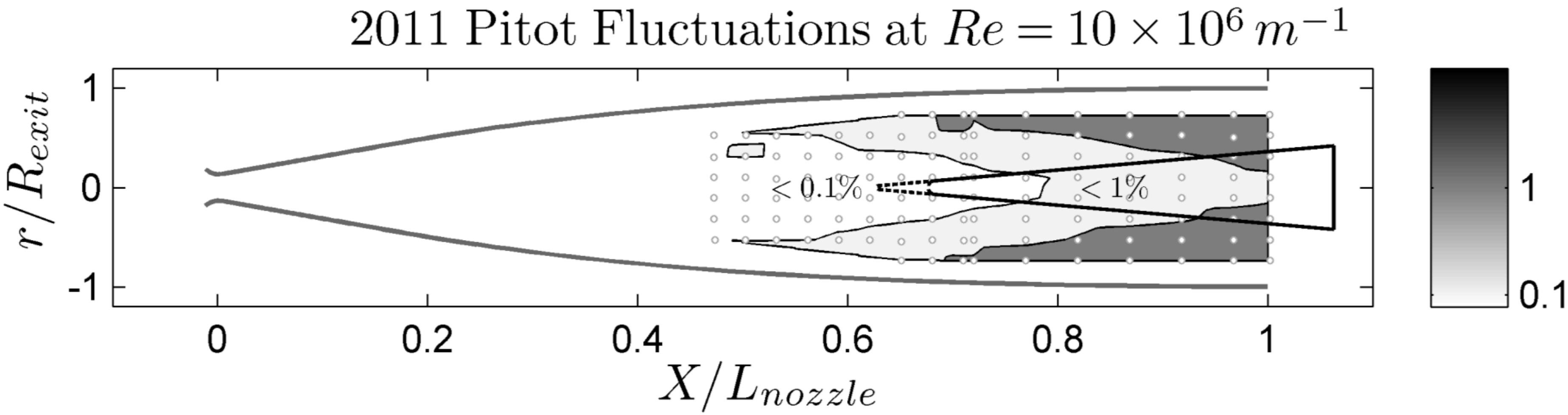
- ***Objective:*** Measure roughness-induced transient growth in a hypersonic boundary layer.
- ***Model:*** Stainless steel, straight, 5-degree half-angle cone with 5 interchangeable nosetips

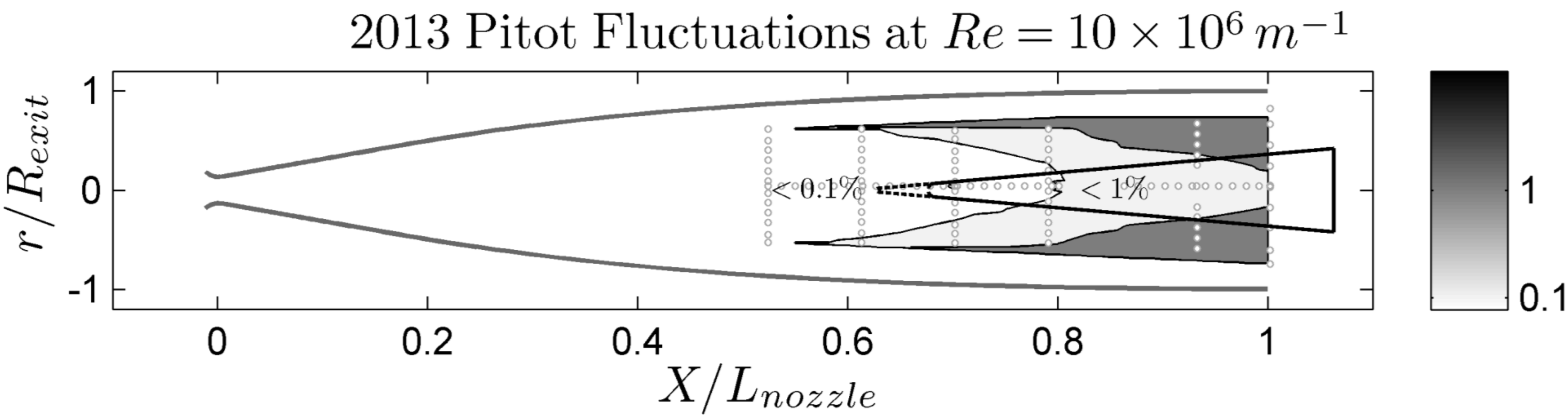
Nose bluntness: 1.59-mm radius nosetip
Roughness type: 1-mm tall DRE array
Roughness location: X/L = 0.25
Roughness wavelength: 3.56 mm
Roughness spacing: 20 degrees
Overall length: 390 mm



What is quiet flow?

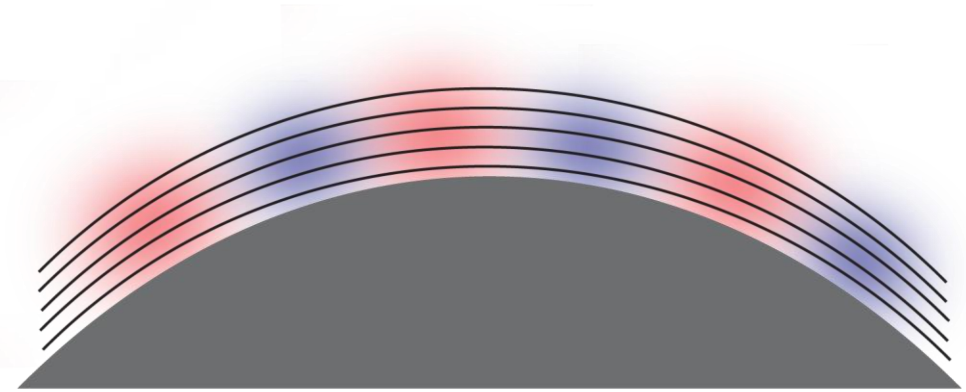
$$\frac{P'_{t2}\, rms}{P_{t2}} \times 100\ [\%]$$





- Conventional hypersonic tunnels have freestream Pitot fluctuations of 2-3%.

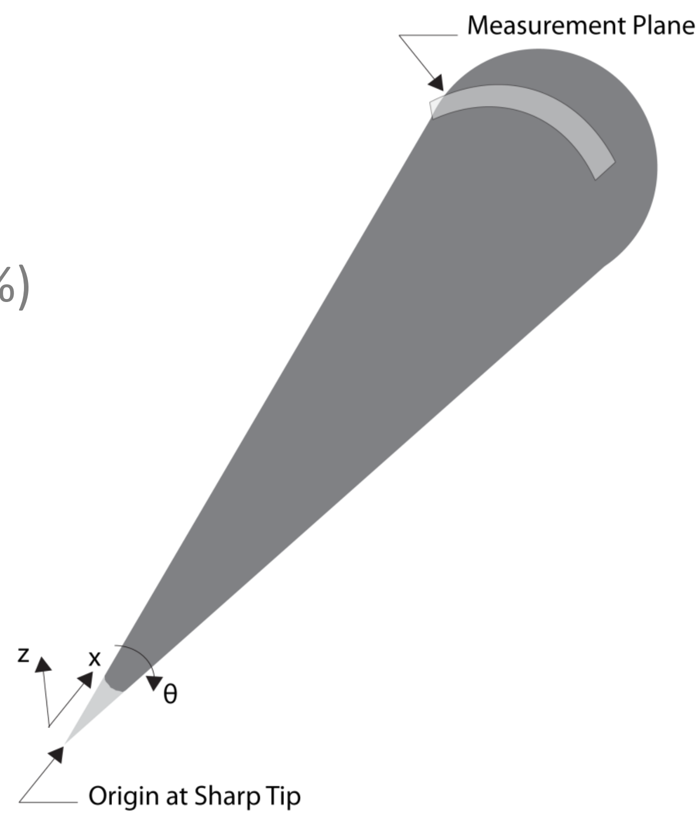
Key challenges



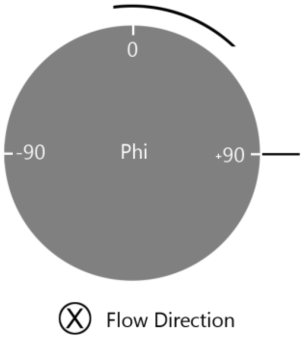
- M6QT’s **40-second run time** requires constructing contours out of 15+ individual runs.

- Conditions to match include:
  - Tunnel stagnation pressure (± 2-3%)
  - Tunnel stagnation temperature (± 3%)
  - Adiabatic wall temperature ratio (± 1%)

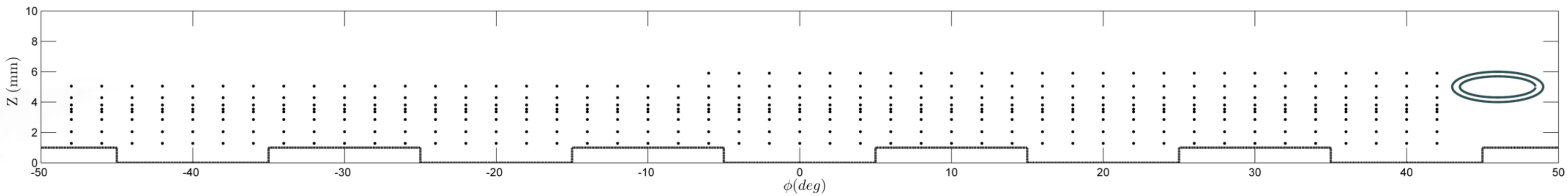
- Each condition’s contour plot required an average of **over 130 compressor hours** to obtain.

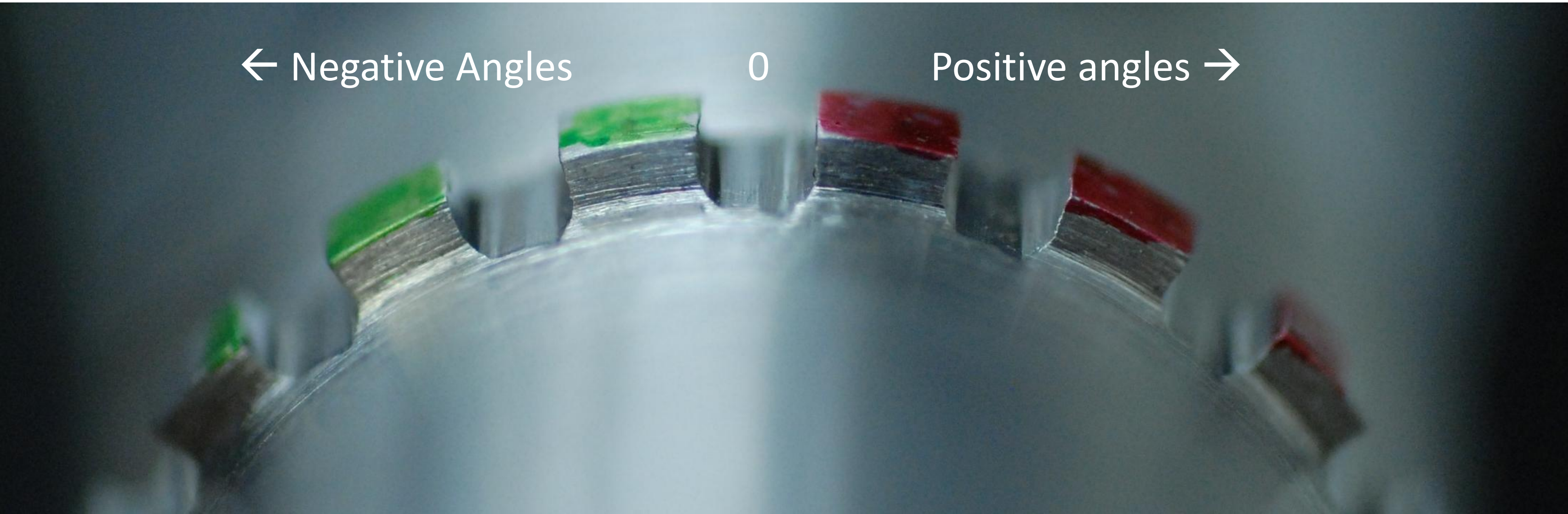


Current experiments



- **Diagnostic:** Kulite pitot probe
- **ID:** 3 mm (wide), 1.4 mm (tall)
- **Azimuthal sampling:** 0.33-0.37 x Pitot width





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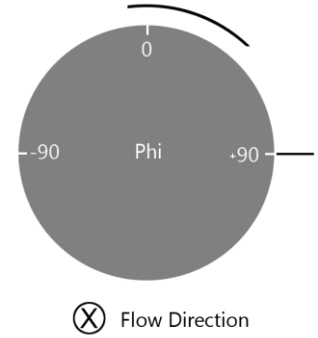
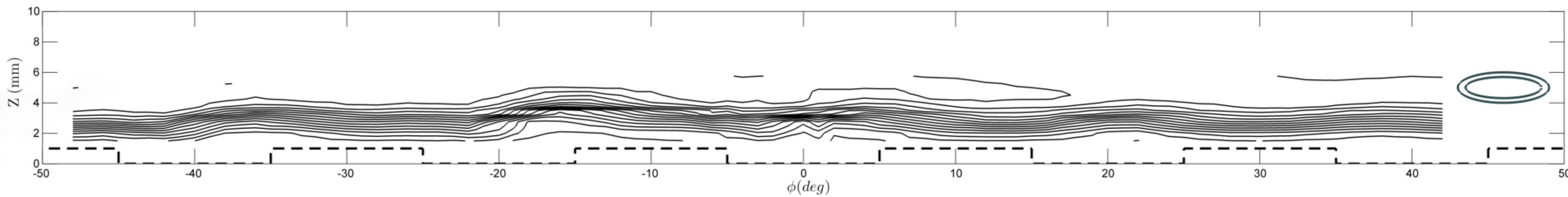
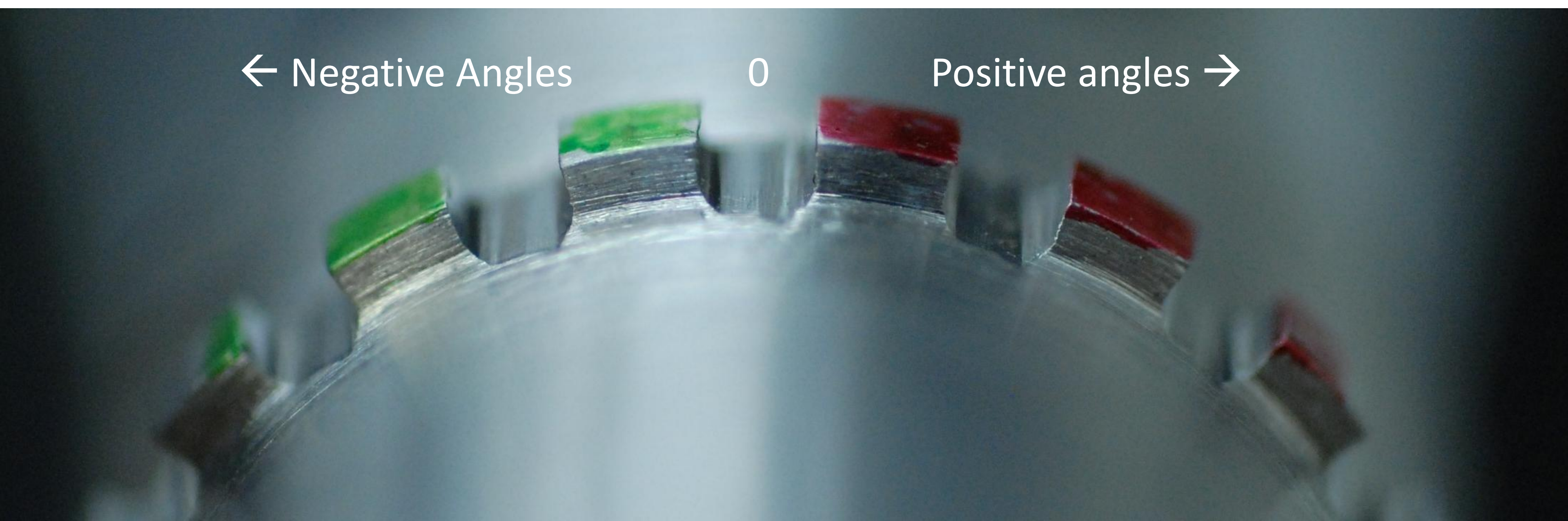


- **Diagnostic:** Kulite pitot probe
- **ID:** 3 mm (wide), 1.4 mm (tall)
- **Pitot width:** 0.27-0.30 x streak width

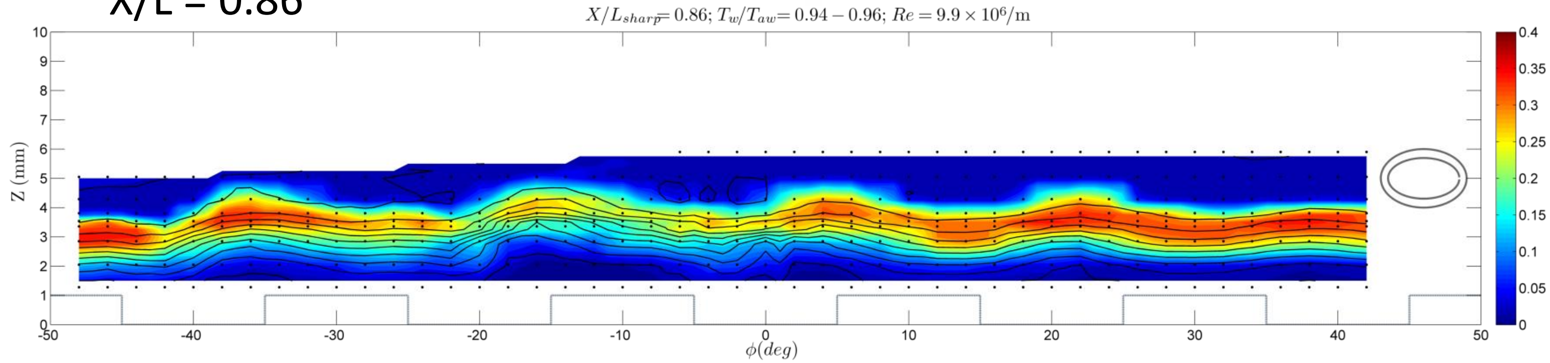




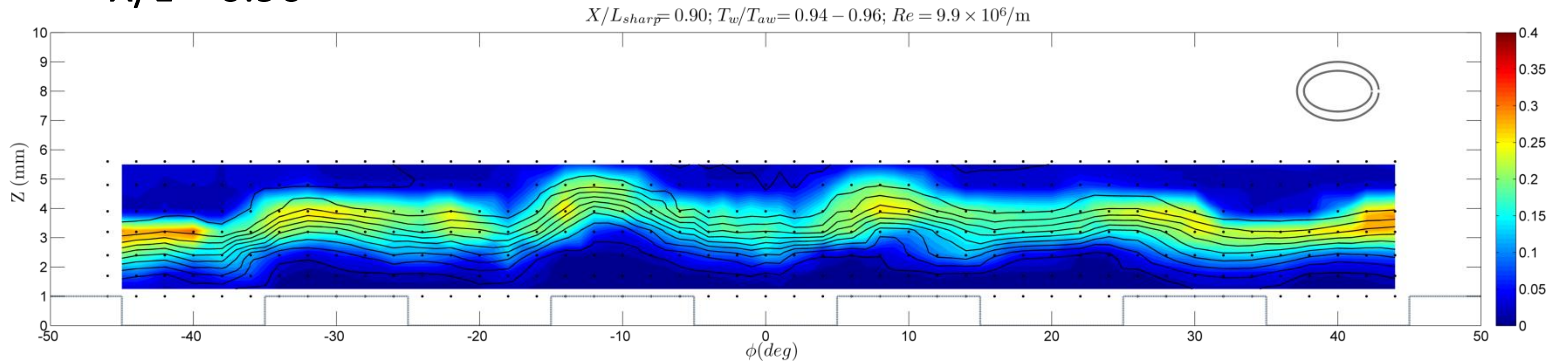
Re = 9.9 x 10^6 /m

Contours: mean pressure
Colormap: unsteady RMS

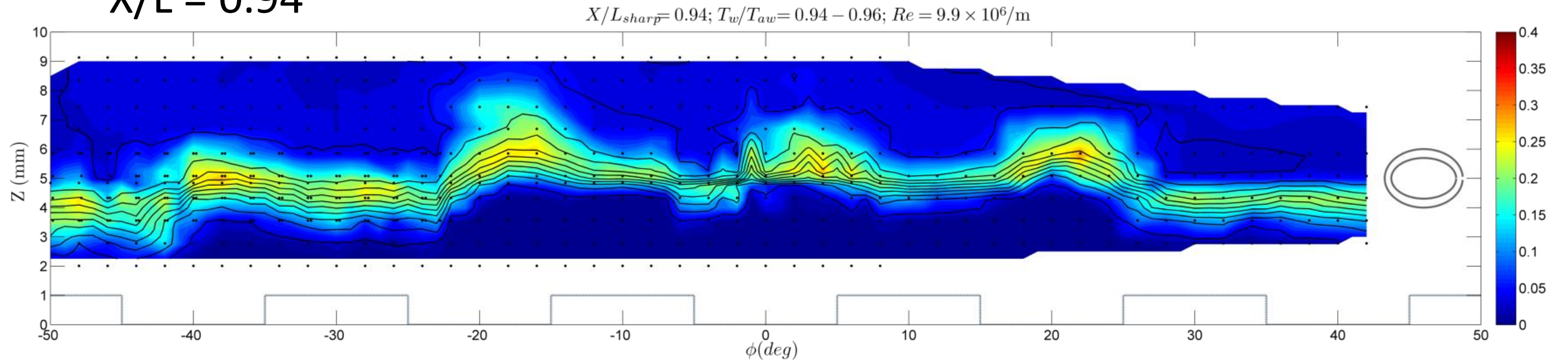
X/L = 0.86



X/L = 0.90



X/L = 0.94



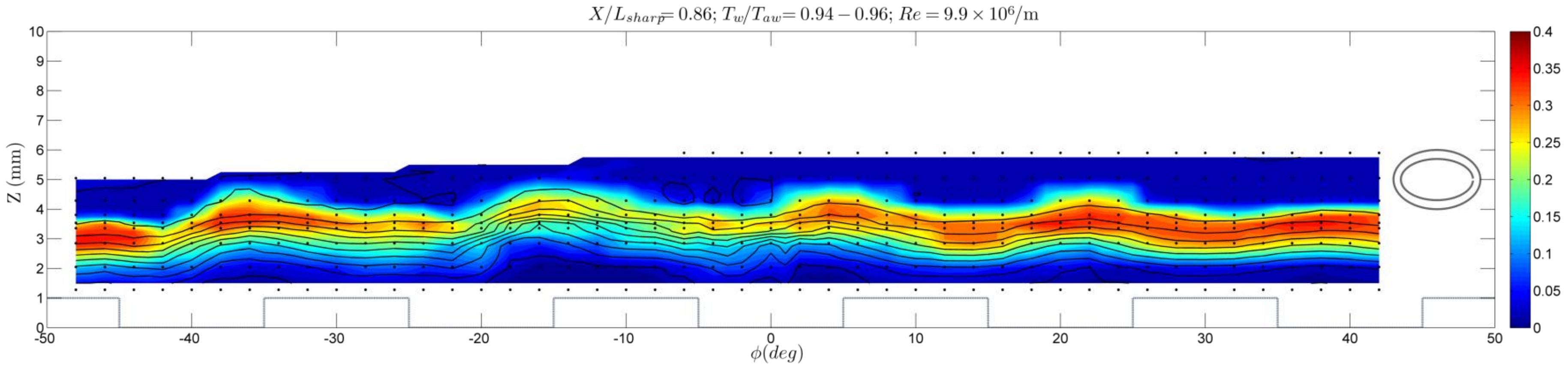
Disturbance pressures

$$p(t,x,y,z) = \overline{P}(x,y) + P'(x,y,z) + p'(x,y,z,t)$$

Spanwise-invariant basic state, averaged across the azimuth

Spanwise-varying steady disturbance

Spanwise-varying unsteady disturbance



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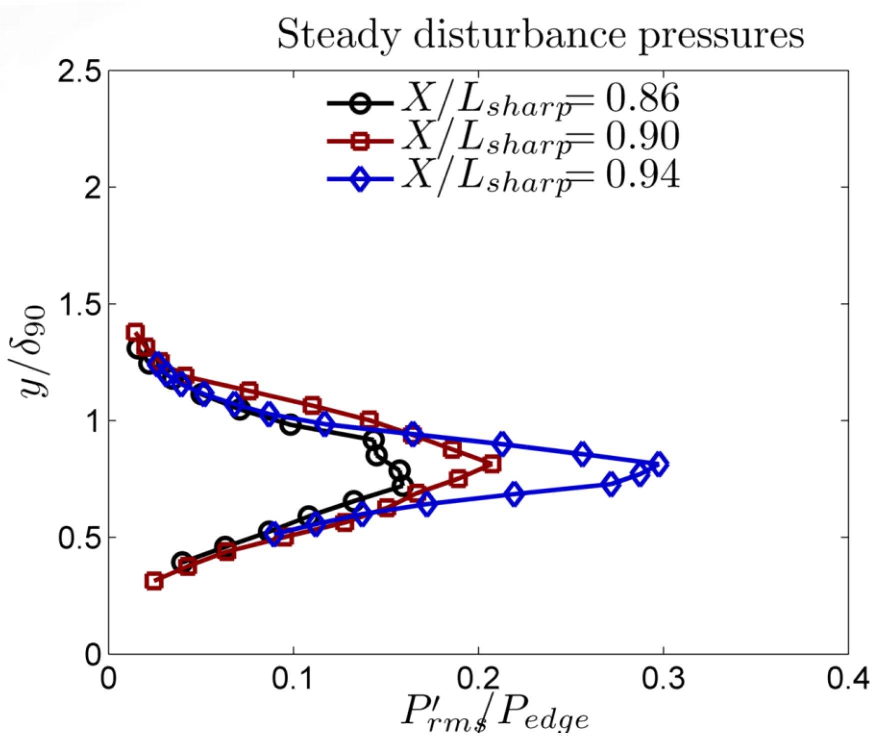

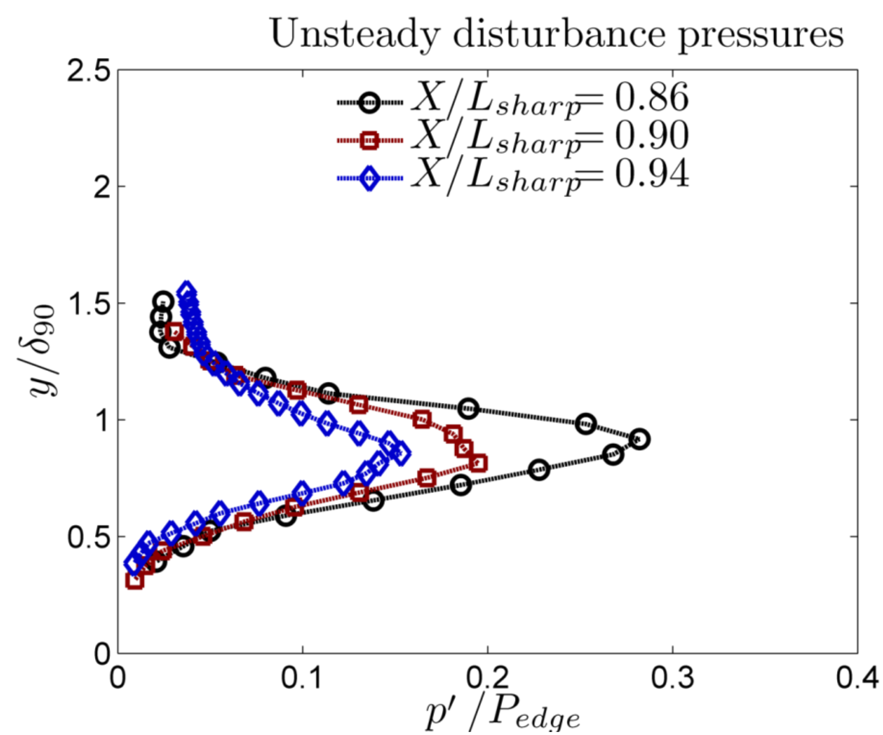

Summary

- Tripping to turbulence with roughness elements in quiet flow is difficult.
- The steady azimuthal disturbance pressures grow in the streamwise direction.
- The unsteady azimuthal disturbance pressures decay downstream.
- Thus far, these hypersonic observations are consistent with low-speed transient growth results.

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- The staff at the Oran Nicks Low Speed Wind Tunnel

For more information, contact:

Nicole Sharp

nicole.sharp@gmail.com

http://nicolesharp.com

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Anonymous
Anonymous
Anonymous
Anonymous
Anonymous
Anonymous
Anonymous
Anonymous
Anonymous
Anonymous
Anonymous
Anonymous
Anonymous
Anonymous
Anonymous
Anonymous
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Bryan Stafford
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