SAND2018-7650PE

Pressure Fluctuations and Fluid-Structure Interactions during Hypersonic Boundary-Layer Transition

Katya Casper

Sandia National Laboratories

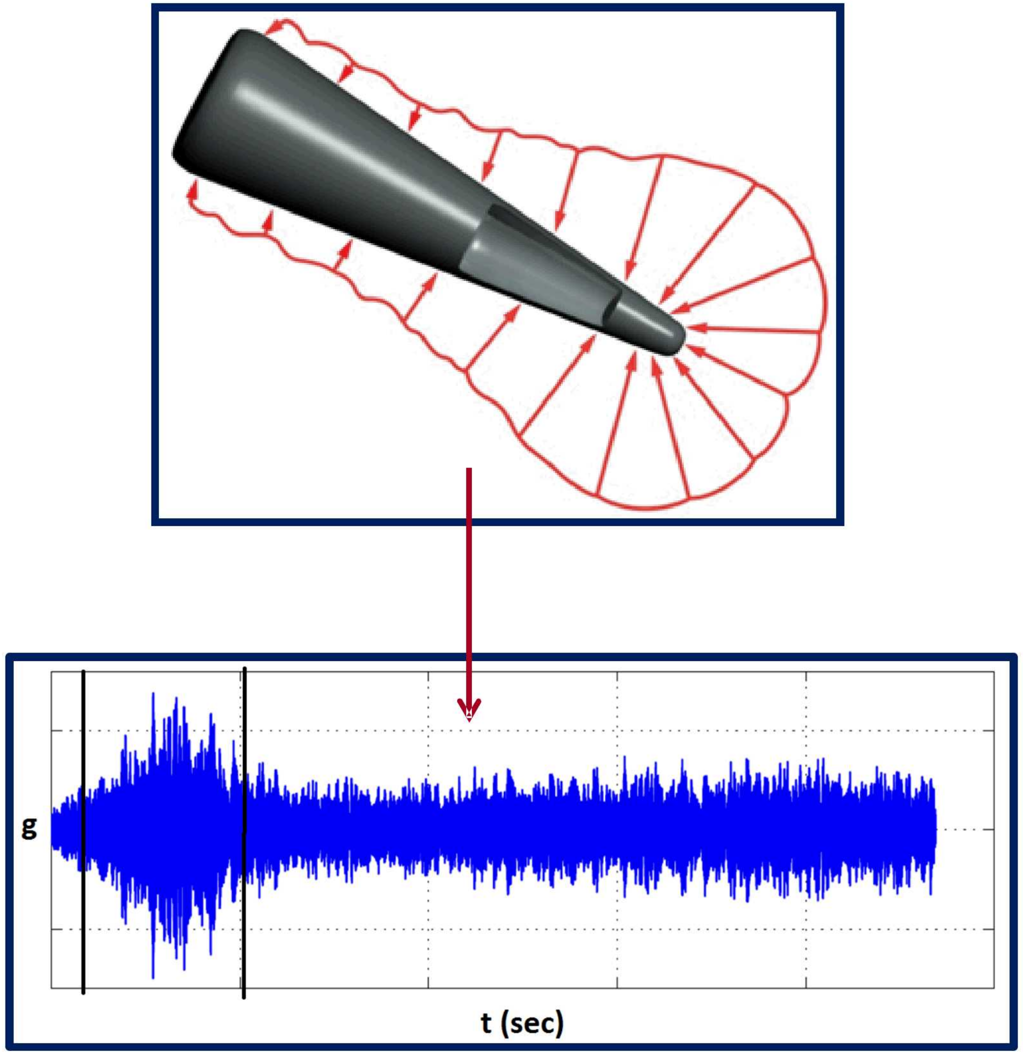
July 31, 2018

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Motivation

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 in hypersonic flow.

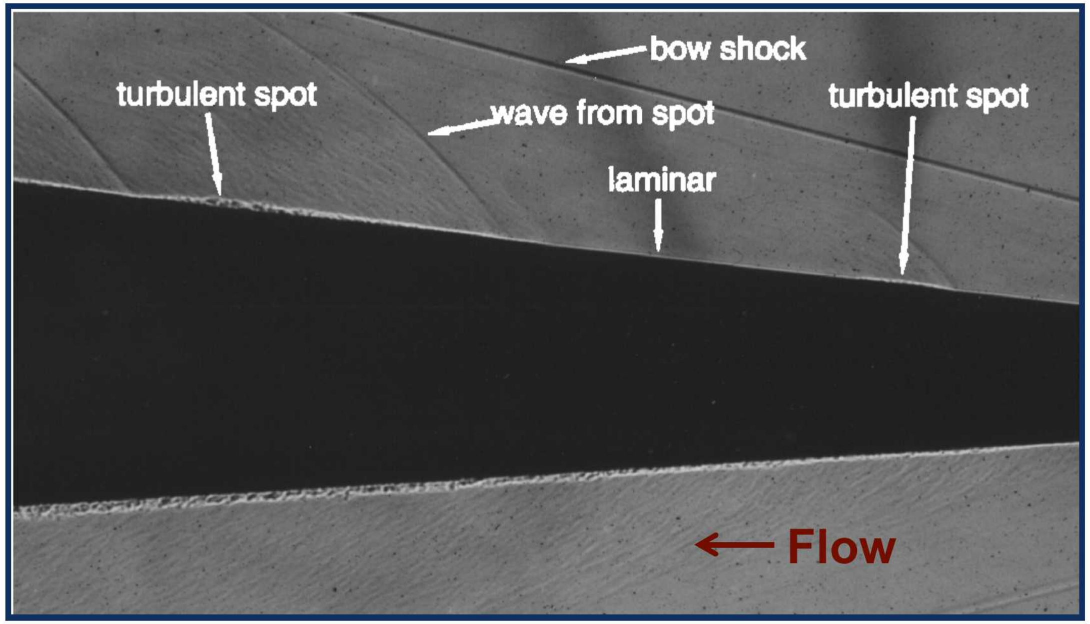


Boundary Layer Transition and Pressure Loading

Pressure fluctuations are generated by turbulent spots in the transitional boundary layer

- Need to model spot growth and spatial distribution to predict the pressure loading.
- Current models based on correlations to incompressible flow data.

We have developed a similar model for high-speed flows using a turbulent-spot approach.

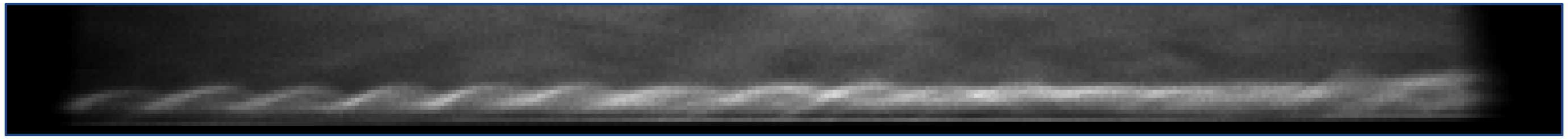


Shadowgraph of turbulent spots on a 5° sharp cone at Mach 4.3 in NOL Ballistics Range, from Reda.

Boundary Layer Transition: Instability Wave Packets

The second-mode instability is one of the dominant boundary-layer instabilities at hypersonic speeds.

- Acts like a trapped acoustic wave in the boundary layer.
- Dominant instability is 2D.
- Typically occurs at frequencies near 200-400 kHz.
  - Too high to drive vibrational response of structure.



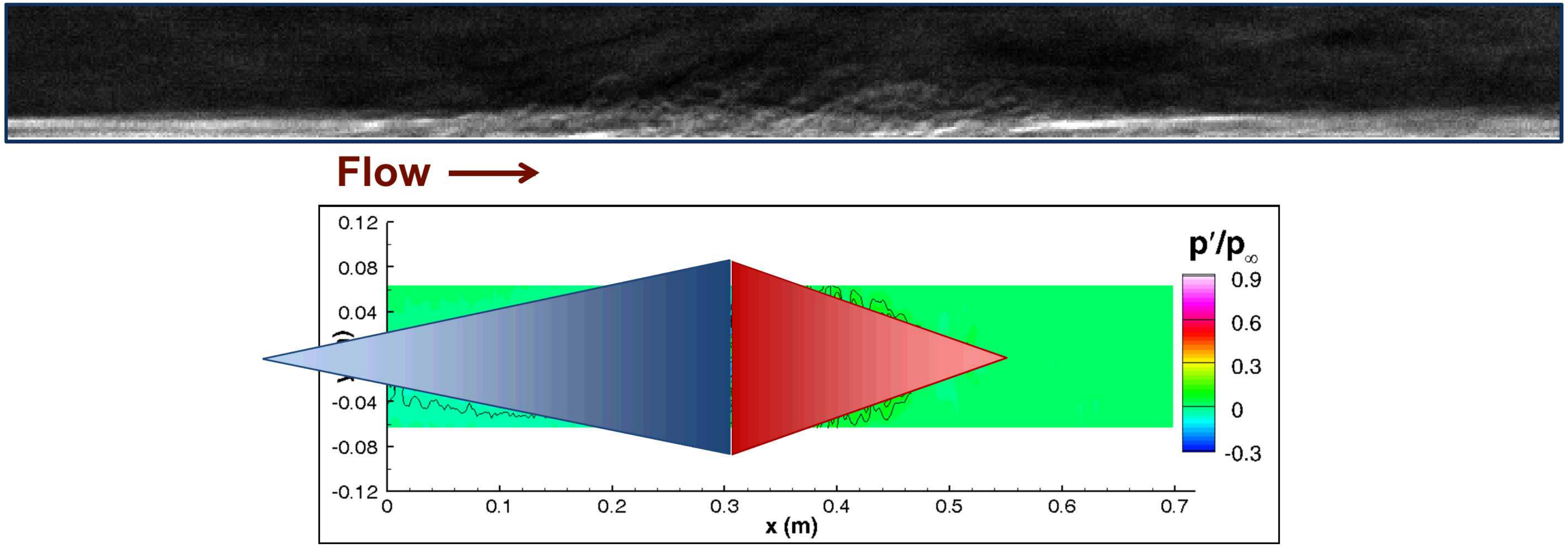
Second-mode waves in Mach 8 boundary layer.

Transitional Boundary Layer, Mach 8

Turbulent Spot Pressure Loading

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

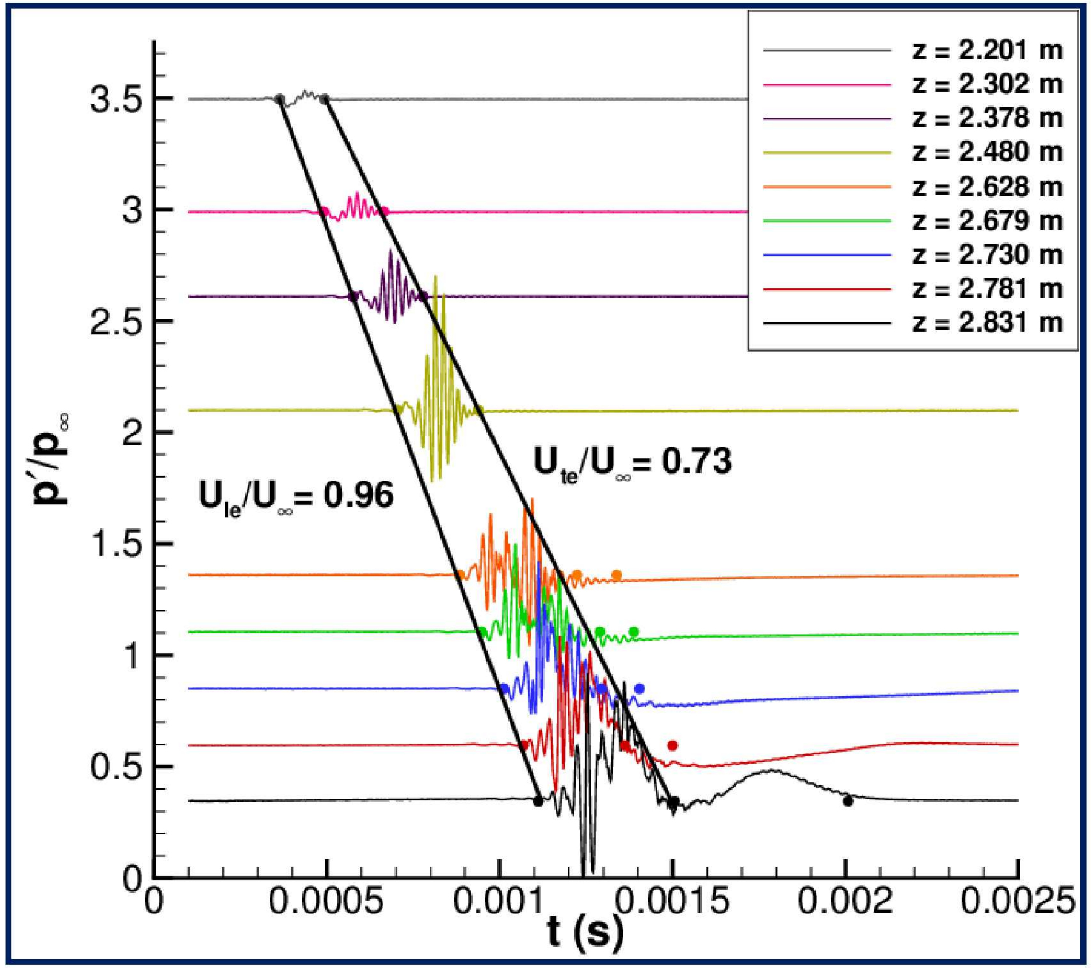
- Individual spots contain broadband turbulent pressure fluctuations
- Intermittent passage of spots drives lower frequency vibration.
- Spots grow and merge into a fully turbulent boundary layer.



Pressure footprint of turbulent spot, Mach 6

How fast do the disturbances grow?

- **Average leading edge convection velocity of 0.95 U_∞.**
- **Trailing edge convection velocity varies with Re between 0.64-0.75 U_∞.**
- Results agree well with DNS and other high-speed experiments.



Leading and trailing edges of controlled disturbances.

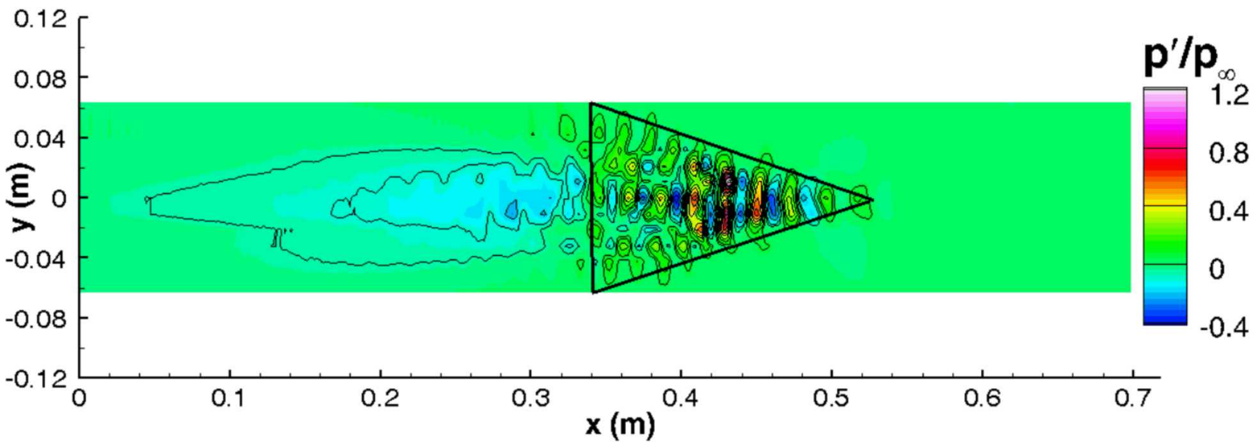
How fast do the disturbances spread laterally?

Triangular footprint is estimated for disturbances at four downstream locations.

- Lateral edges of disturbances as they change downstream are used to compute lateral spreading angle.

Found angle of 15 degrees, much higher than expected.

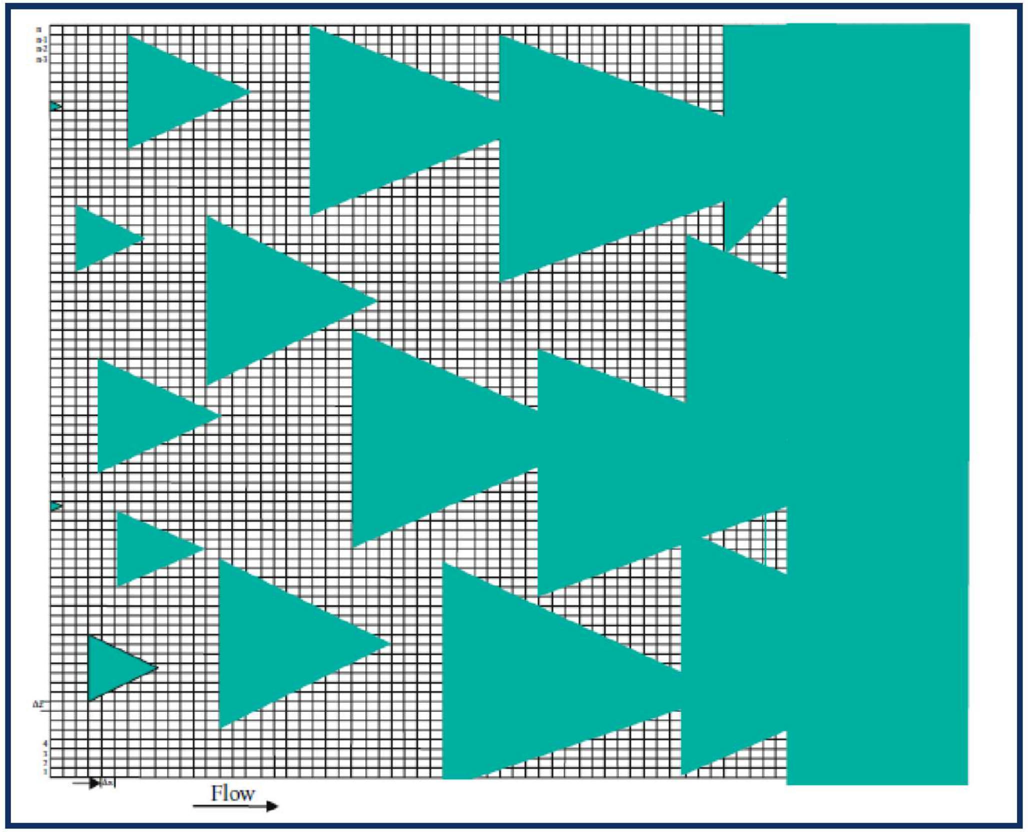
- High-frequency pressure fluctuations have never been used to define the spot footprint before.
- May provide a different spreading angle than other experimental or computational methods.
  - **Still one of the largest uncertainties in our models.**



Turbulent Spot Approach to Modeling Transitional Pressure Fluctuations

Need transition statistics to describe where spots are located and how often they are born.

- Intermittency
- Burst rate
- Average burst length



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

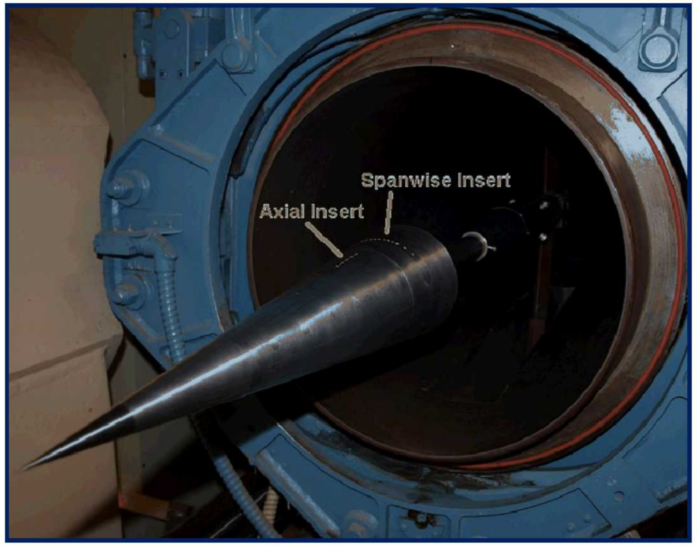
Experimental Setup

We want to study natural transitional boundary layers on a cone at Mach 5 and 8 to obtain transitional statistics.

- Simultaneous schlieren imaging and high-frequency pressure measurements.

Seven degree stainless-steel sharp cone in Sandia's Hypersonic Wind Tunnel.

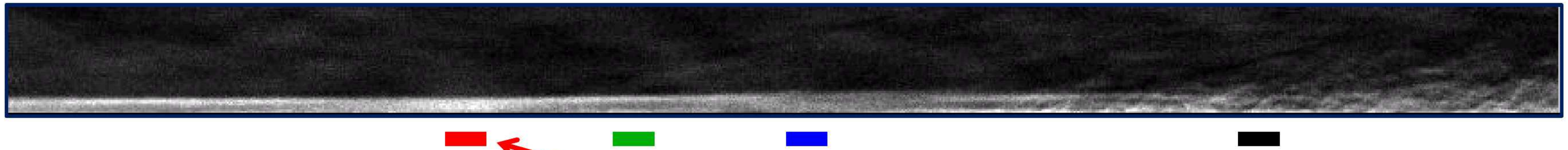
- Axial array with closely spaced high-frequency pressure transducers.
- Directly beneath schlieren viewing area.



Model installed in HWT.

Axial pressure-transducer array.

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



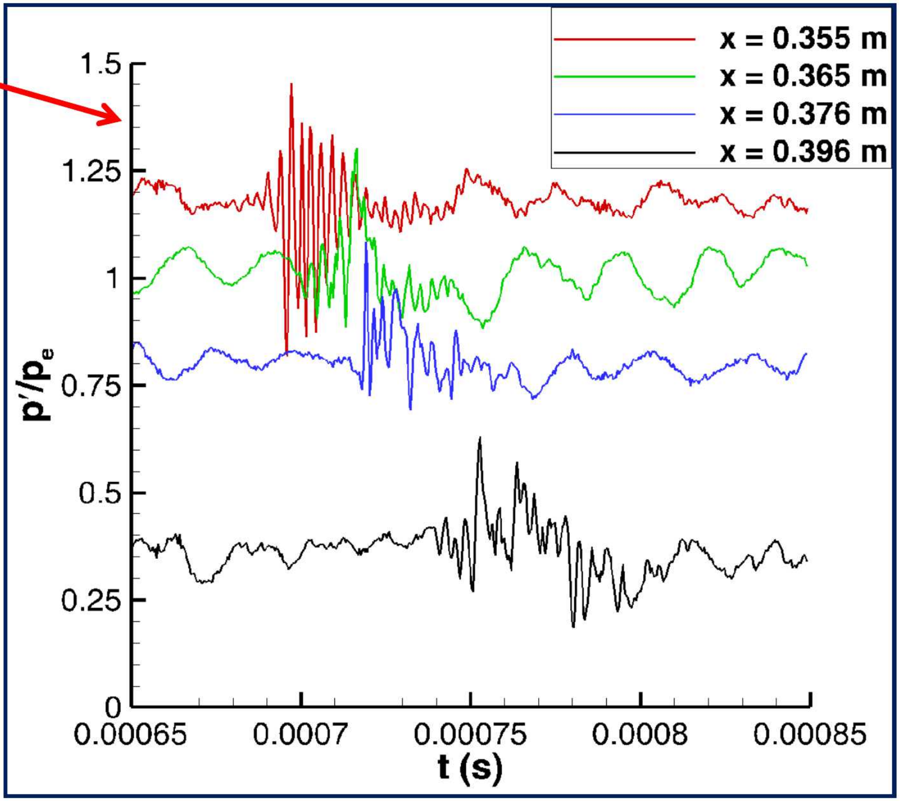
Schlieren Videos

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.

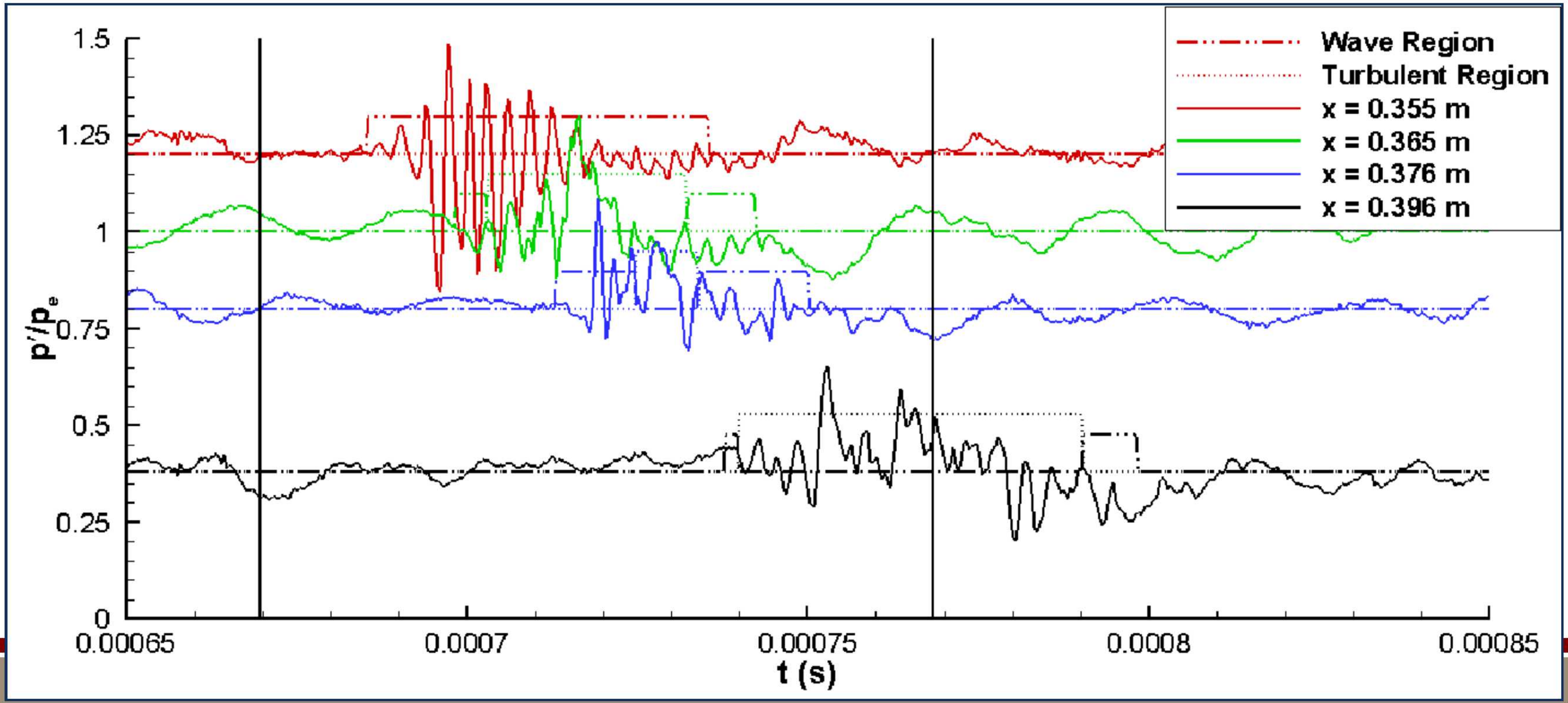


Simultaneous Pressure Traces

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.
  - **These techniques rely on thresholds that must be set from user judgement, and they change with Re, M.**
  - **Still an area of high uncertainty.**



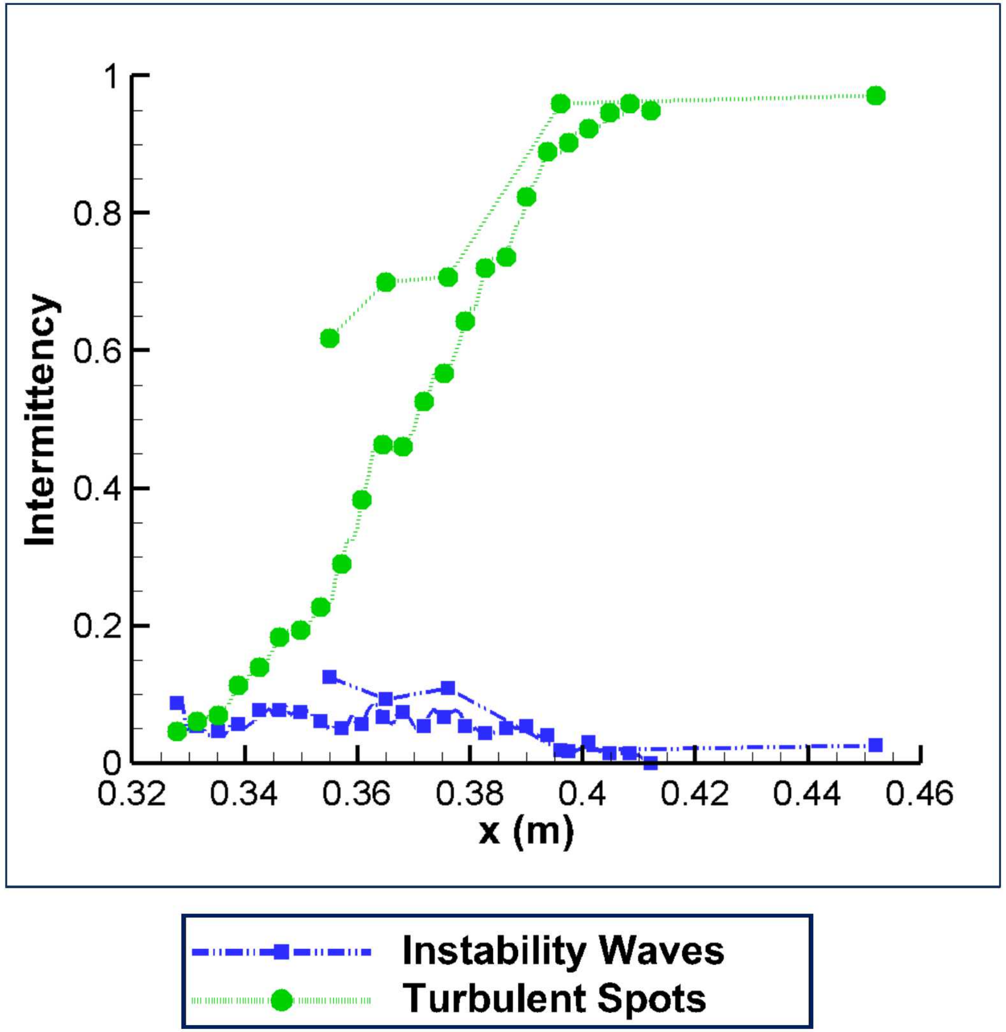
Mach 5 Transition Statistics

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

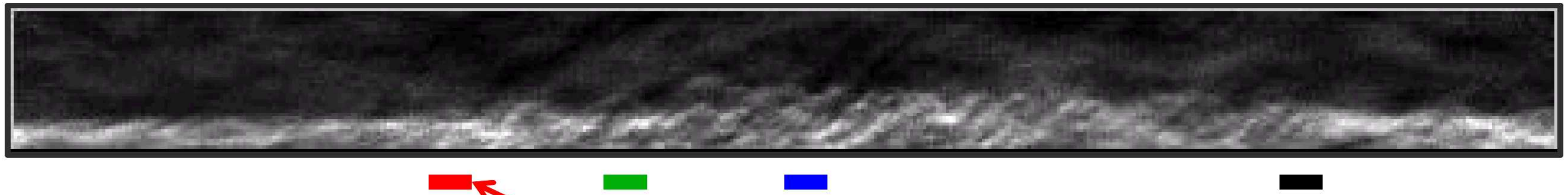
- Compute separate statistics for instability waves and turbulent spots.
- Both measurement techniques show reasonable agreement.

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



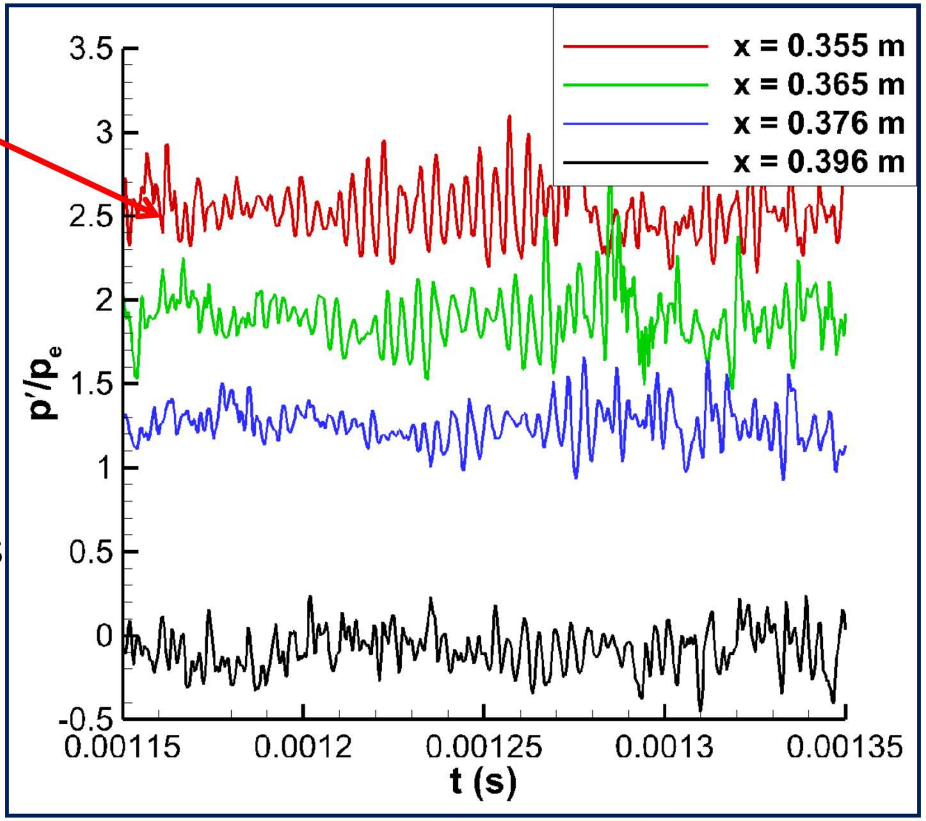
Schlieren Videos

Flow alternates between second-mode waves and turbulence.

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

Important to separate waves from turbulence in this case.

- Wavelet transform technique used to do this
- Then, use this to compute boundary-layer intermittency and burst rates for waves and turbulence.



Simultaneous Pressure Traces

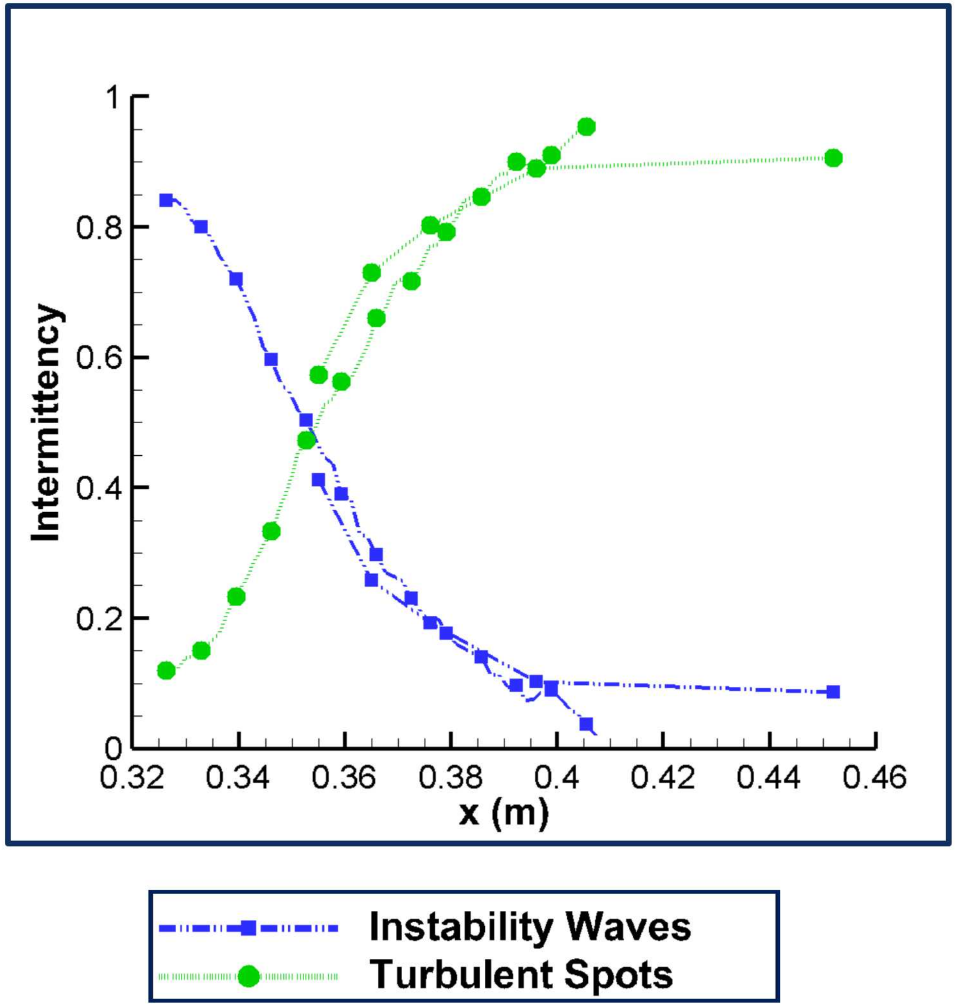
Natural Transition Statistics: Intermittency

Instability waves

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

Turbulent spots

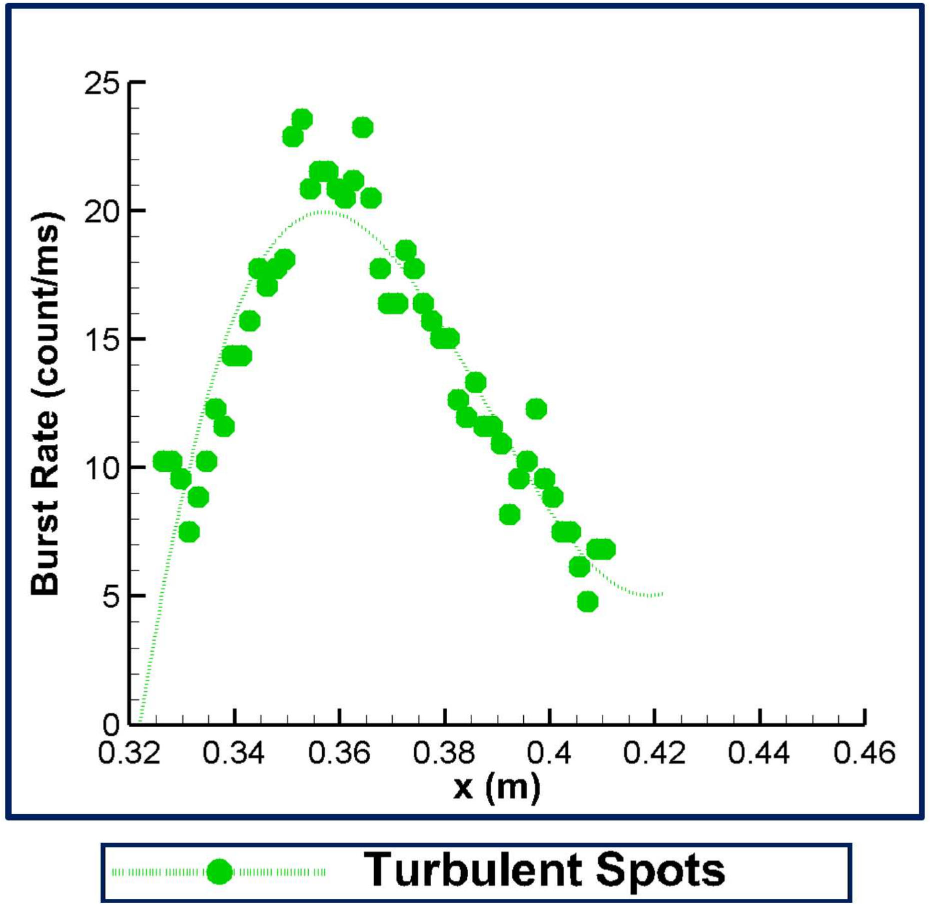
- Gradually begin to dominate flow.
- Turbulent intermittency rises as instability wave intermittency decreases.



Natural Transition Statistics: Burst Rate

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

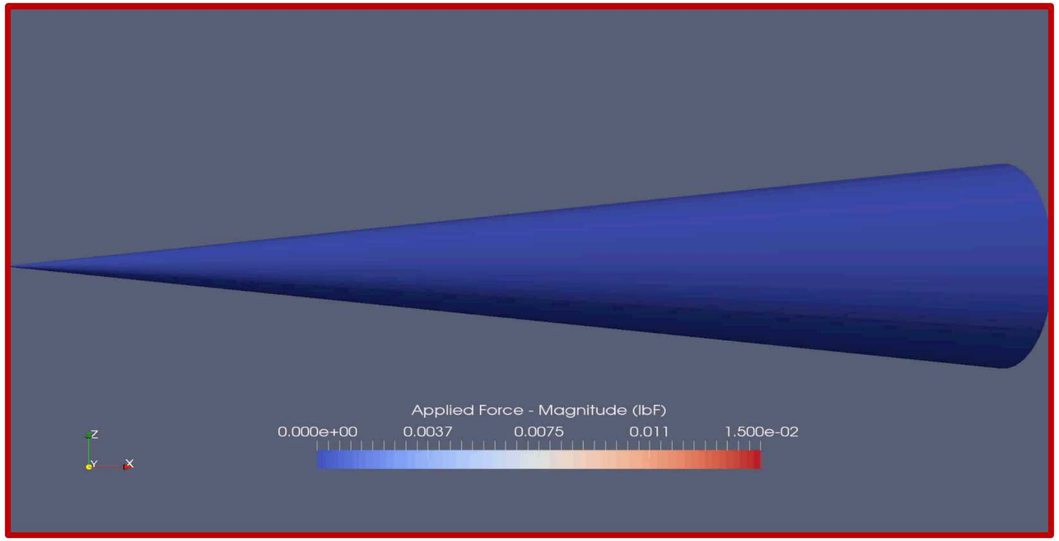
- Equal burst rate for instability waves and turbulence.
- High burst rate when intermittency is near 0.5.
- Burst rate decreases as spots merge into turbulence at locations further downstream.



Impact and Application

- **Forms some of the first datasets in hypersonic flow characterizing spot growth and transition statistics.**
  - Previous measurements are limited and few and far between.
- **Datasets are actively being used at SNL.**
  - Implemented in turbulent spot models for transitional flow at SNL.
  - Used for flight vehicle computations.

- **This effort was important for workforce development.**
  - Joint work between SNL and Purdue university for my MS/PhD degrees.
  - I continued on to SNL full-time.
  - **The need for hypersonic experimentalists continues and we are seeing a major shortfall in qualified candidates at Sandia.**



What challenges still persist ?

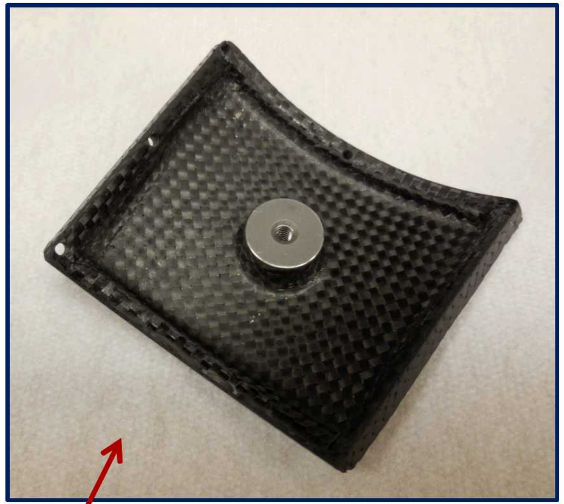
- Uncertainty in lateral spreading angle.
- Uncertainty in thresholds set for computing transition statistics.
- **Generalizing to additional cases at nonzero AoA.**
- **Generalizing to other geometries.**

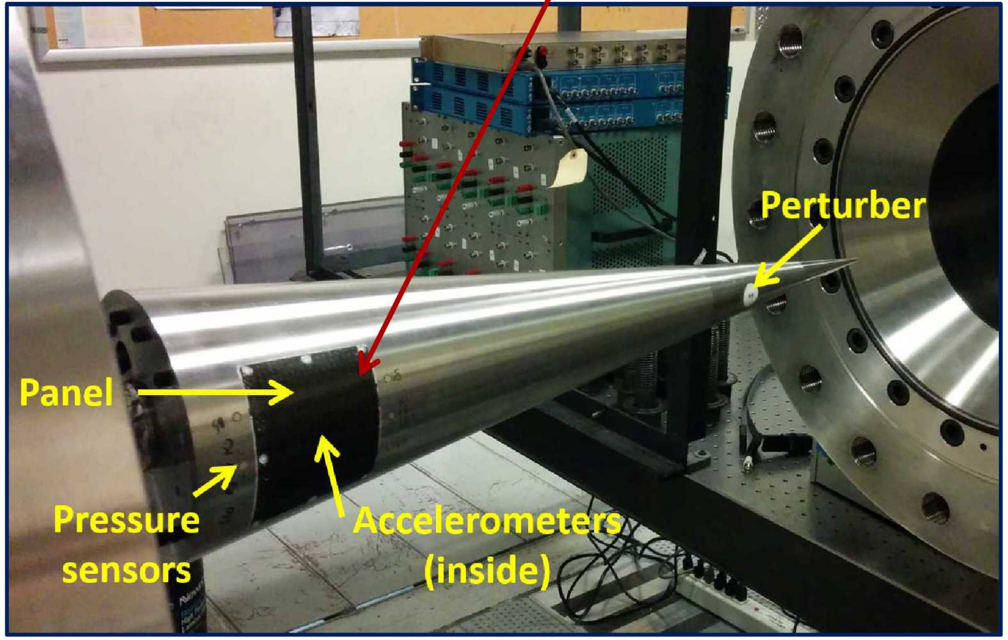
What is the vibrational response to this environment?

Very limited hypersonic fluid-structure interaction experiments prior to this work.

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.





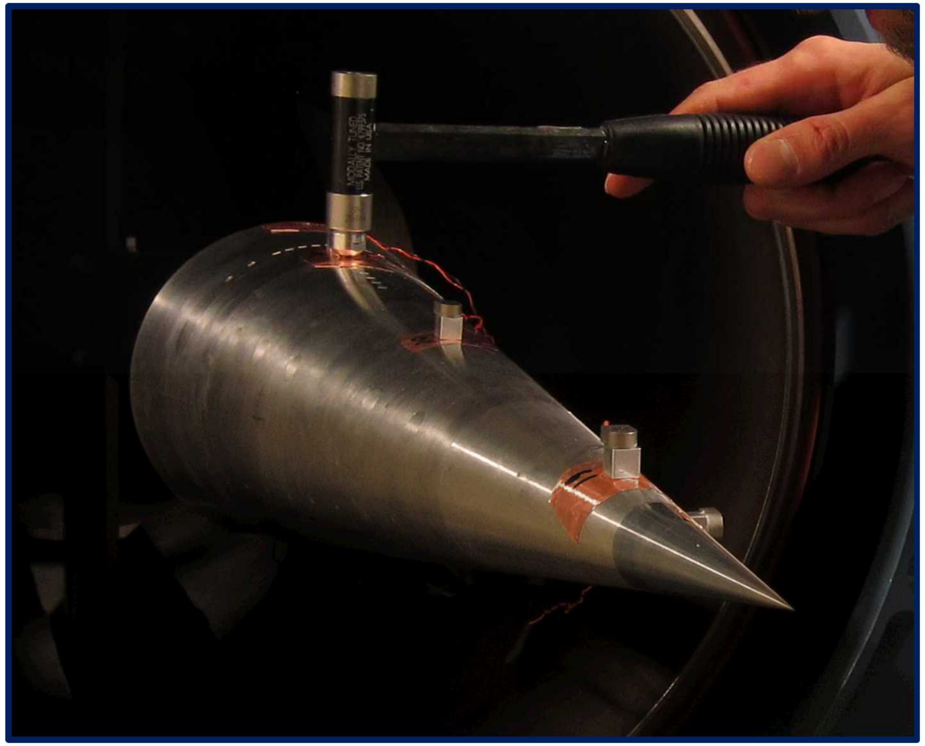
A spark perturber is used to create periodic turbulent spots in the boundary layer.

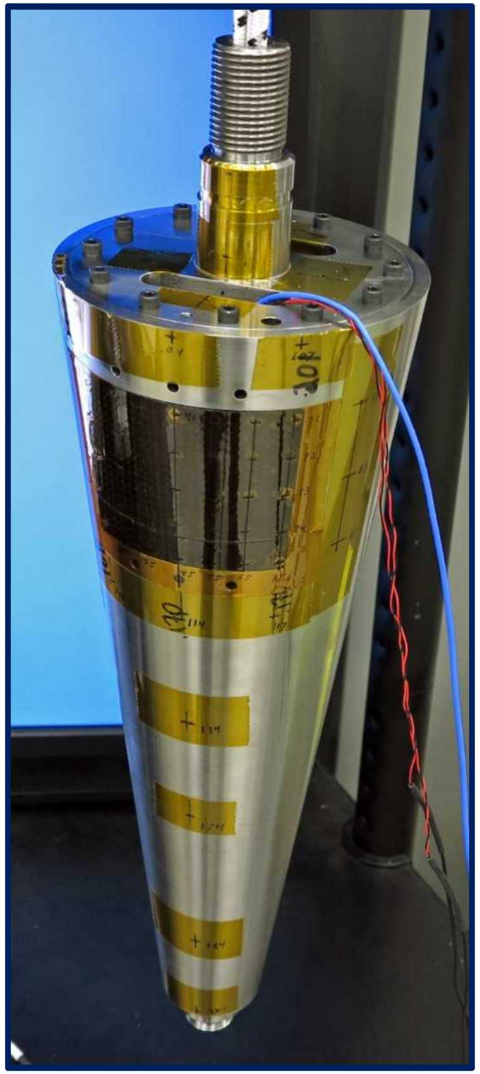
- Simplified validation case for modeling and simulation.

Structural Characterization

Hammer test was performed to determine the structural natural frequencies of the panel and model.

- Measure structural response to a known input.
- Mode frequencies are obtained up to 10 kHz.
- Can also characterize mode shapes.

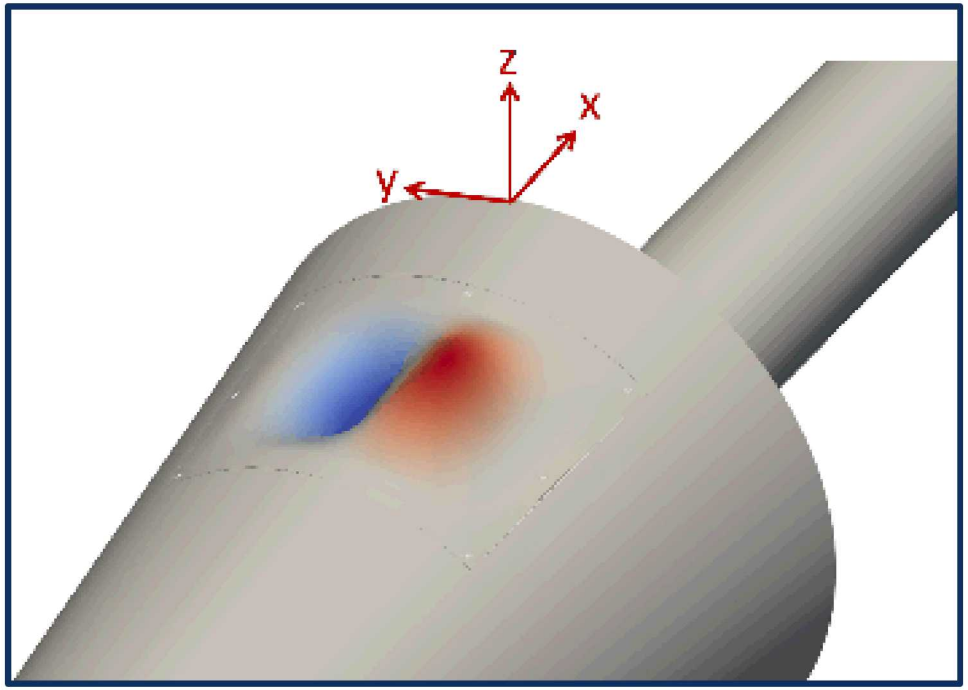




P_y Mode, f_s = 2.1 kHz

Sinusoidal mode shape in spanwise (y) direction.

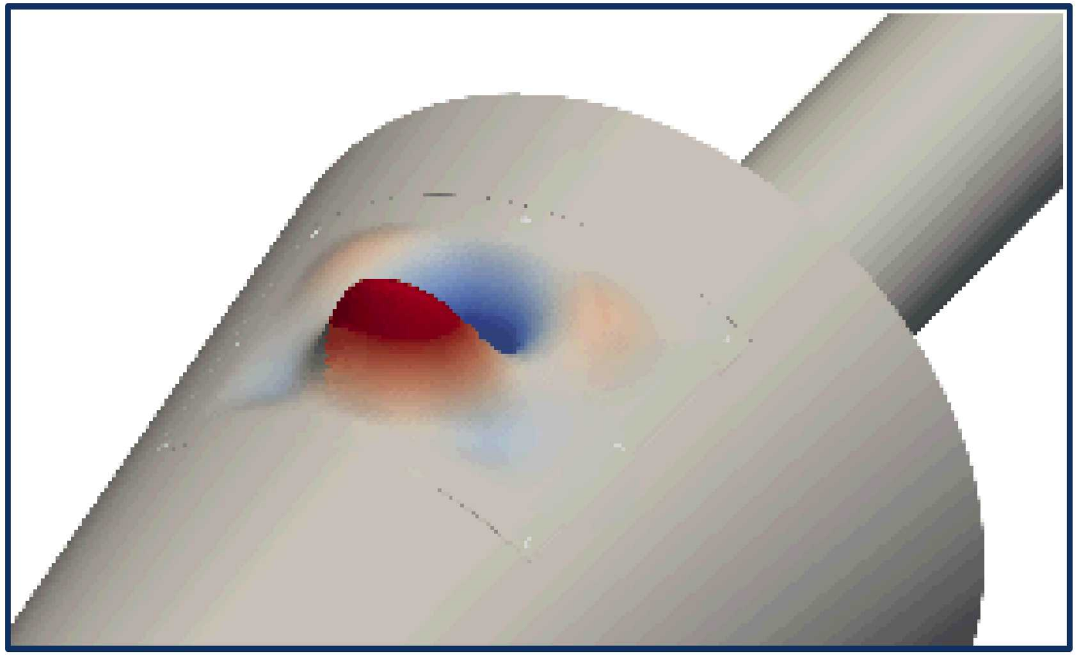
- Oscillates with time.
- Peak amplitude away from panel center.
  - Finite size accelerometer will see motion primarily in y direction.
  - Also z direction motion from spanwise rocking.
- (2,1) mode shape
- Note: mode shape displacement is exaggerated!



P_x Mode, f_s = 3.4 kHz

Sinusoidal mode shape in streamwise (x) direction.

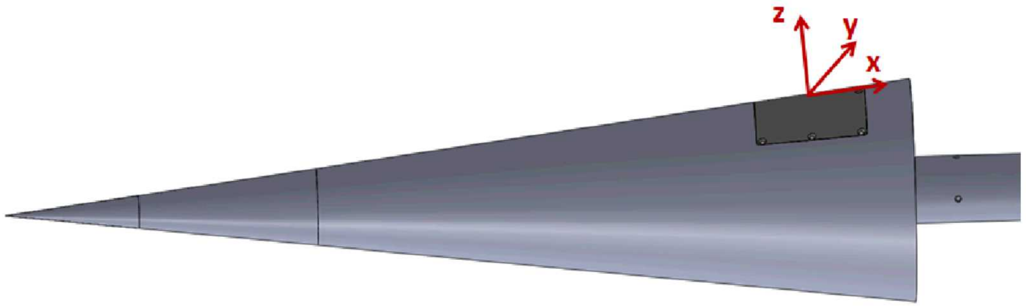
- Oscillates with time.
- Peak amplitude away from panel center.
  - Accelerometer of finite size will see dominate x motion.
  - Will also see z motion from accelerometer rocking.
- (3,2) mode shape.

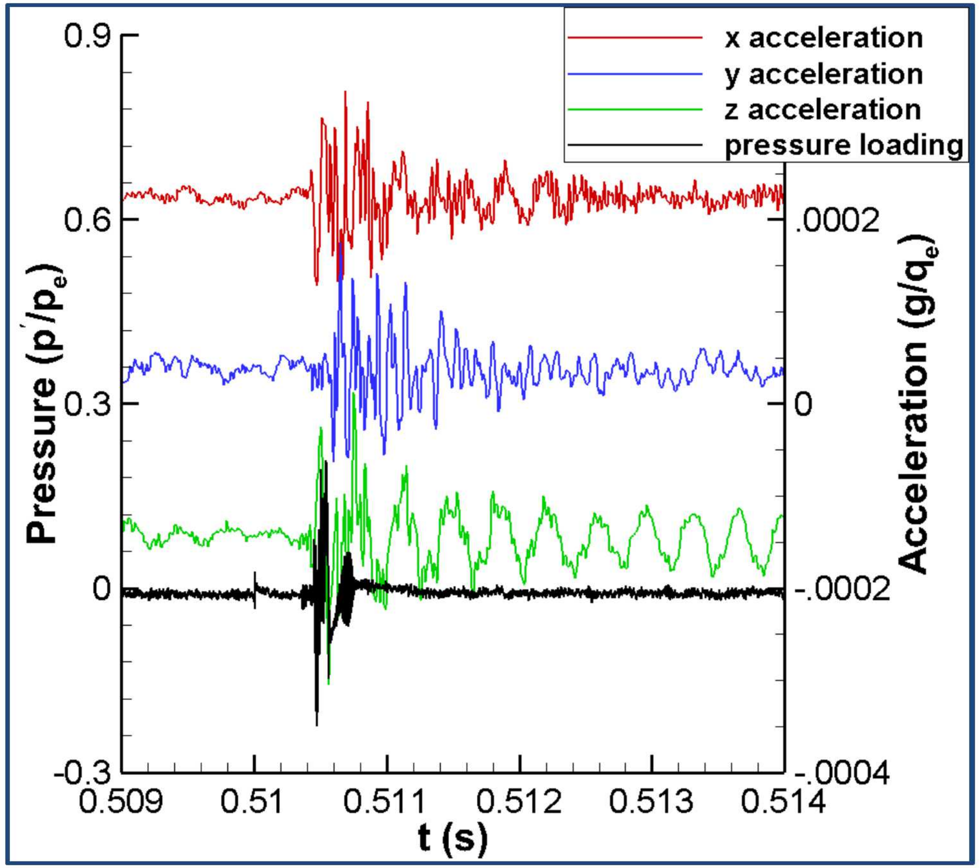


Response to Isolated Turbulent Spots

Panel shows a clear response to spot excitation

- Response lasts longer than forcing input.
- Directionally dependent because of mode shapes of excited structural natural frequencies.

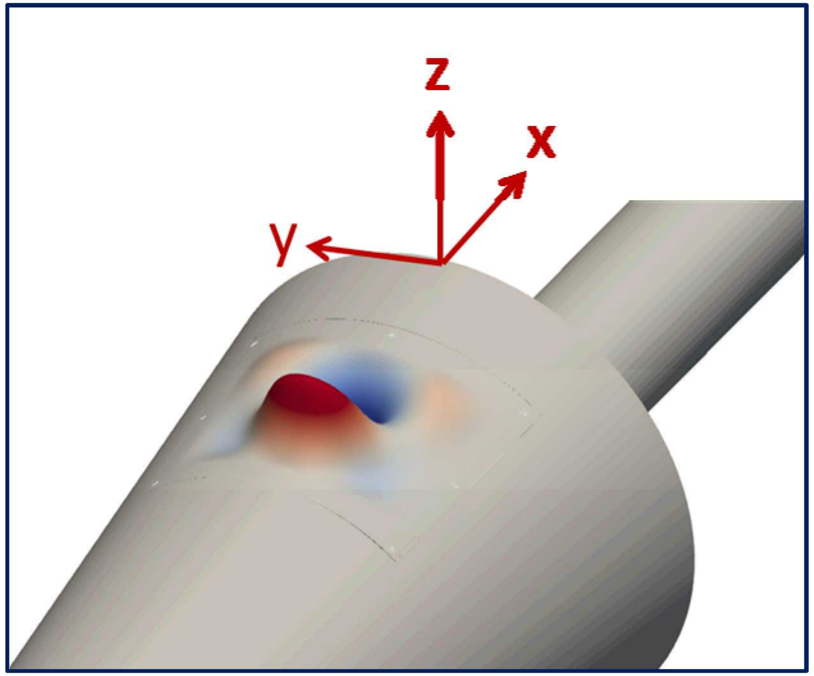


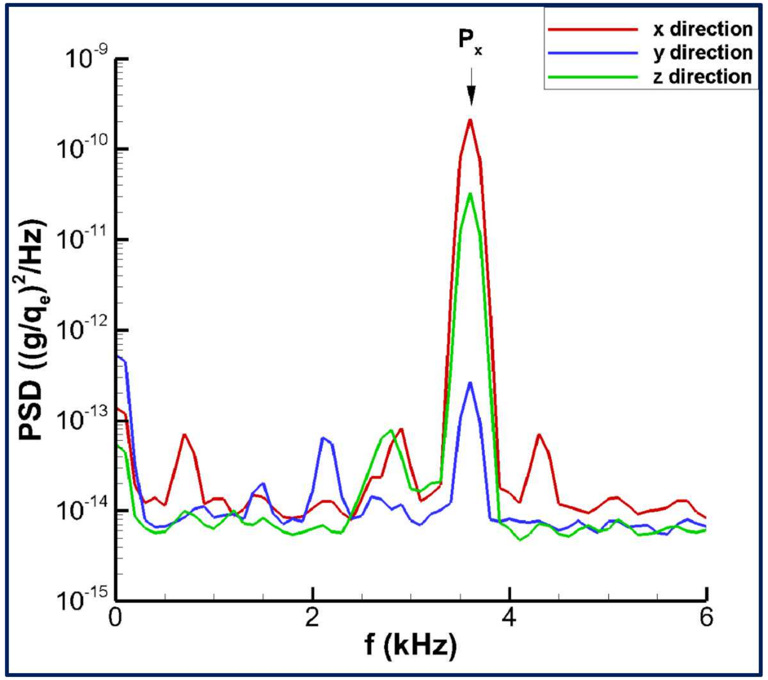


Response to Periodic Spots at Structural Natural Frequencies

Forcing panel at a structural natural frequency excites a strong modal response.

- Dominant response in mode shape directions predicted by structural characterization.
- Mode matched case.



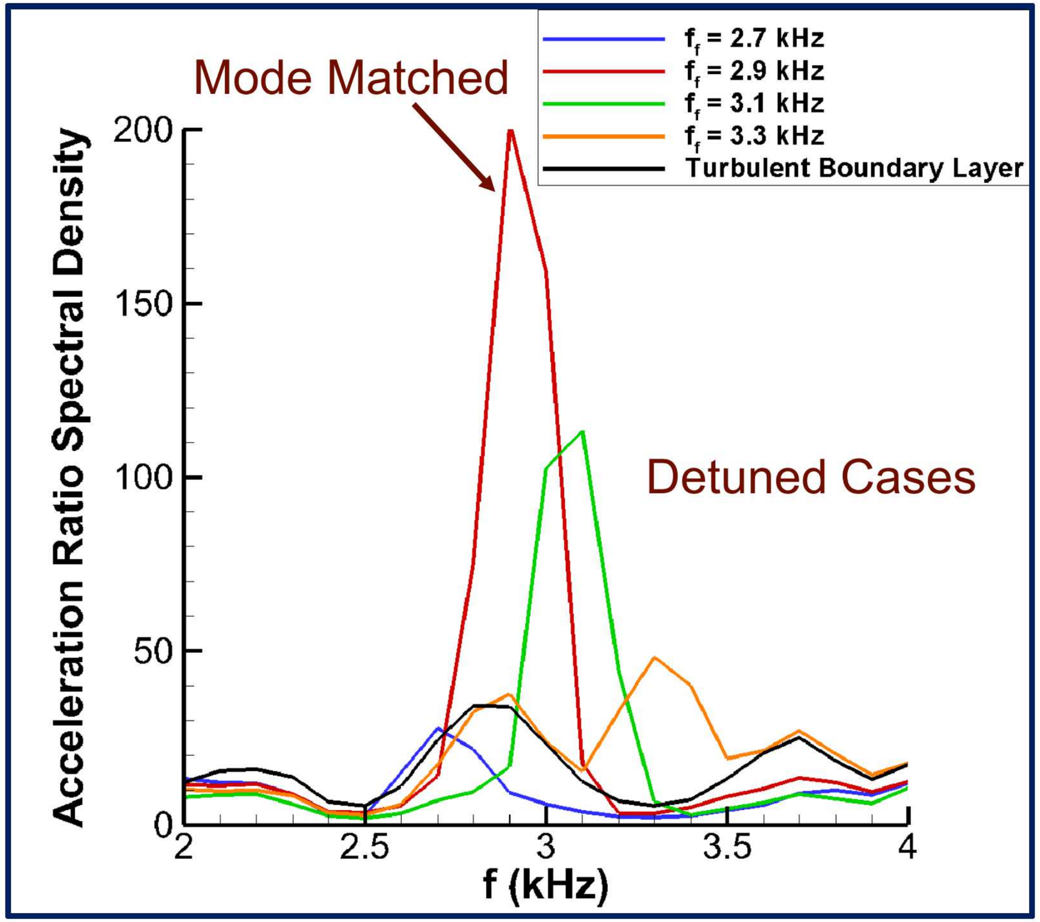


Response to Periodic Spots at Detuned Frequencies

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.

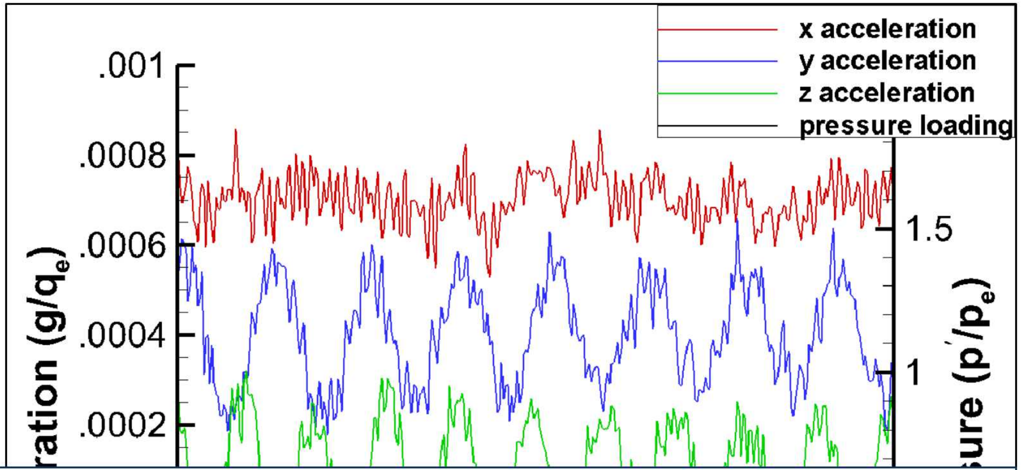


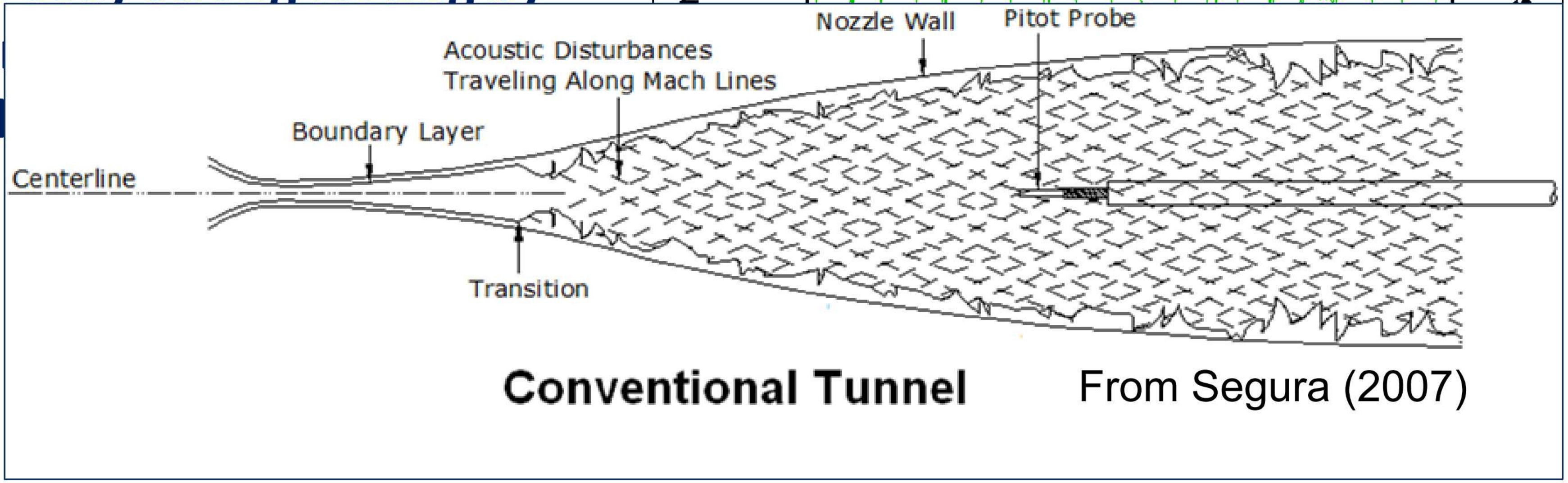
Effect of Tunnel Noise

Similar measurements were made under noisy-flow conditions at Mach 5 in the Sandia Hypersonic Wind Tunnel.

Already strong forcing by tu ad

-





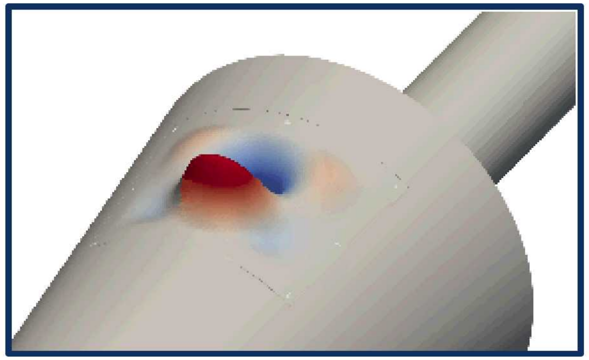
From Segura (2007)

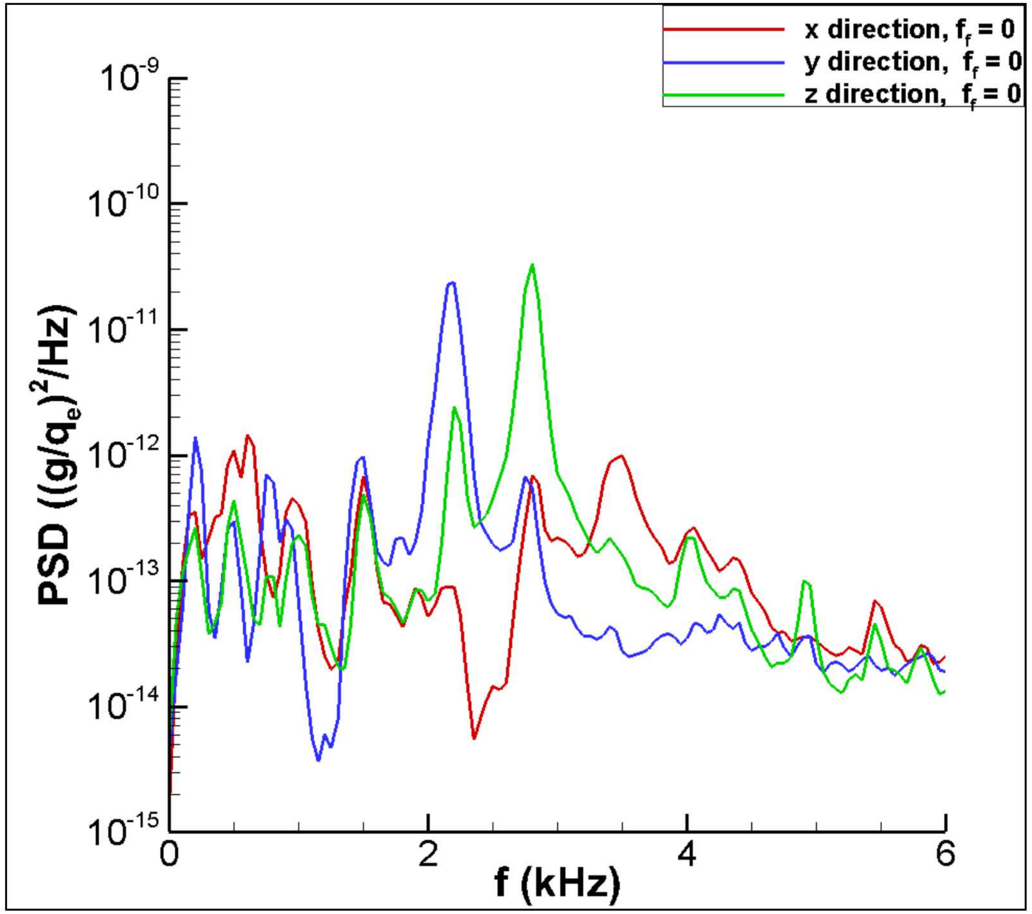
Effect of Tunnel Noise

Already strong forcing by tunnel noise without additional spot loading

Forcing at this frequency strongly excites the P_x mode.

- Dominant response in x and z because of the mode shape.



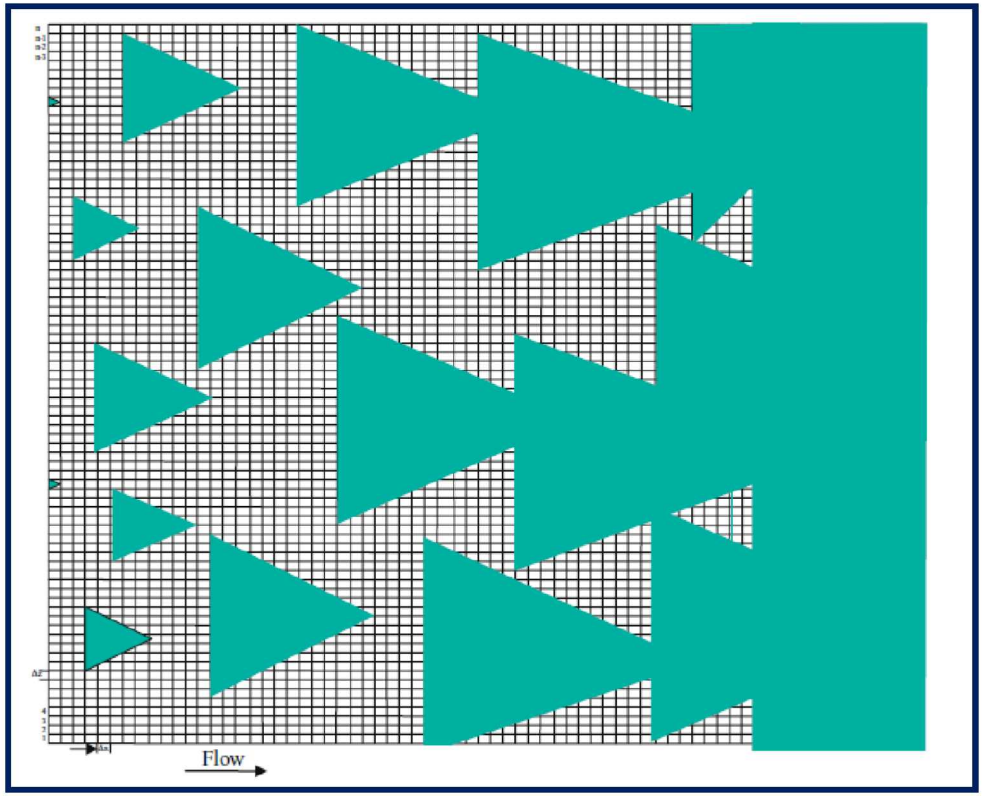


Flight-like Environments

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).



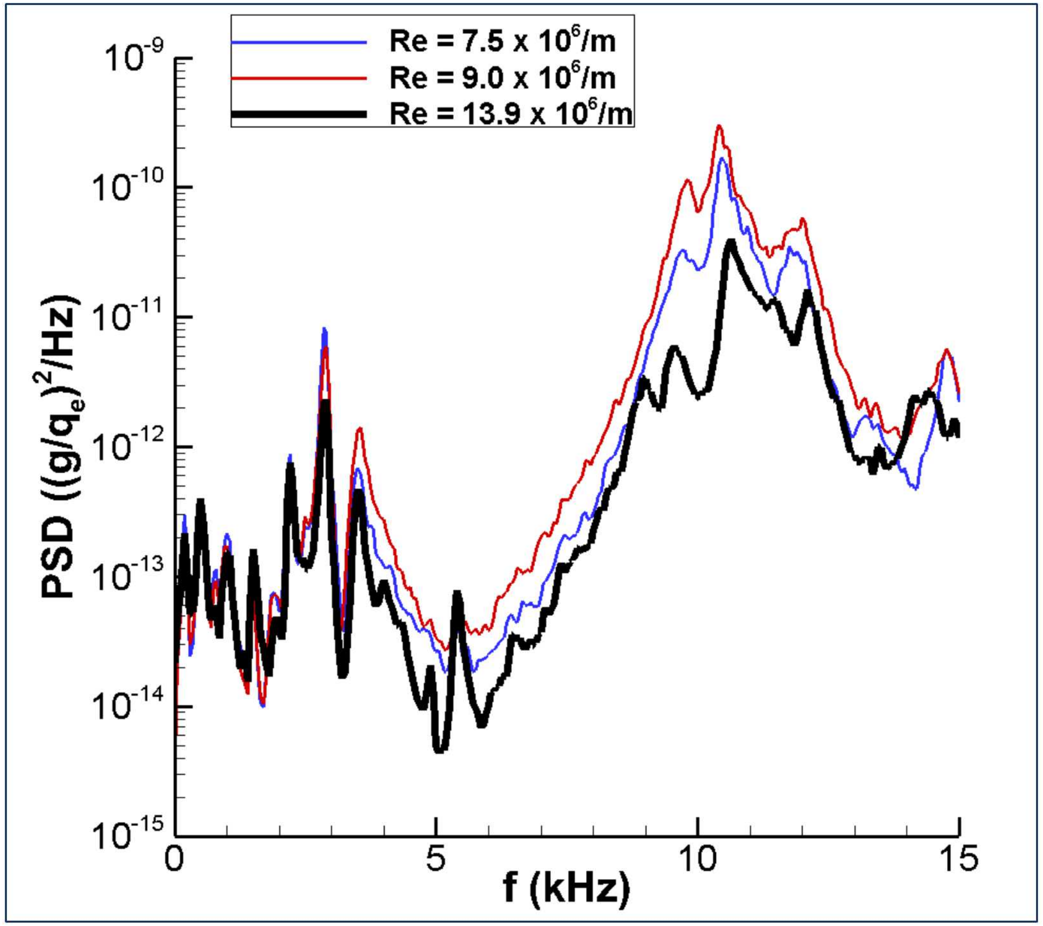
Natural Transition at Mach 5

Observe elevated vibrations during transition, at frequencies > 3 kHz.

- Re = 7.5-19.7 x 10^6/m
- How does this relate to the turbulent spots?

Vibrations drop for a fully turbulent boundary layer.

- Re = 13.9 x 10^6/m

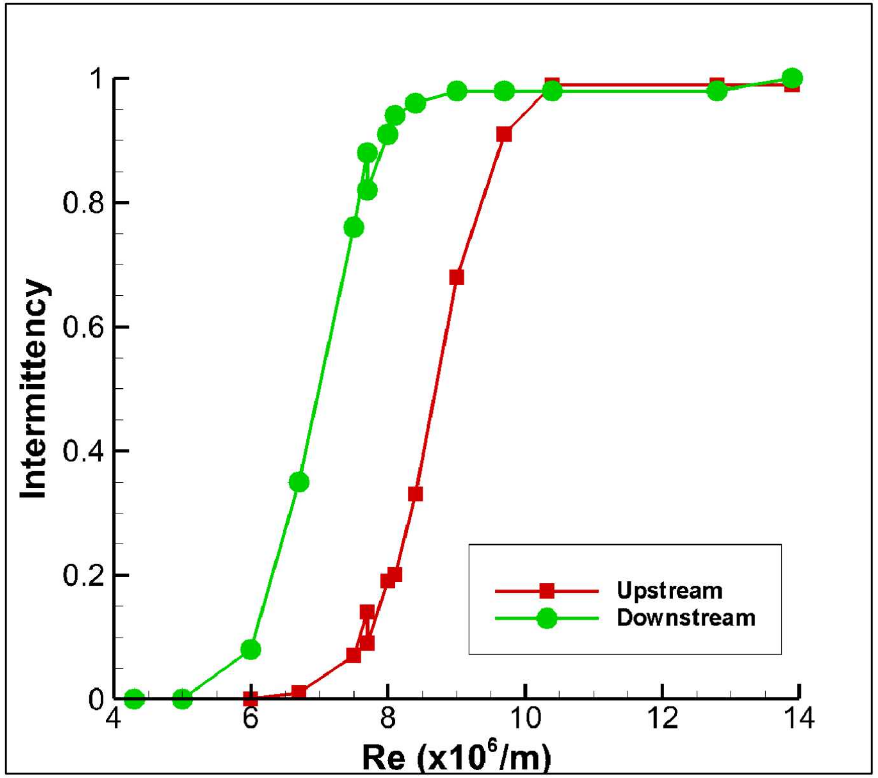


Z-Acceleration Spectra

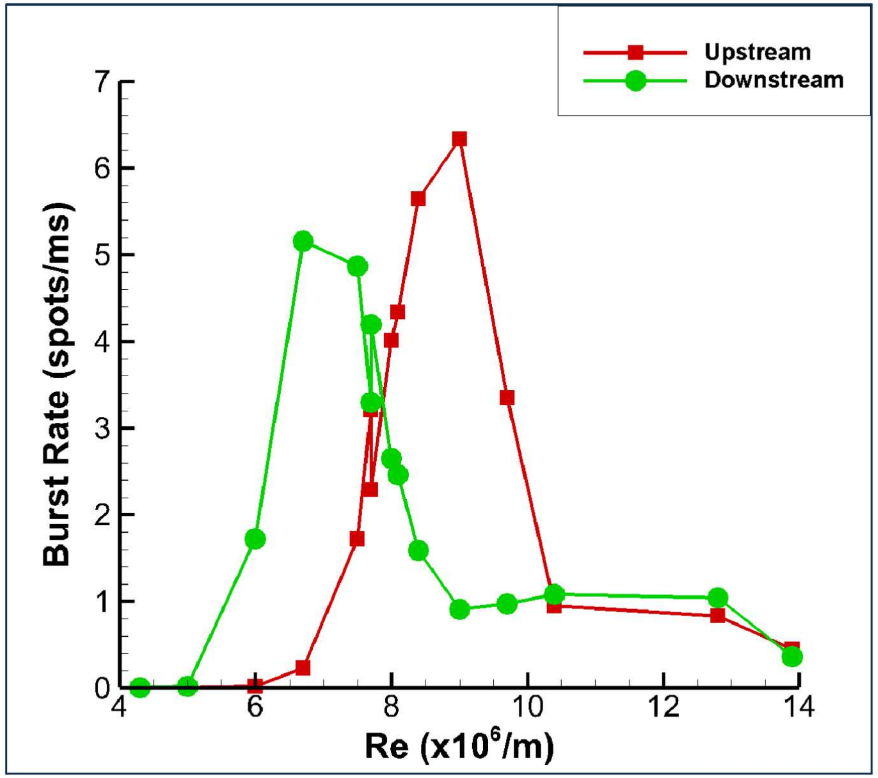
Natural Transition at Mach 5

Compute boundary layer statistics from PCB132 sensors upstream and downstream of panel.

- Peak burst rate occurs midway through transition.
- Average burst rate gives and estimate of the dominant forcing frequency of the panel.



Boundary-Layer Intermittency

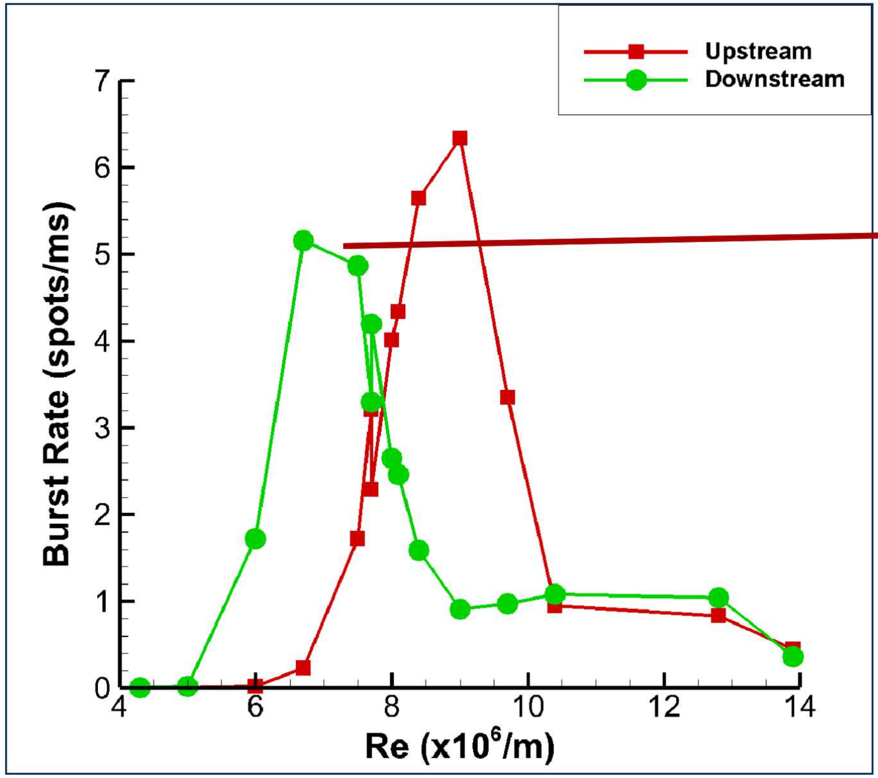


Turbulent Burst Rate

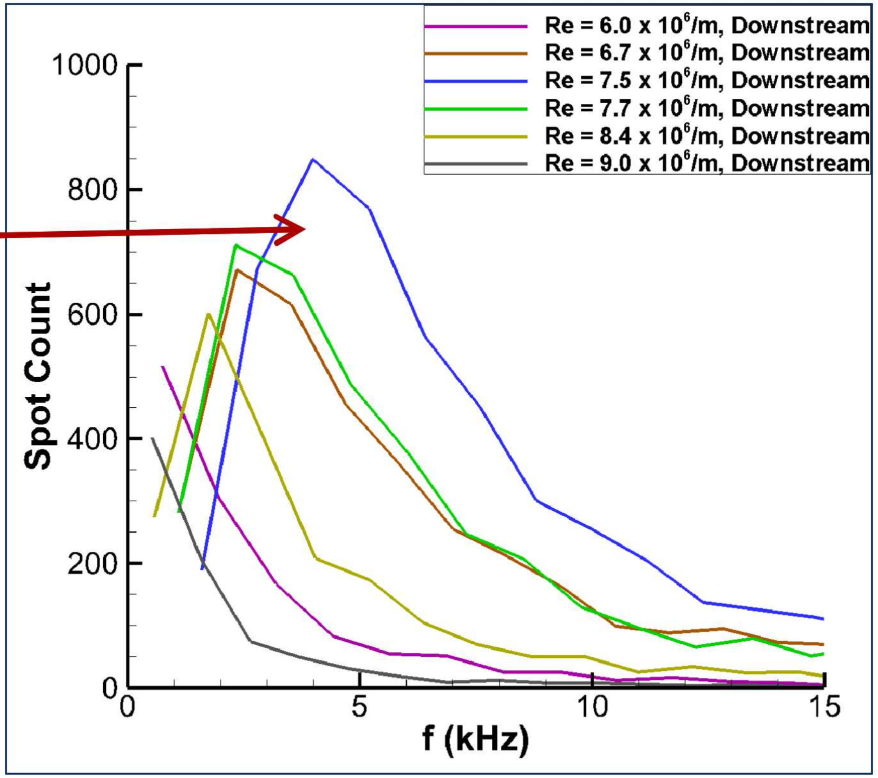
Natural Transition at Mach 5

Non-uniform spot spacing in natural transition.

- PDF of spots, shows highest probability at average burst rate.
- Higher frequency forcing over broad range of frequencies.



Turbulent Burst Rate

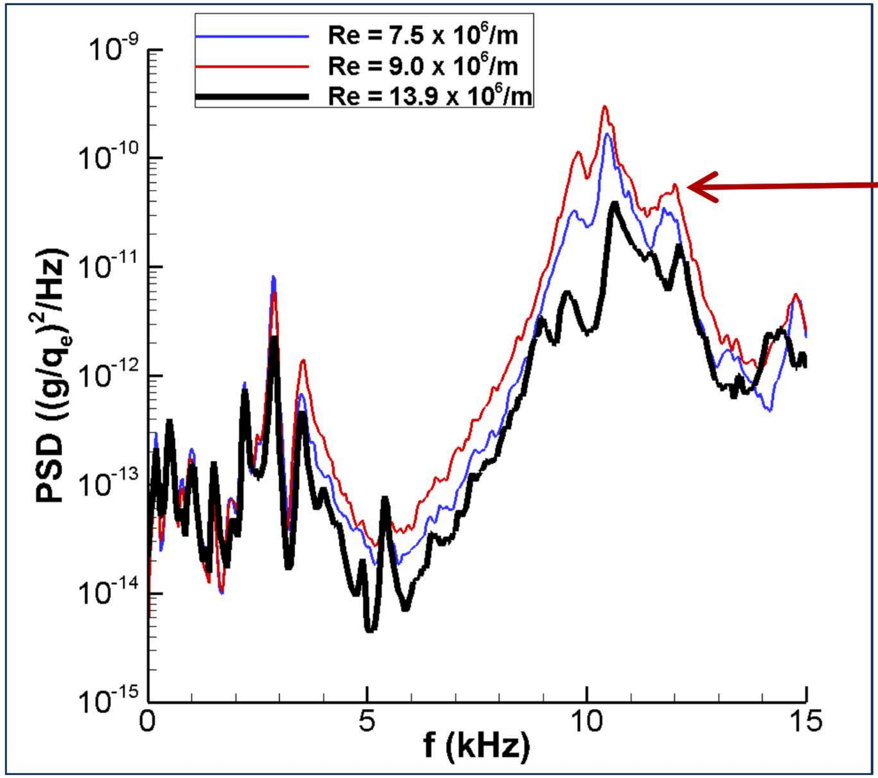


Spot Forcing Distribution

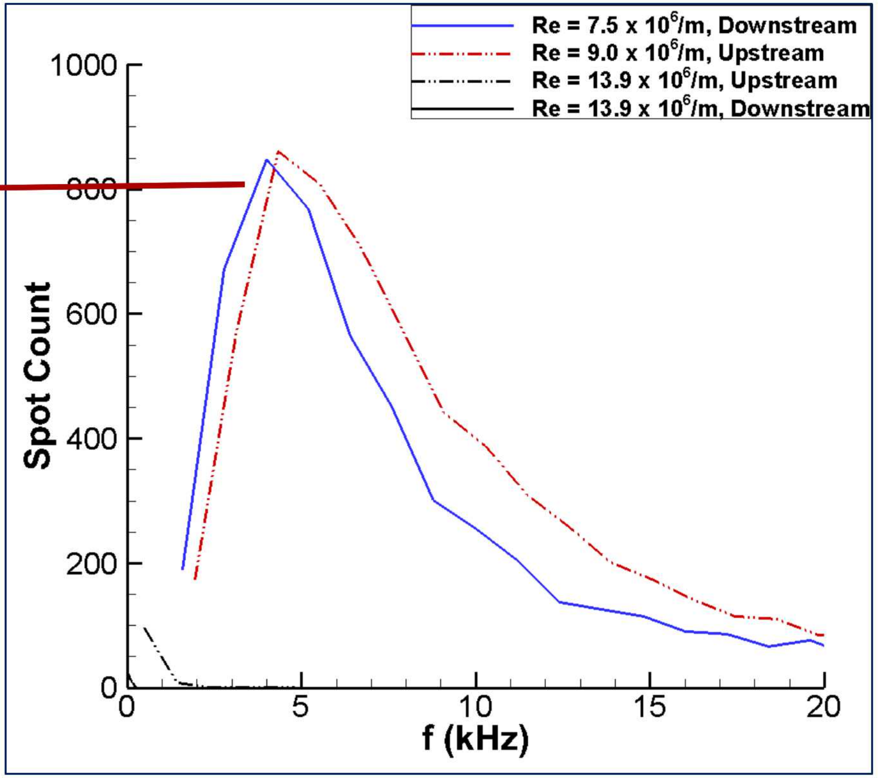
Flight-Like Environments

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.



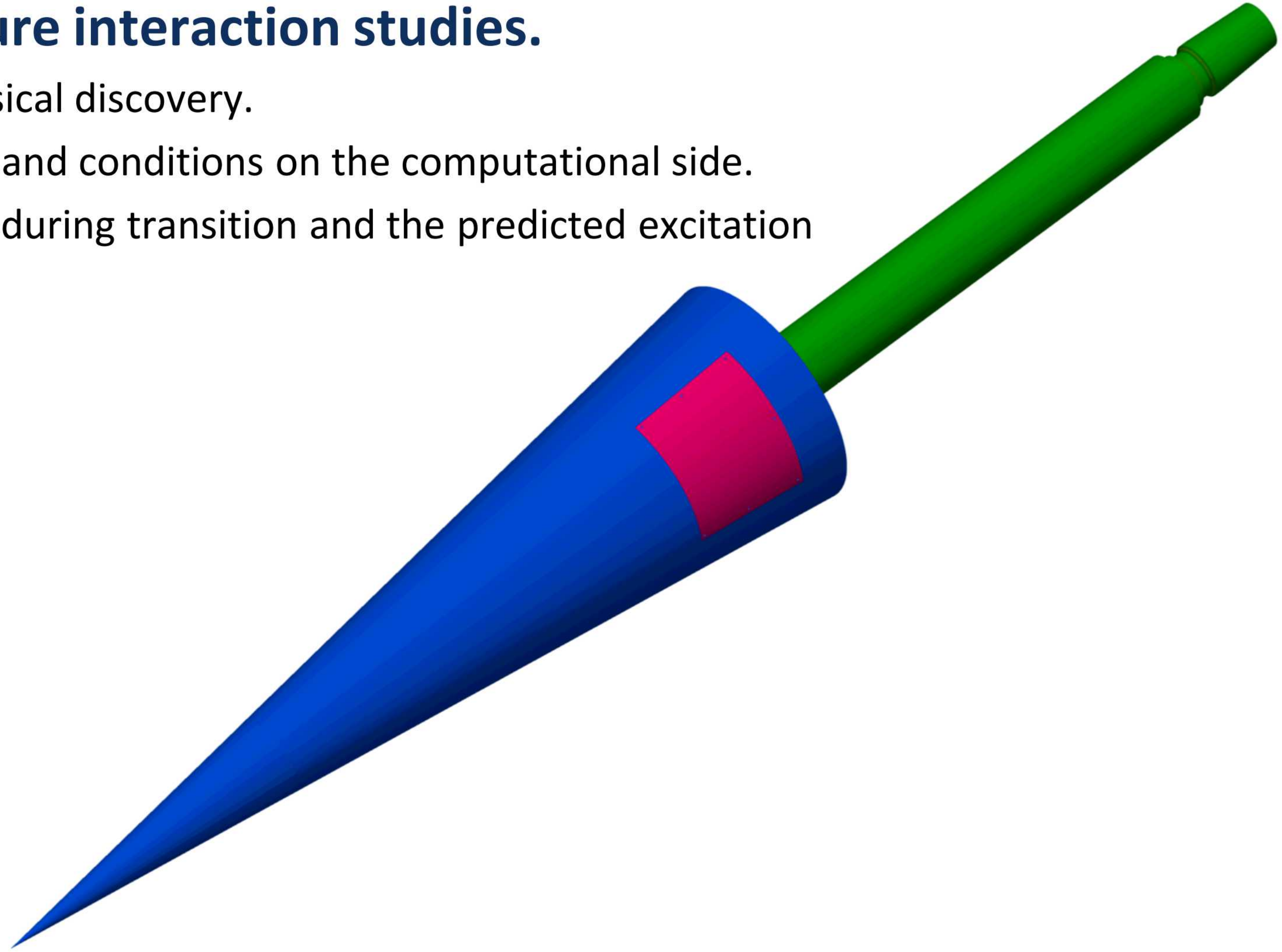
Z-Acceleration Spectra



Spot Forcing Distribution

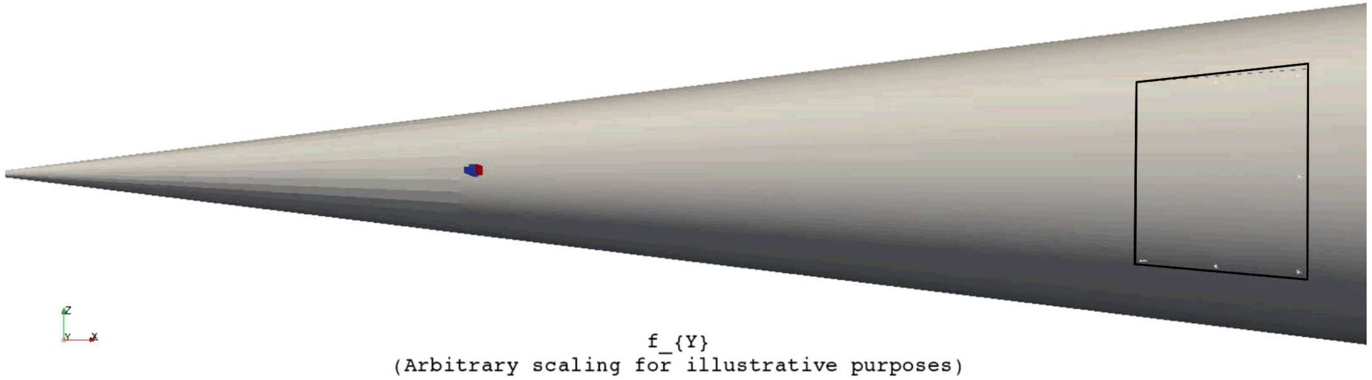
Impact

- **Few previous hypersonic fluids-structure interaction studies.**
  - Novel dataset used for code validation and physical discovery.
  - Being implemented for actual flight geometries and conditions on the computational side.
  - Provides a tie between the turbulent burst rate during transition and the predicted excitation frequencies of a structure.

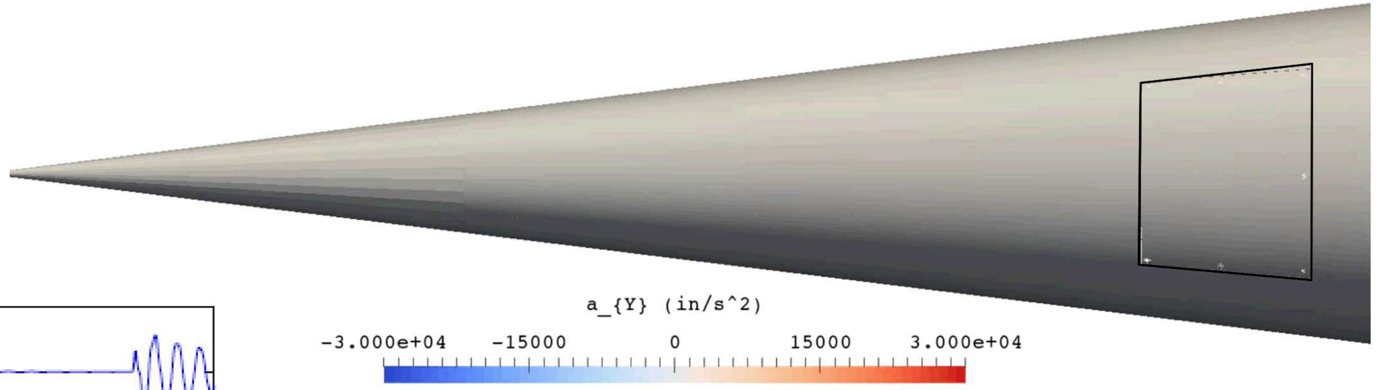


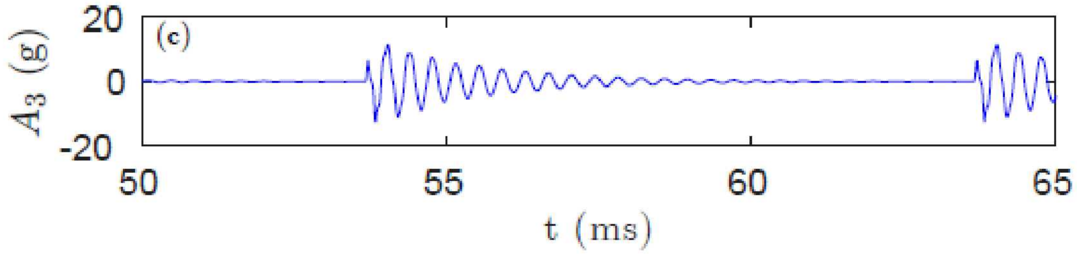
Computational Efforts: Simple Validation Case

Loading from Single Spots



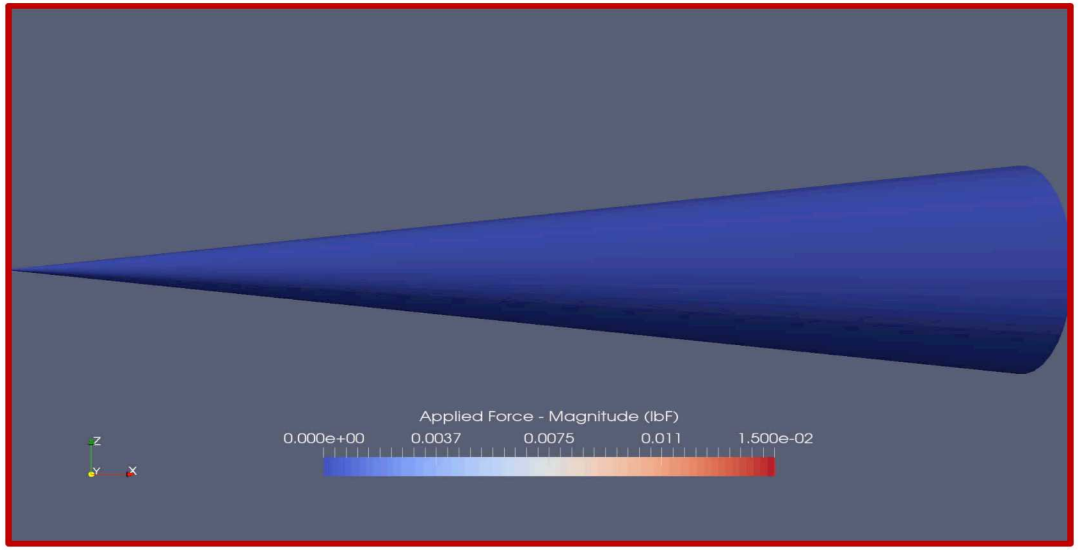
Predicted Structural Response

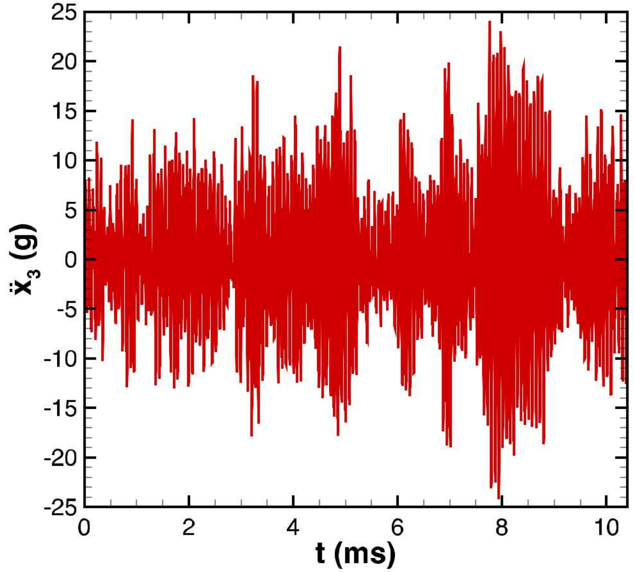




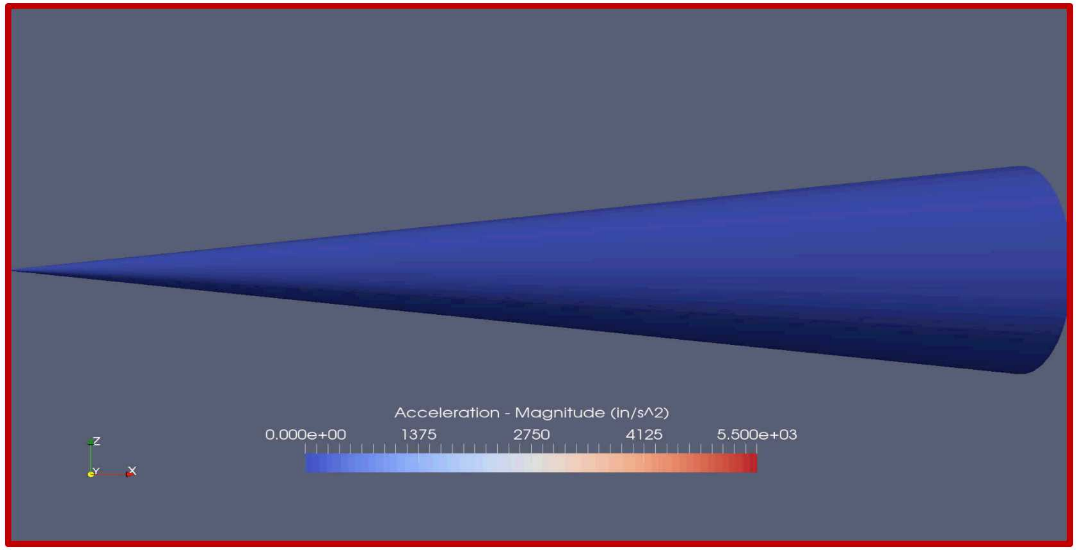
Computational Efforts: Flight-like Case

Loading from Multiple Spots



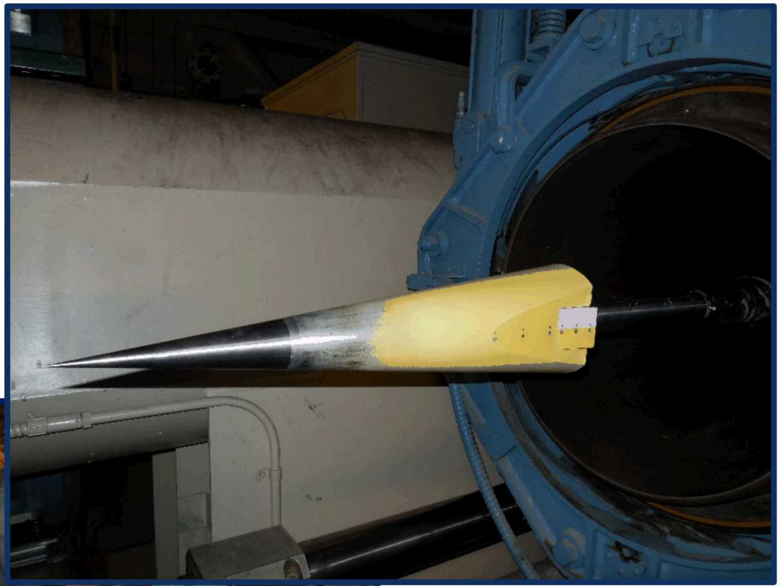


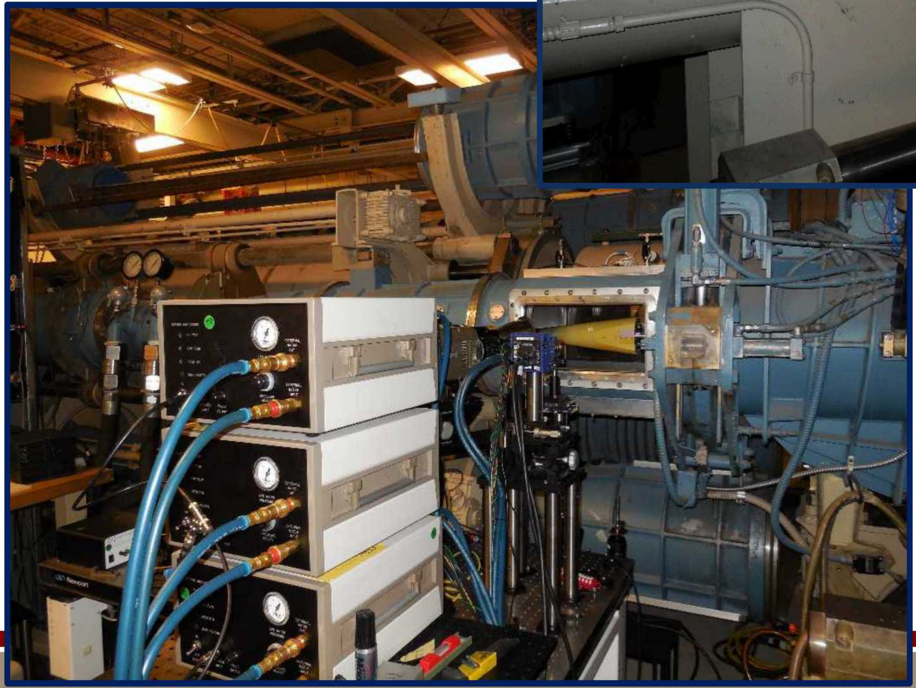
Predicted Structural Response



What challenges still persist?

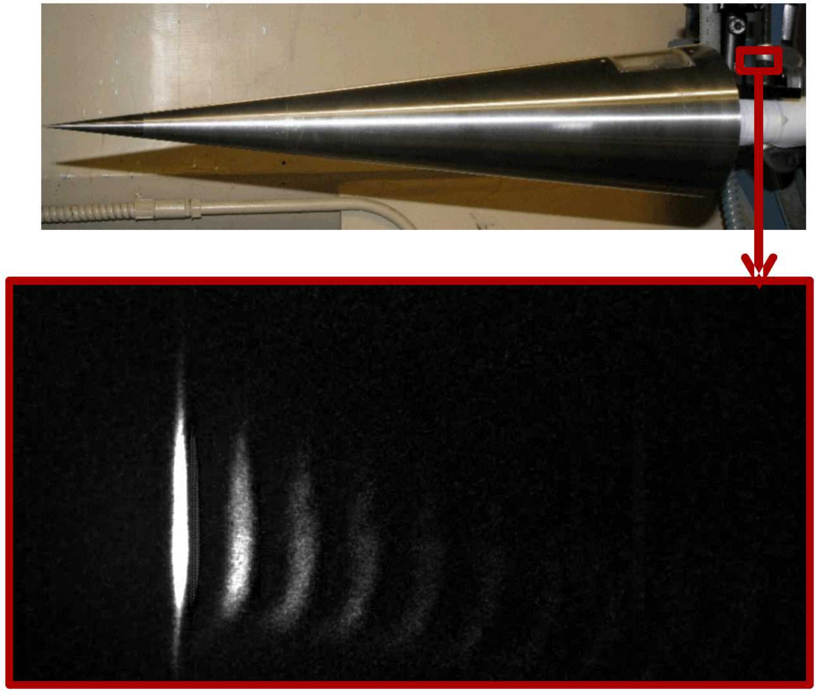
- **Still need additional experiments covering other parameters**
  - Predictions at angle of attack or on more complex geometries.
  - Temperature effects in flight.
  - Two-way coupled or nonlinear structures.





Future Research

- What are the next scientific questions in your field and why are they important?
  - **Continue to mature datasets and computational comparisons.**
    - Move to more complex cases
  - **Hypersonic wake flows**
    - Potential FSI input for a flight vehicle.
    - Affects signatures.
  - **Better diagnostics for hypersonic flows**
    - Extend temperature and pressure sensitive paint techniques to higher frequencies and better sensitivity.
    - Laser based flow field diagnostics, e.g. FLEET.
    - Better structural diagnostics: digital image correlation, miniature high-frequency accelerometers.



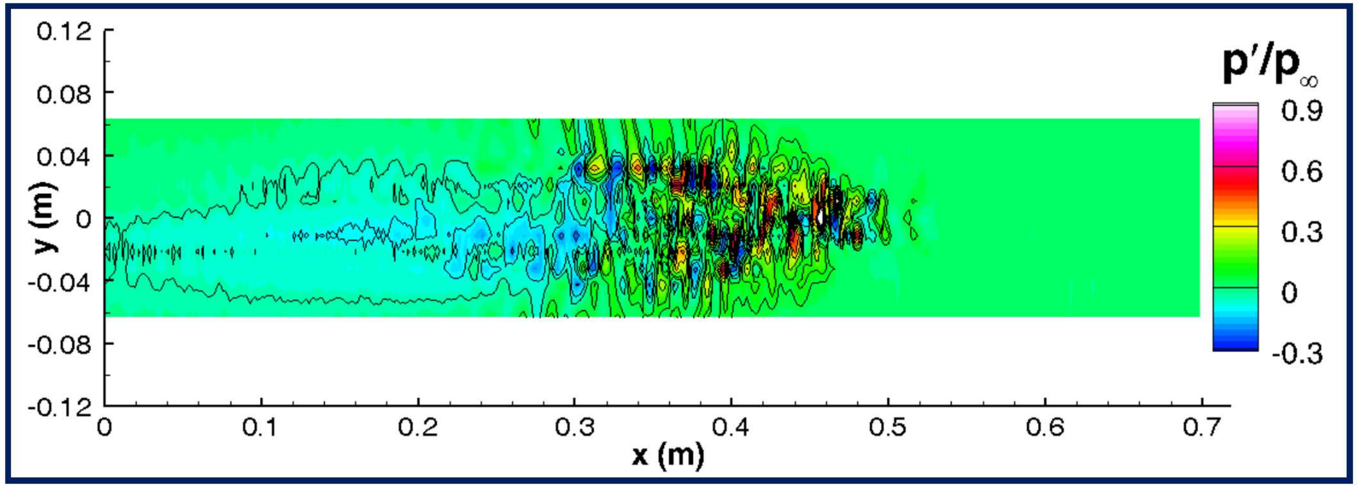
Summary: Hypersonic Transitional Boundary Layer Pressure Fluctuations

Outcome: Measured turbulent spot growth parameters and transitional statistics for typical hypersonic transitional boundary layers.

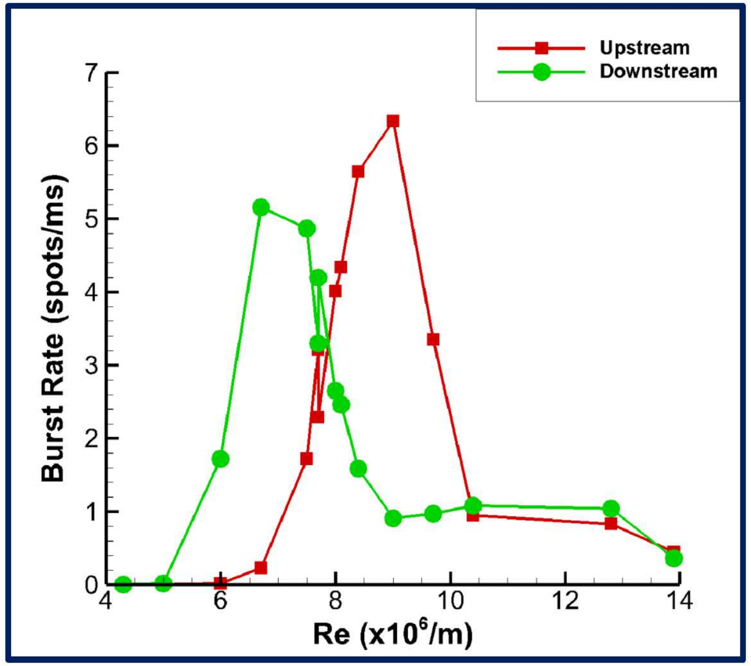
- Previous spot modeling efforts focused on incompressible flow.

Impact and Use:

- Most of this work was performed jointly between SNL and Purdue University
- Workforce development – I continued this into my full time position at SNL.
- In use at SNL for flight vehicle predictions.



Pressure footprint of turbulent spot, Mach 6



Turbulent burst rates for hypersonic flow

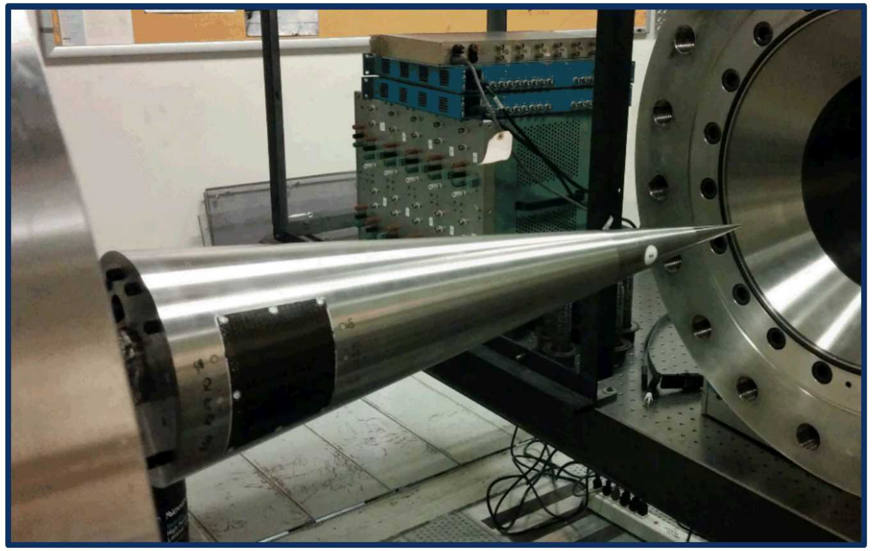
Summary: Hypersonic Fluid-Structure Interactions

Outcome: Characterized thin panel response to hypersonic transitional and turbulent boundary layers under noisy and quiet flows

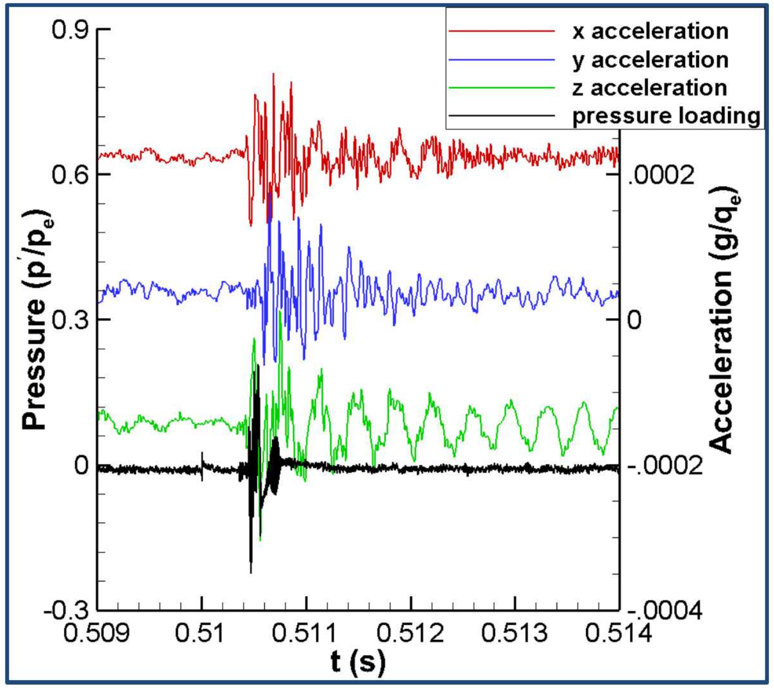
- One of few hypersonic FSI datasets, used for code validation and physical discovery.
- Tied vibrational responses to turbulent burst rates during boundary-layer transition.

Impact and Use:

- Used for code validation and flight vehicle predictions at SNL.



Hypersonic fluid-structure interaction panel model



Panel response to turbulent spots.