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Sandia National Laboratories

Aeroloading and Structural Response Measurements in Hypersonic Flow

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Aerosciences Department

Sandia National Labs

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Sandia Sites

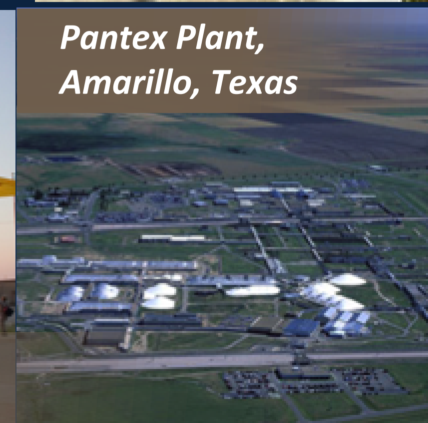
Sandia National Laboratories

Albuquerque, New Mexico

Livermore, California

Kauai, Hawaii

Waste Isolation Pilot Plant, Carlsbad, New Mexico



Pantex Plant, Amarillo, Texas

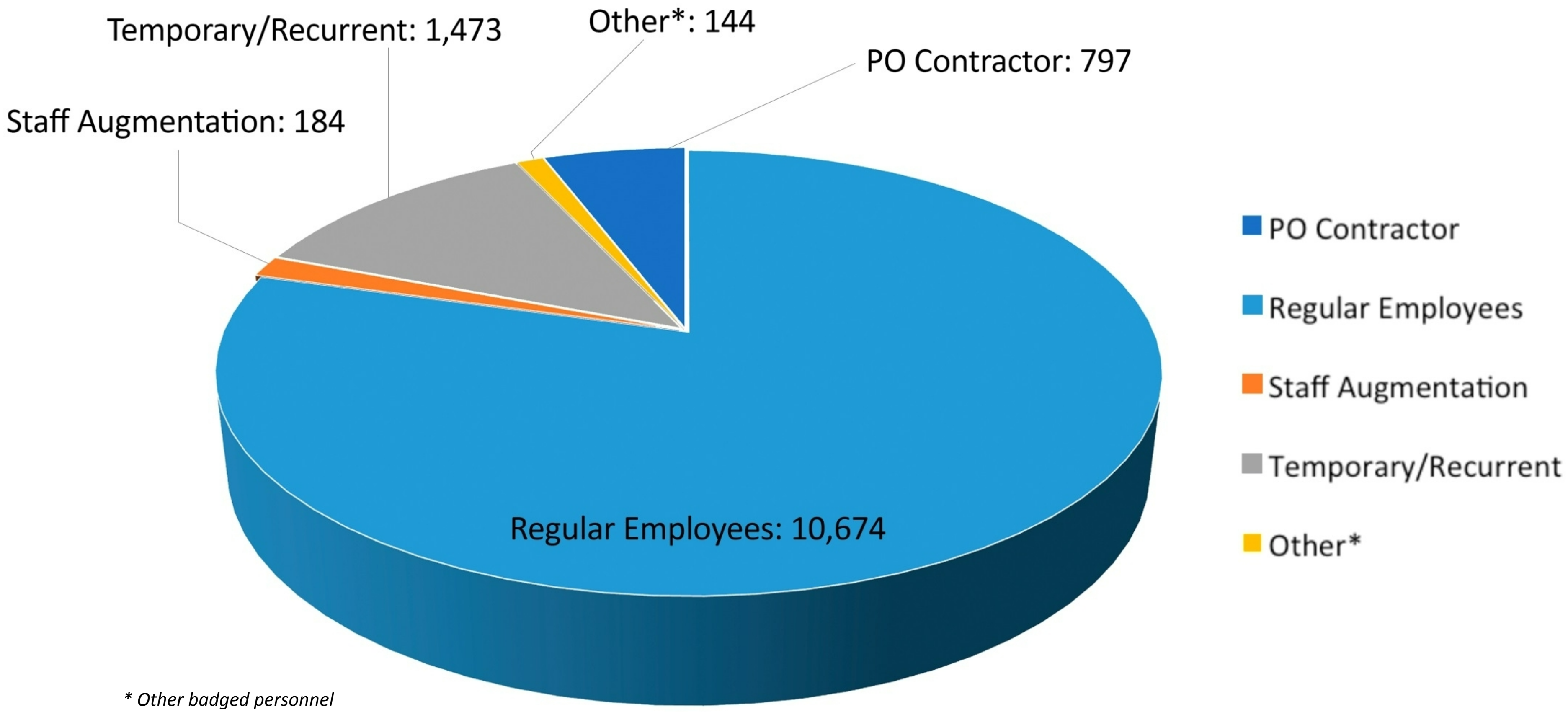
Tonopah, Nevada

Our Workforce

Sandia National Laboratories

- Total Sandia workforce: 13,332
- Regular employees: 10,574
- Advanced degrees: 6,085 (57%)

Data as of January 31, 2017

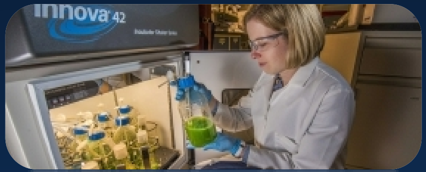


** Other badged personnel*

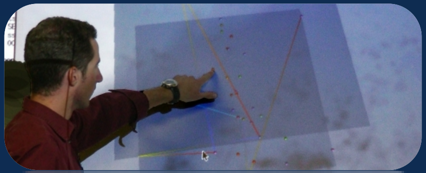
Fulfilling Our National Security Mission

Nuclear Weapons

Global Security



Energy & Climate

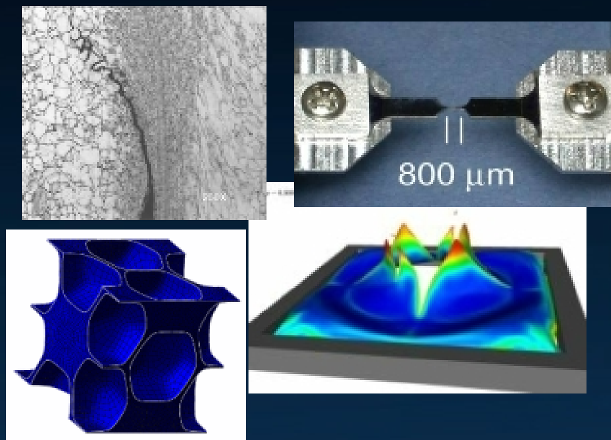


Defense Systems & Assessments

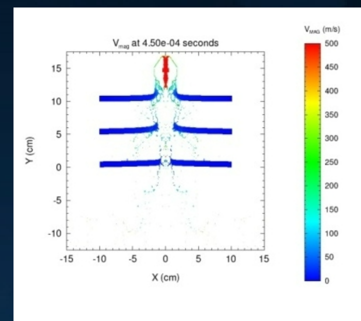
Engineering Sciences Core Technical Areas

Sandia National Laboratories

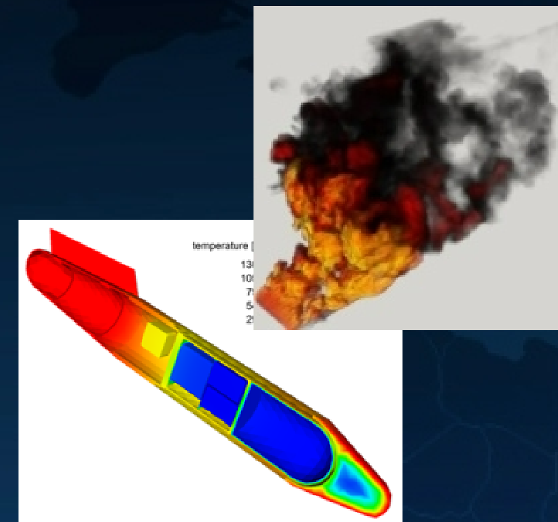
Solid Mechanics



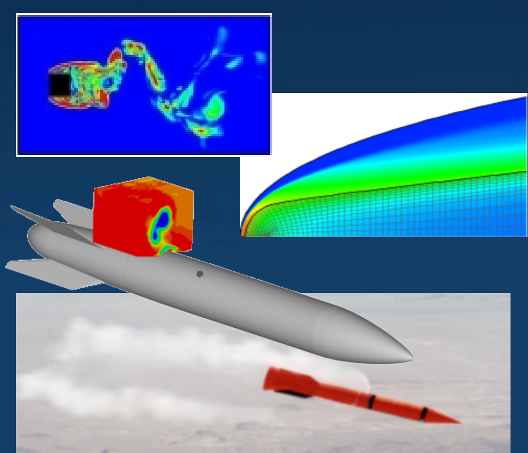
Shock Physics and Energetics



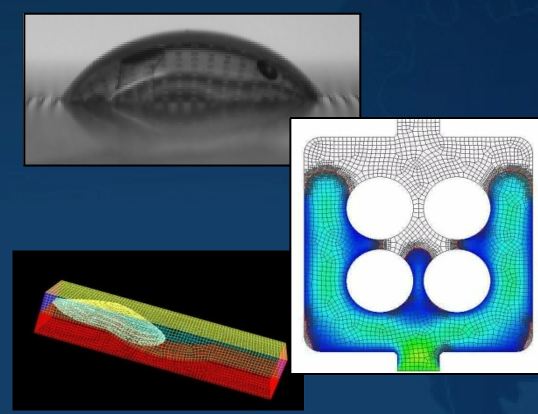
Thermal and Combustion Sciences



Aerosciences



Fluid Mechanics



Structural Dynamics

Experimental Aerosciences Facility

Trisonic Wind Tunnel (TWT)

- Mach 0.5 – 3
- Gravity bombs, missiles

Hypersonic Wind Tunnel (HWT)

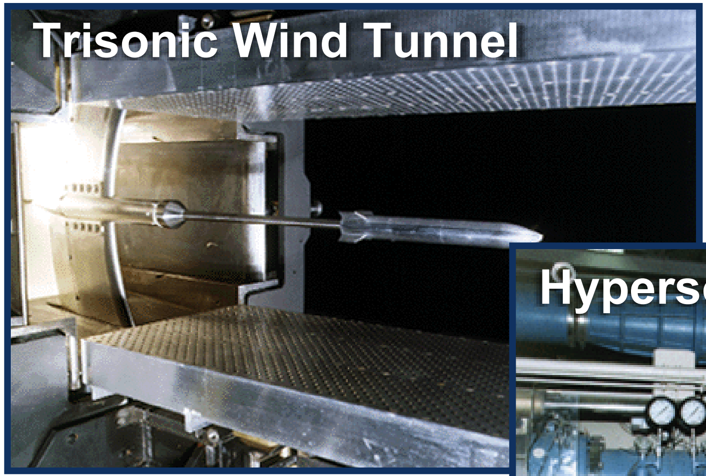
- Mach 5, 8, 14
- Re-entry vehicles, rockets

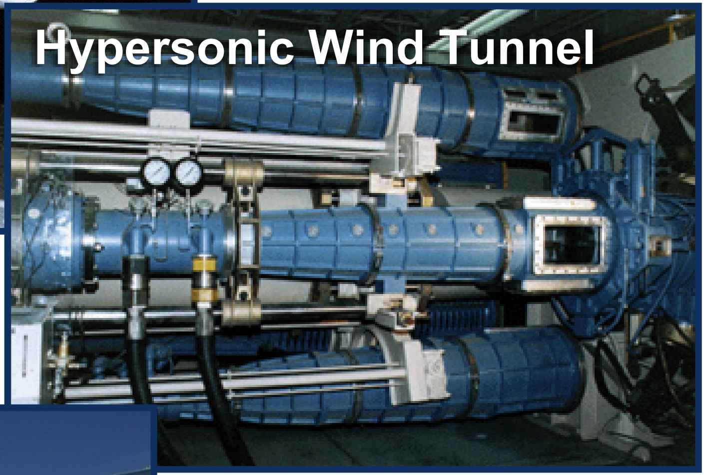
High-Altitude Chamber (HAC)

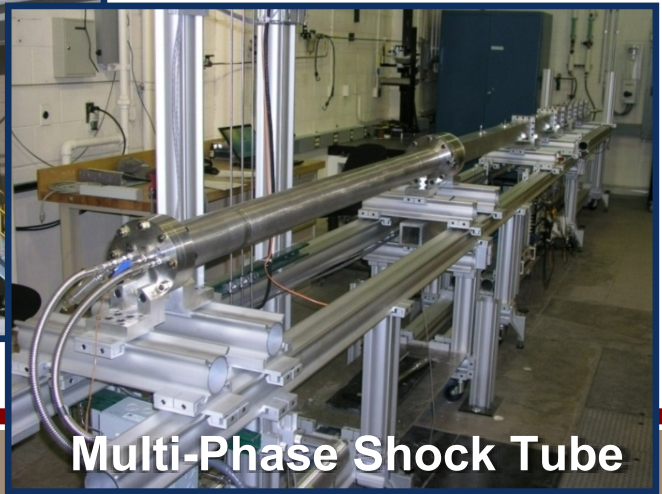
- Satellite components

Multi-Phase Shock Tube (MST)

- Explosives research



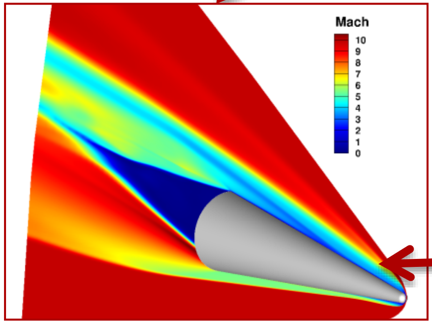


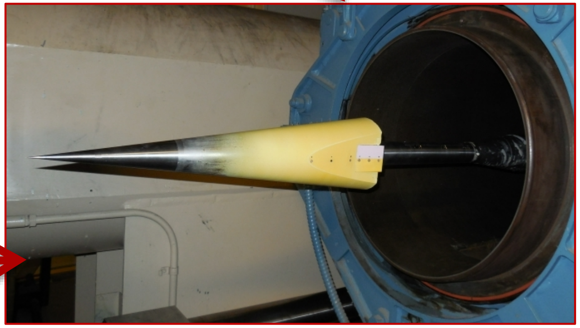


The Role of Experimental Ground Test Facilities

- Cheaper and shorter lead time than flight testing.
- Ground tests offer a more controlled environment than flight.
- Opportunity to collect detailed data with advanced diagnostics.
- Integral part of physical discovery as well as model validation.

Flight Test





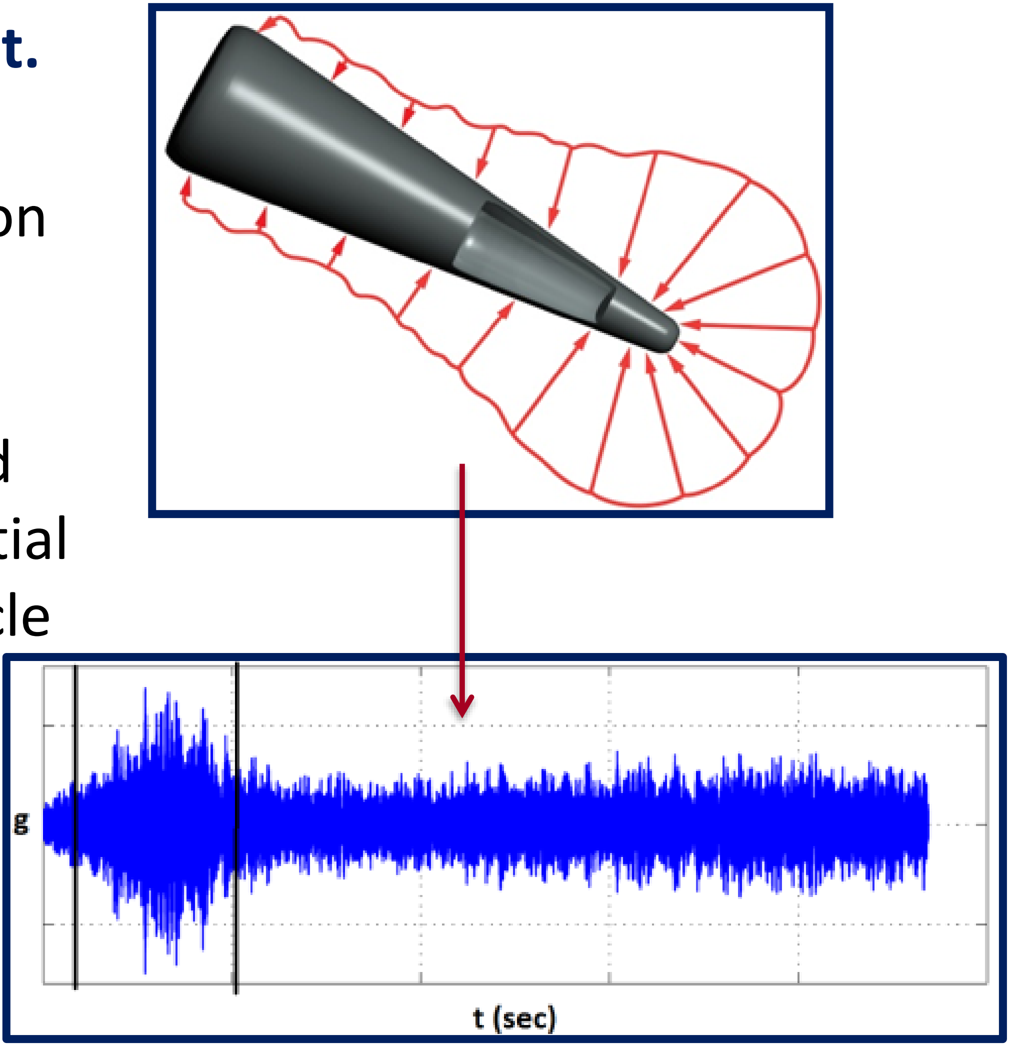
Modeling & Simulation

Ground Test

Motivation

Vehicle vibration is a function of the external loading environment.

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

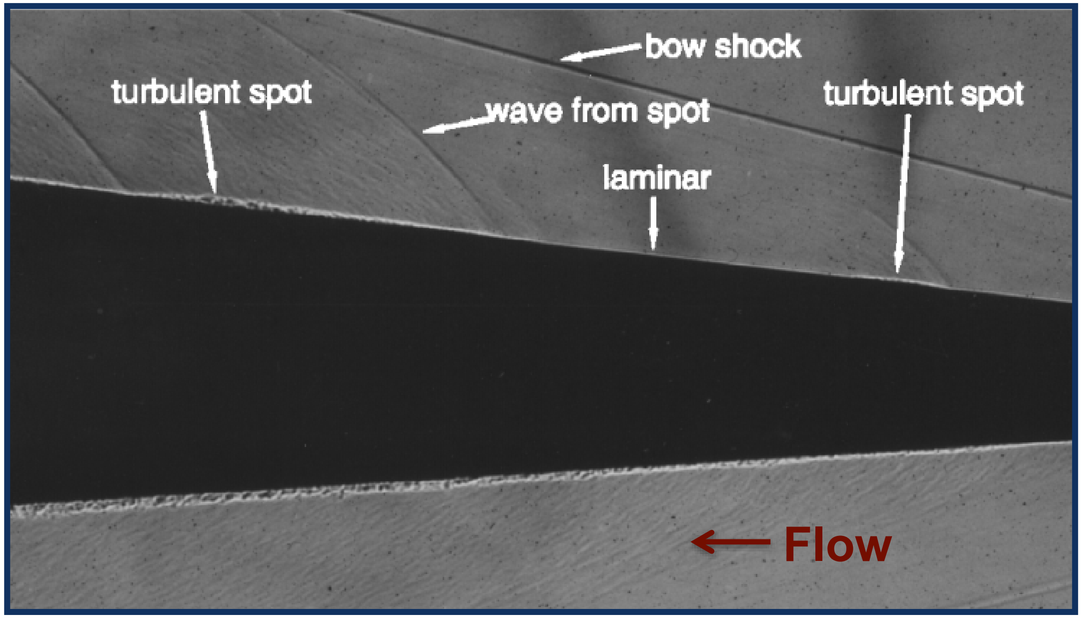


Boundary Layer Transition and Pressure Loading

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

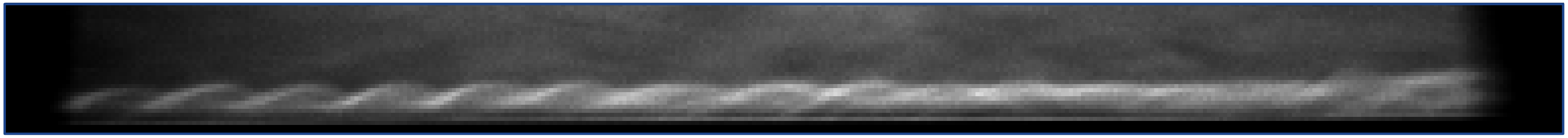
- Need to model spot growth and spatial distribution to predict the pressure loading.
- Current models based on correlations to incompressible flow data.

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.

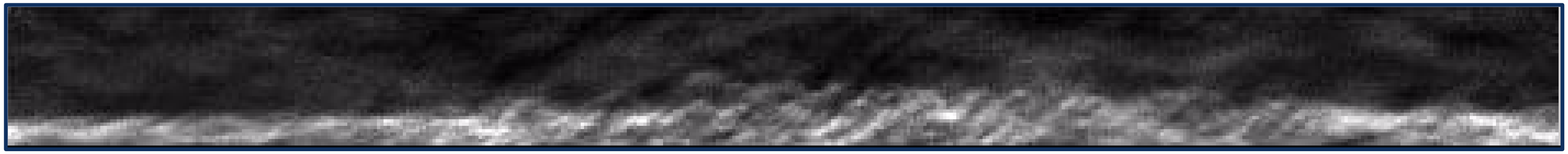
Boundary Layer Transition: Instability Wave Packets



Second-mode waves in Mach 8 boundary layer.

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.

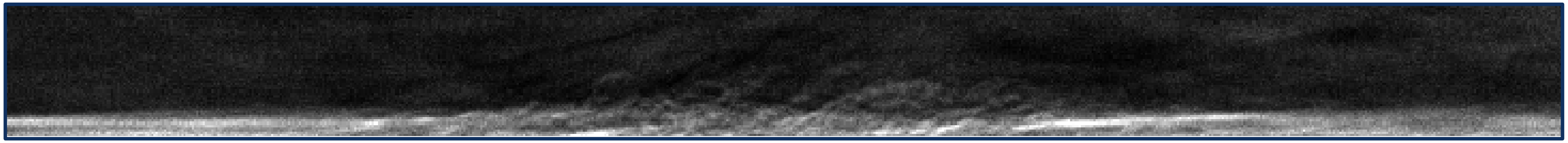


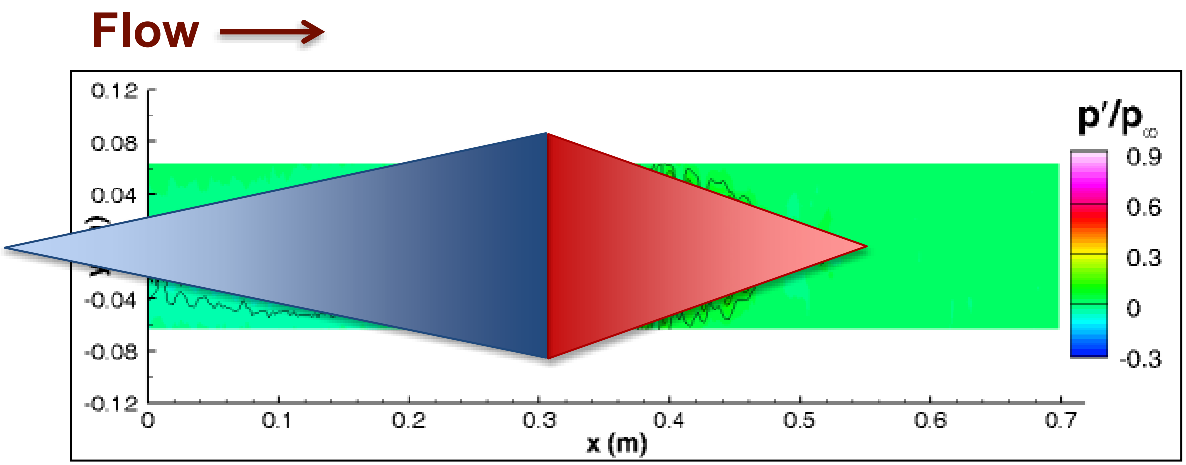
Transitional Boundary Layer, Mach 8

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.

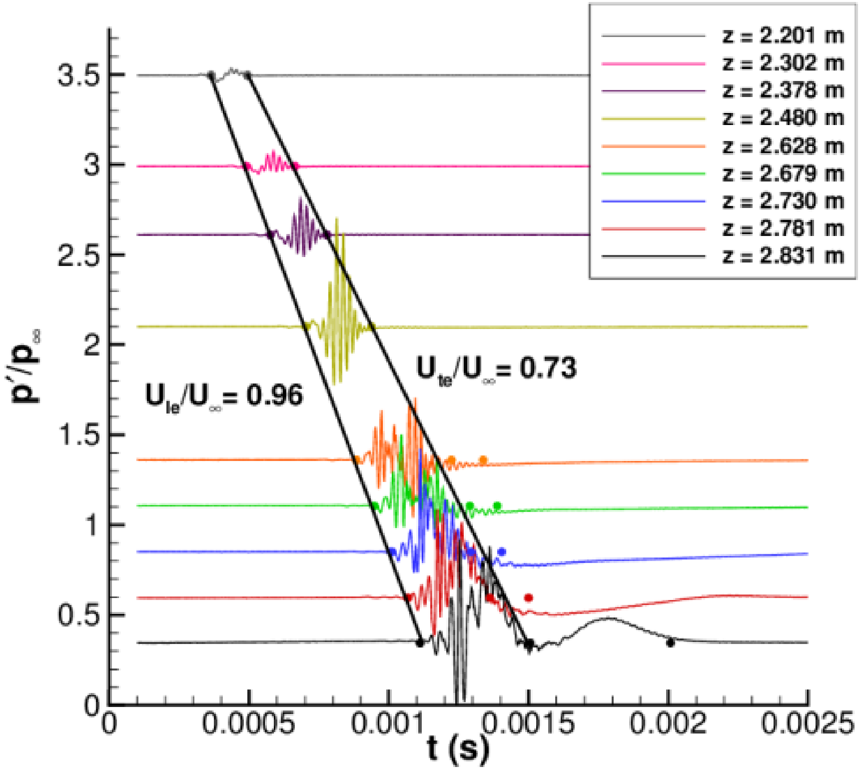




Pressure footprint of turbulent spot, Mach 6

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.

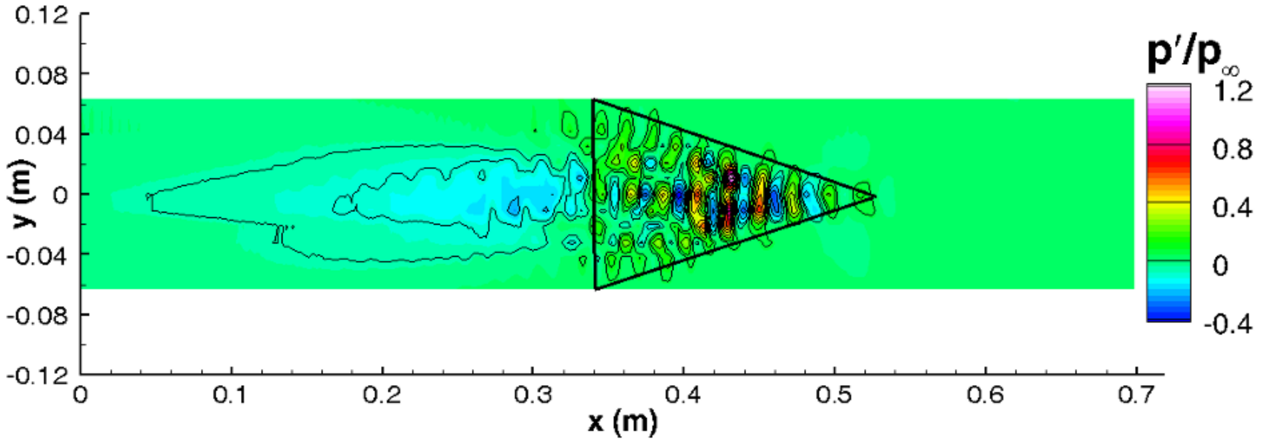
How fast do the disturbances spread laterally?

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.

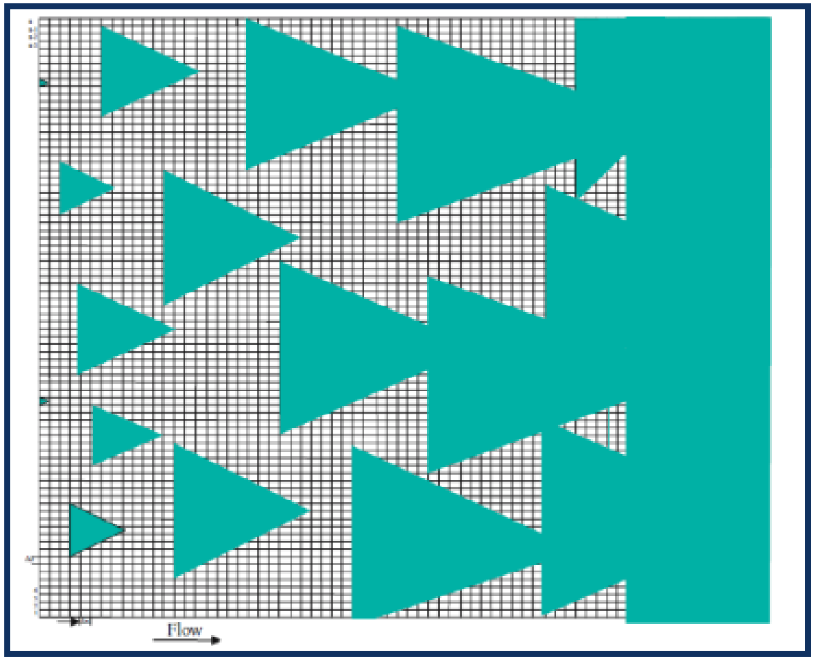
- High-frequency pressure fluctuations have never been used to define the spot footprint before.
- May provide a different spreading angle than other experimental or computational methods.



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



Turbulent spot model simulation, from Vinod (2007).

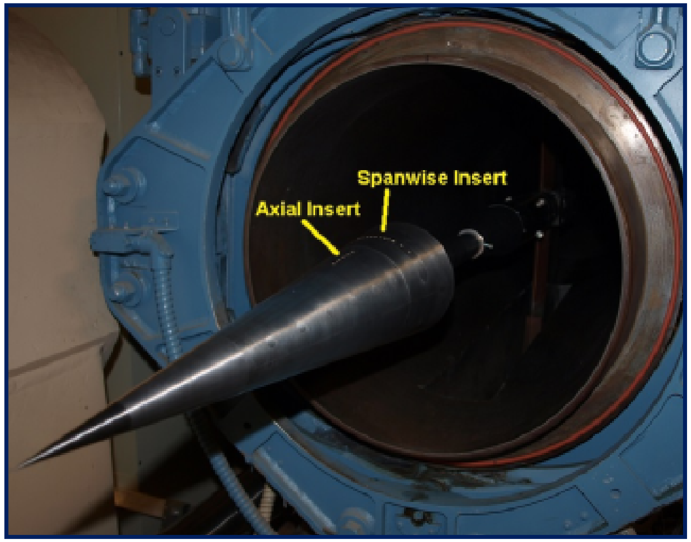
Experimental Setup

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

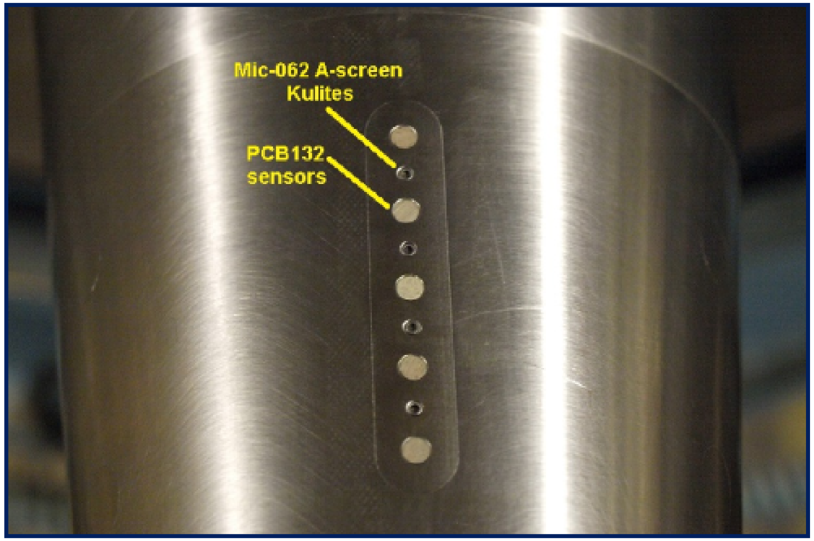
- Simultaneous schlieren imaging and high-frequency pressure measurements.

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.

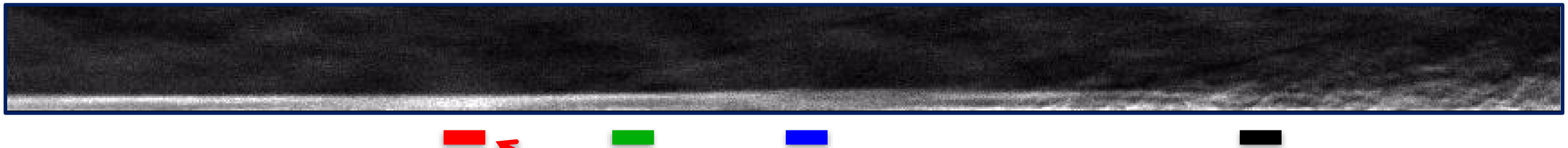


Model installed in HWT.



Axial pressure-transducer array.

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



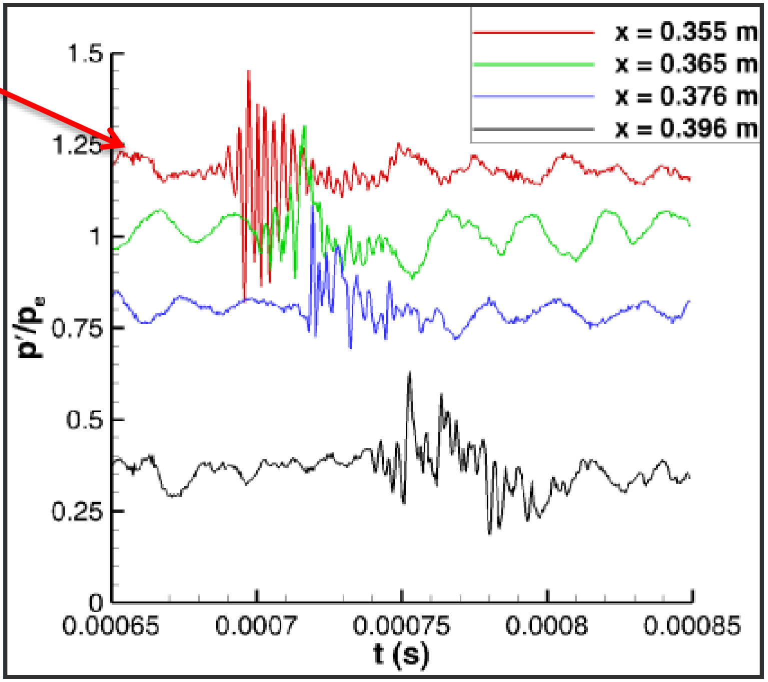
Schlieren Videos

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

- Observed in both schlieren videos and simultaneous pressure measurements.

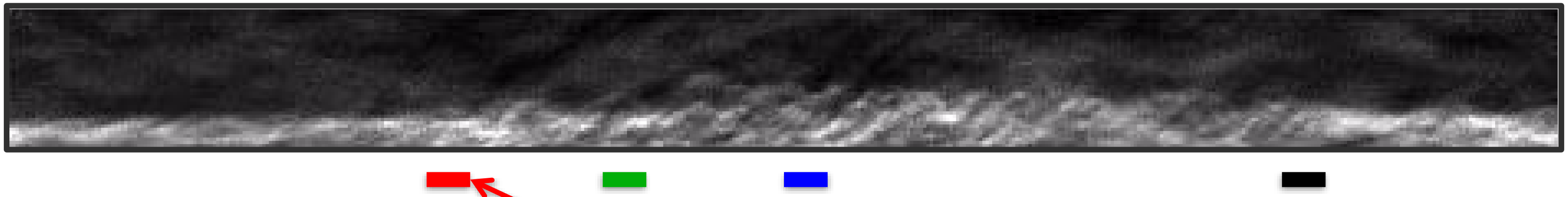
Disturbances are surrounded by a smooth laminar boundary layer.

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



Pressure Traces

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



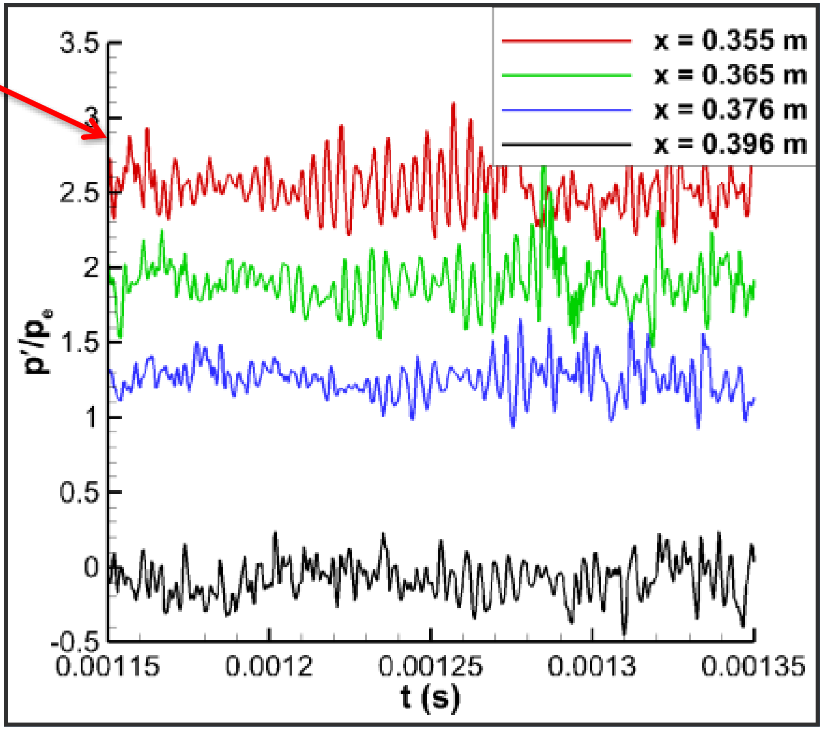
Schlieren Videos

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.



Pressure Traces

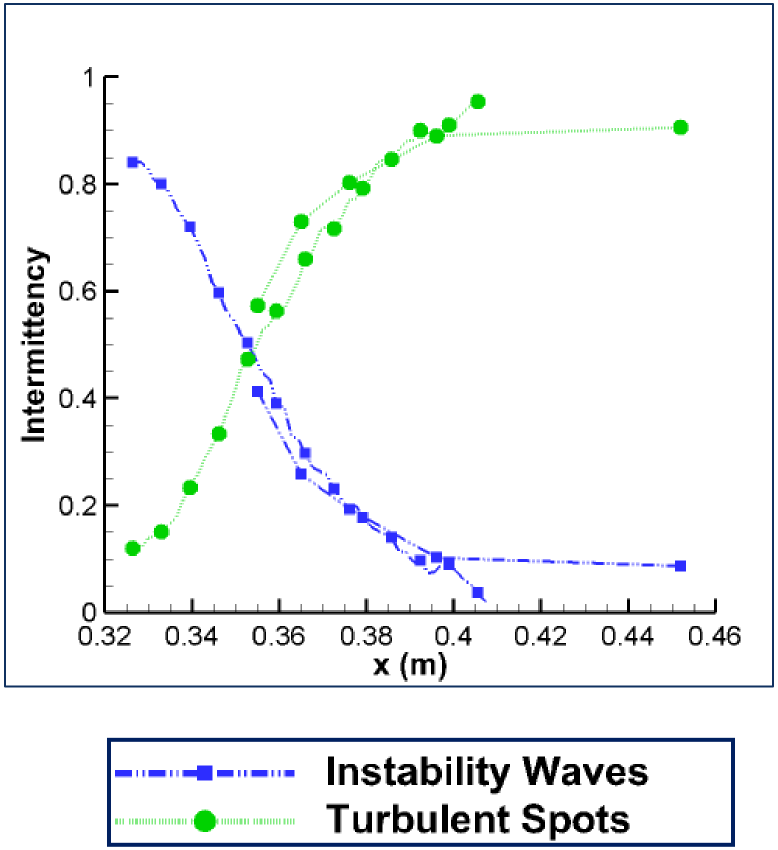
Natural Transition Statistics: Intermittency

Instability waves

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

Turbulent spots

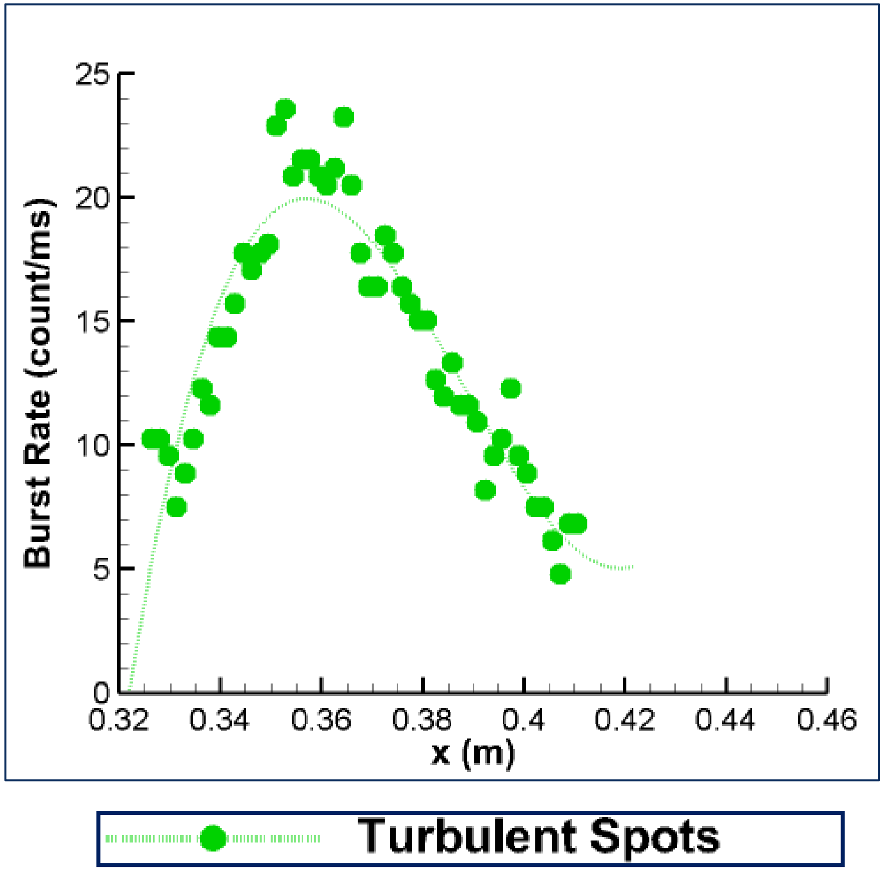
- Gradually begin to dominate flow.
- Turbulent intermittency rises as instability wave intermittency decreases.



Natural Transition Statistics: Burst Rate

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

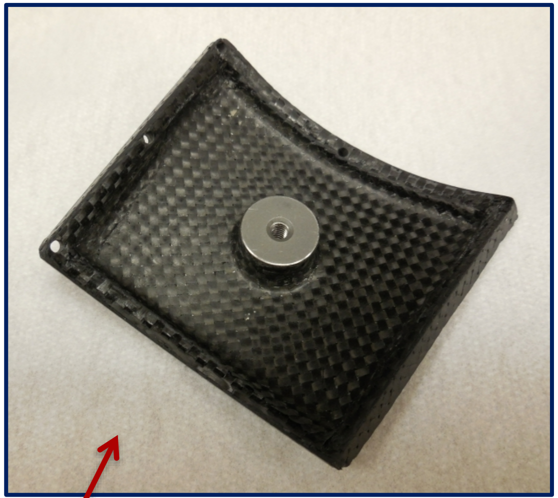
- Equal burst rate for instability waves and turbulence.
- High burst rate when intermittency is near 0.5.
- Burst rate decreases as spots merge into turbulence at locations further downstream.



What is the vibrational response to this environment?

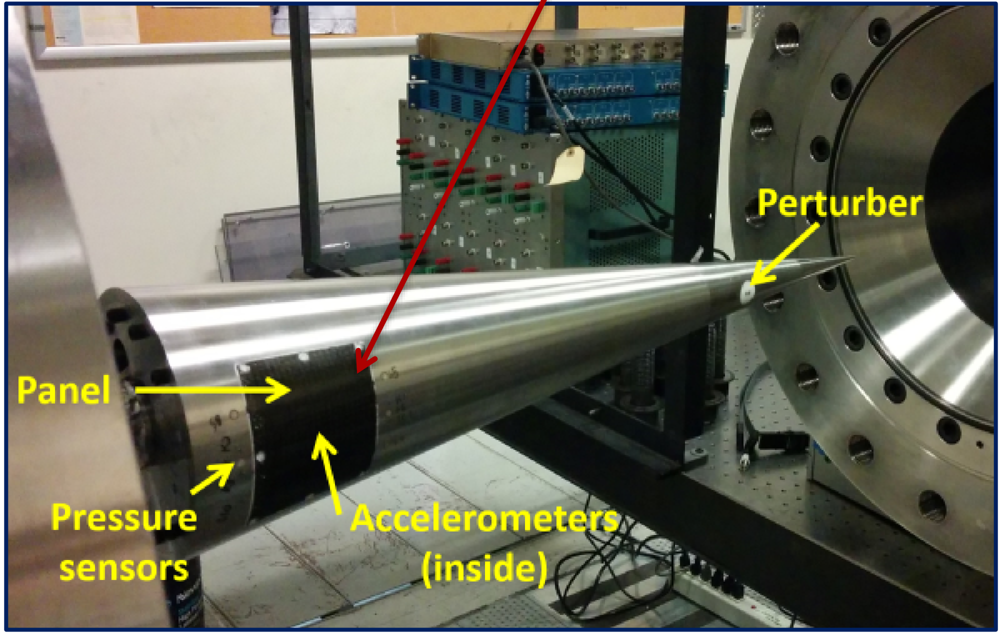
Designed a cone with integrated thin panel that will vibrate from flow excitation.

- 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.

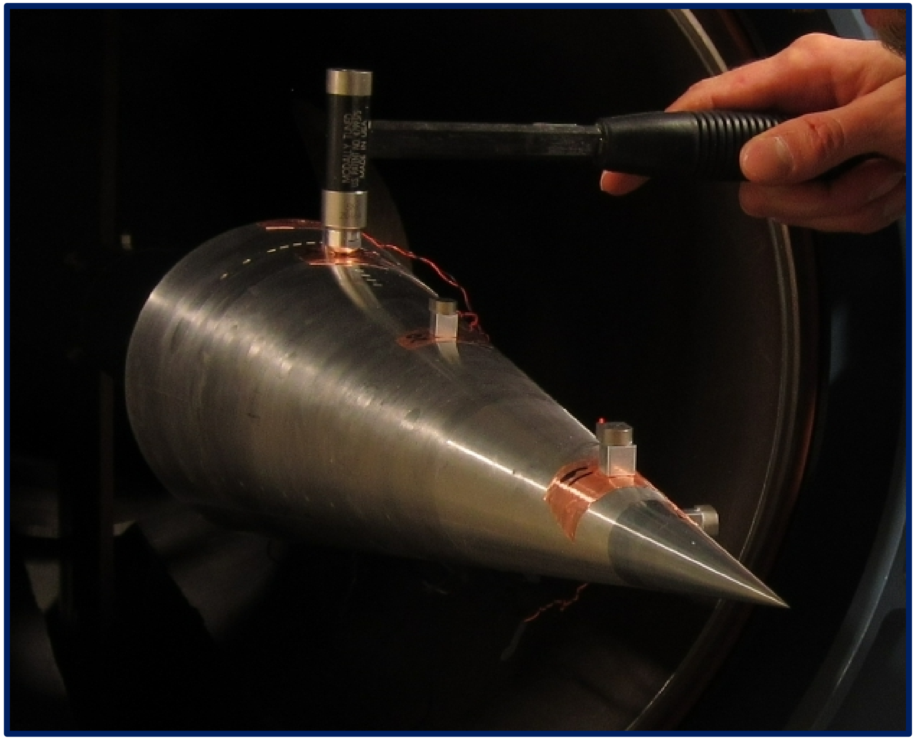
- Simplified validation case for modeling and simulation.

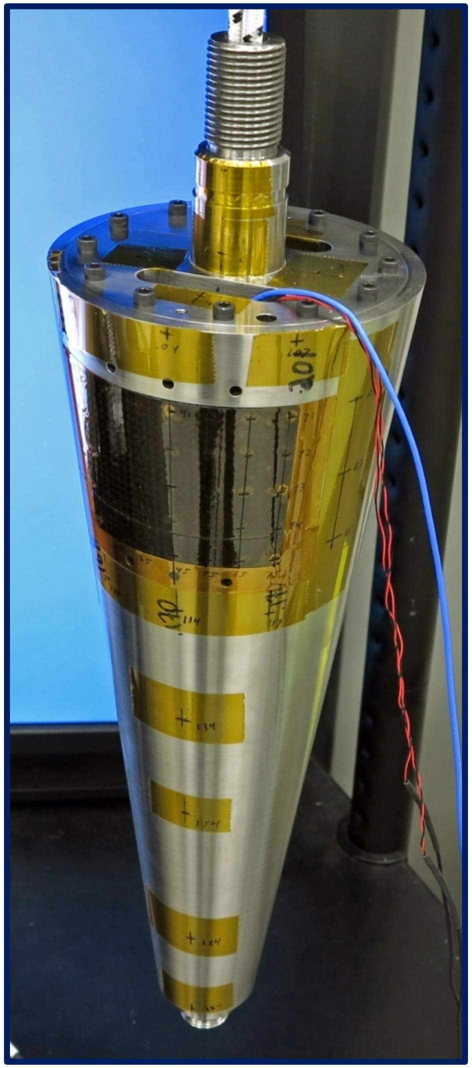


Structural Characterization

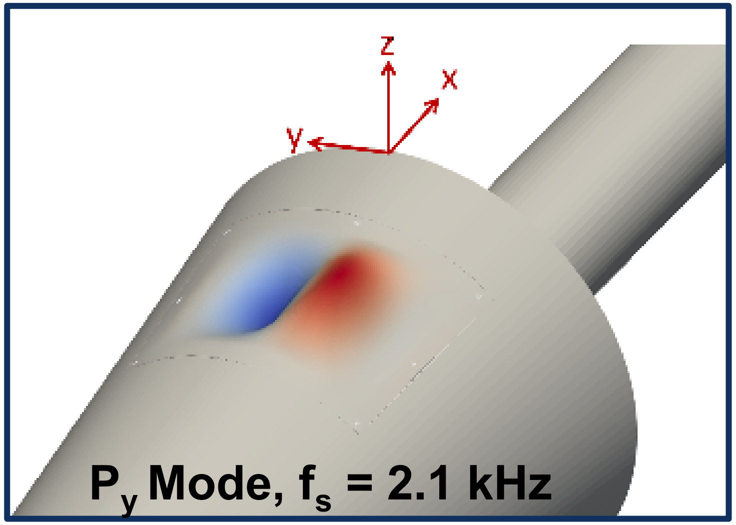
Hammer test was performed to determine the structural natural frequencies of the panel and model.

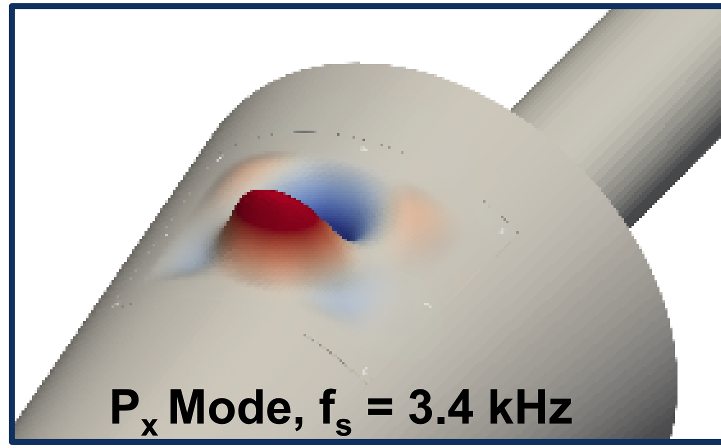
- Measure structural response to a known input.
- Mode frequencies are obtained up to 10 kHz.
- Can also characterize mode shapes.

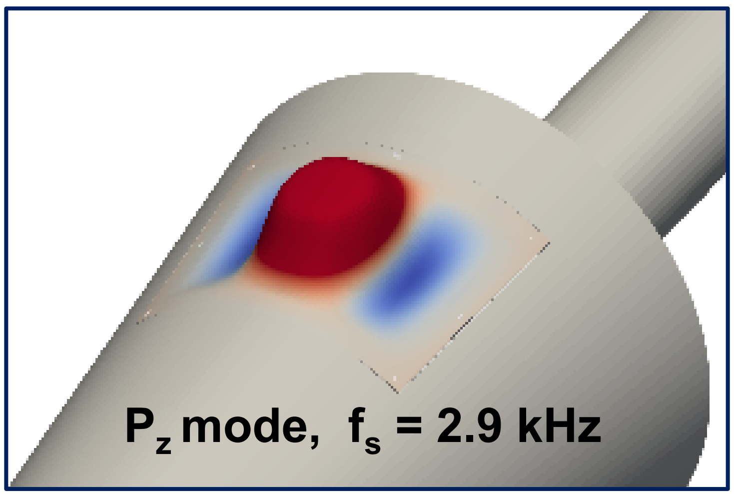


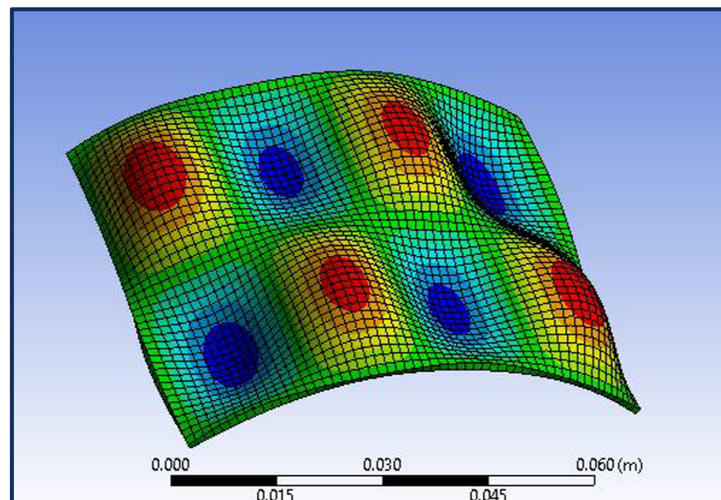


Measured mode shapes







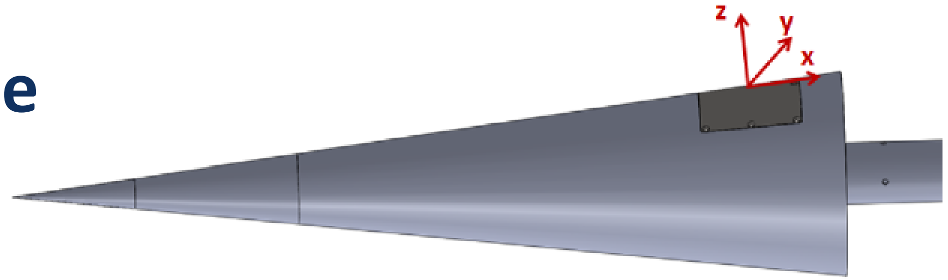


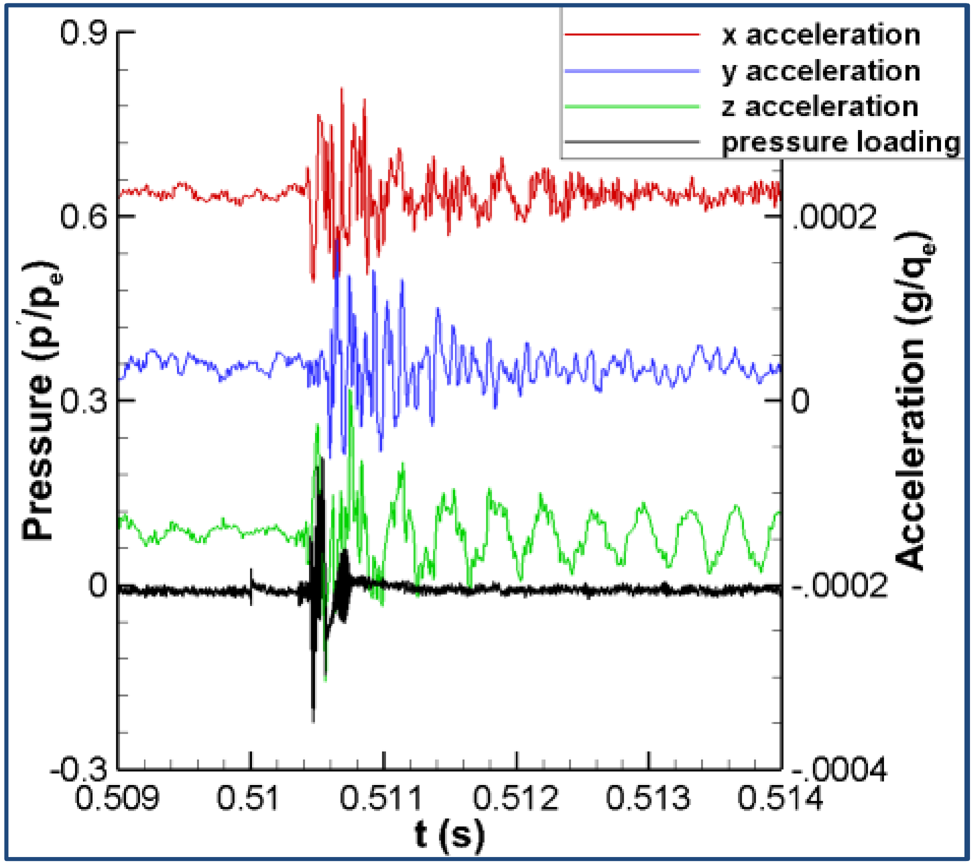
*from collaborations with Prof. Earl Dowell, Duke University

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.

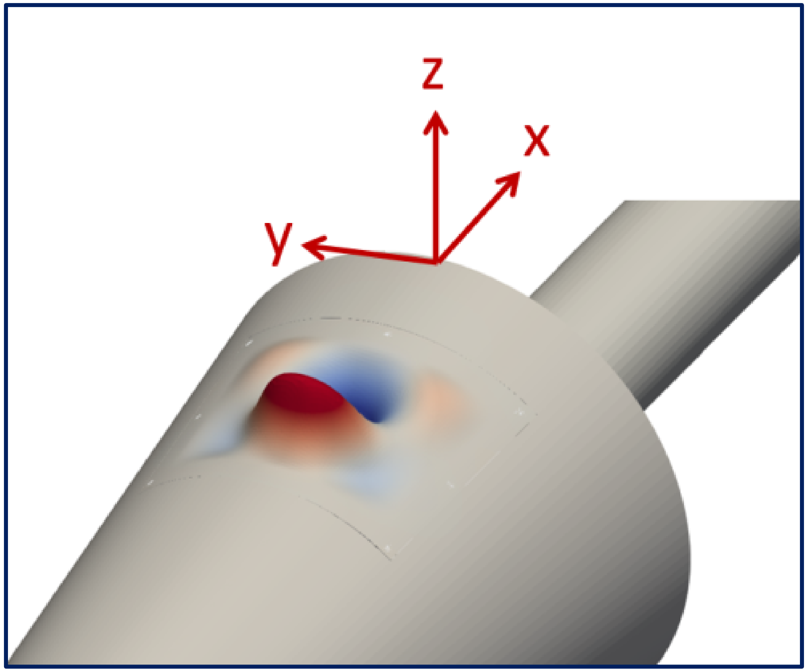


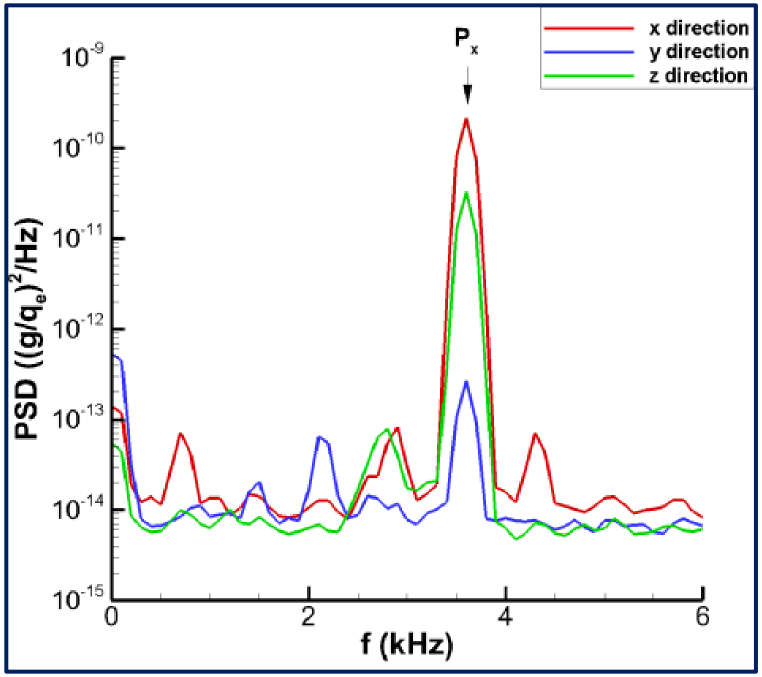


Response to Periodic Spots at Structural Natural Frequencies

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.





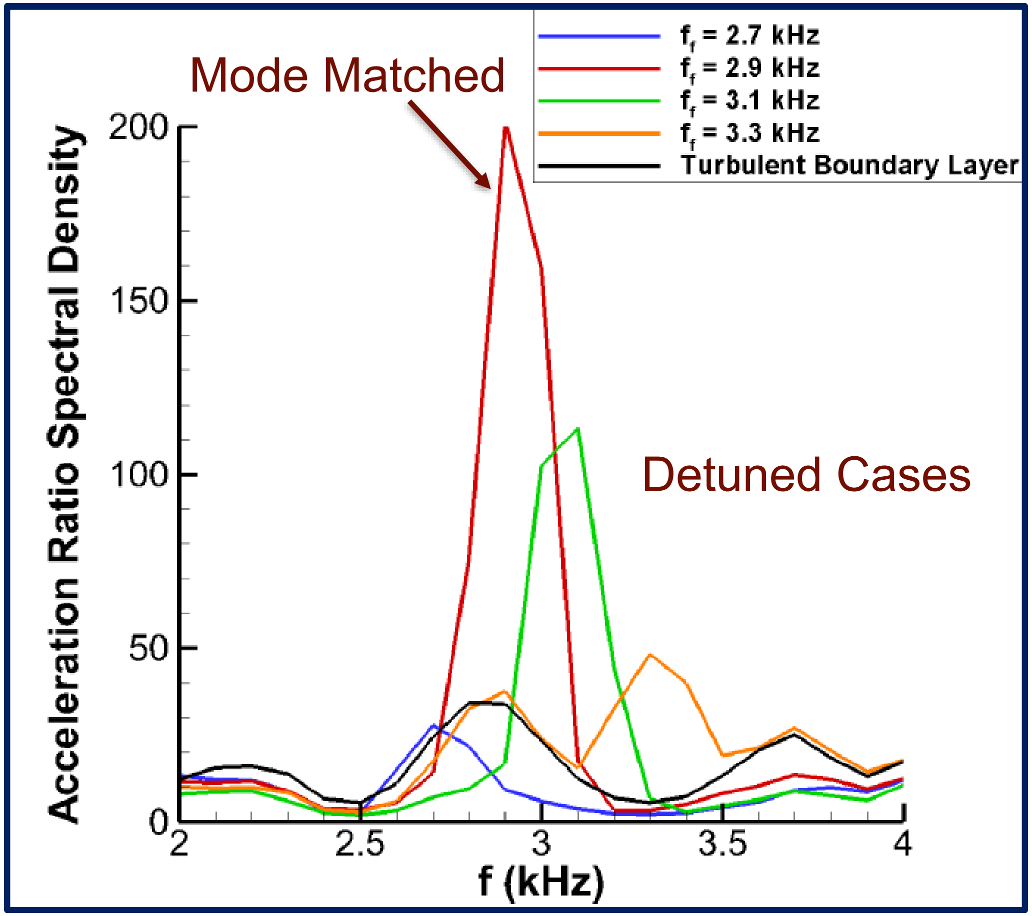
Response to Periodic Spots at Detuned Frequencies

Sandia National Laboratories

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

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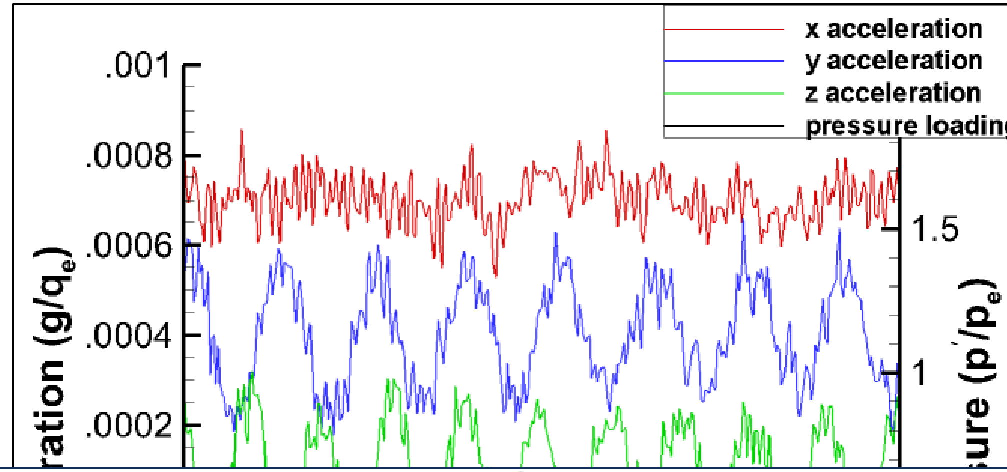
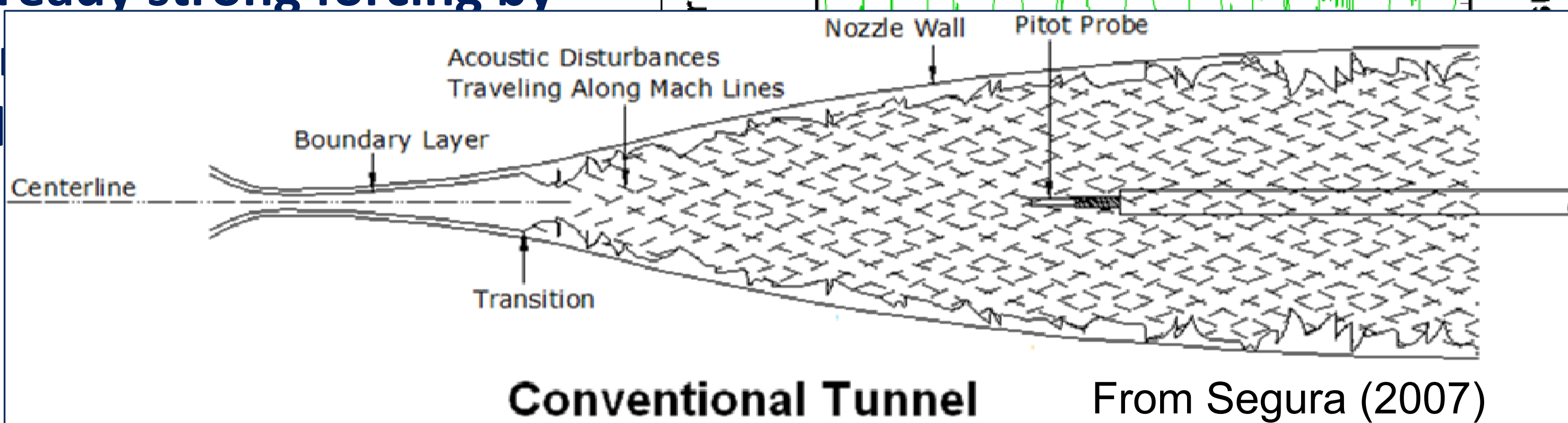




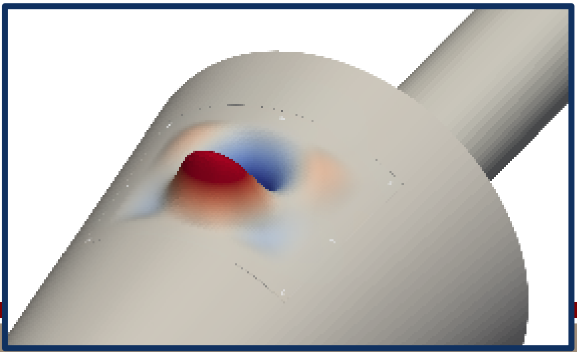
From Segura (2007)

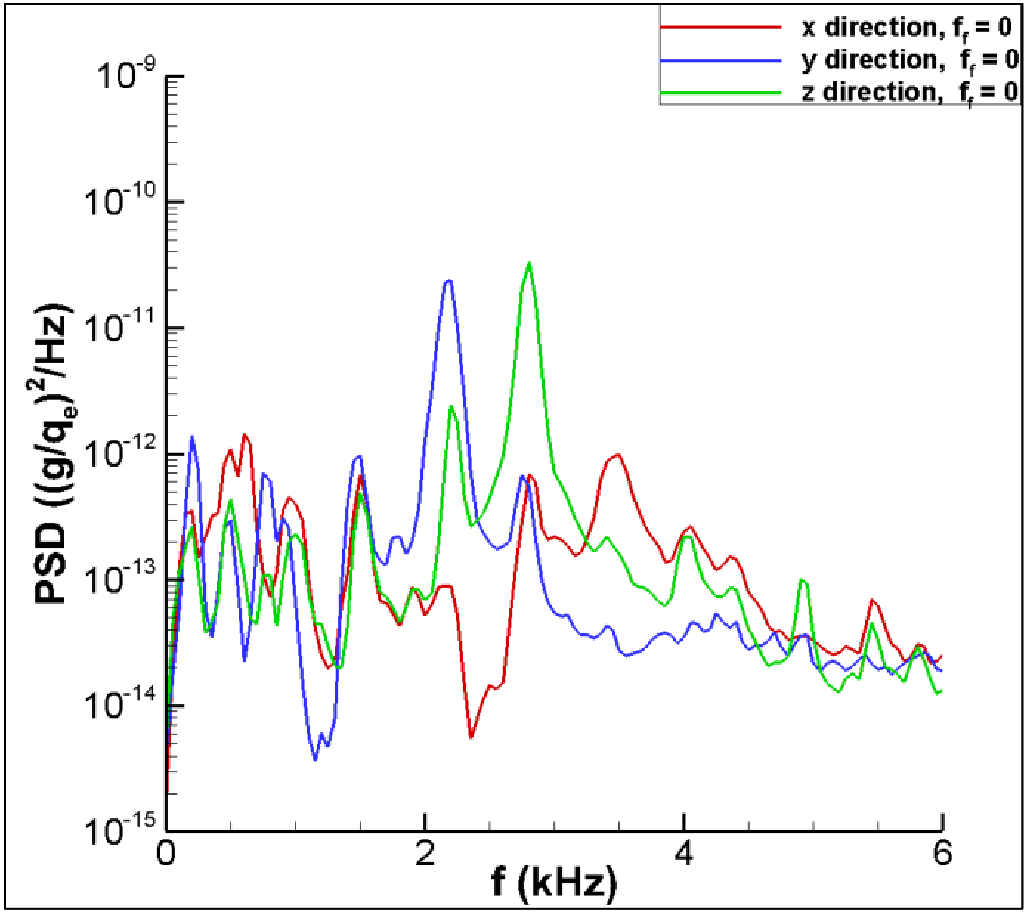
Effect of Tunnel Noise

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.



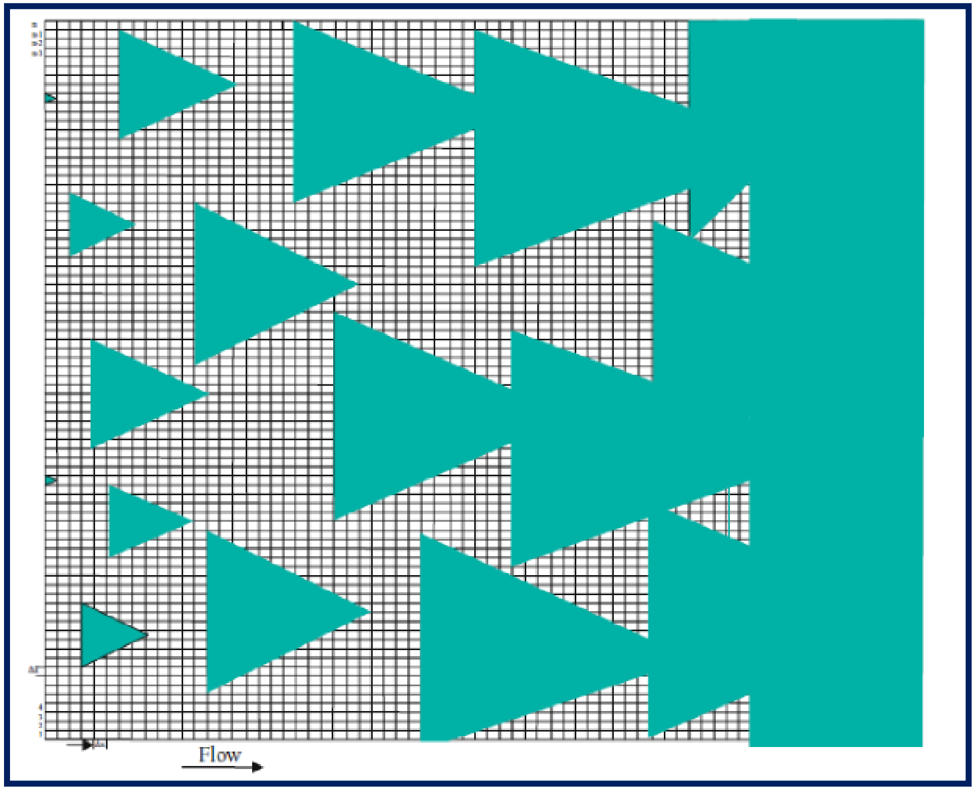


Flight-like Environments

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).



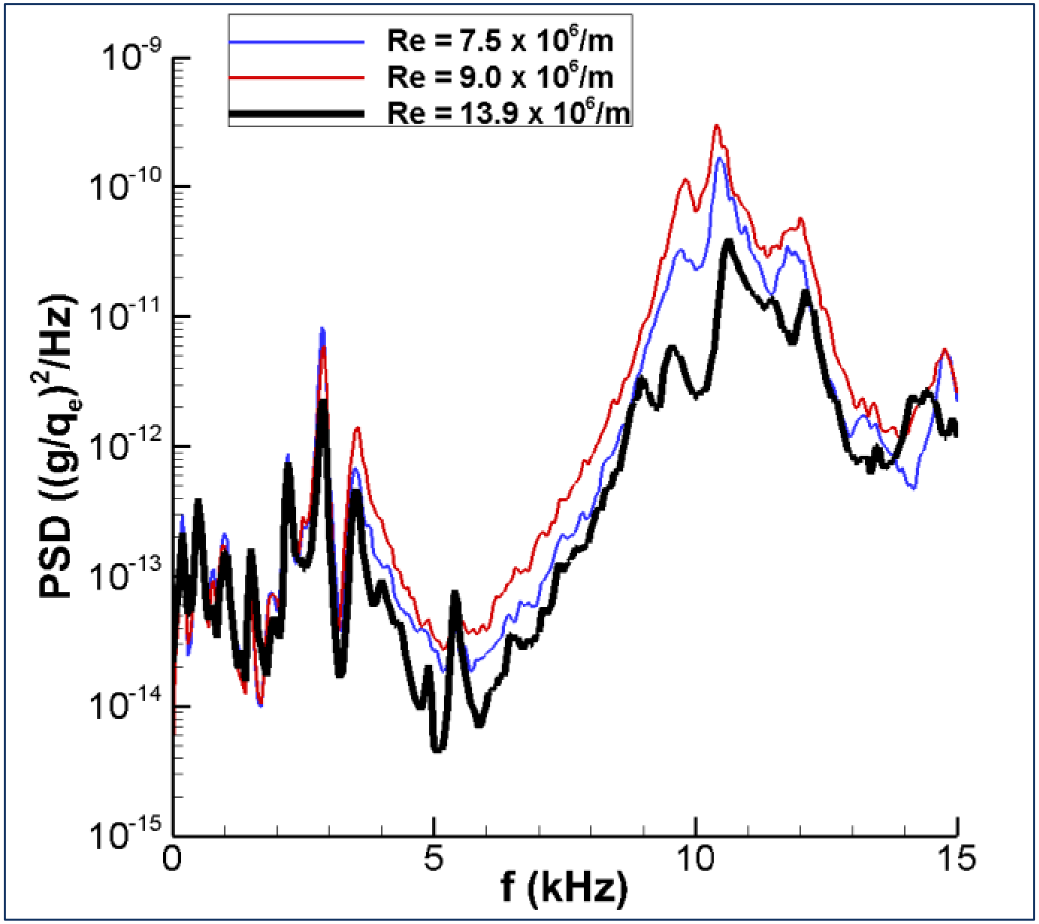
Natural Transition at Mach 5

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

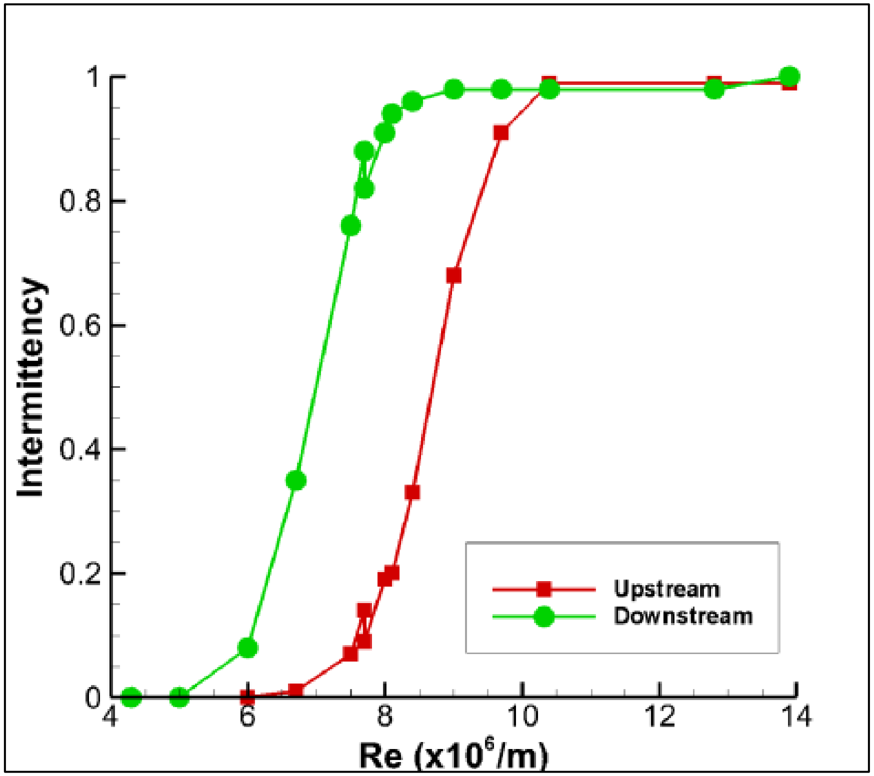


Z-Acceleration Spectra

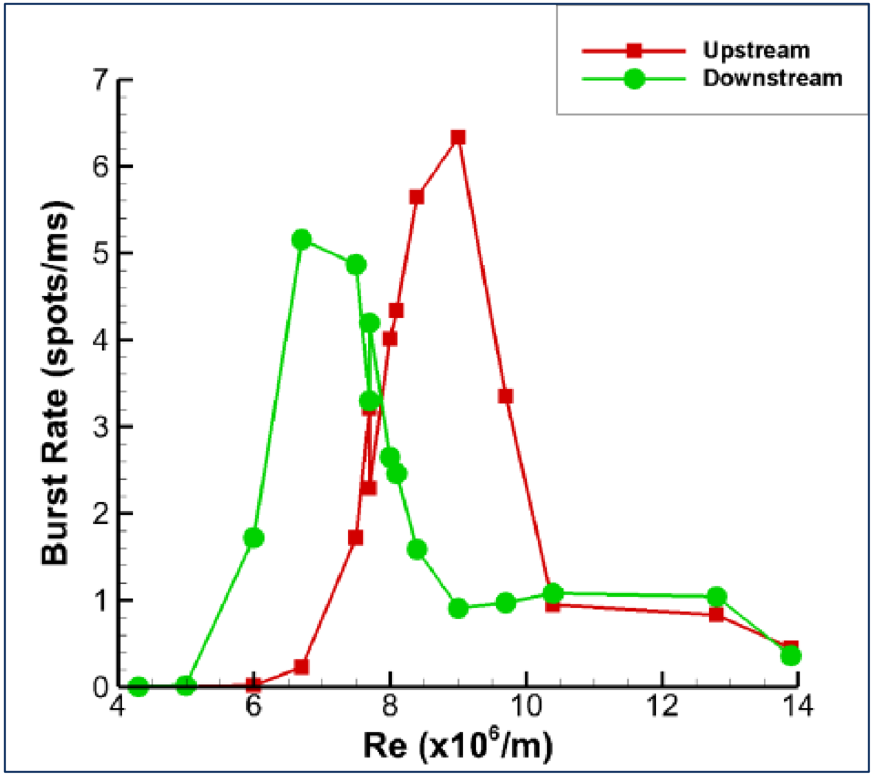
Natural Transition at Mach 5

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

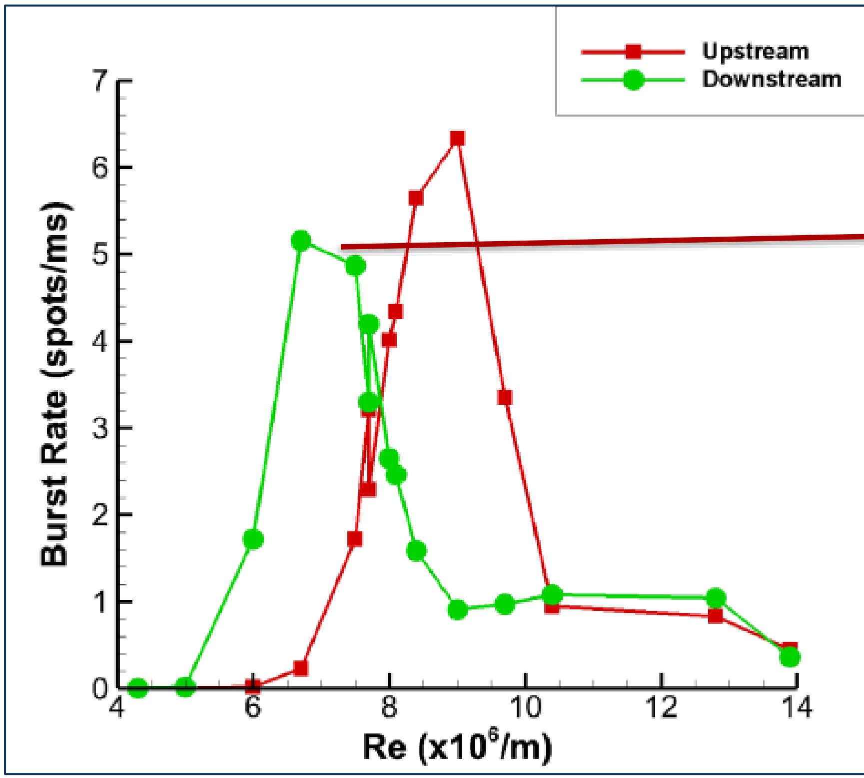


Turbulent Burst Rate

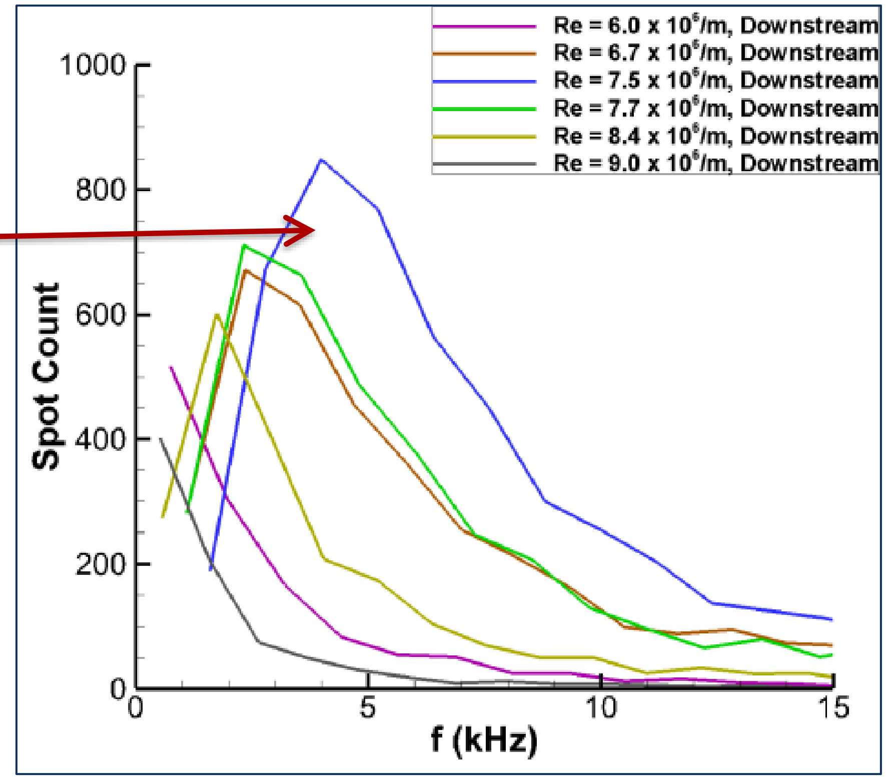
Natural Transition at Mach 5

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

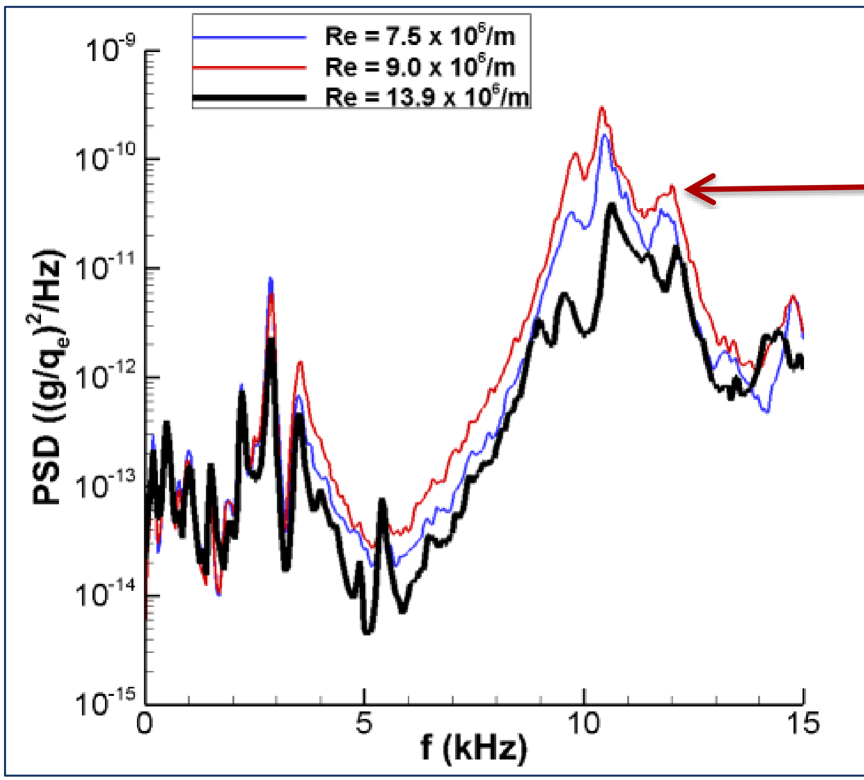


Spot Forcing Distribution

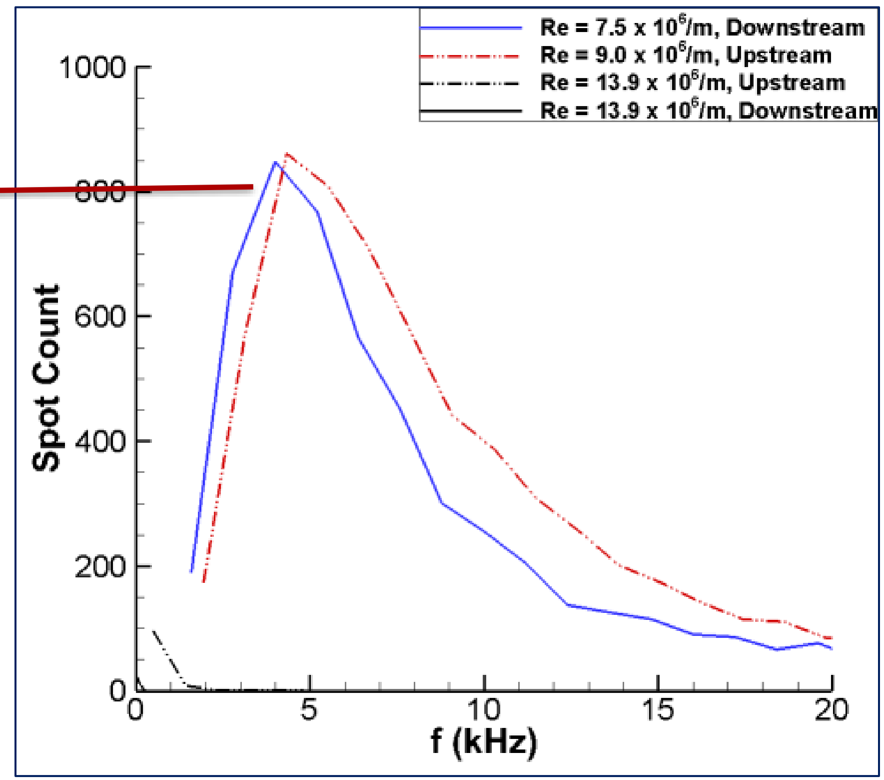
Flight-Like Environments

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

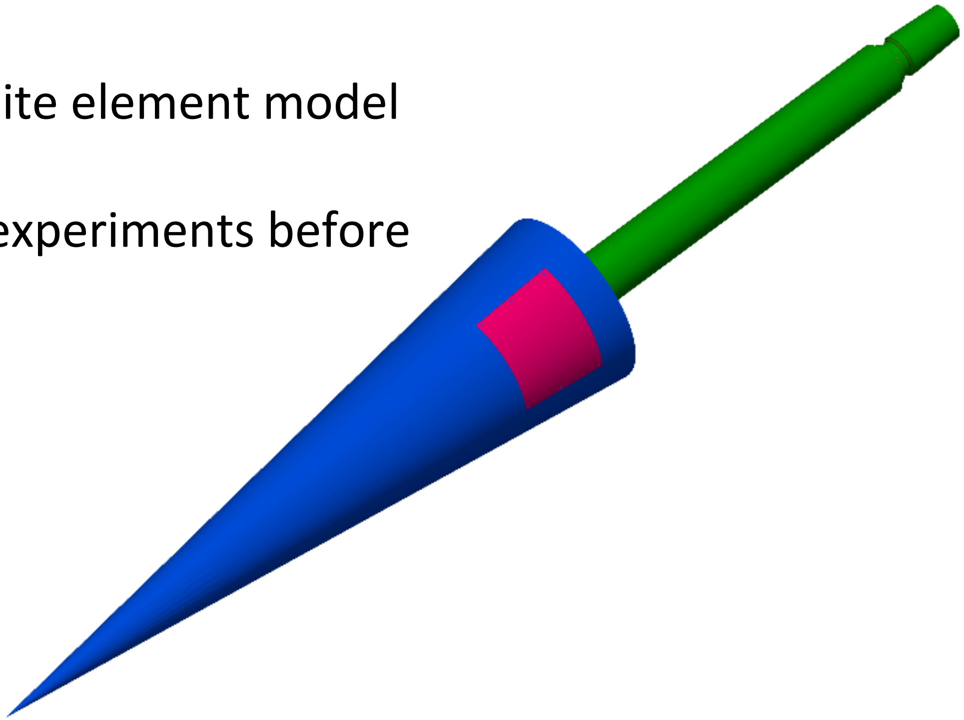
Computational Efforts

Environment:

- Developed a probabilistic model for the transitional pressure loading.
- Describes the birth, evolution, and pressure loading of turbulent spots in a transitional boundary-layer.
- Input parameters and transition locations are obtained from ground test data.

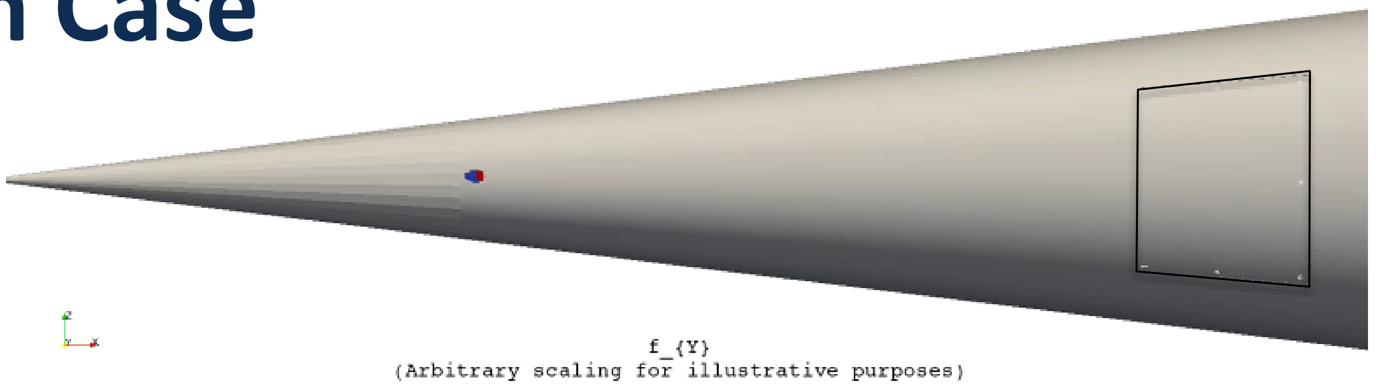
Structural response:

- Transitional model is coupled to a finite element model to predict structural response.
- Code is validated using wind-tunnel experiments before being applied to flight cases.

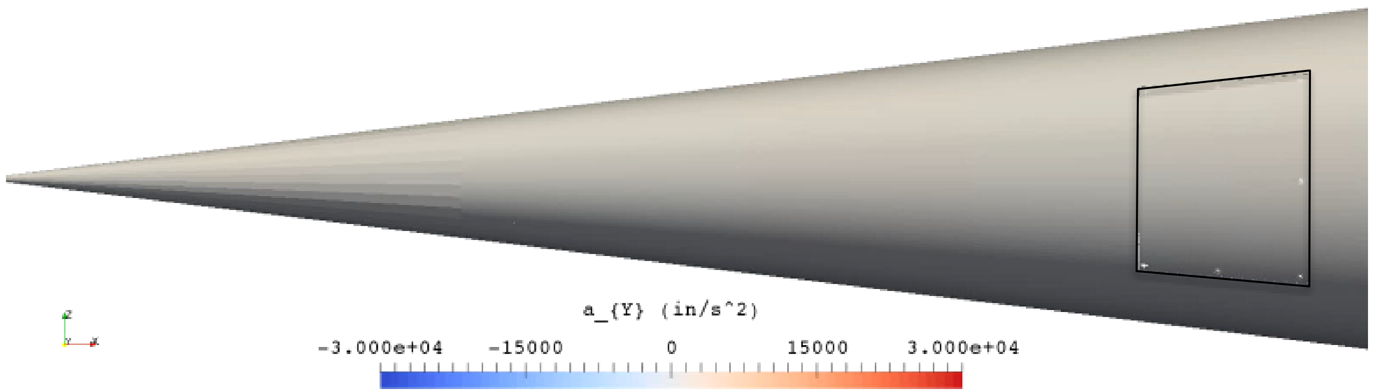


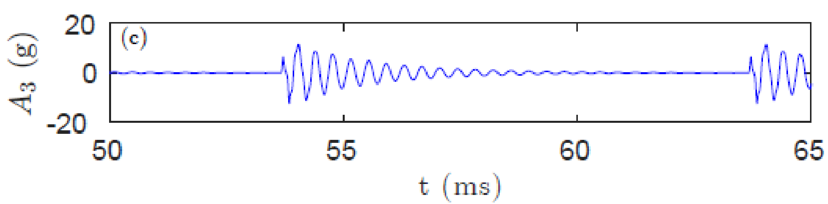
Computational Efforts: Simple Validation Case

Loading from Single Spots



Predicted Structural Response

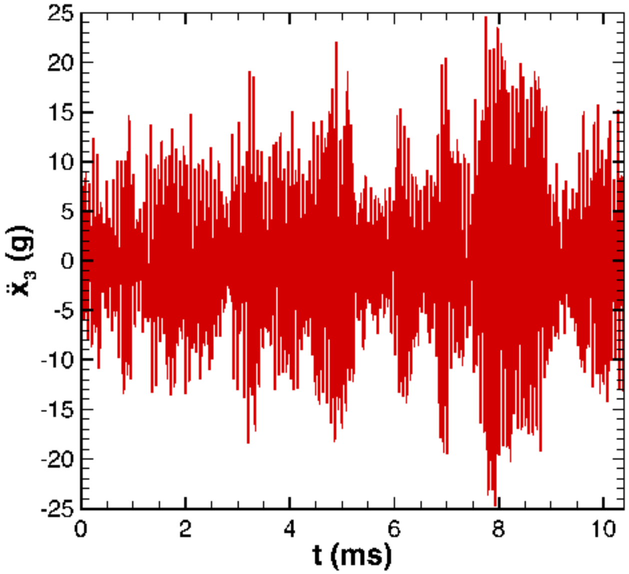


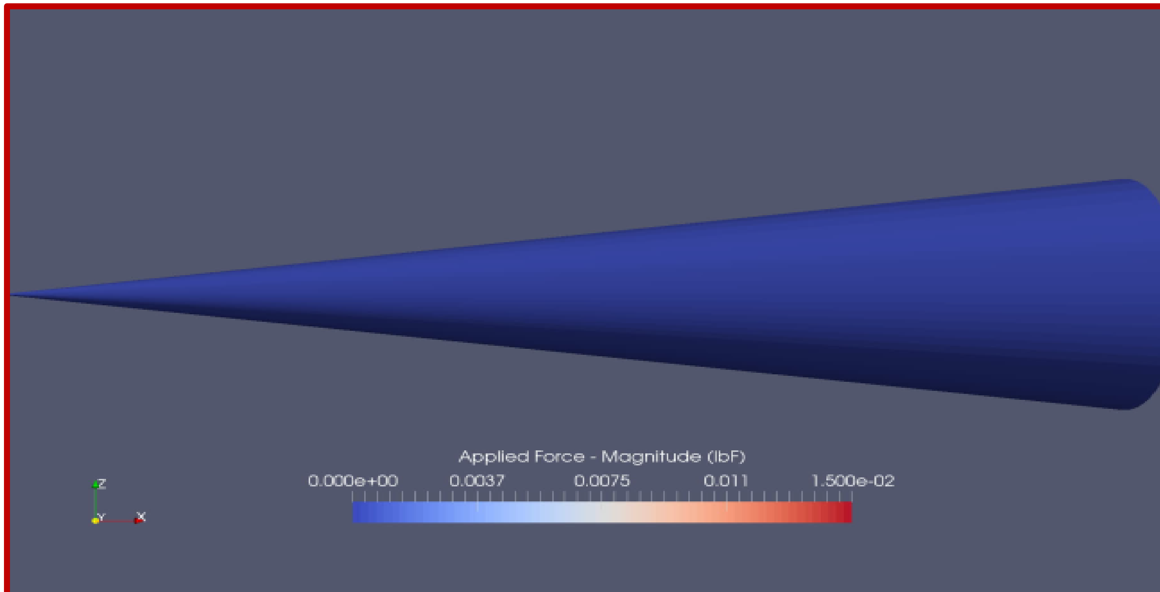


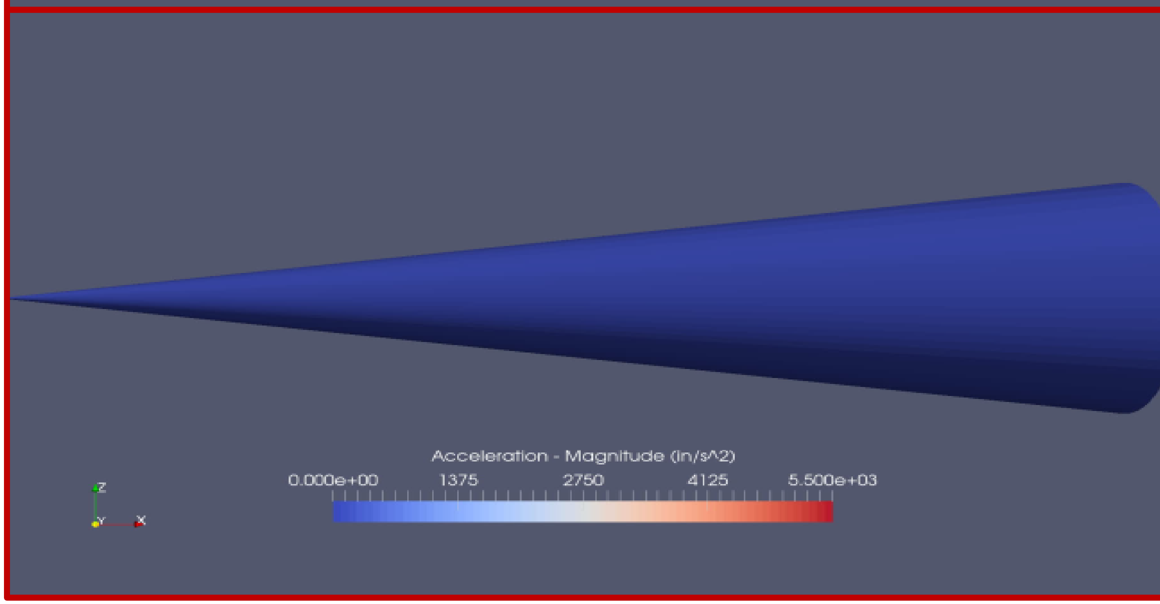
Computational Efforts: Flight-like Case

Loading from Multiple Spots

Predicted Structural Response

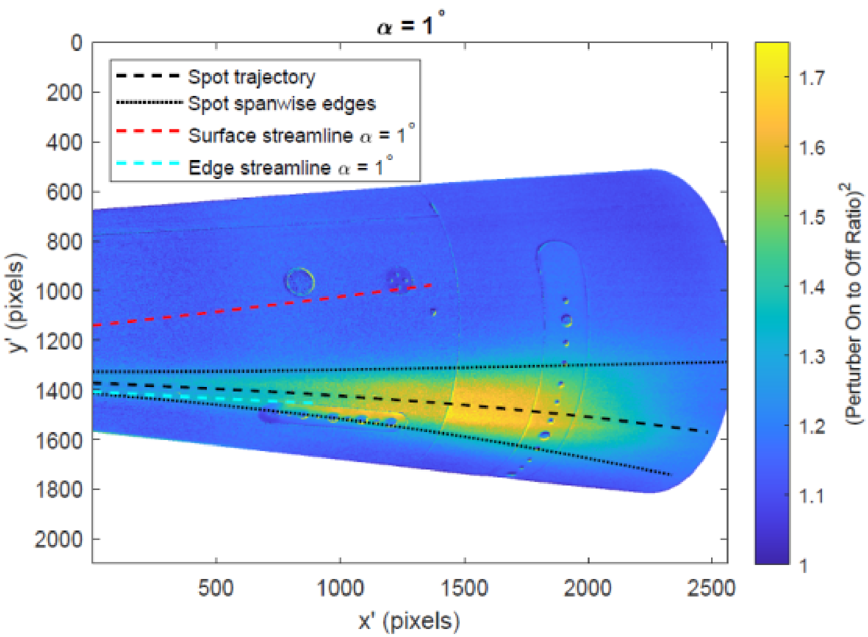


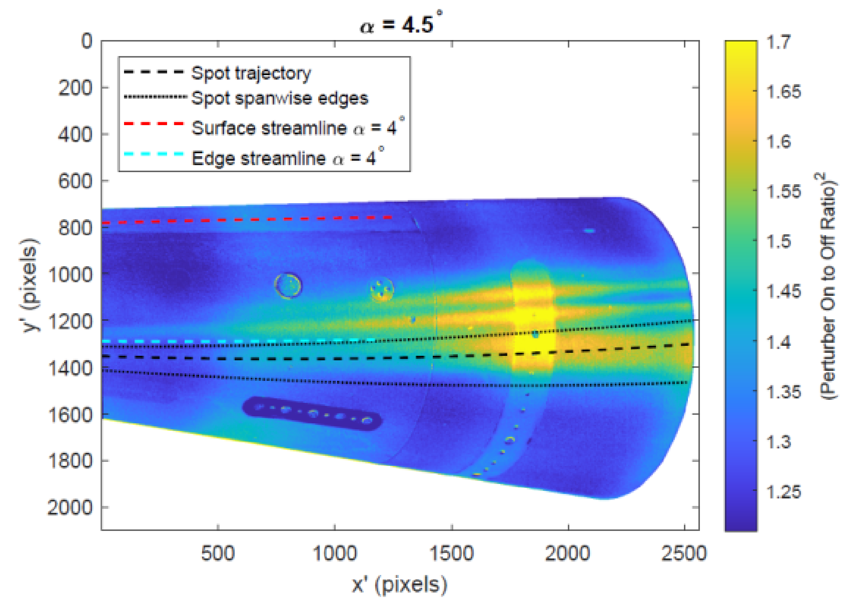




What happens at angle of attack?

- More recent work is looking at spot trajectory at angle of attack.
- Used a spark perturber at high repetition rates to track the thermal footprint of the spots at angle of attack.
  - Spots tract the edge streamlines closely.
  - Additional instrumentation in future testing will better define the spot trajectory and growth parameters.





Future Vehicle Concepts

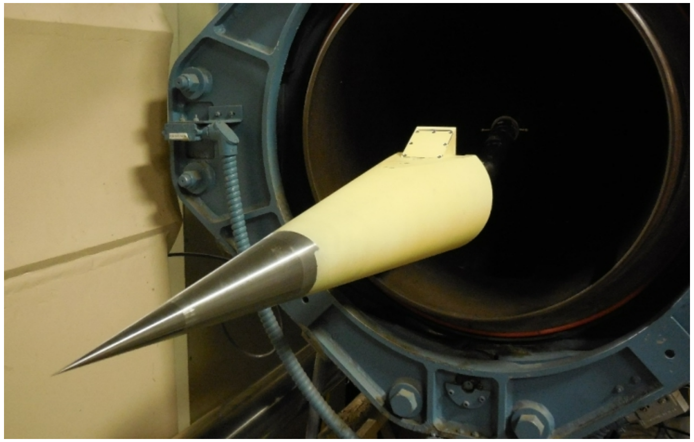
We are also studying fluid-structure interactions on more complex vehicles.

- A cone-slice wedge geometry has been chosen as a characteristic design for complex FSI studies.
- Characterizing the response of panel to shock-boundary layer interactions above it.
- Control surface deflections of 10, 20, and 30 degrees.

Geometry tested at Mach 5 and 8 through a range of laminar, transitional, and turbulent Re.

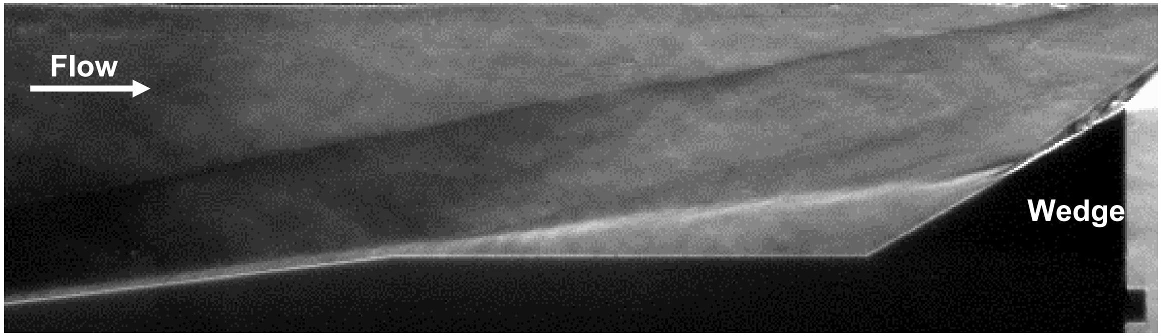
Fluid loading and structural response has been characterized by:

- Dense sensor instrumentation
- High-speed schlieren
- Oil-flow
- Temperature sensitive paint
- Digital image correlation
- FLDI



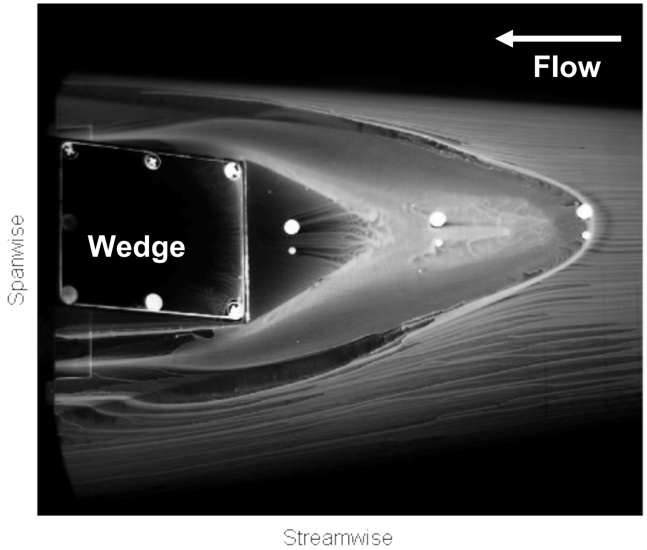
Flow Characteristics

High-Speed Schlieren

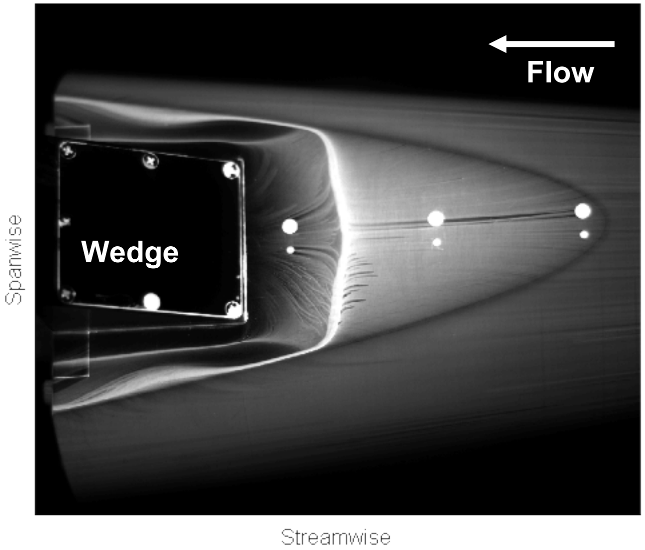


30˚ wedge, Low Re case; P_0 = 325 psi, T_0 = 1280 R

Oil Flow Visualization



30˚ wedge, Low Re case; P_0 = 340 psi, T_0 = 1579 R

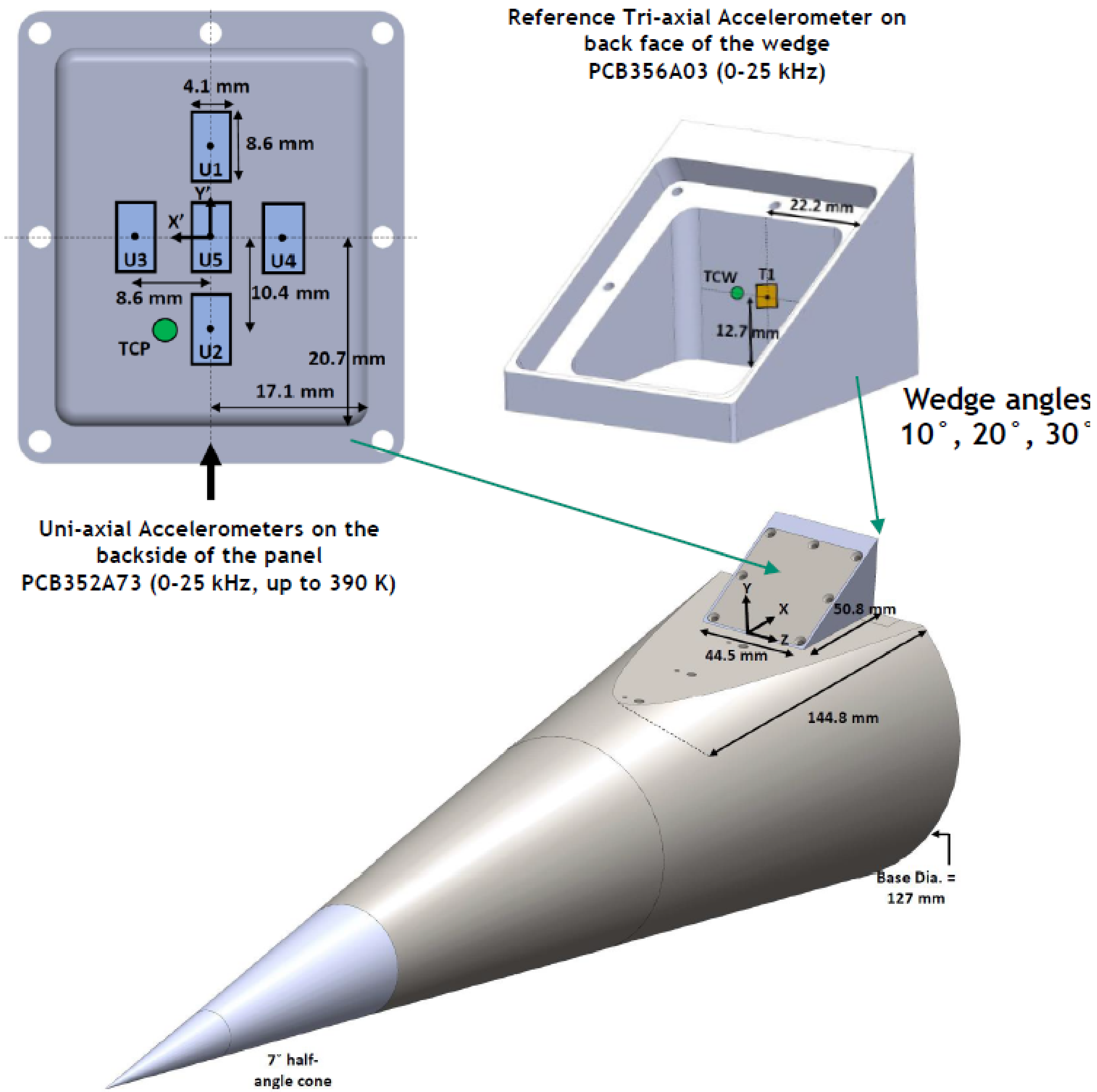


30˚ wedge, High Re case; P_0 = 800 psi, T_0 = 1100 R

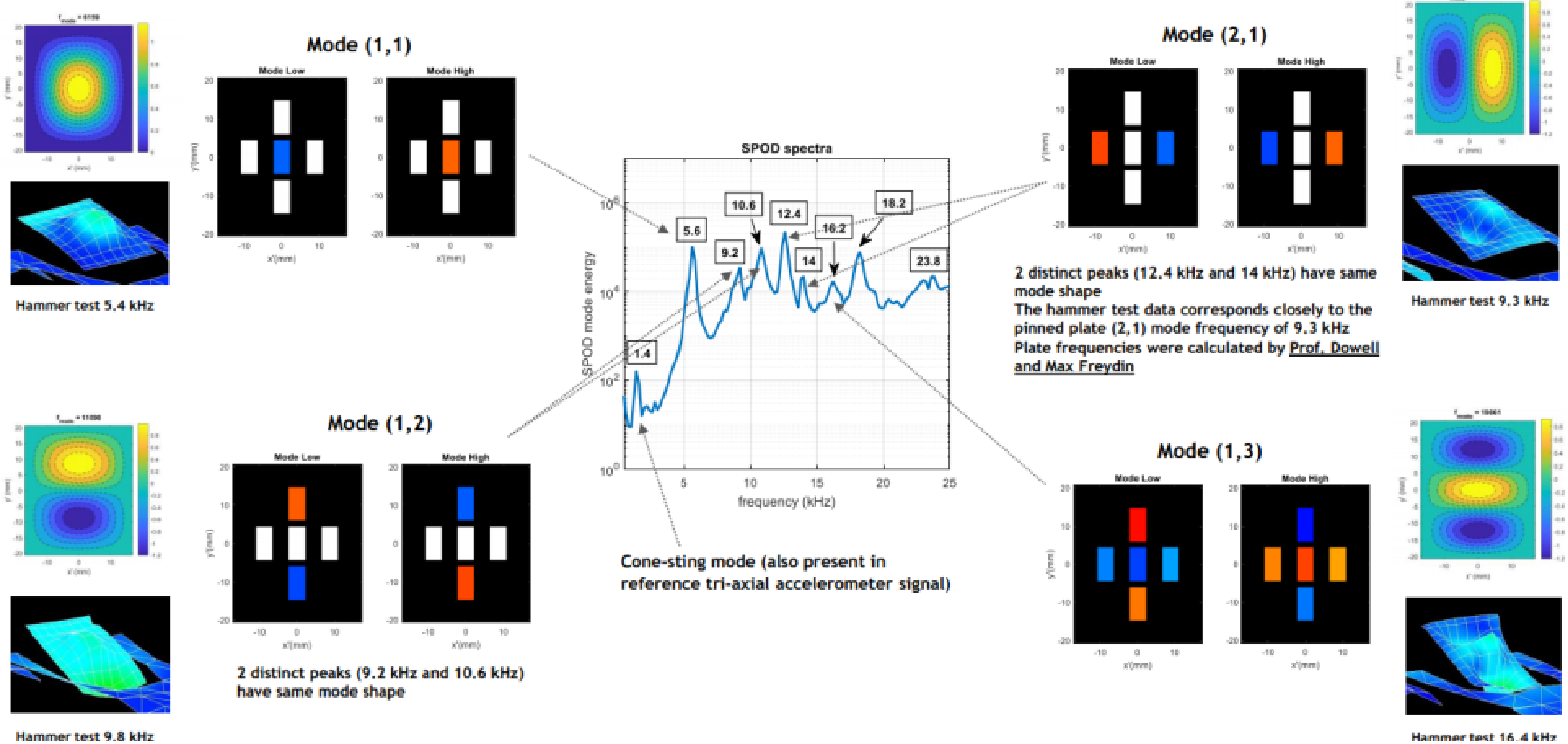
Sensor Instrumentation

Thin panel was incorporated into the wedge.

- Response to fluid excitation tracked with backside accelerometers.
- Temperature of panel and frame tracked with internal thermocouples.
- Pressure measurements were made upstream of the panel and on a solid wedge geometry.

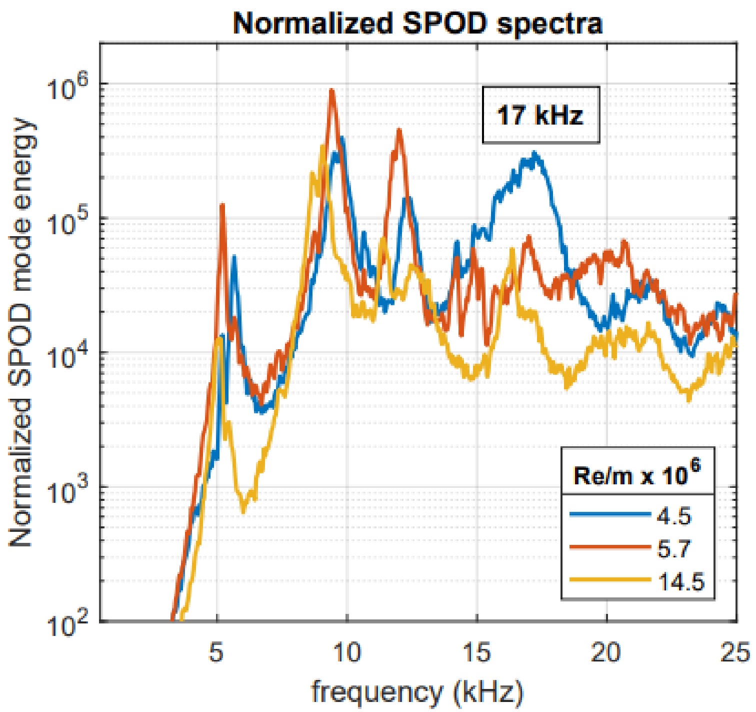


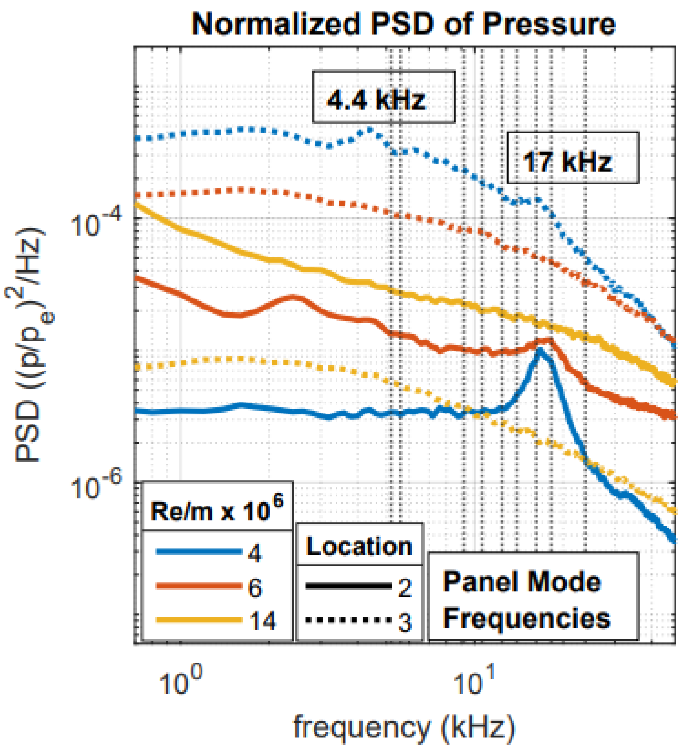
Measured Mode Shapes



Panel Response

- **In general, all primary panel modes are excited by the flow.**
  - Where higher pressure fluctuations are observed, higher amplitudes of response occur.
  - Most responses normalize by dynamic pressure.
- **We see an exception to this when we have an unsteady separation with reattachment on the panel.**
  - Worst case was a laminar separation.

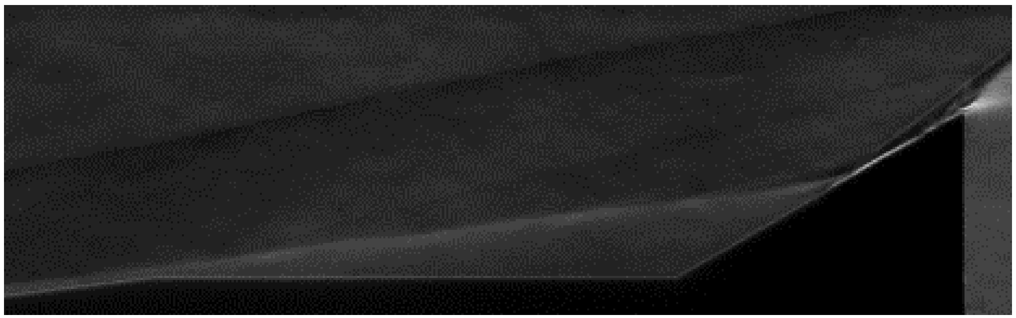




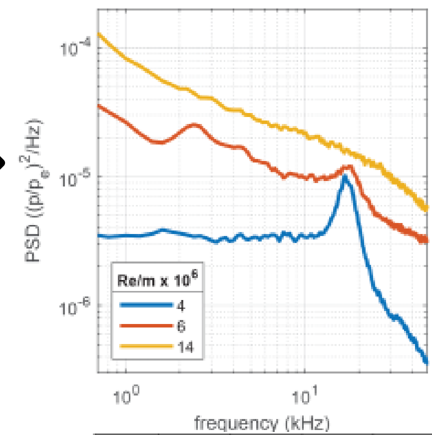
Unsteady Shear Layer Effect on SBLI

Sandia National Laboratories

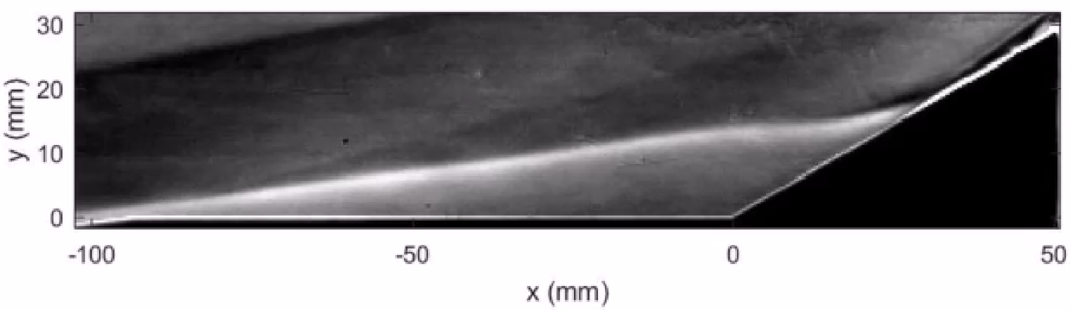
Schlieren movie of shock-induced separation flapping and impinging on a panel in a control surface at Mach 8.



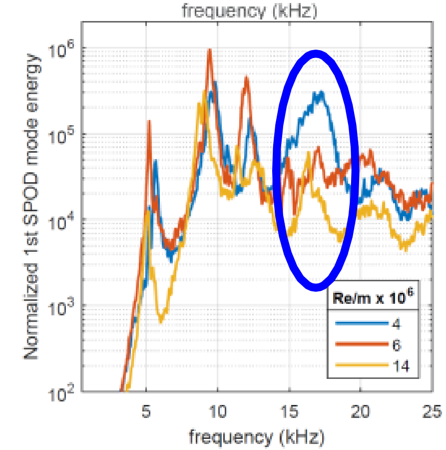
Pressure sensors show a flapping mode at 17 kHz



Post-processed to show only motion at 17 kHz.



This 17 kHz mode emerges in the panel response at matching Reynolds Numbers

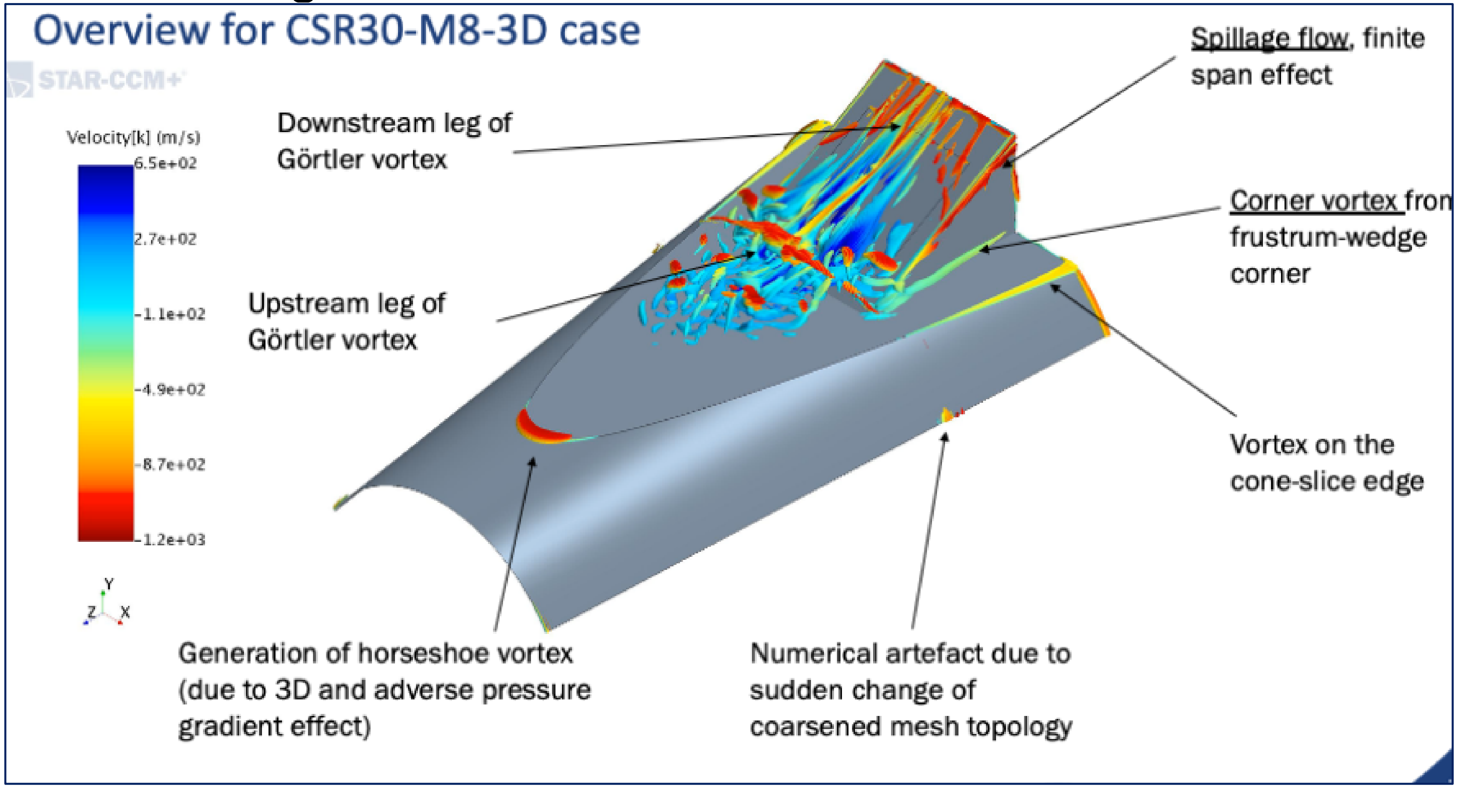


Computational Comparisons

We are comparing experimental results to computations by academia.

- Adam Jirasek, USAFA
- Daning Huang, PSU

Computations help us better understand the flow structure and sources of unsteadiness that might drive the structure.



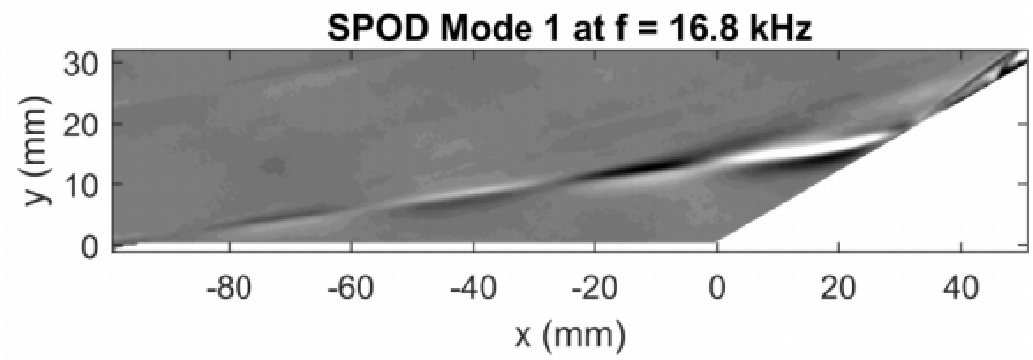
Key Flow Features, From Daning Huang, PSU

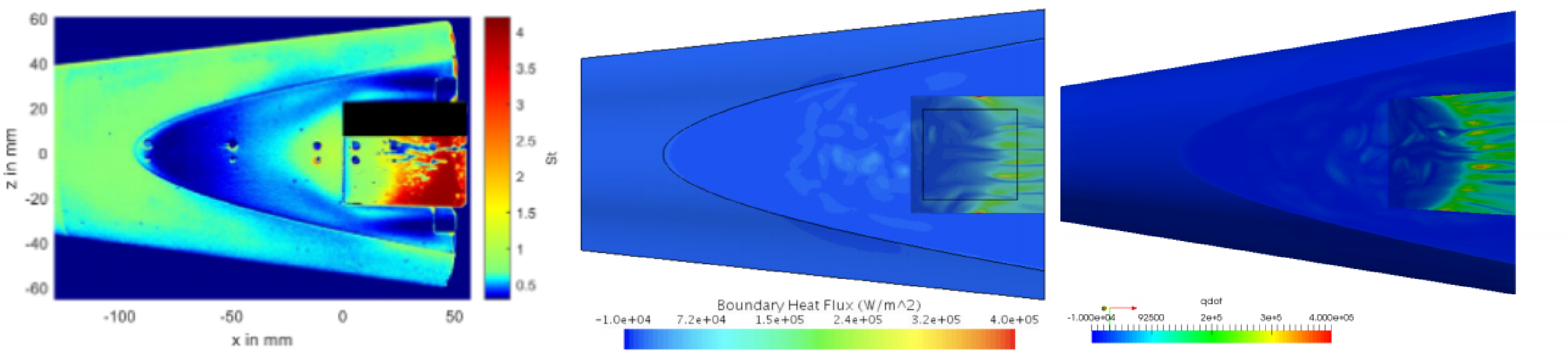
Computational Comparisons

Mean and surface comparisons of flow field show good similarity between experiments and computations.

- Also reasonable agreement between both computational methods.

Dynamic features also show good agreement and will allow us to better understand the unsteady flow physics leading to structural response.





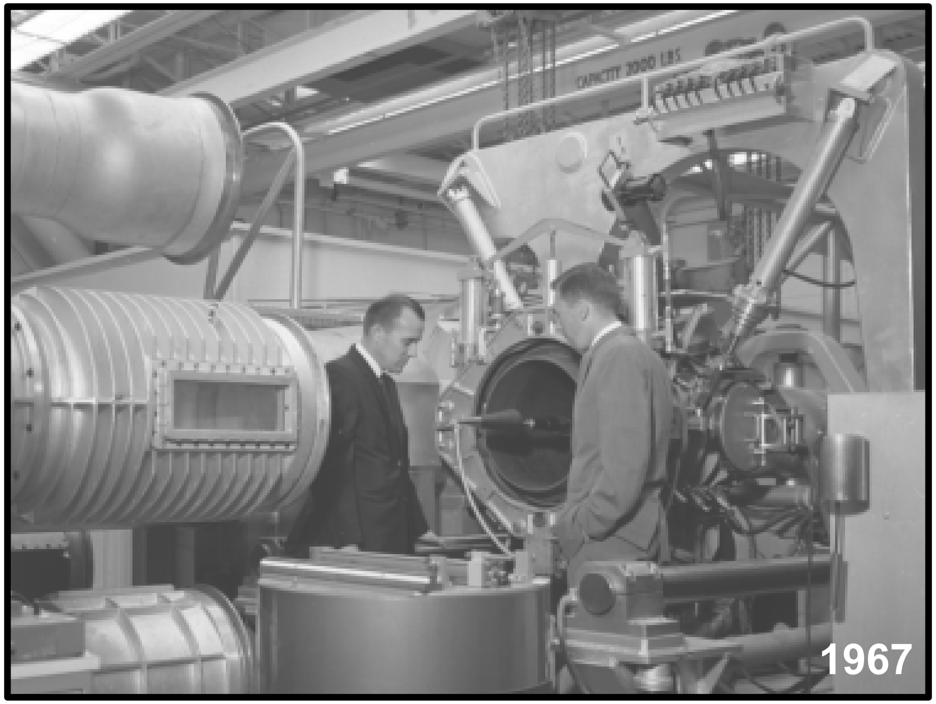
(a) Experiment (TSP) (b) Numerical - PSU (c) Numerical - USAFA

Experimental and Computed Heat Transfer

Summary

Sandia's wind tunnels have a long history of contributing to the nation.

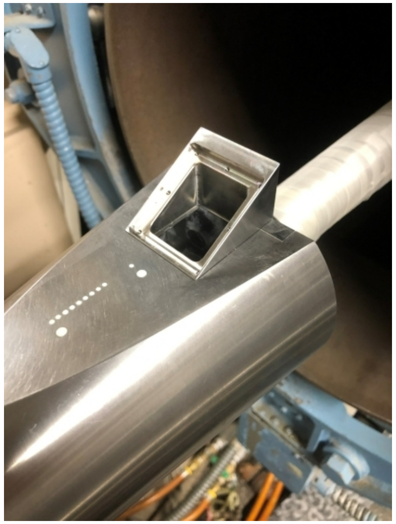
- Even in an era of computational simulation for engineering practice, wind tunnels are key to aerospace technology.
- Our mission is not just aerodynamic characterization of vehicles, but also providing data to develop and validate modeling and simulation.
- Advanced diagnostics are a key part of modern wind tunnel testing.

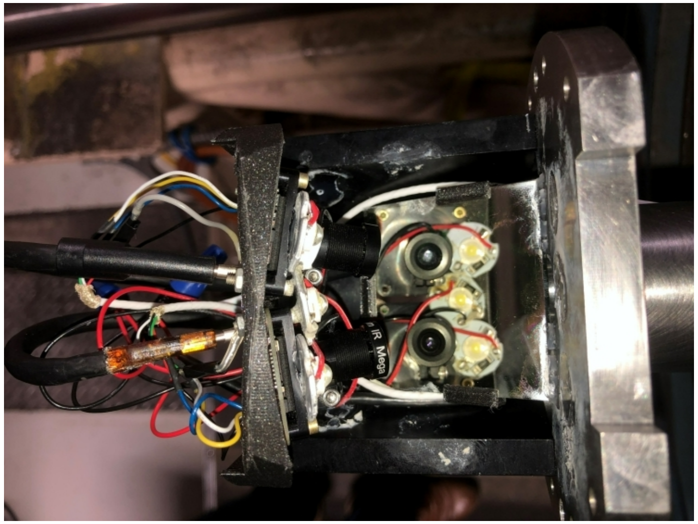


Internal Digital Image Correlation

Internal DIC wind tunnel test was recently completed to better characterize the spatial distribution of the panel structural response and any static deformation.

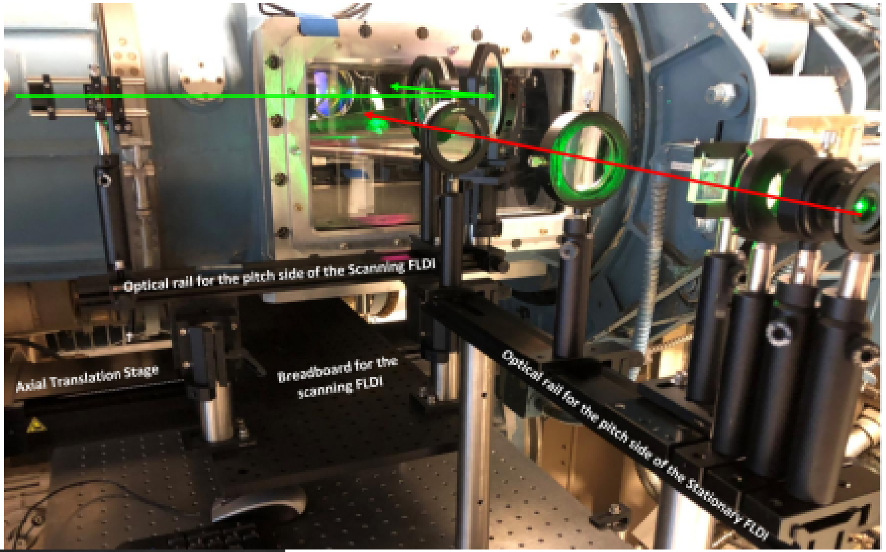
- Avoids noise/data contamination by looking through the flow field.
- Limits camera size (and framing rate) that can be used.
- Stereo setup is used for increased out-of-plane resolution.

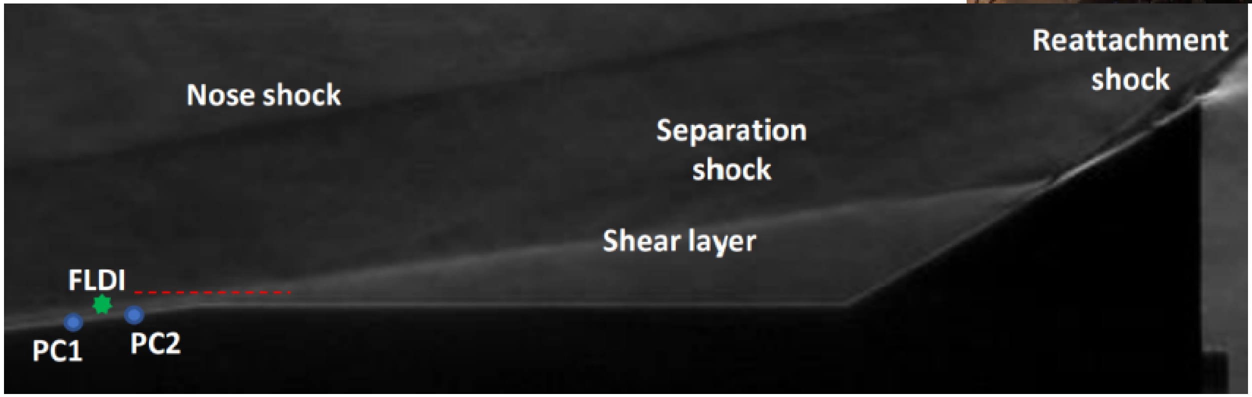




Focused Laser Differential Interferometry (FLDI) in HWT

- A folded two-probe FLDI was setup on a single breadboard that can be mounted on a stage and traversed along the HWT.
- In a stationary run, the probe was placed inside the boundary layer and in between two PCBs (see green star) for comparison.
- **Frequency response of 2.5 MHz!**





Focused Laser Differential Interferometry (FLDI) in HWT

- 2nd mode wave frequencies and wave-speeds match well with surface pressure measurements.
- Further data characterizes the shear layer frequencies that create unsteady loading at surfaces.