SAND2020-0064C

Hypersonic Boundary-Layer Transition:

Government / Academic Collaborations as a Means to Accelerate Research and Development

Katya Casper
Sandia National Labs

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Orlando, FL
January 7, 2020

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Schneider's Transition Journey

- **BS from Caltech in 1981**
- **Navy Ocean Systems Center from 1981-83**
  - Worked on torpedoes.
- **MS from Caltech in 1984**
- **PhD from Caltech in 1989**
  - Low speed turbulent spot studies.

Manooch Koochesfahani

Dan Lang

Steve Schneider

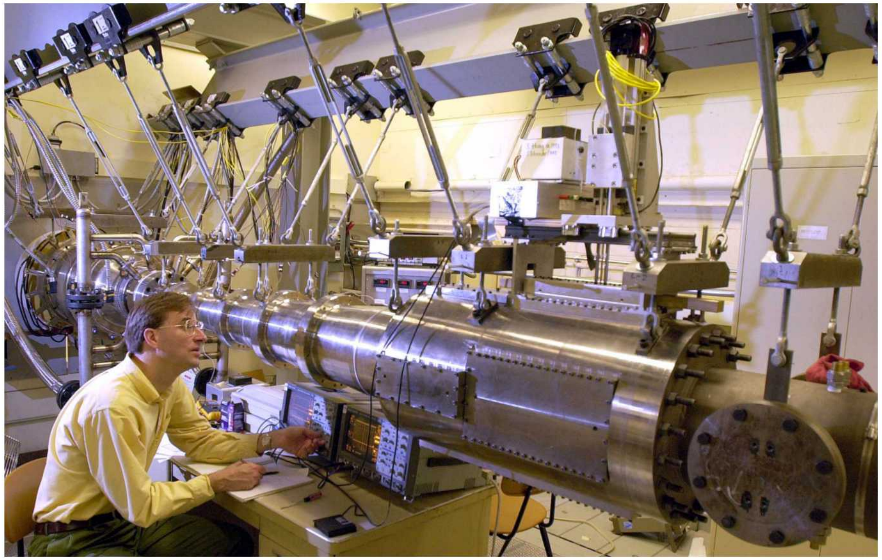
Anatol Roshko

Roddam Narasimha

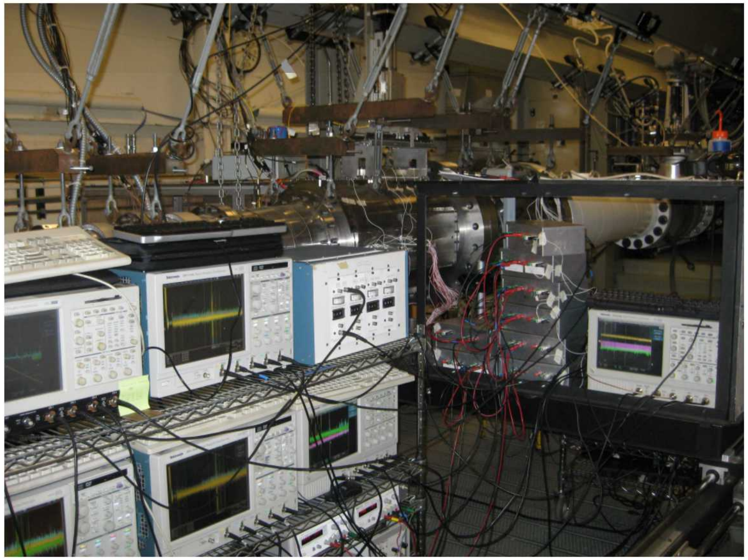
Caltech, October 1986

Boeing/AFOSR Mach-6 Quiet Tunnel

- Evolved from a small university research tunnel to a national asset
- Small experiments with 1-2 oscilloscopes evolved to complex cases with many sensors (10+oscilloscopes) and advanced diagnostics



BAM6QT circa 2001



BAM6QT circa 2010

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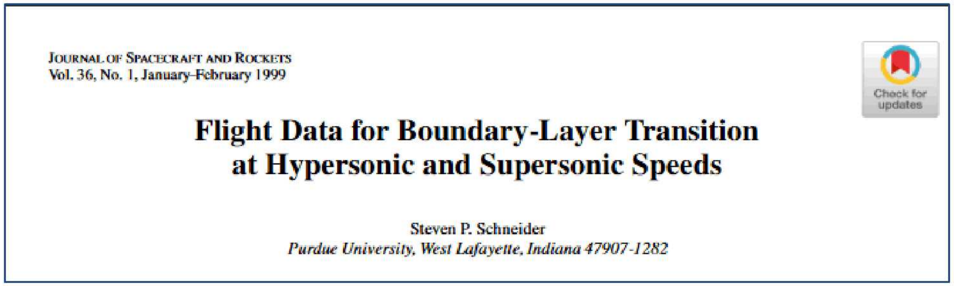
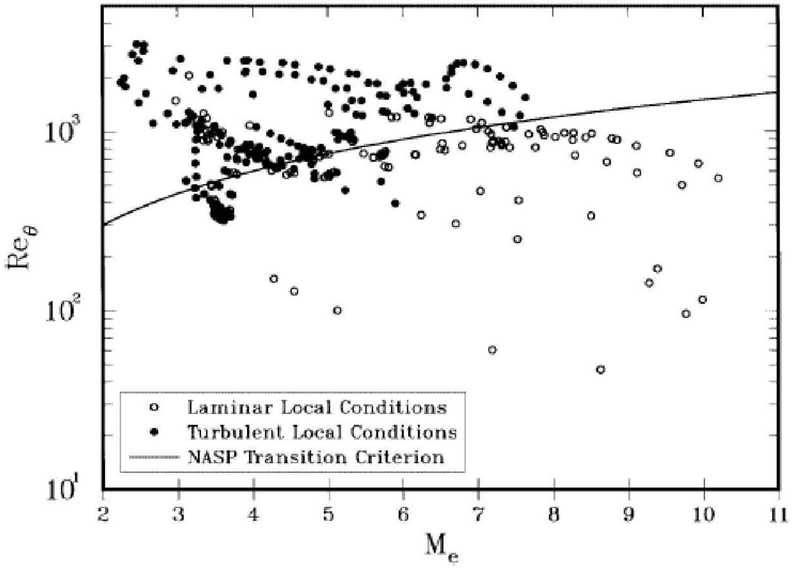
- **Schneider wanted to compare wind-tunnel experiments to flight data, so began to look for available data in the mid 90s**
  - Inspired by comment that flight data was not repeatable.
- **In 1998, Schneider presented a summary of unclassified flight data he had found at an AIAA conference in Albuquerque**
  - Dave Kuntz (retired SNL) saw the presentation and commented on the data included within it!


JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 36, No. 1, January–February 1999

Check for updates

Flight Data for Boundary-Layer Transition at Hypersonic and Supersonic Speeds

Steven P. Schneider
Purdue University, West Lafayette, Indiana 47907-1282



Sandia National Labs

This eventually lead to a continuing partnership with Sandia National Labs, beginning in 2002.

- Wrote 2 classified reports summarizing flight data
  - This is no small task (there are A LOT of old reports)
- Advises on transition-related projects.
- Backpacks

SS

Sun 3/10/2019 1:55 PM

Steven Schneider (via inReach) <no.reply.inreach@garmin.com>

[EXTERNAL] inReach message from Steven Schneider

To Casper, Katya Marie

Click here to download pictures. To help protect your privacy, Outlook prevented automatic download of some pictures in this message.

Camp here. Hike out early tomorrow ahead of heavy rain

View the location or send a reply to Steven Schneider: https://inreach.garmin.com/textmessage/txtmsg?extId=35b5fa68-6298-474f-bde8-1337e54c6a38&adr=kmcaspe%40sandia.gov

Steven Schneider sent this message from: Lat 33.028175 Lon -108.10858

Do not reply directly to this message.

This message was sent to you using the inReach two-way satellite communicator with GPS. To learn more, visit http://explore.garmin.com/inreach.

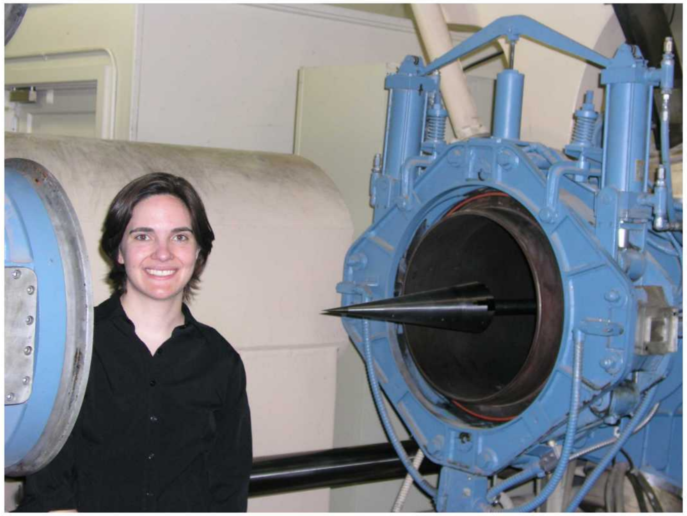
Internships at Sandia

Sandia National Laboratories

Encourages students to work with and collaborate with industry and research laboratories!

I applied for internship at SNL as an undergrad in 2006

- No funding was available for an experimental summer internship
  - Resume emailed out to SNL department
  - Schneider saw it and hired me as a summer intern at Purdue.
- Returned to Purdue in 2007 for a Masters and PhD
  - Combined research with a 5 year year-round graduate internship at SNL throughout grad school.

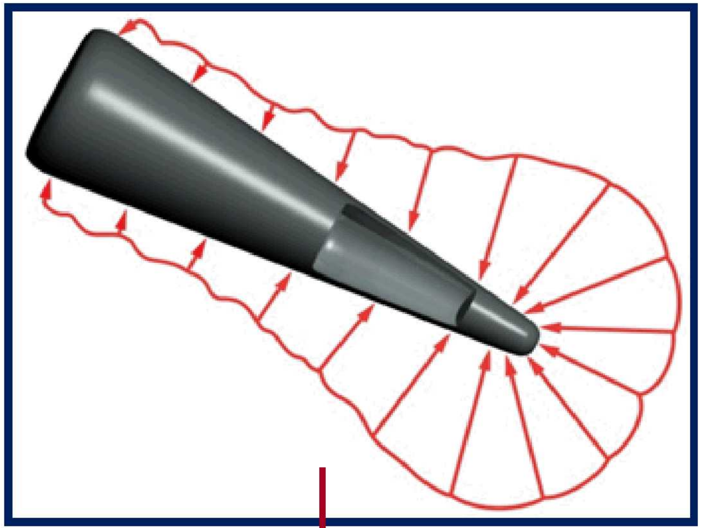


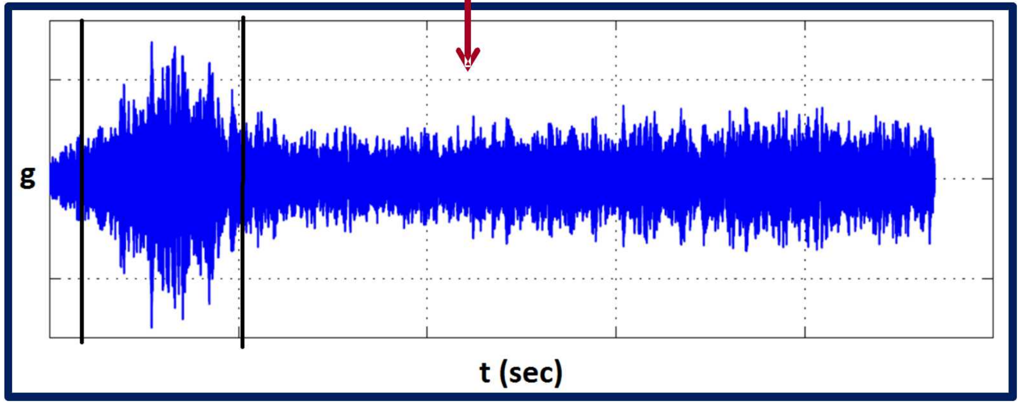
SNL Internship Project (and MS/PhD Work)

Sandia National Laboratories

Vehicle vibration is a maximum when a reentry vehicle undergoes laminar to turbulence boundary-layer transition.

- Pressure fluctuations peak during boundary-layer transition.
- Need to model fluctuations and spatial distribution to define the vehicle environments.
- Need to understand how component response is generated as a result of these environments.



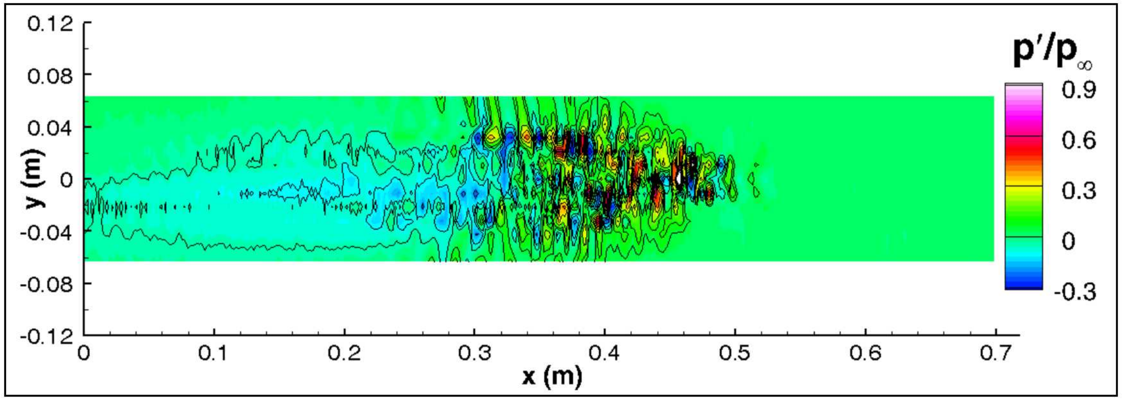


Turbulent Spot Pressure Loading

Transitional pressure loading is generated by intermittent turbulent spots in the boundary layer.

- Individual spots contain broadband turbulent pressure fluctuations
- Intermittent passage of spots drives lower frequency vibration.
- Spots grow and merge into a fully turbulent boundary layer.

Flow ⟶



Pressure footprint of turbulent spot, Mach 6

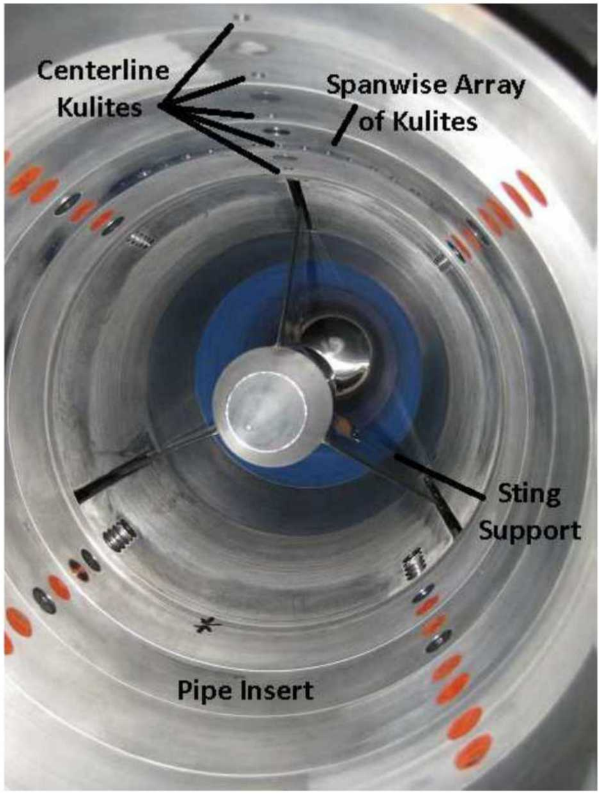
Turbulent Spot Pressure Loading

Not possible without quiet tunnel nozzle wall

- Allows long working length for large spots to develop.
- Can obtain high spatial resolution with arrays of sensors.

Provided Sandia needed parameters for modeling turbulent spot pressure fluctuations during hypersonic transition.

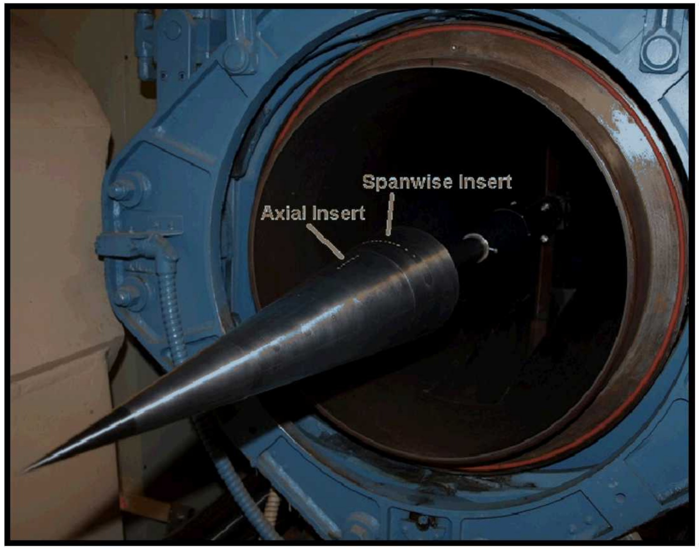
- Spot convection velocities
- Spanwise spreading angle
- Pressure footprint of spot



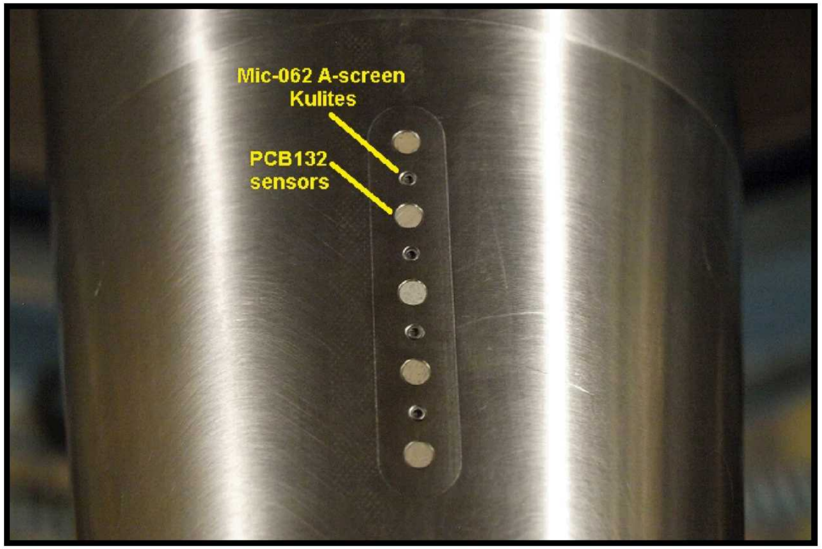
Transition Statistics

Seven degree stainless-steel sharp cone.

- Axial and spanwise arrays of high-frequency pressure transducers.
- Directly beneath schlieren viewing area in some cases.
- Model traveled back and forth between Purdue and Sandia.

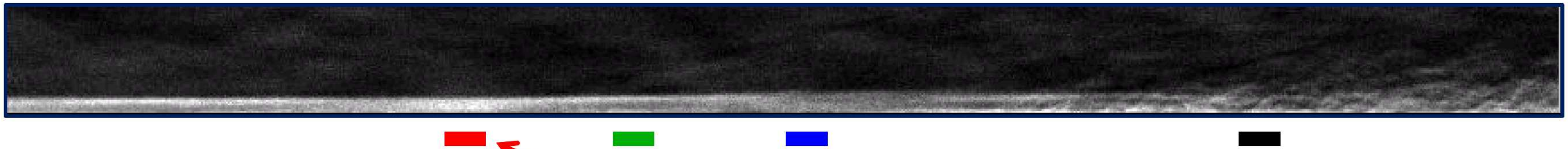


Model installed in the Sandia Hypersonic Wind Tunnel.



Axial pressure-transducer array.

Mach 5 Measurements, Re = 9.75 x 10^6/m



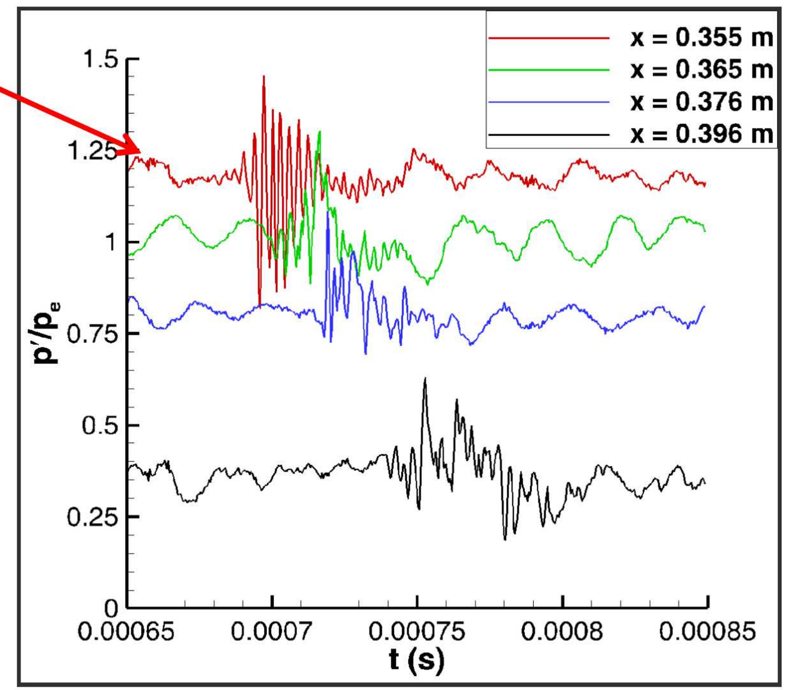
Schlieren Videos

Intermittent formation of second-mode wave packets that then break down to isolated turbulent spots.

- Observed in both schlieren videos and simultaneous pressure measurements.

Disturbances are surrounded by a smooth laminar boundary layer.

- To model this behavior, need to be able to distinguish instability waves from turbulence.



Pressure Traces

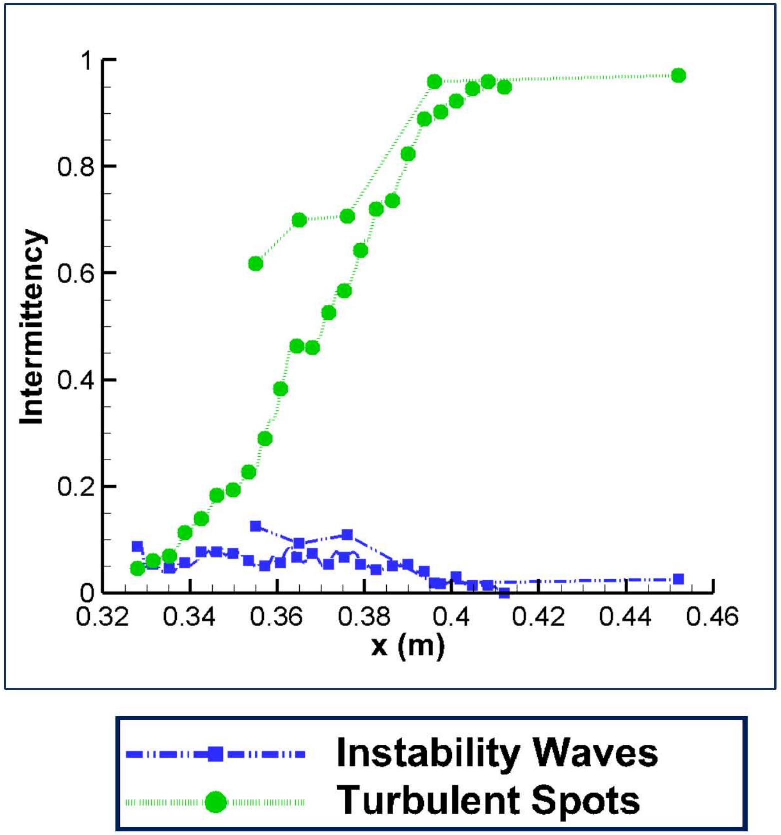
Mach 5 Transition Statistics

Developed techniques to separate waves from turbulence in both pressure measurements and schlieren videos.

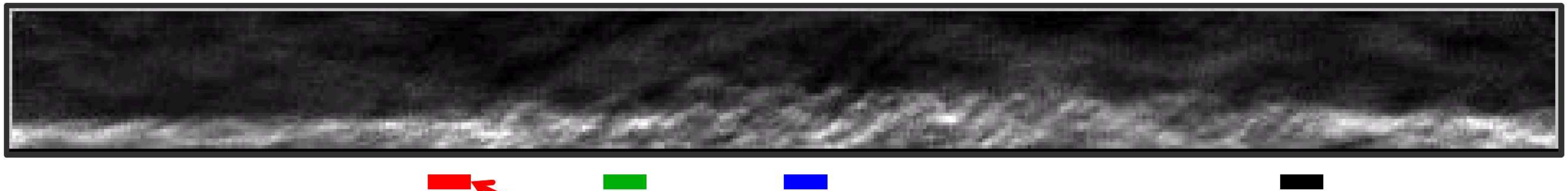
- Compute separate statistics for instability waves and turbulent spots.
- Both measurement techniques show reasonable agreement.

Waves remain a small part of transitional region.

Turbulent intermittency rises rapidly through transition.



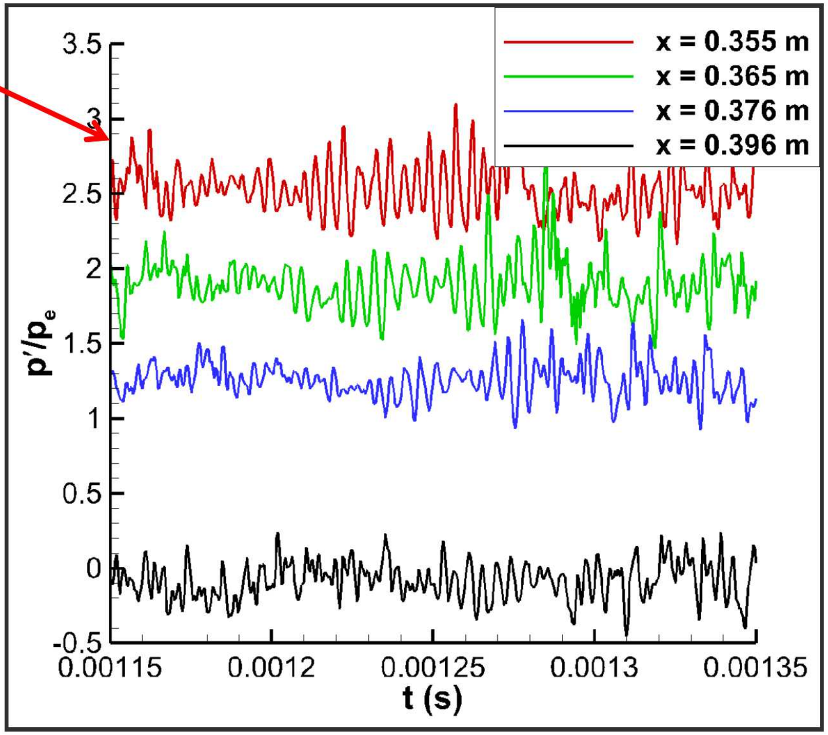
Computation of Boundary-Layer Statistics, Mach 8, Re = 9.74 x 10^6/m



Schlieren Videos

Flow alternates between second-mode waves and turbulence.

- Smooth, laminar boundary layer not observed in transitional region.



Pressure Traces

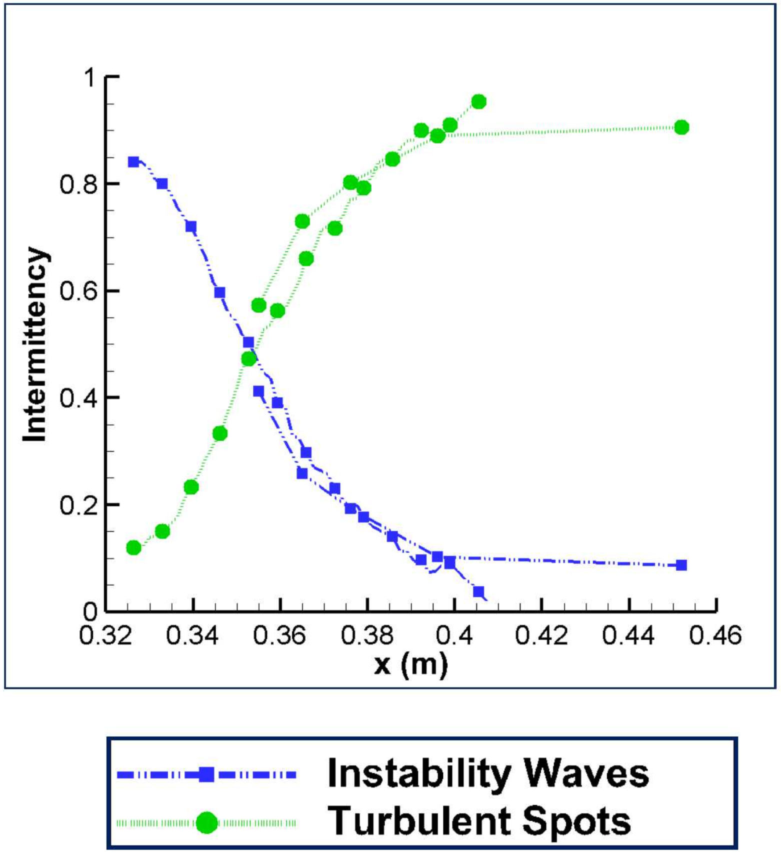
Natural Transition Statistics: Intermittency

Instability waves

- Significant part of the flow prior to development of turbulent spots.

Turbulent spots

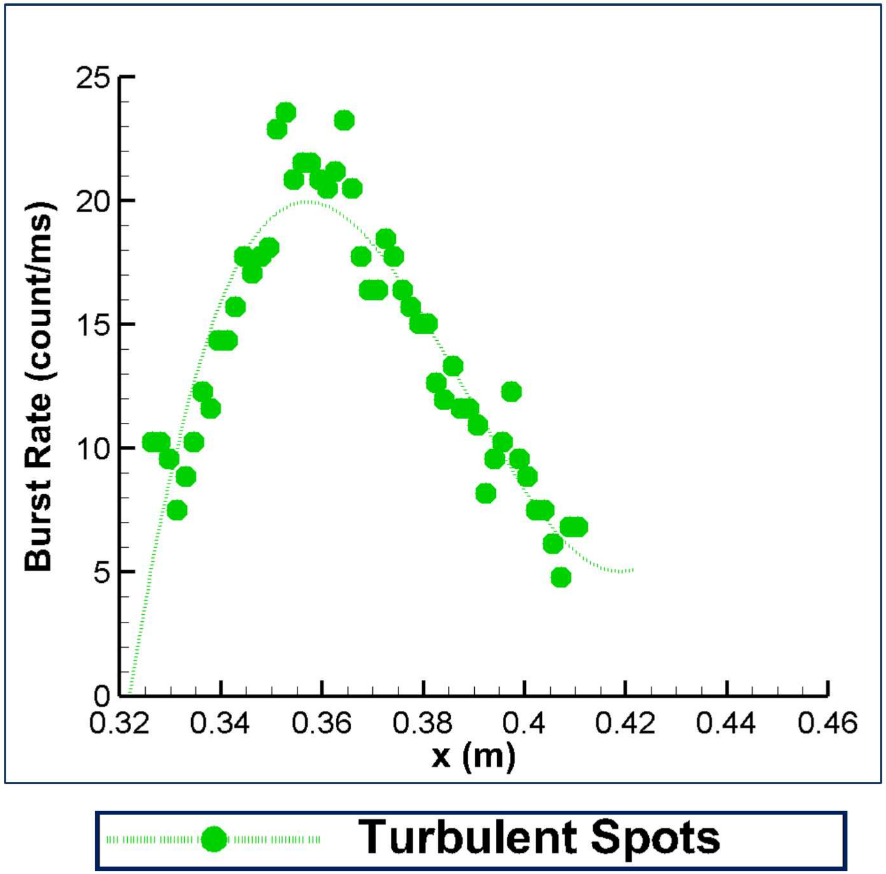
- Gradually begin to dominate flow.
- Turbulent intermittency rises as instability wave intermittency decreases.



Natural Transition Statistics: Burst Rate

Burst-rate computations shows flow switches between turbulence and waves.

- Equal burst rate for instability waves and turbulence.
- High burst rate when intermittency is near 0.5.
- Burst rate decreases as spots merge into turbulence at locations further downstream.



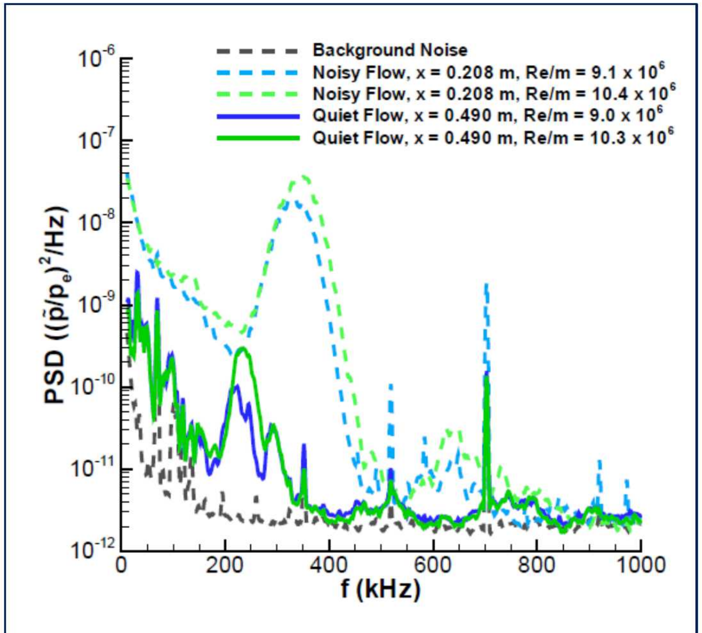
Tie spot statistics to pressure loading

Tie statistics to pressure fluctuations measured during transition

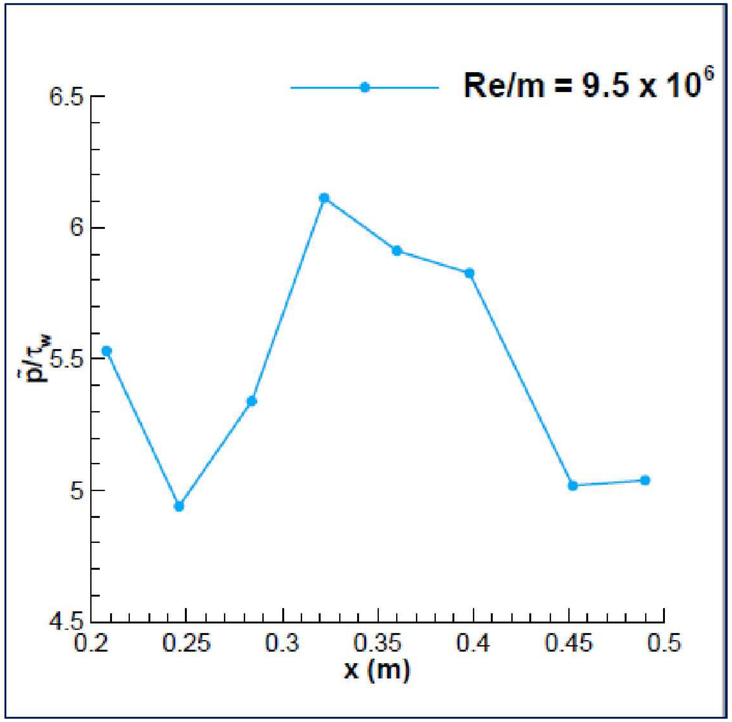
- Lower frequency fluctuations from passage of intermittent turbulent spots.

Could also study second-mode wave growth and breakdown leading to the spot formation.

- Compared under noisy and quiet flow thanks to Purdue/SNL collaboration.



Comparison of second-mode waves under noisy and quiet flow (BAM6QT)



Pressure Fluctuations during Transition

Both Purdue and Sandia Benefit…

Purdue/SNL collaboration allowed:

- Access to quiet tunnel results
- Wider Mach number range for noisy results (Mach 5, 6, 8, and 14)
- Access to SNL expertise and computations
- Internship experience

Graduation in 2012

- Took a full-time job at Sandia
- No more Indiana! Or so I thought….

Back to Indiana for 4 SNL sponsored wind tunnel tests between 2013 and 2017.

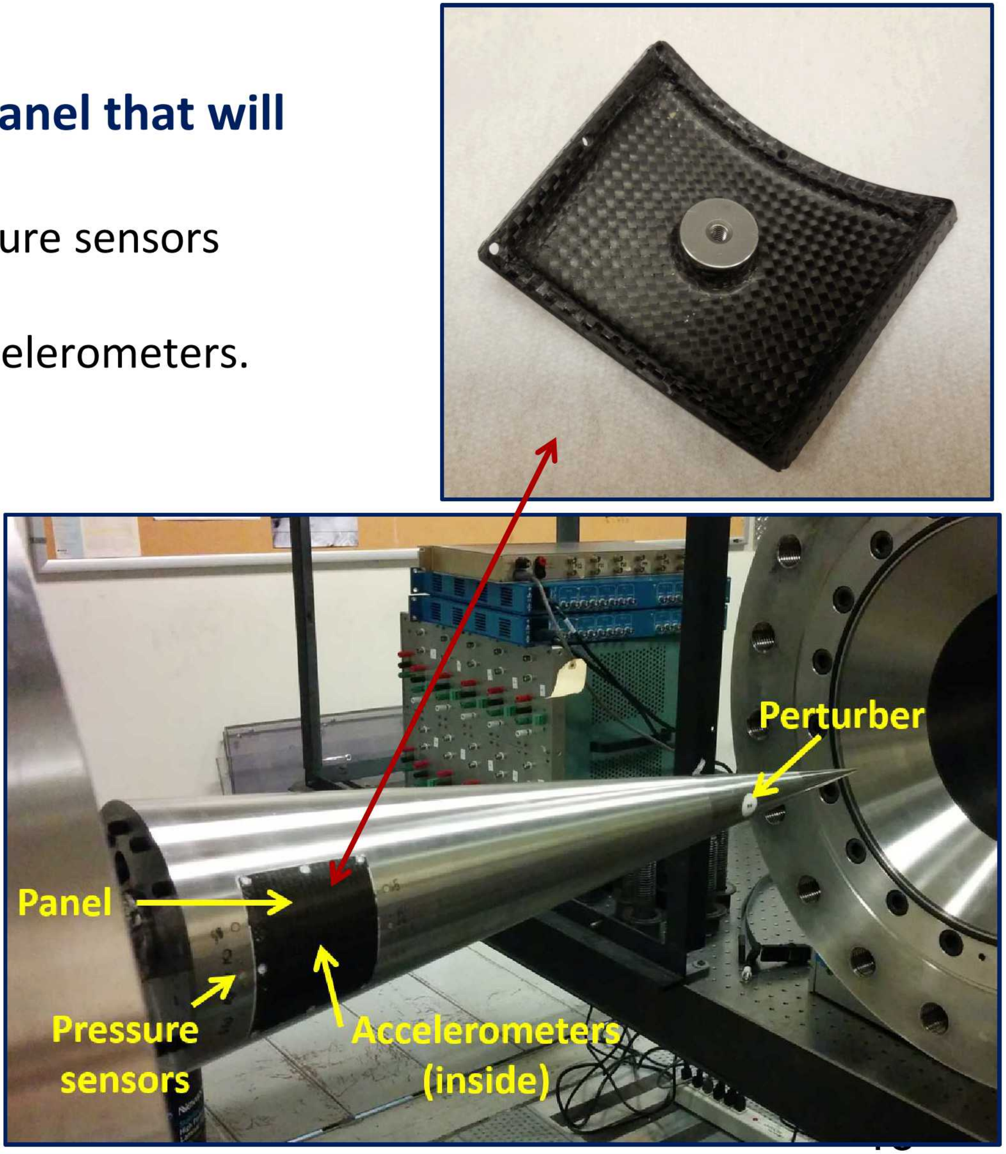
What is the vibrational response to this environment?

Designed a cone with integrated thin panel that will vibrate from flow excitation.

- Boundary layer characterized using pressure sensors upstream and downstream of panel.
- Panel response measured inside with accelerometers.

A spark perturber is used to create periodic turbulent spots in the boundary layer.

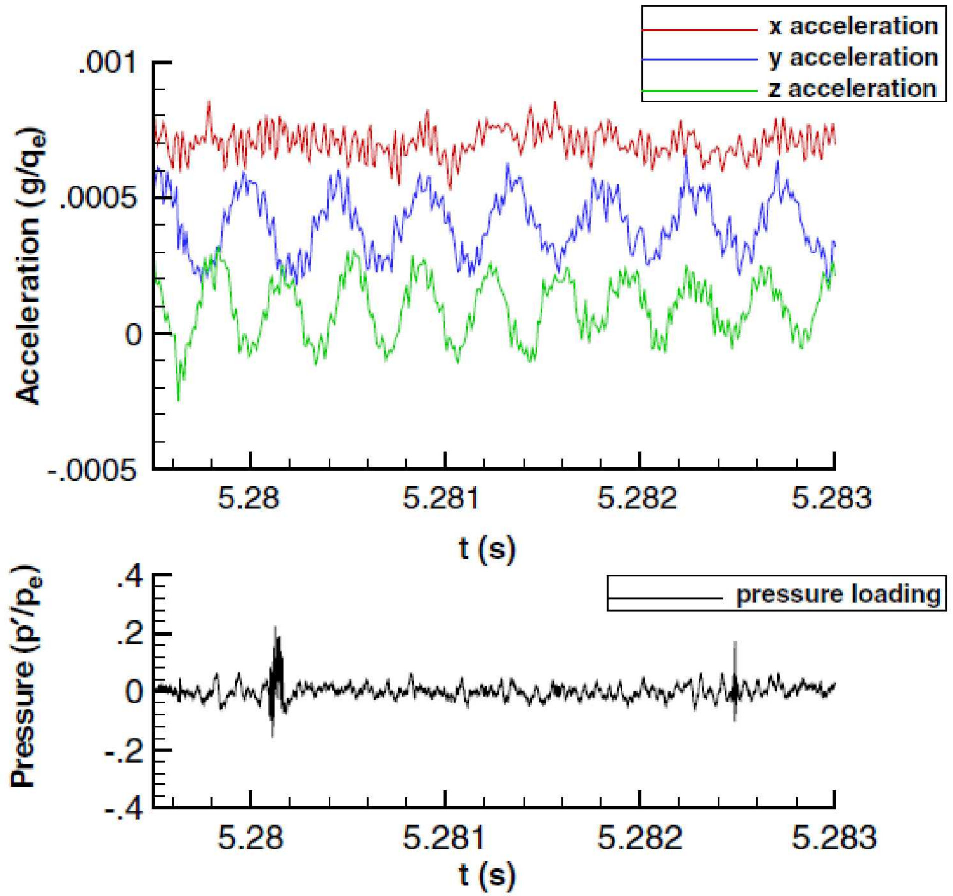
- Simplified validation case for modeling and simulation.



Initial Testing

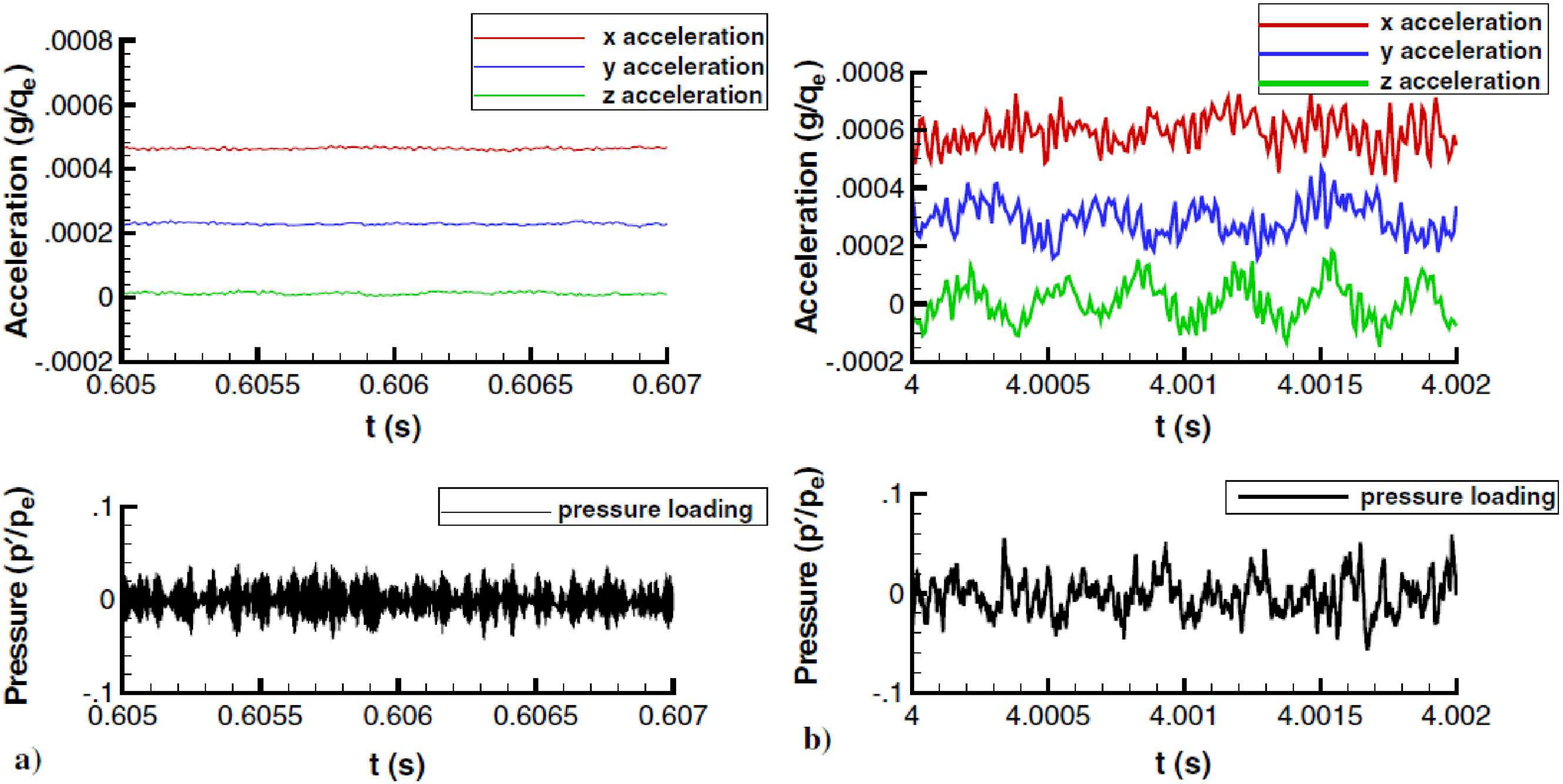
We started testing at Mach 5 and 8 at Sandia, in noisy flow.

- No matter what we did, there was no effect of the turbulent spots we were generating.



Tunnel noise matters!

- Turns out tunnel noise strongly excites the panel structural modes
- In a noisy tunnel, an isolated spot has no effect on the panel response.



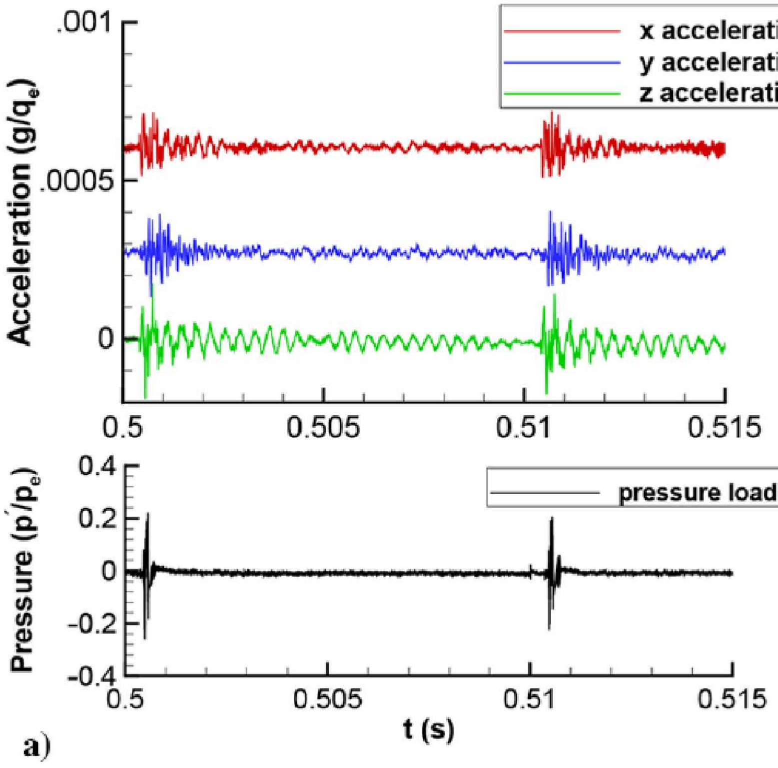
Quiet

Noisy

Back to Indiana…. again

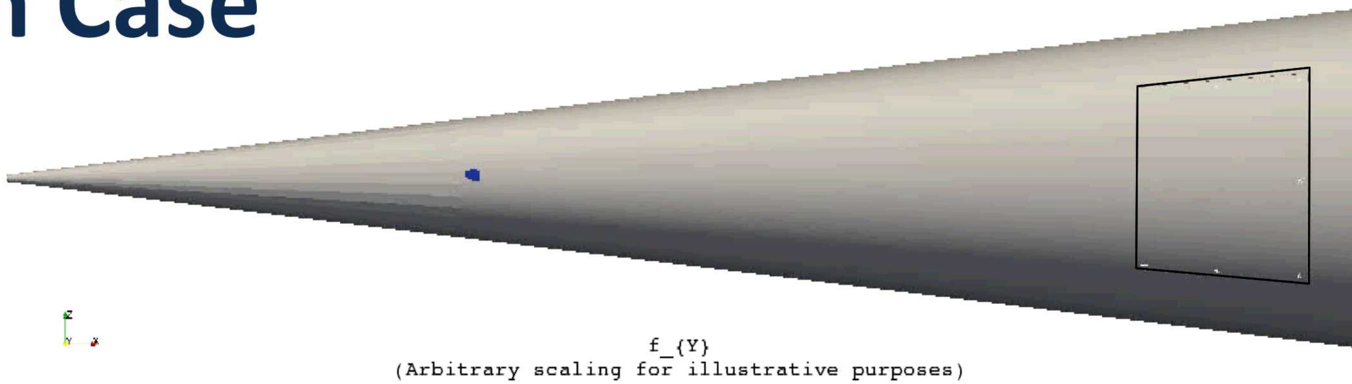
Needed quiet flow to study the isolated effect of turbulent spots on the panel

- Returned to Purdue for a quiet flow tunnel entry.
- Gave us great data!

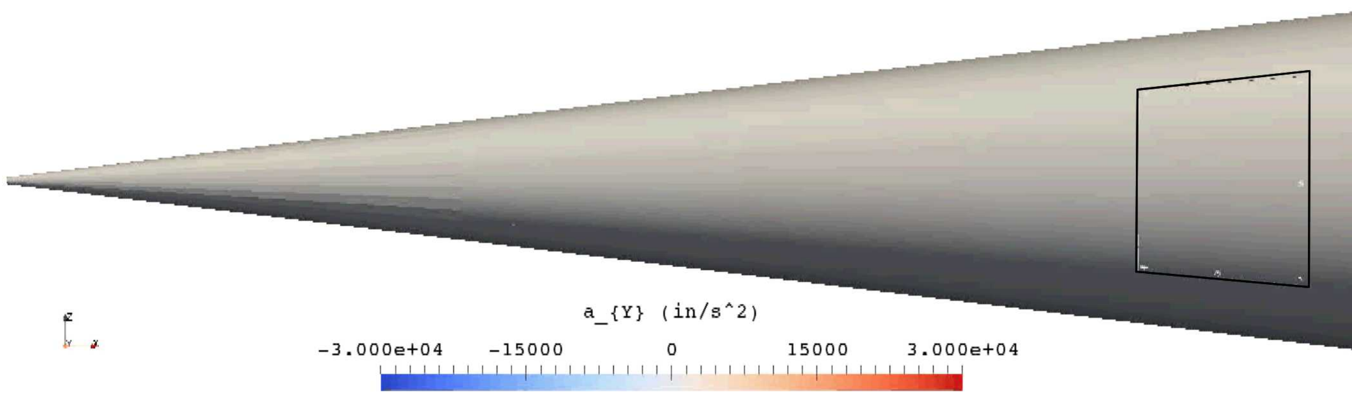


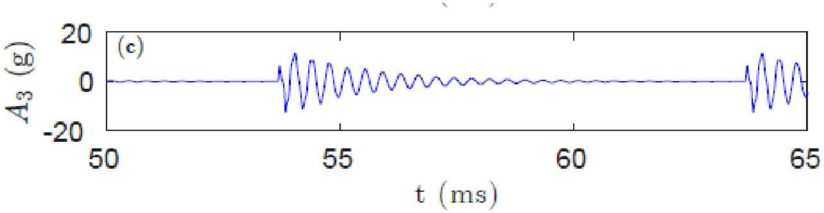
Computational Efforts: Simple Validation Case

Loading from Single Spots



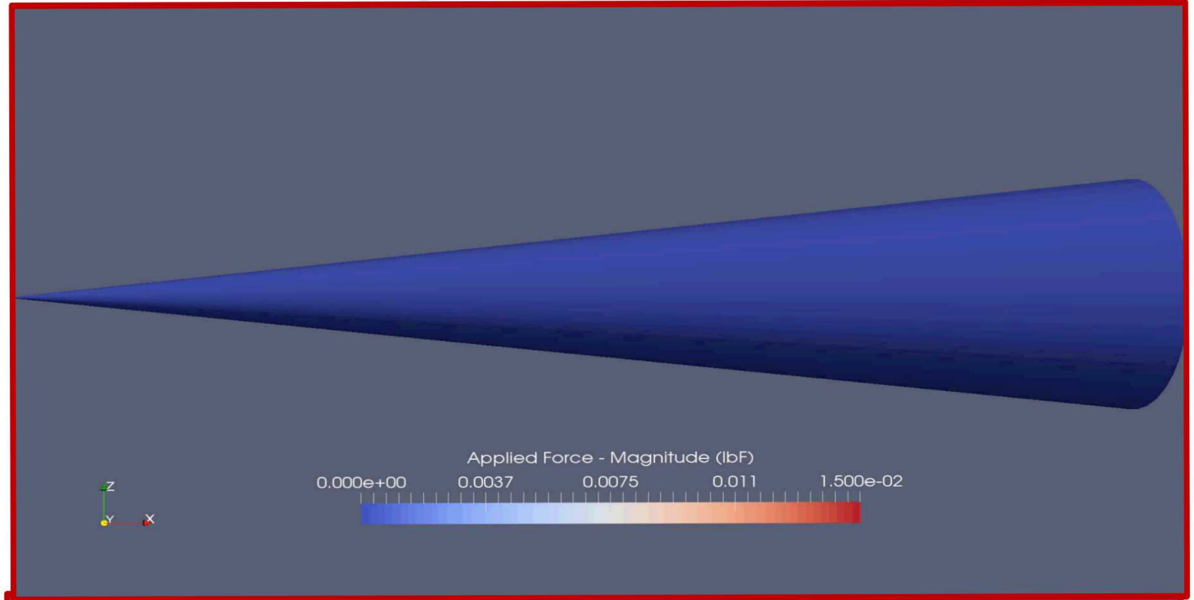
Predicted Structural Response



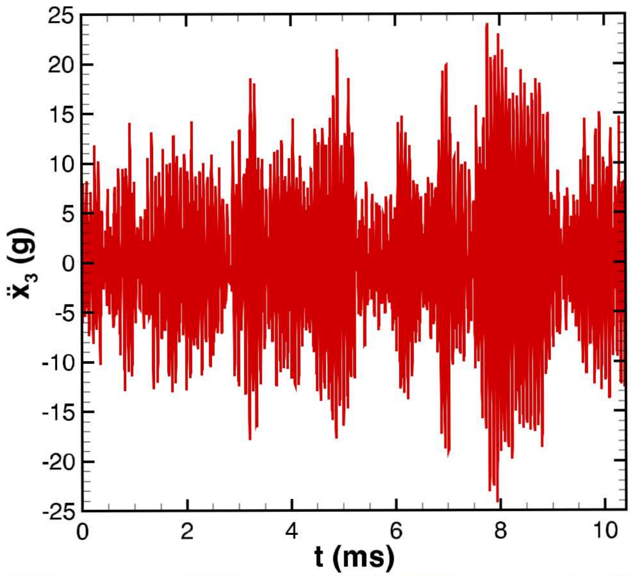


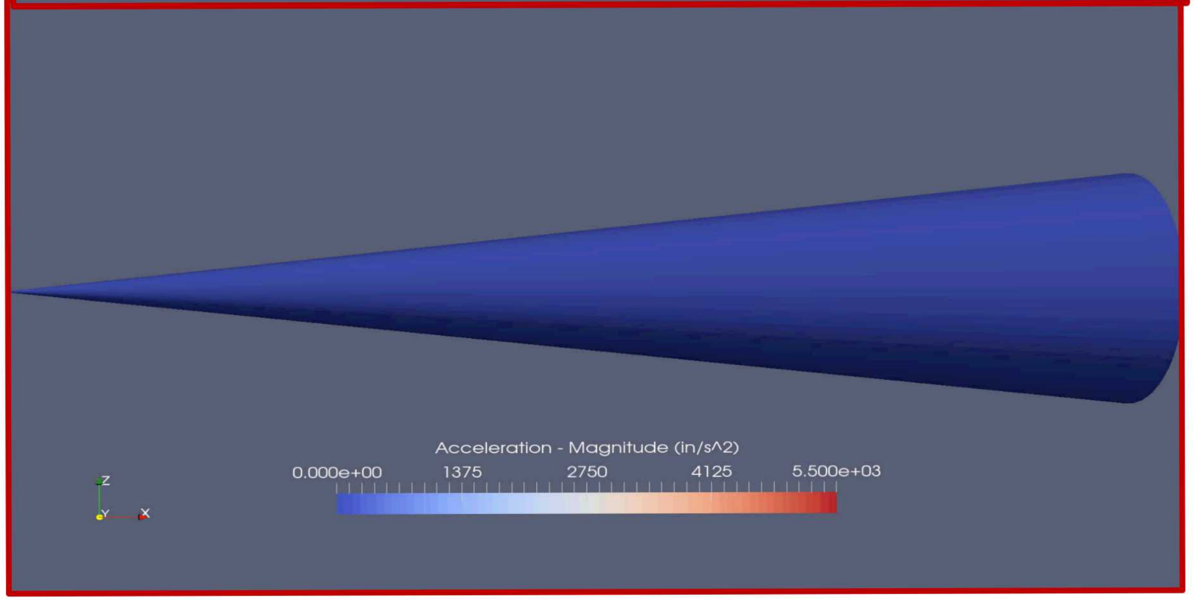
Computational Efforts: Flight-like Case

Loading from Multiple Spots



Predicted Structural Response

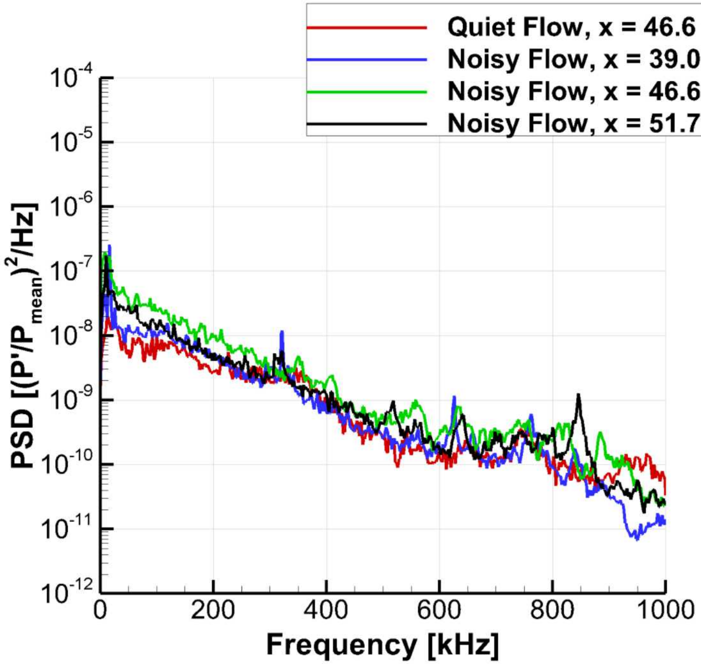




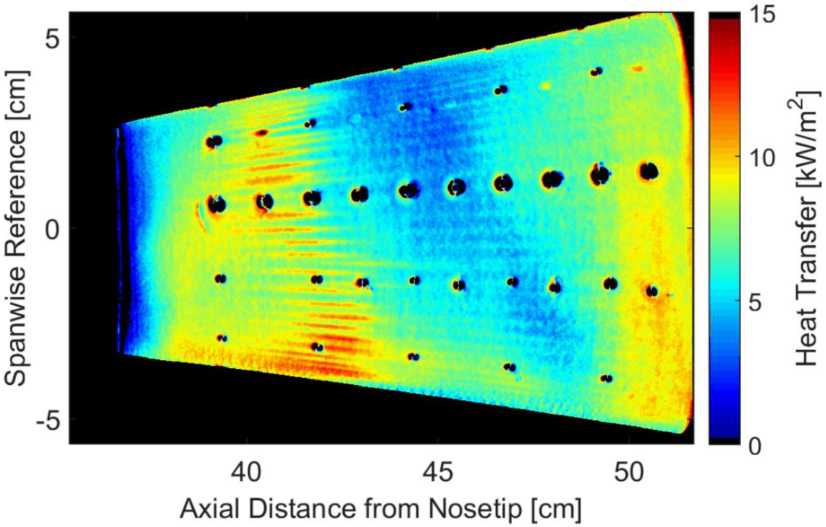
PO to Purdue: Quiet Flow Turbulence Measurements on a Flared Cone

Laminar fluctuations are a reflection of tunnel noise but what's the effect on turbulent pressure spectra?

- Funded Purdue to compare turbulent spectra under noisy and quiet flow.
  - Brandon Chenowyth
- Turns out it is a fairly limited effect
- Limited to low frequencies!



Turbulent Pressure Spectra

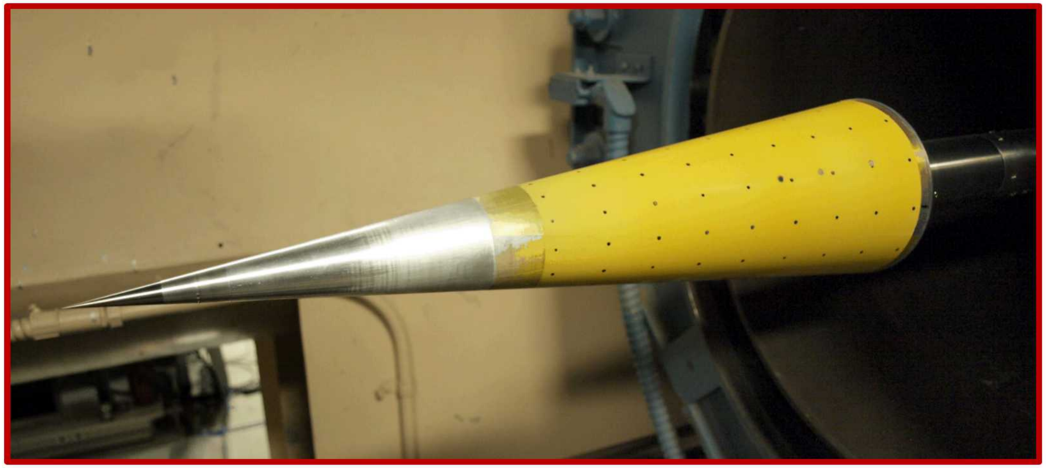


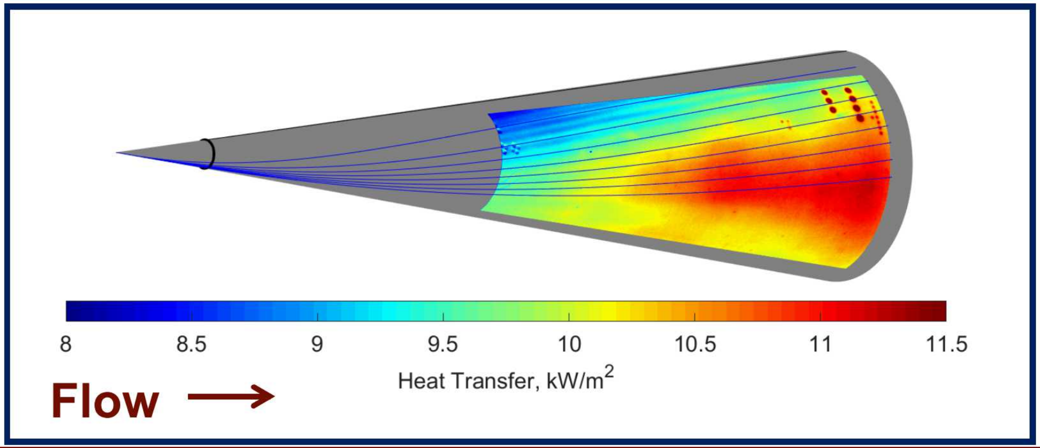
Transition to Turbulence on Flared Cone under Quiet Flow

Another solution: Bring out another Purdue Intern!

Josh Edelman

- **Temperature-Sensitive Paint (TSP) implementation at SNL**
- **Crossflow Studies at Purdue and Sandia National Labs**
  - How do trends compare between Mach numbers?
  - Can we connect noisy and quiet wind tunnel data?
- **Validation case for SNL computations.**





Purdue Academic Alliance

More formal collaboration framework now in place.

- Partnership between Sandia, Purdue Propulsion, and the BAM6QT to developed advanced laser-based diagnostics (FLEET).

Additional SNL interns/alumni from Purdue!

- Katie Gray
- Clayton Smith

Team Schneider!

- Lockheed-Martin – Craig Skoch
- NASA Langley – Shann Rufer / Amanda Chou
- BAE Systems – Erick Swanson
- AFRL – Matt Borg
- Notre Dame – Tom Juliano
- Sandia National Labs – Katya Casper
- Applied Physics Lab – Brad Wheaton / Dennis Berridge
- Raytheon – Chris Ward
- USAFA – Roger Greenwood
- Purdue – Brandon Chynoweth
- Boeing – Matthew Lakebrink
- DARPA contractor – Josh Edelman

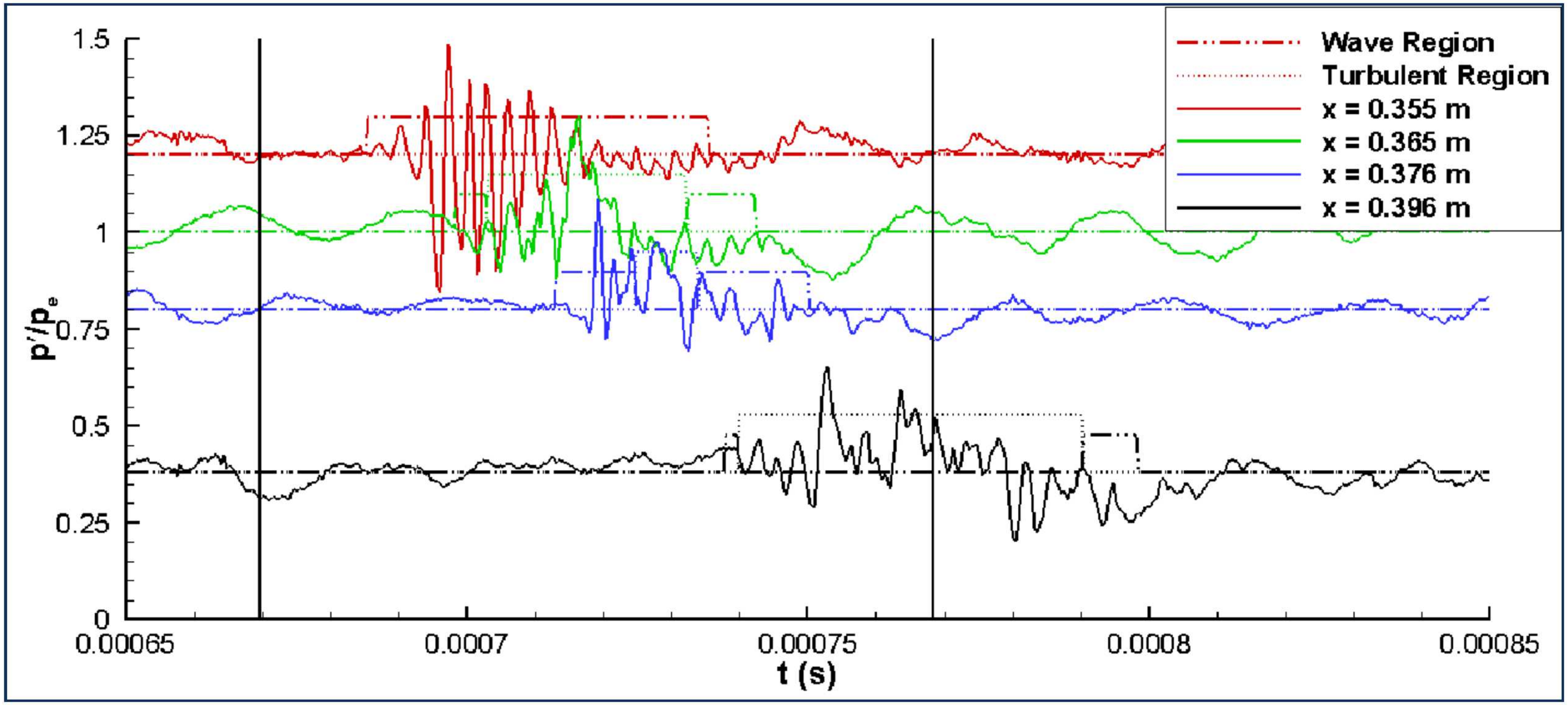
Many other MS Students and Mach 4 prototype alumni not listed here!

Backup Slides

Separating Instability Waves from Turbulence

Separate instability waves from turbulence using a wavelet transform technique, and the frequency range of fluctuations.

- Technique does a reasonable job separating the two regions.
- Can see evidence of waves at leading and trailing edges of turbulent disturbances.

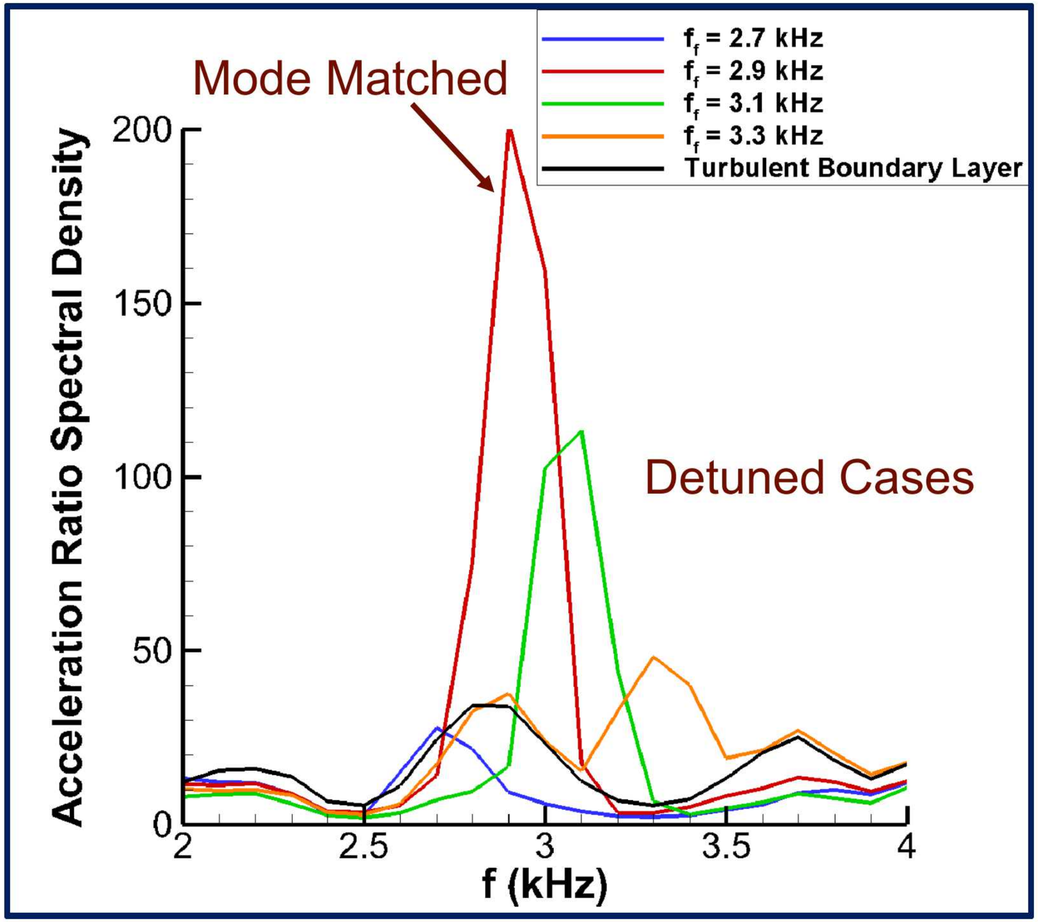


Response to Periodic Spots at Detuned Frequencies

Ratio response to baseline response measured under a laminar boundary layer.

- Largest panel response when forcing frequency matches a structural natural frequency.
  - **200 times larger than under a laminar boundary layer!**
- Smaller responses at detuned frequencies.

Worse-case scenario for component response.

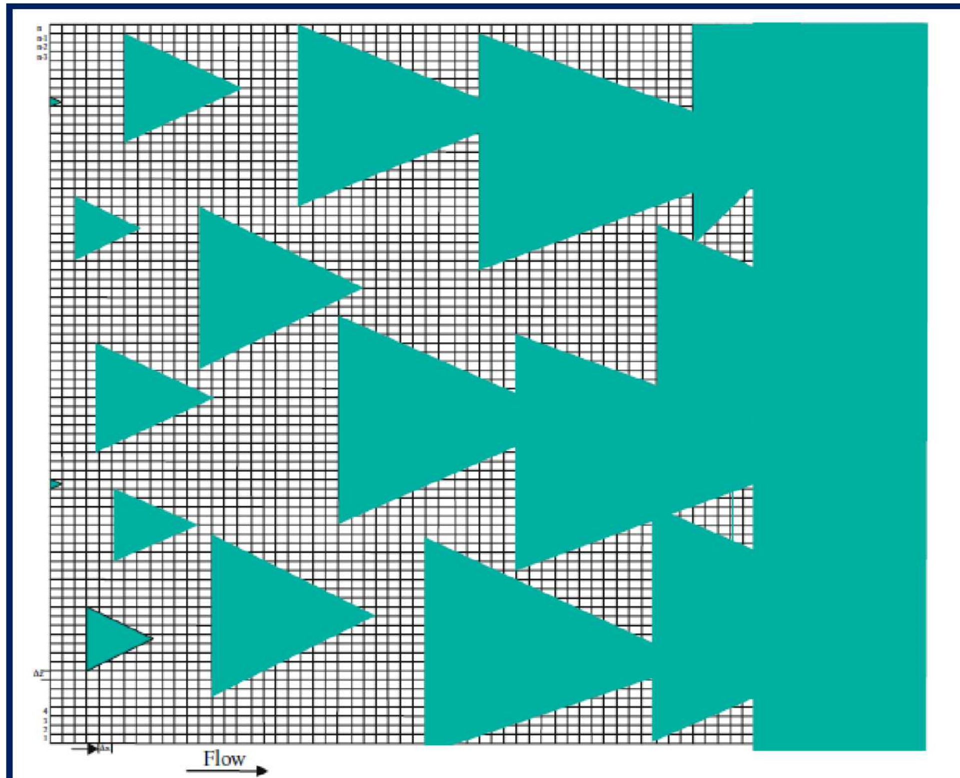


Flight-like Environments

In a flight scenario, natural transition contains a more random distribution of spot locations and generation times.

- As the freestream Reynolds number (Re) increases, approach more fully turbulent flow over the vehicle.
- How does this effect the panel response?

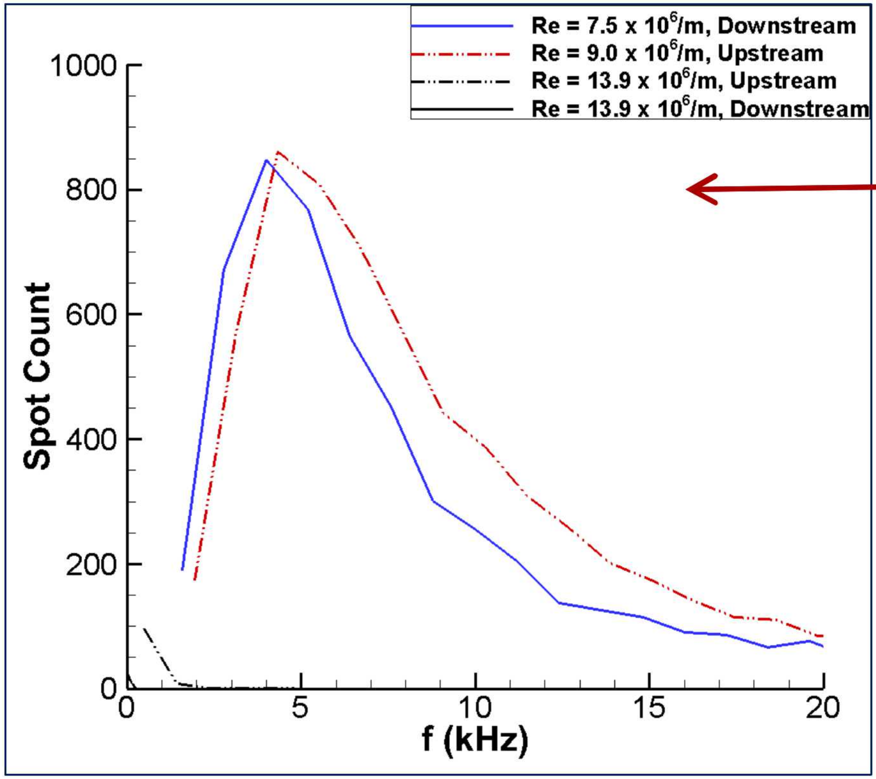
Incompressible turbulent-spot model simulation, Vinod (2007).



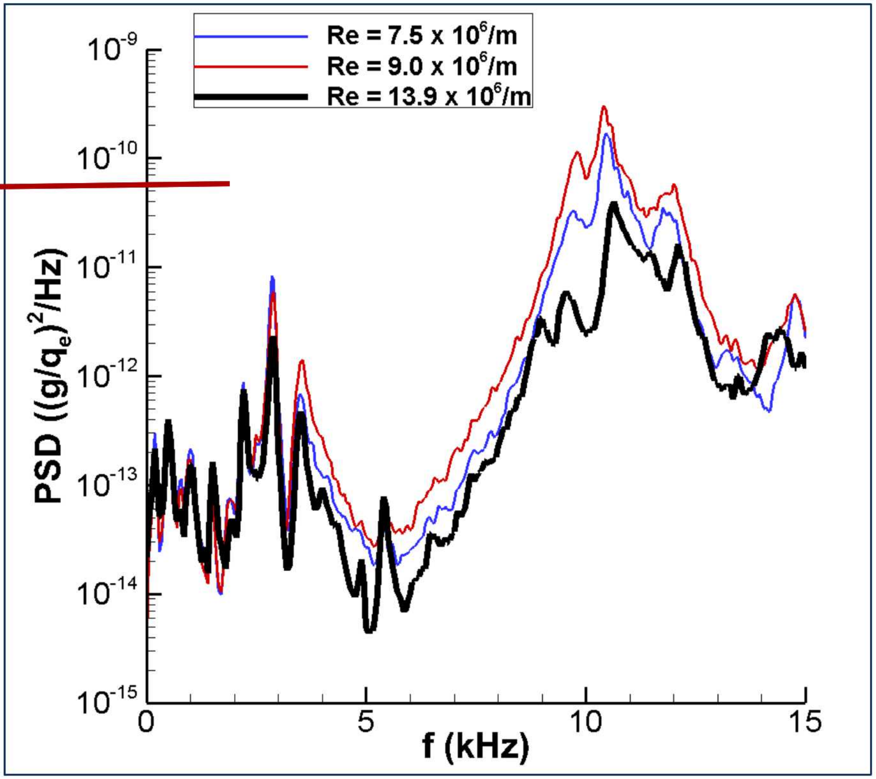
Flight-Like Environments

Spot forcing distributions corresponds to elevated vibrational frequencies over a broad, high-frequency range during transition.

- Vibrations drop for turbulent flow as burst rate decreases.



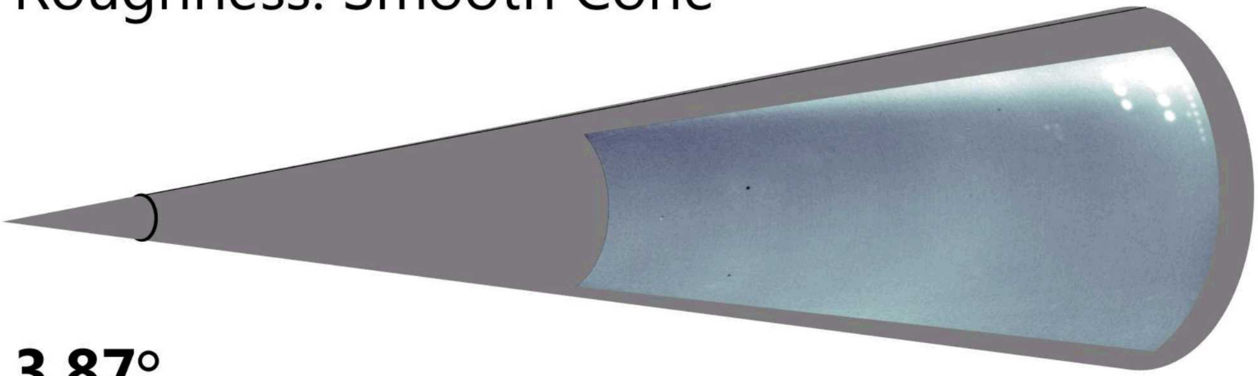
Spot Forcing Distribution



Z-Acceleration Spectra

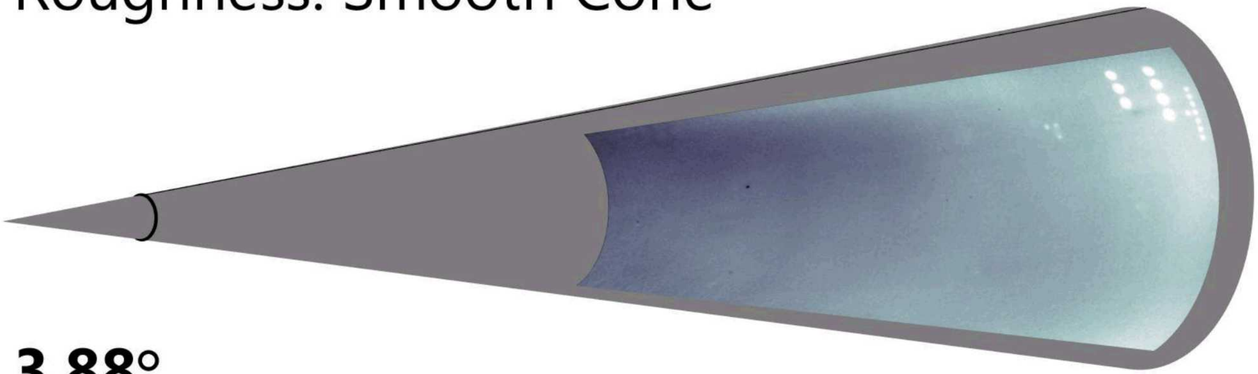
Mach 5 & 8, Smooth Cone

Re = 6.3e6 /m, M = 5
Roughness: Smooth Cone



3.87°

Re = 11.3e6 /m, M = 8
Roughness: Smooth Cone



3.88°