Towards Turbulent-Spot Models of Pressure Fluctuations during Hypersonic Boundary-Layer Transition

SAND2014-1951C

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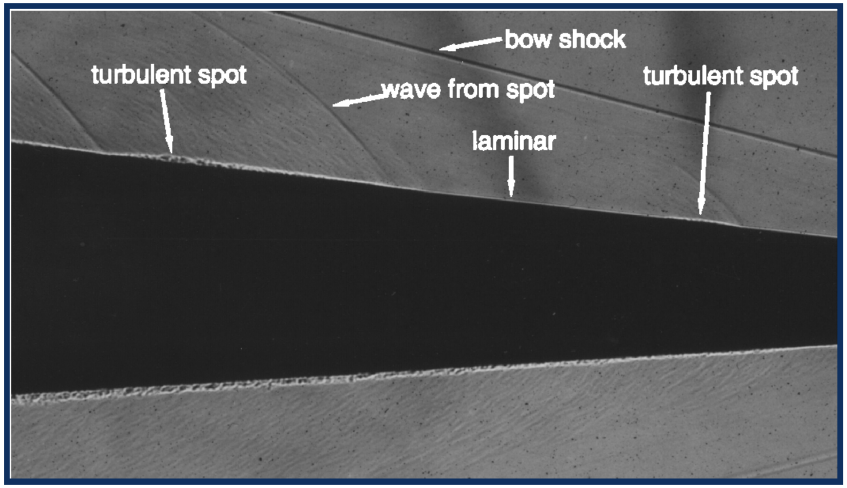
Motivation

Pressure fluctuations peak during boundary-layer transition.

- Need to model fluctuations and spatial distribution for structural design of reentry vehicles.
- Current models based on correlations to incompressible flow data.

We seek to develop more accurate model using a turbulent-spot approach.

- Model already developed for pressure fluctuations on a flat plate in incompressible flow.
- Boundary-layer physics change at high M.



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

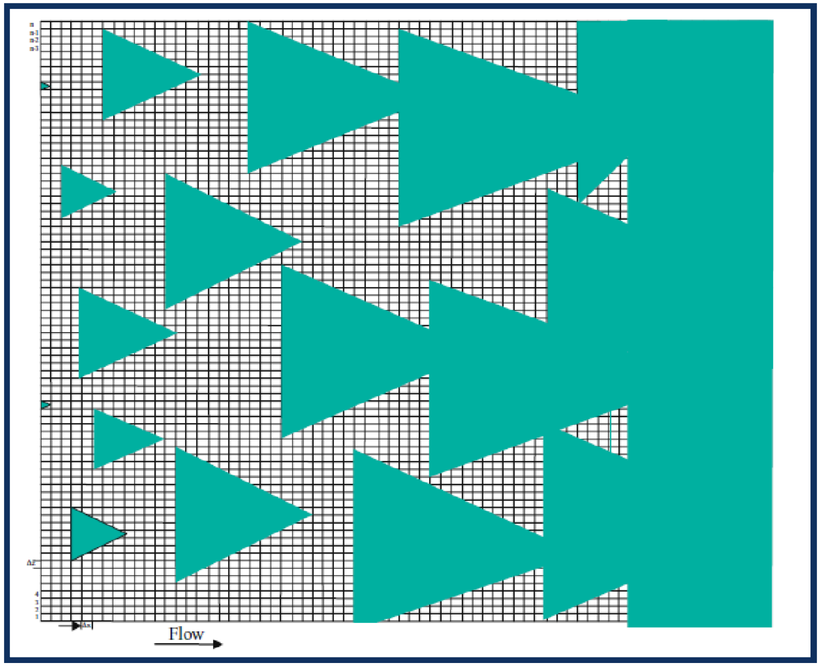
Turbulent Spot Approach to Modeling Transitional Pressure Fluctuations

Need accurate measurements of the growth and the internal structure of the spots as input to model.

- Pressure field
- Convection velocity
- Spanwise spreading angle

Need transition statistics.

- Intermittency
- Burst rate
- Average burst length



Turbulent spot model simulation, from Vinod (2007).

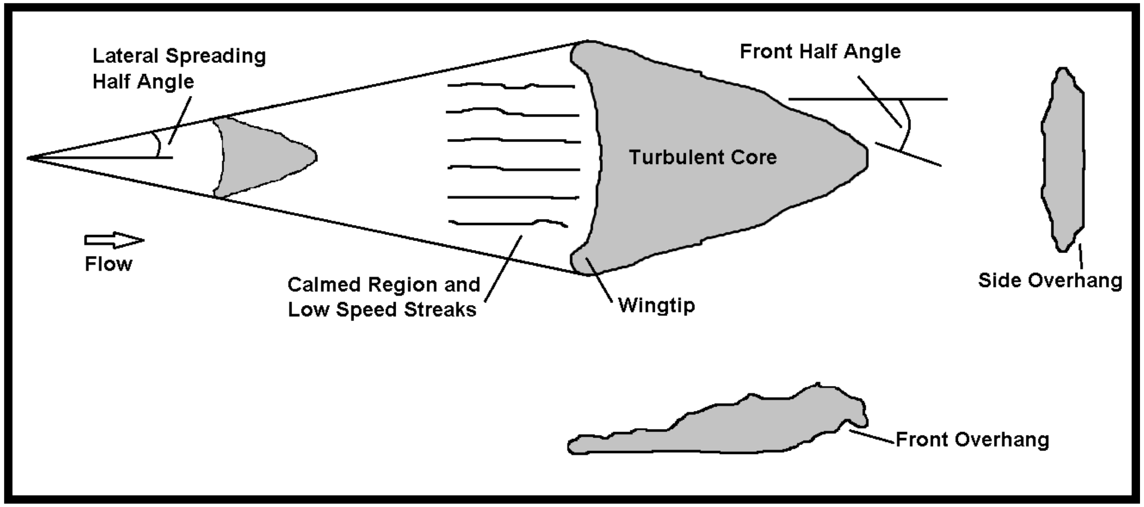
Turbulent Spot Geometry

Spot growth is characterized by:

- Lateral spreading half angle
- Front half angle or leading and trailing edge velocities.

Spot model also relies on

- Spatial distribution of pressure fluctuations.
- How spots merge.



Schematic of a turbulent spot.

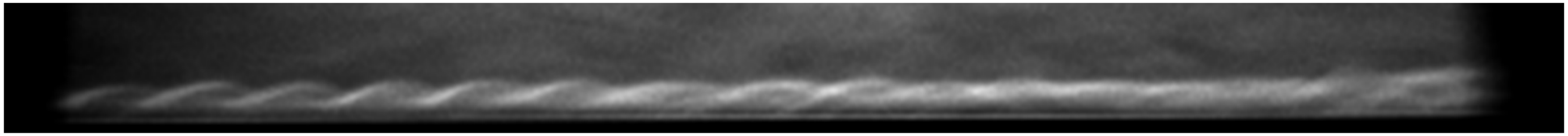
Instability Wave Packets

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.

- Reflects between the model surface and near the boundayr-layer edge as it travels downstream.
- Dominant instability is 2D.

Appears as rope waves in schlieren images.



Second-mode waves in Mach 8 boundary layer.

Part 1: Isolated Disturbances

Our goal was to use a flow perturber to initiate controlled, isolated wave packets and turbulent spots.

- Study evolution of pressure field beneath the disturbances.
- Compute growth properties of disturbances.
- Feed these values into transition models.

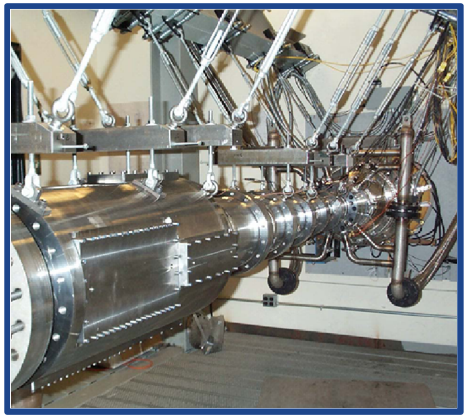
Boeing/AFOSR Mach-6 Quiet Tunnel

Ludwieg tube design.

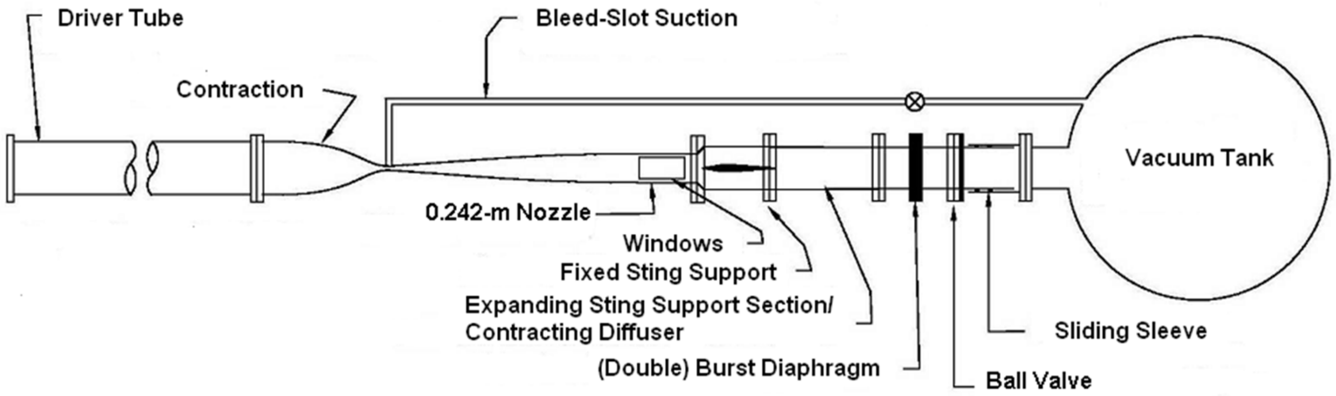
Can be operated under noisy and quiet flow.

For quiet flow:

- Contraction boundary layer is removed using bleed slots.
- Laminar boundary layer restarted at throat.
- Long, highly-polished nozzle to reduce growth of instabilities.
- Laminar flow is maintained downstream of nozzle exit.



BAM6QT nozzle and test section.



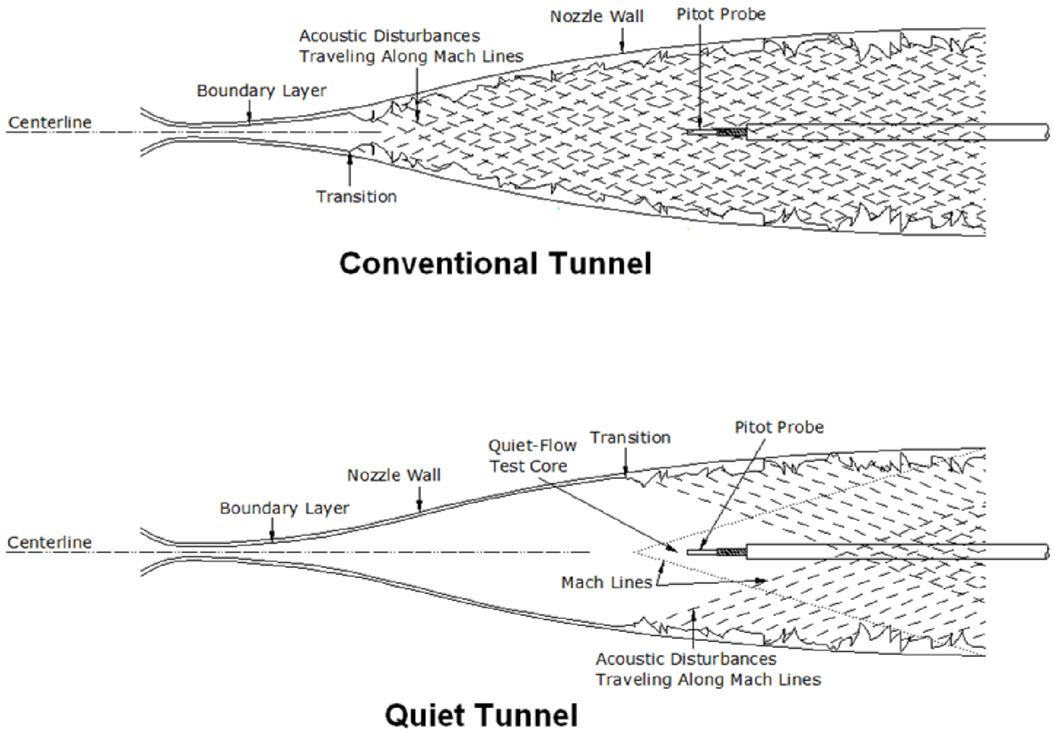
Conventional vs. Quiet Tunnels

Conventional Tunnels:

- High noise near 2-5% of the mean.
- Noise can cause much earlier transition than flight.

Quiet Tunnel:

- Low noise around 0.05%.
- Comparable to flight.



Schematic of difference between conventional and quiet tunnels, from Segura (2007).

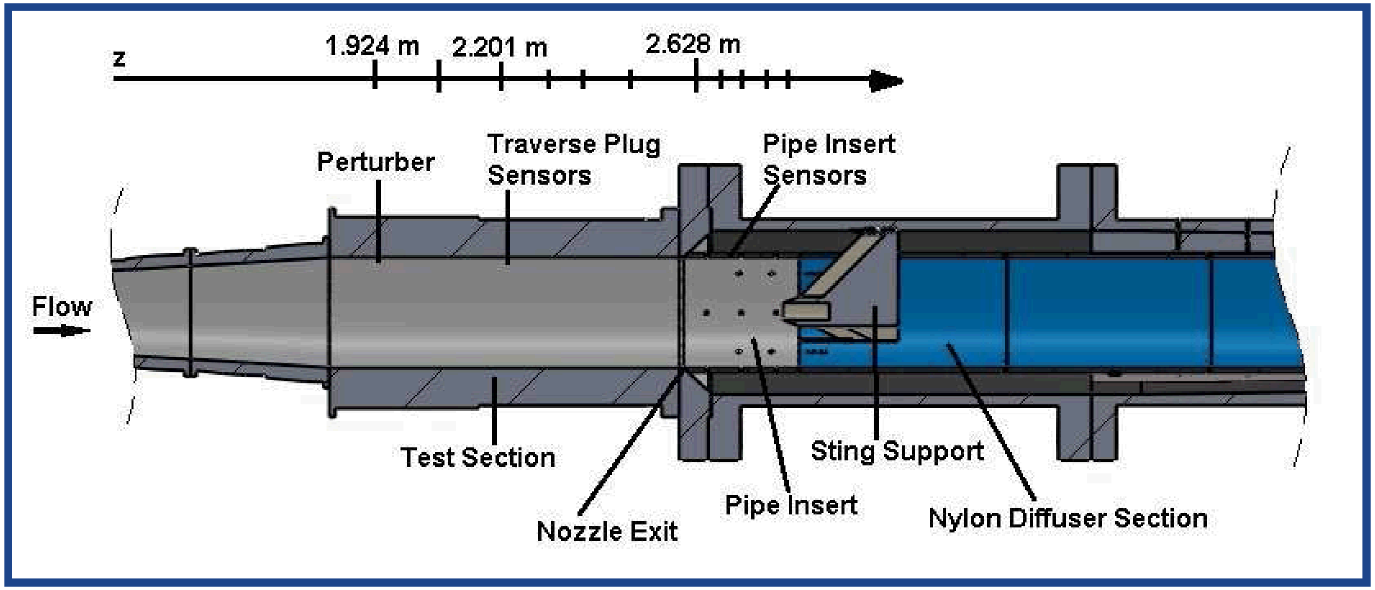
Experimental Setup

Perturber on top wall of tunnel, upstream of sensors.

Row of 9 pressure transducers on top wall of tunnel.

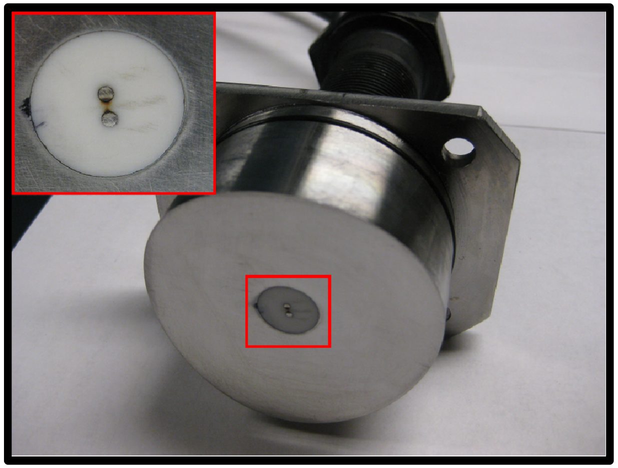
- 4 within axisymmetric nozzle
- 5 in downstream pipe insert

Moveable, spanwise array of pressure transducers in pipe insert.

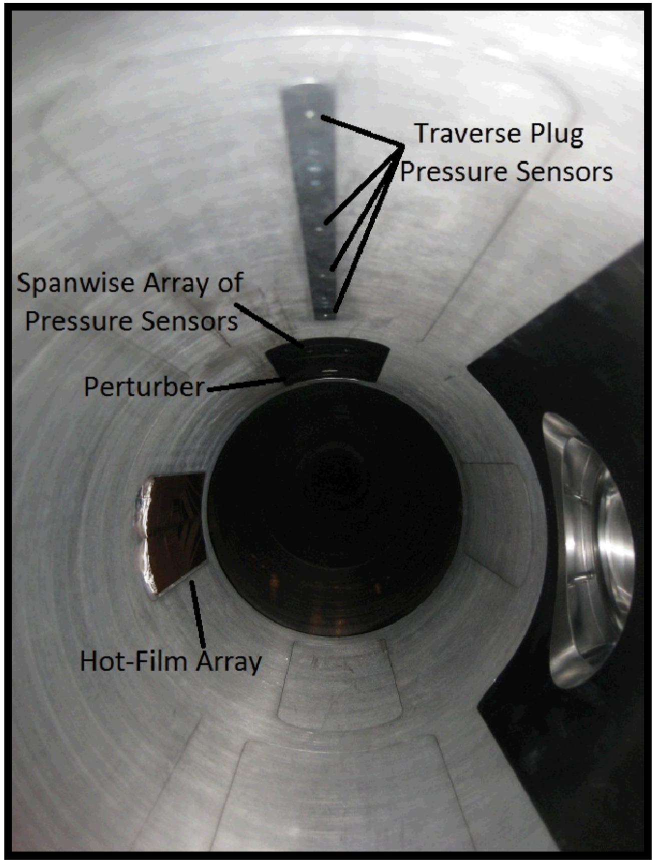


Setup schematic.

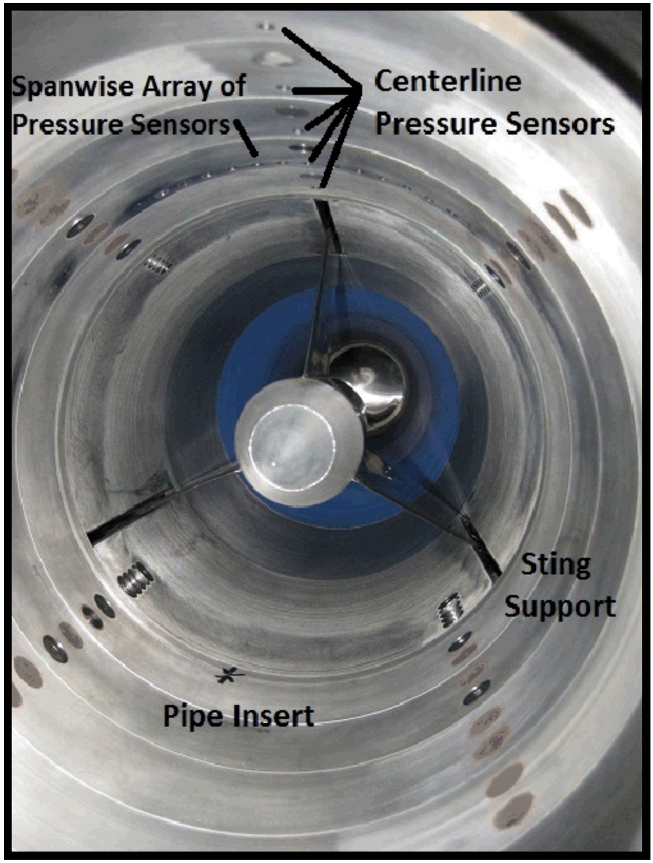
Experimental Setup



Perturber electrodes.



Looking upstream into nozzle.



Looking downstream into pipe insert.

Centerline measurements at $Re = 6.33 \times 10^6/m$

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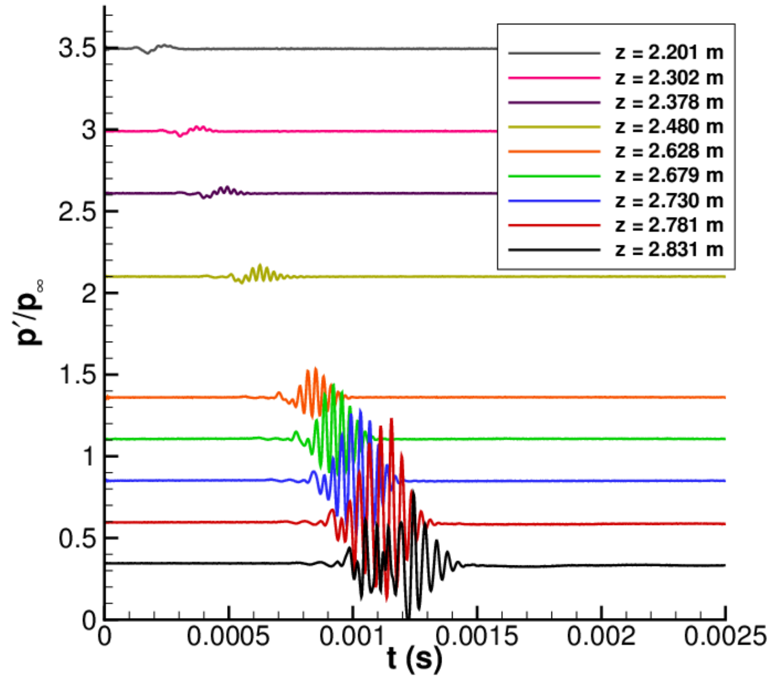
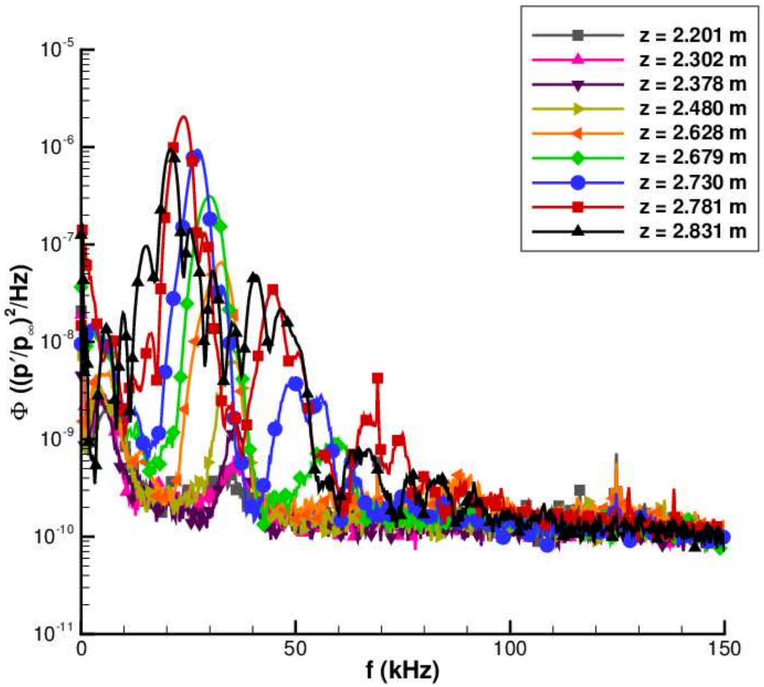
Perturbation initially generates a linear wave packet.

- Packet grows and becomes nonlinear by z = 2.679 m.
- Additional peaks appear in the spectra by z = 2.730 m.
- Start to get rise in broadband frequencies by z = 2.831 m.



Time traces.

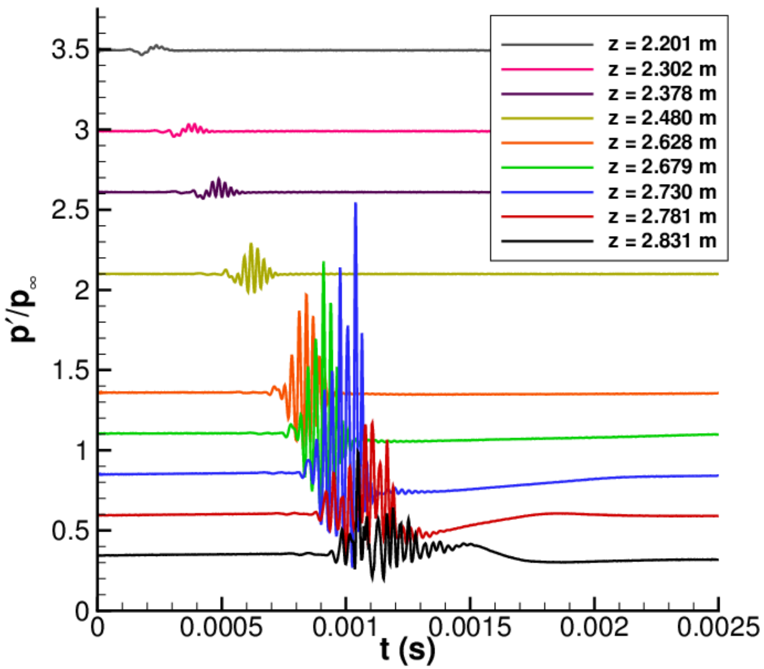


Power spectral density.

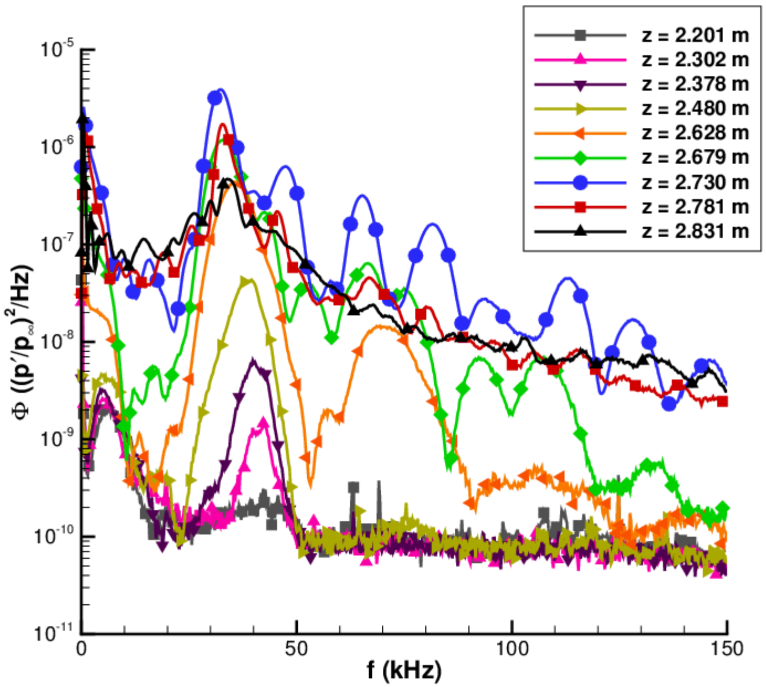
Centerline measurements at $Re = 8.25 \times 10^6/m$

Small second-mode waves grow and develop along nozzle length.

- Peak frequency is 30-40 kHz.
- Large amplitude fluctuations visible before breakdown.
- Second-mode waves still visible on either side of turbulent fluctuations.



Time traces.



Power spectral density.

Centerline measurements at $Re = 10.8 \times 10^6/m$

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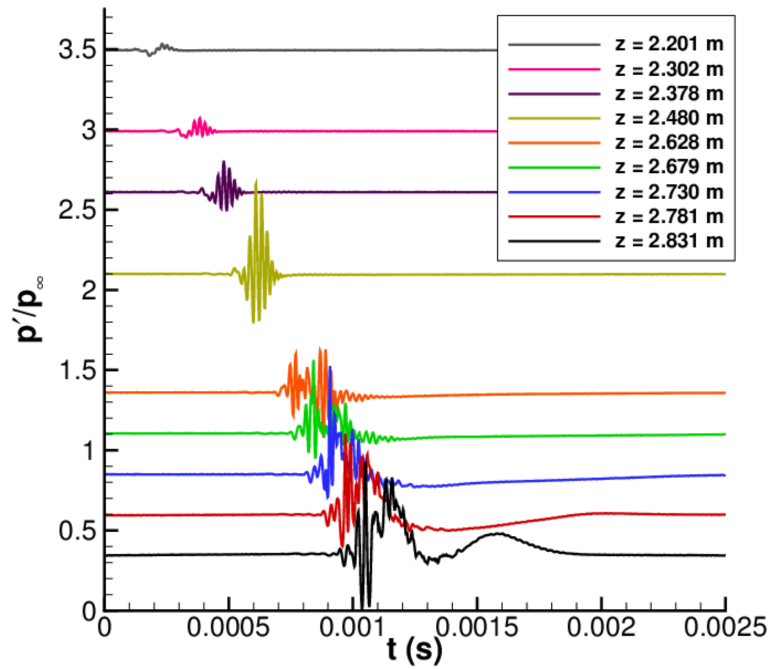
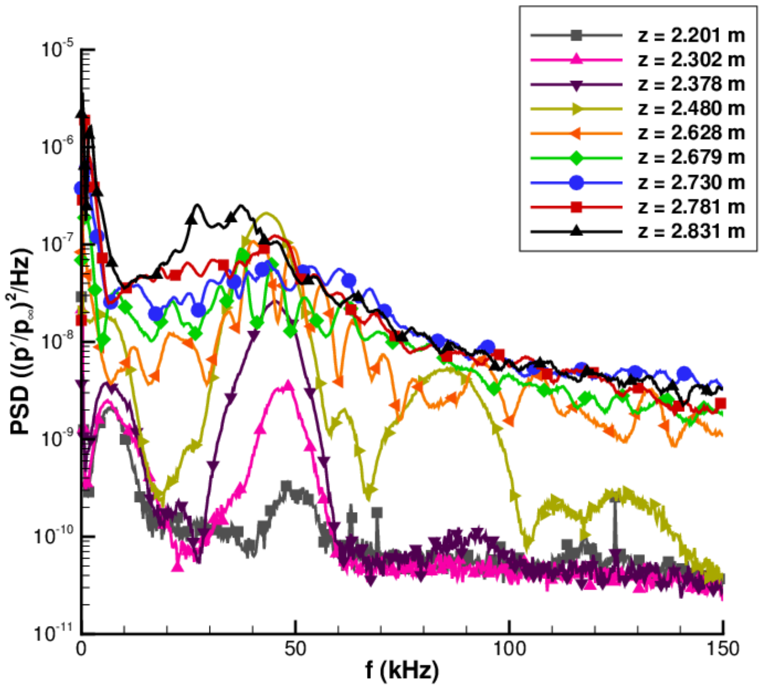
Small second-mode waves grow larger in amplitude further upstream.

- Peak frequency is 45-50 kHz.
- Breakdown occurs before z = 2.628 m.
- Second-mode waves still visible on either side of turbulent fluctuations.



Time traces.

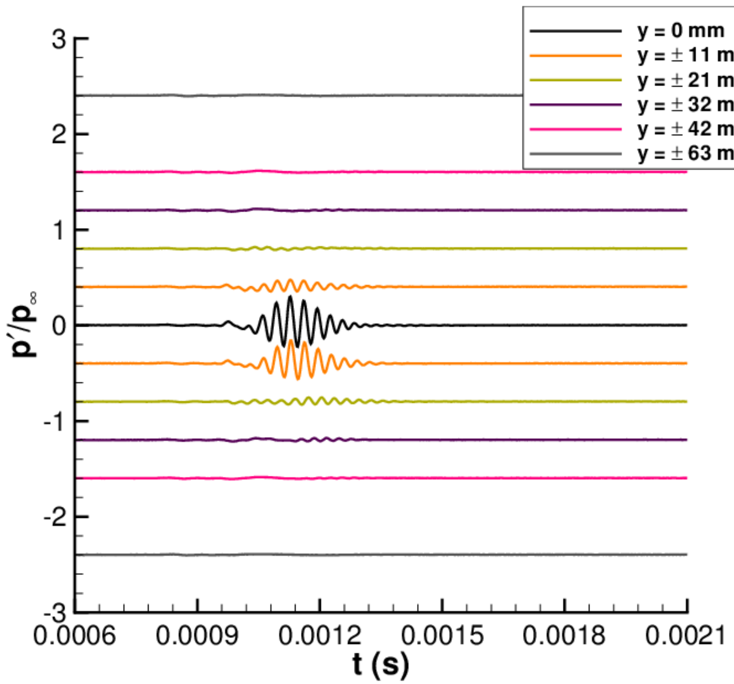


Power spectral density.

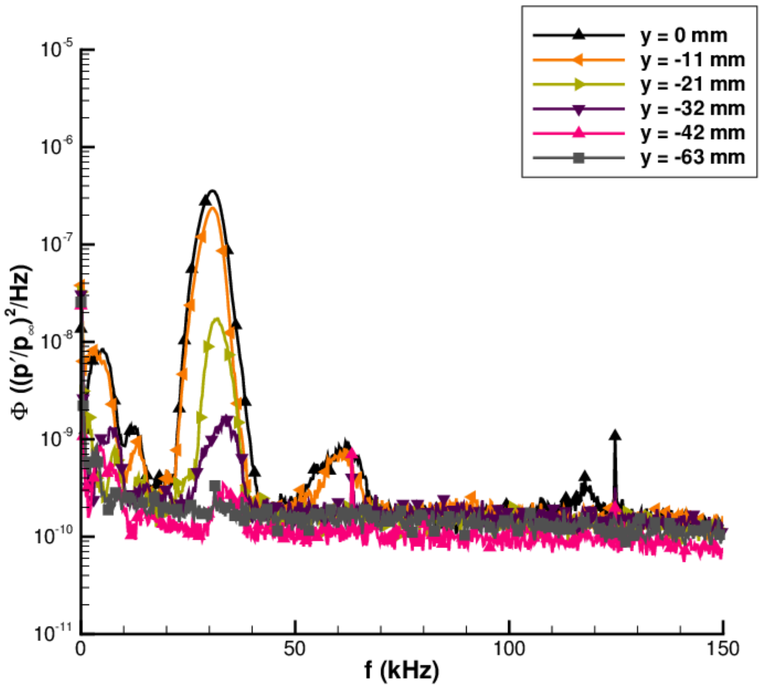
Spanwise measurements at $Re = 6.3 \times 10^6/m$

Spanwise array of sensors shows the disturbance pressure field.

- Largest amplitude instability fluctuations on centerline.
- Smaller amplitude disturbances to the sides.
- Disturbances begin breakdown to turbulence on centerline.

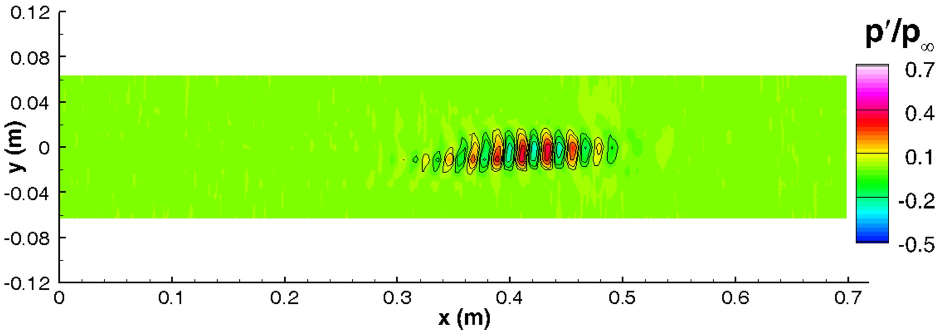


Time traces.

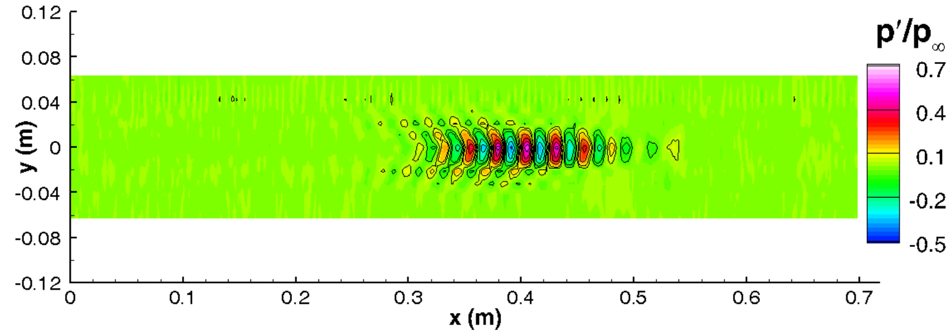


Power spectral density.

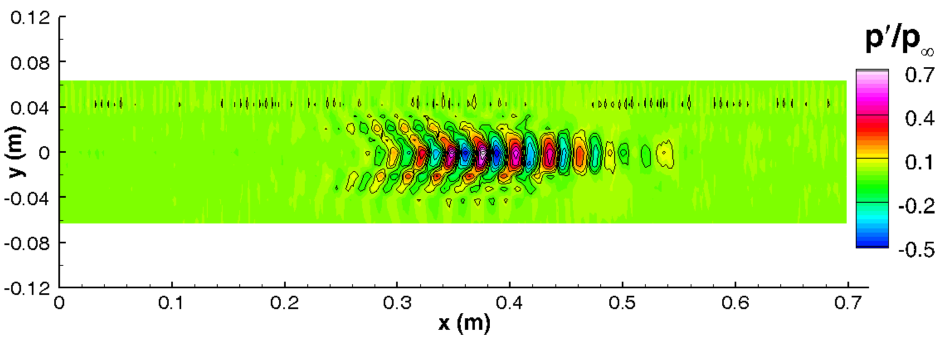
Contour plots of spanwise measurements at Re = 6.3 x 10^6/m



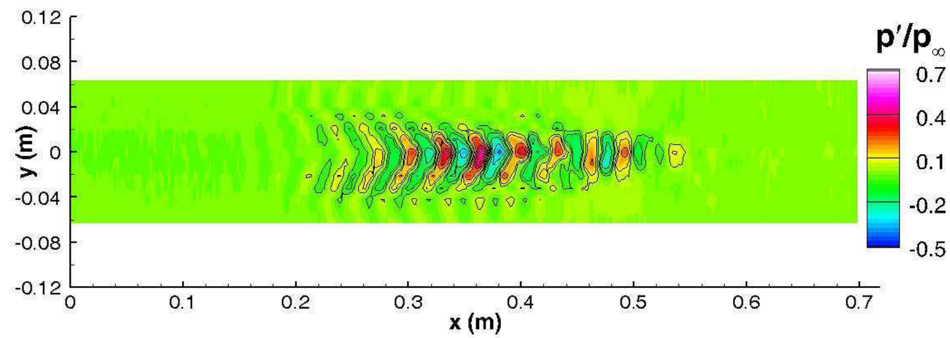
z = 2.679 m



z = 2.730 m

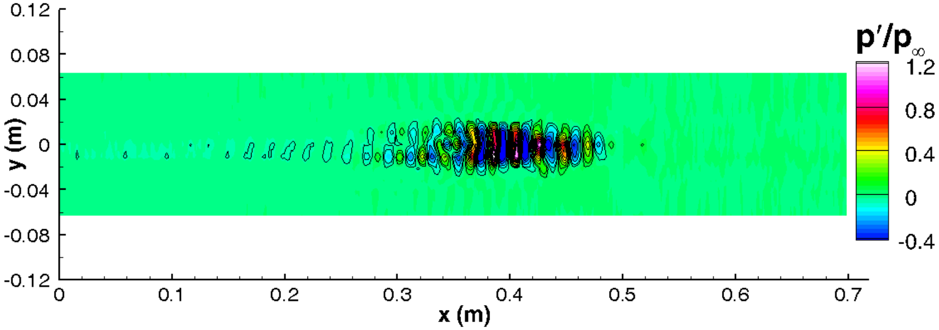


z = 2.781 m

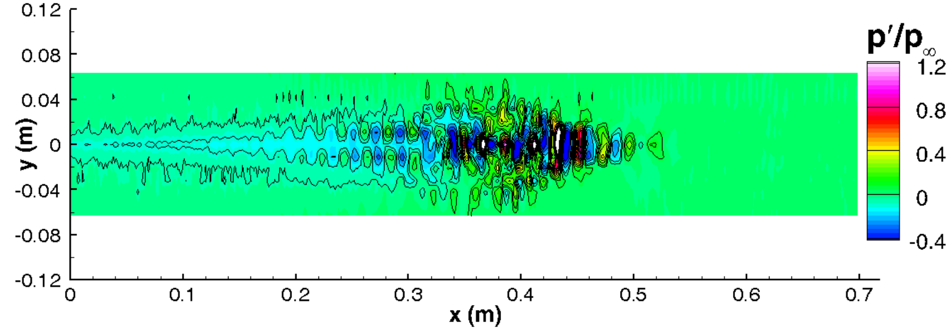


z = 2.831 m

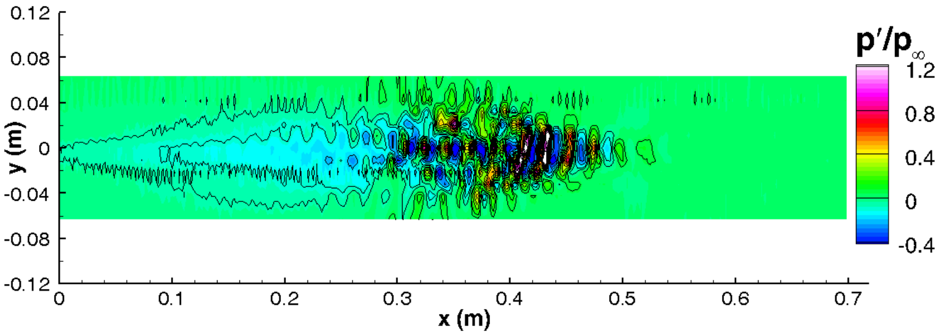
Contour plots of spanwise measurements at Re = 8.3 x 10^6/m



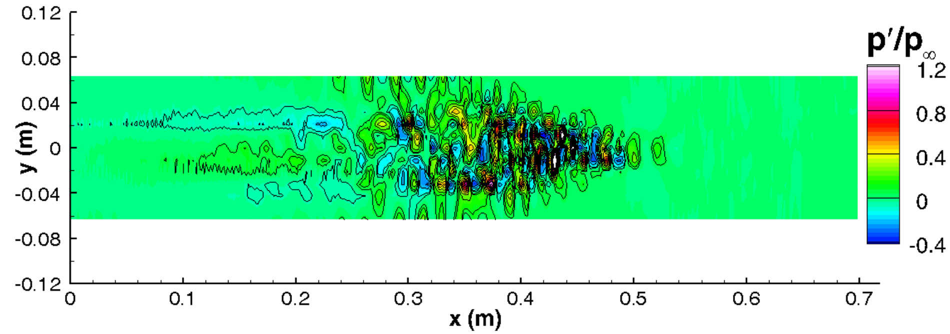
z = 2.679 m



z = 2.730 m

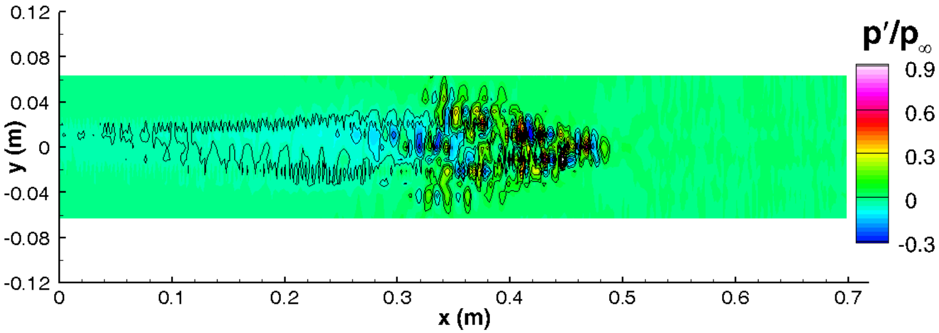


z = 2.781 m

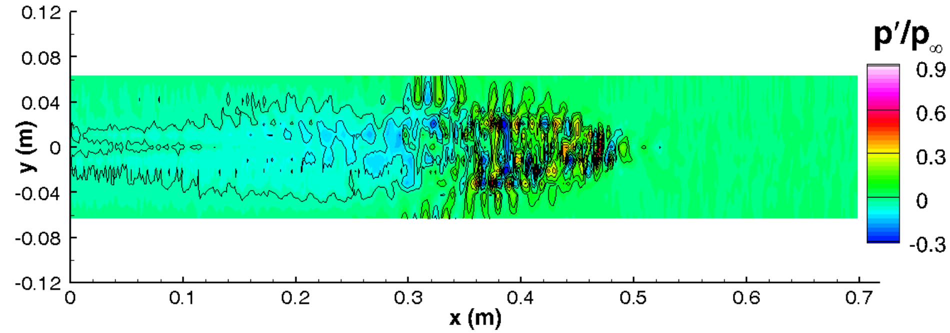


z = 2.831 m

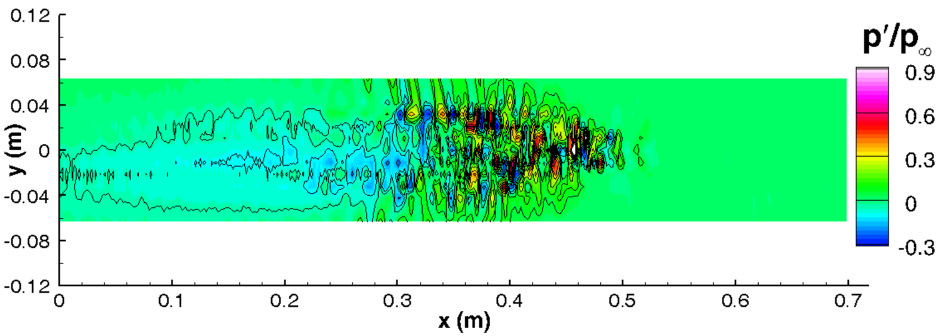
Contour plots of spanwise measurements at Re = 10.8 x 10^6/m



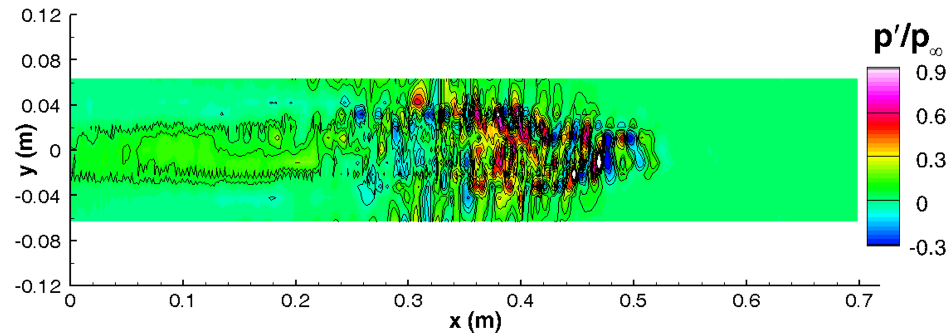
z = 2.679 m



z = 2.730 m



z = 2.781 m

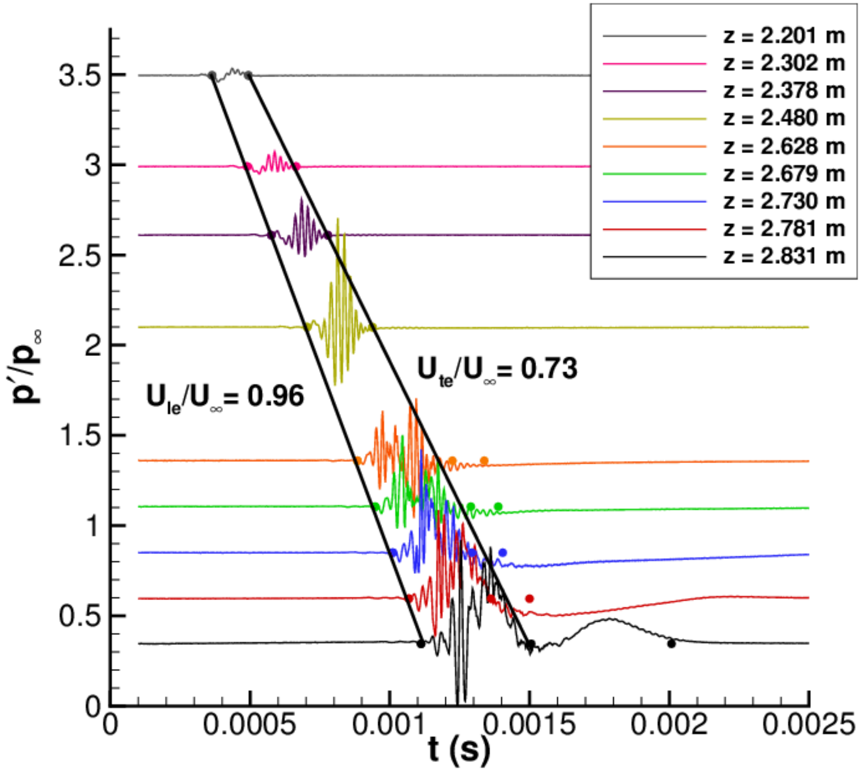


z = 2.831 m

Convection Velocities near Re = 10.8 x 10^6/m

Computed velocities agree well with DNS and other high-speed experiments.

- Average leading edge convection velocity of 0.95 U_∞.
- Trailing edge convection velocity varies with Re between 0.64-0.75 U_∞.



Leading and trailing edges of controlled disturbances

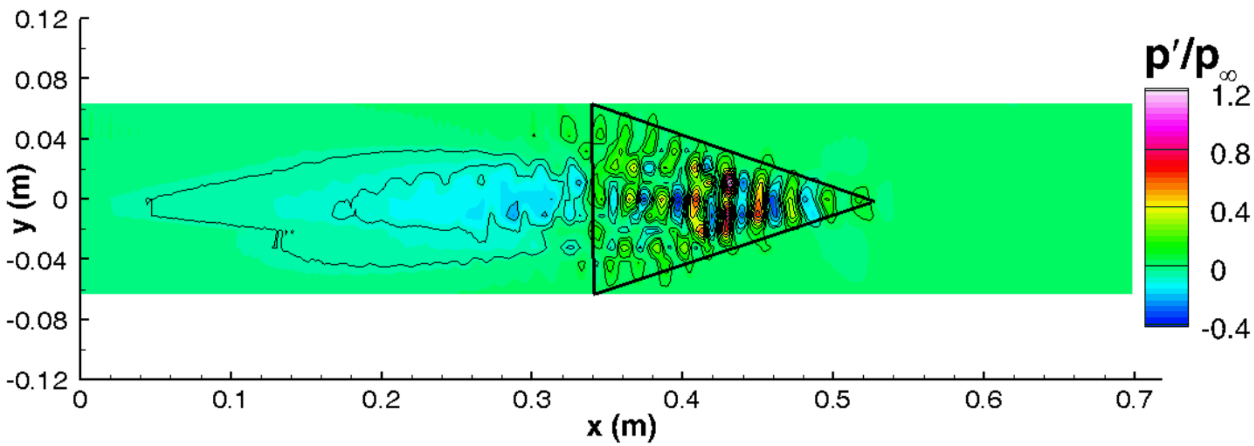
Lateral Spreading Angle, Re = 8.3 x 10^6/m

Triangular footprint was 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.



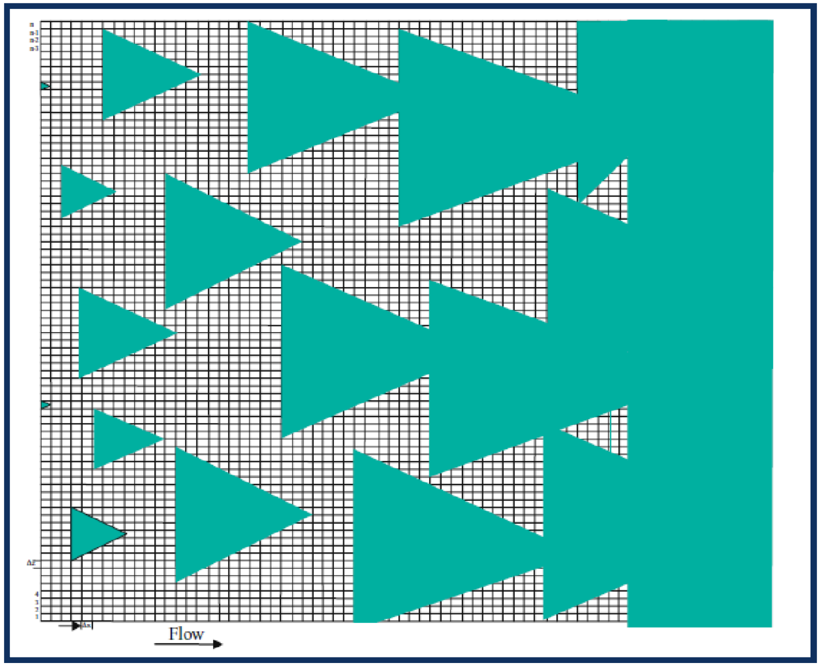
Turbulent Spot Model Parameters

Spot growth is characterized by:

- ✓ Leading and trailing edge convection velocities.
- ✓ Lateral spreading half angle.

Spot model also relies on:

- ✓ Spatial distribution of pressure fluctuations.
- ✗ How spots merge.



Turbulent spot model simulation, from Vinod (2007).

Part 2: Transition Statistics

Still need statistics of disturbance formation during natural transition.

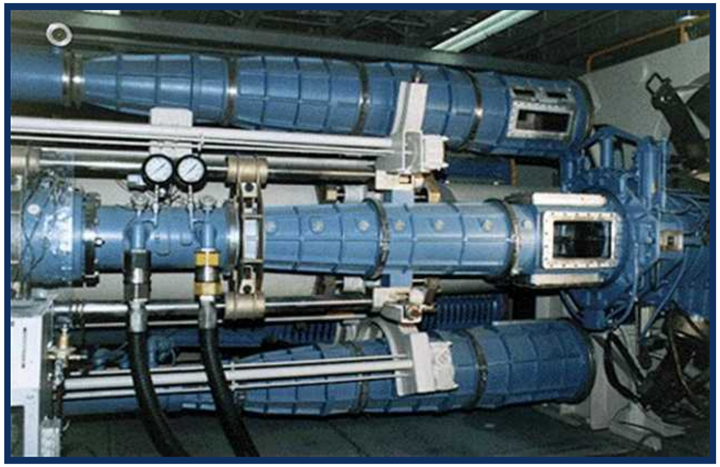
Simultaneous schlieren and high-frequency pressure measurements were made on a cone at Mach 5 and 8:

- Varied the freestream Reynolds number to move transition over the interrogation region.
- Compute intermittency, burst rate, and average burst length throughout the transition region.
- Combine results with spot growth parameters and pressure fluctuation field.

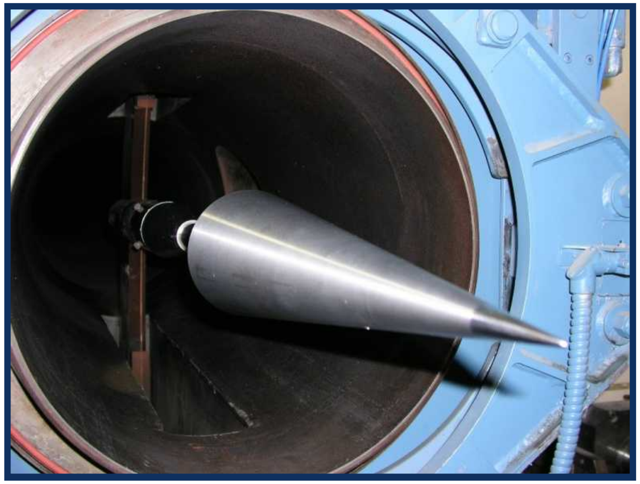
Sandia Hypersonic Wind Tunnel (HWT)

Conventional Blowdown Tunnel

- Interchangeable Nozzles
  - Mach 5
  - Mach 8
  - Mach 14
- Test Gas
  - Air for Mach 5
  - Nitrogen for Mach 8 and 14



Interchangeable HWT Nozzles

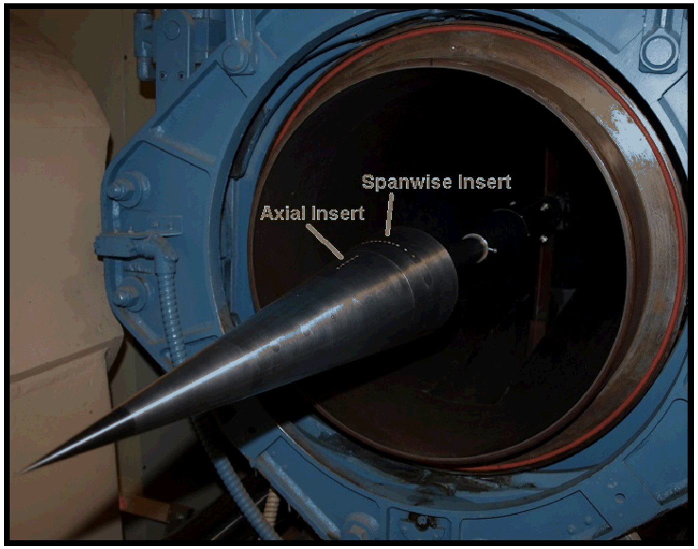


Model installed in HWT

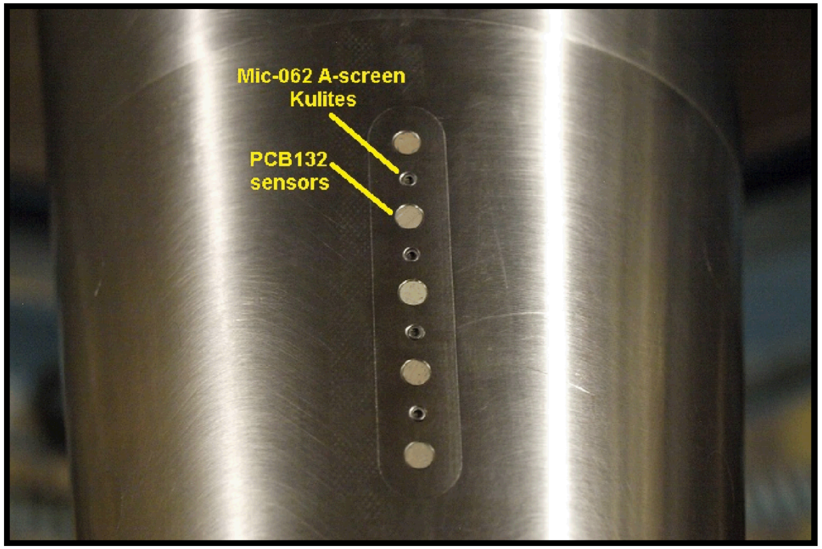
Wind-Tunnel Model

Seven degree stainless-steel sharp cone.

- Axial array with 9 closely spaced high-frequency pressure transducers.
  - Directly beneath schlieren viewing area.
- Studying only higher frequency PCB132 measurements.
  - Can measure fluctuations between 11 kHz - 1 MHz.



Model installed in HWT.



Axial pressure-transducer array.

High-Speed Schlieren System

Flashpoint II 1220A Monolight white light source

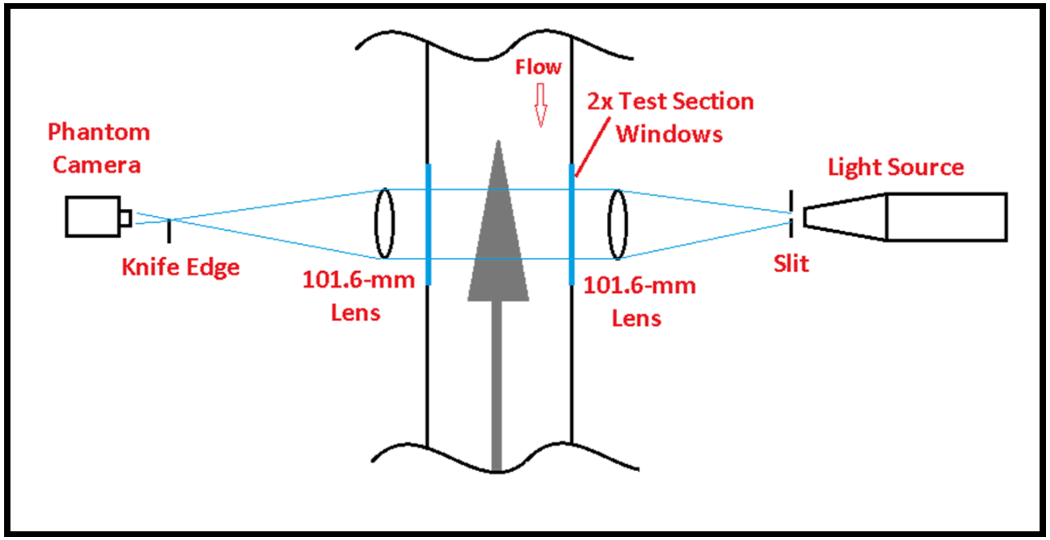
- Duration of 1-2 ms

Phantom v12.1 high-speed camera

- 285 ns exposure time

System provides:

- Ability to capture 10 schlieren movies doing a typical run.
- Several hundred usable images recorded per movie.
- Frame rate varied between 70–300 kHz.
- 1024 x 80 to 512 x 32 pixel resolution.



Schematic of Schlieren System

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

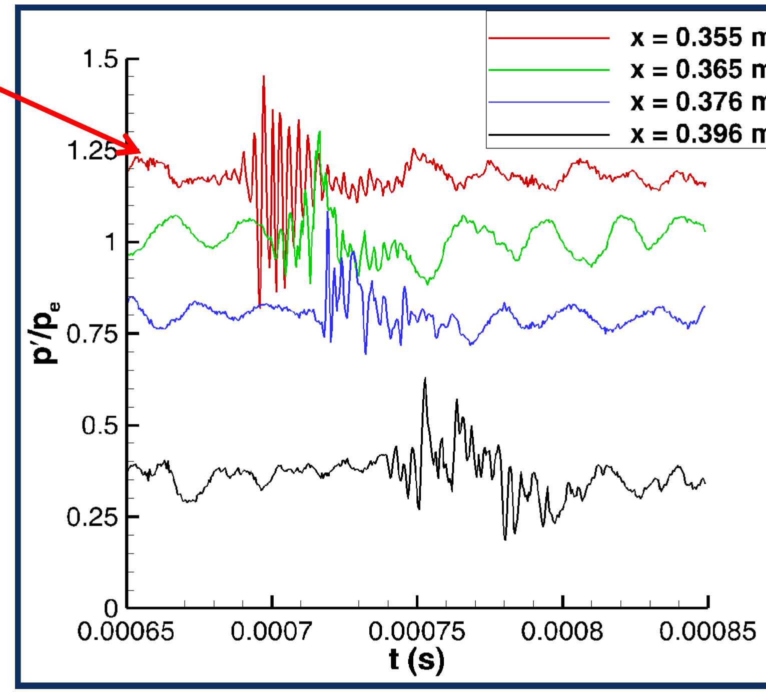
Schlieren Videos

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.

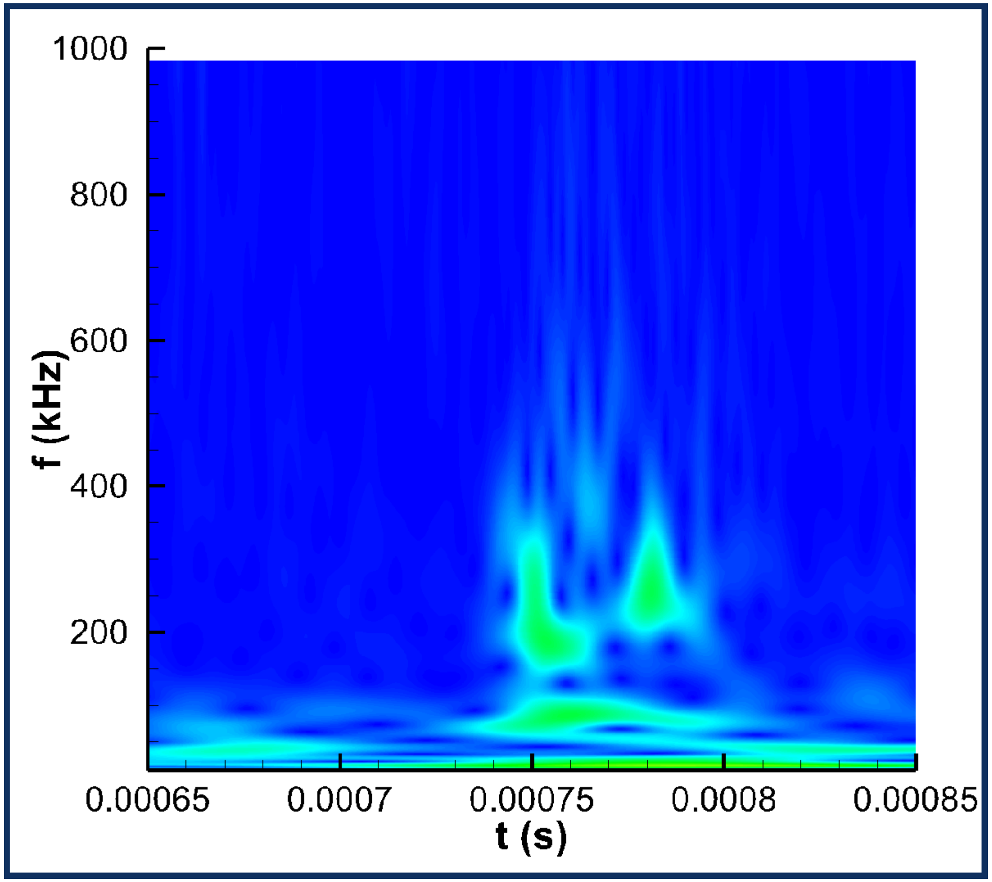


Pressure Traces

Separating Waves from Turbulence: Pressure Measurement Technique

Wavelet transform technique was developed for pressure measurements.

- High-frequency region has highest amplitude for wave packets.
    - Still large content for turbulent spots.
- Low-frequency region develops for turbulent spots.
    - Can be used to mark turbulent regions.

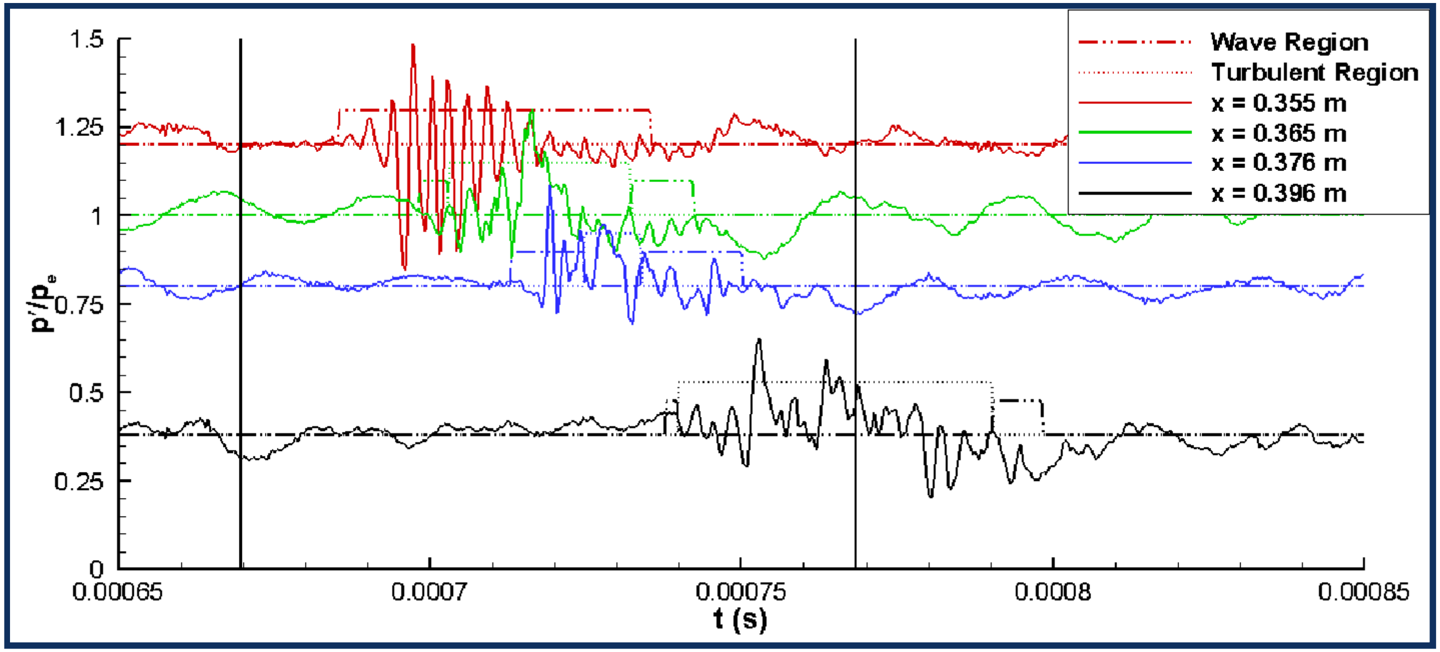


Wavelet transform of pressure traces

Separating Waves from Turbulence: Pressure Measurement Technique

Indicator signals computed for both instability wave and turbulent regions.

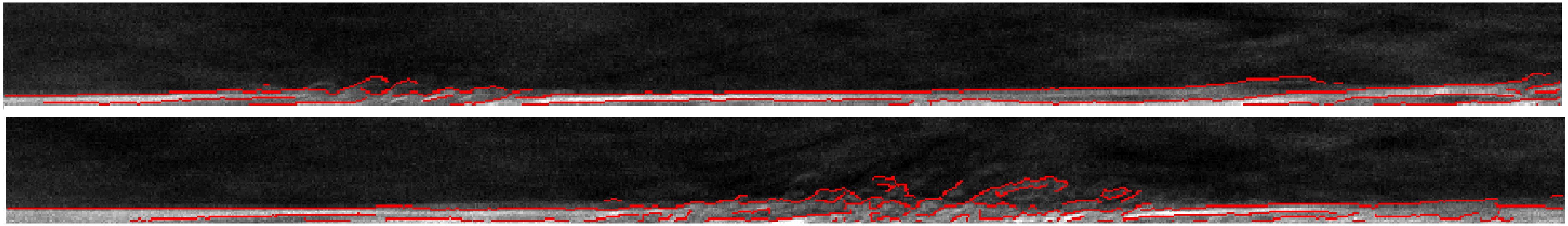
- Technique does a reasonable job separating the two regions, but threshold level still need to be refined.
- Can see evidence of waves at leading and trailing edges of turbulent disturbances.



Separating Waves from Turbulence: Schlieren Measurement Technique

Two-step procedure to separate instability waves from turbulence.

- Boundary-layer thickness initially used to mark turbulent regions.
  - Instability waves are likely also marked as turbulent in this step.
- Correlation technique used to find periodicity in boundary layer indicative of second-mode waves.
  - Marks regions of waves, even if they have previously been identified as turbulent in step one.



Edge detection applied to typical schlieren images.

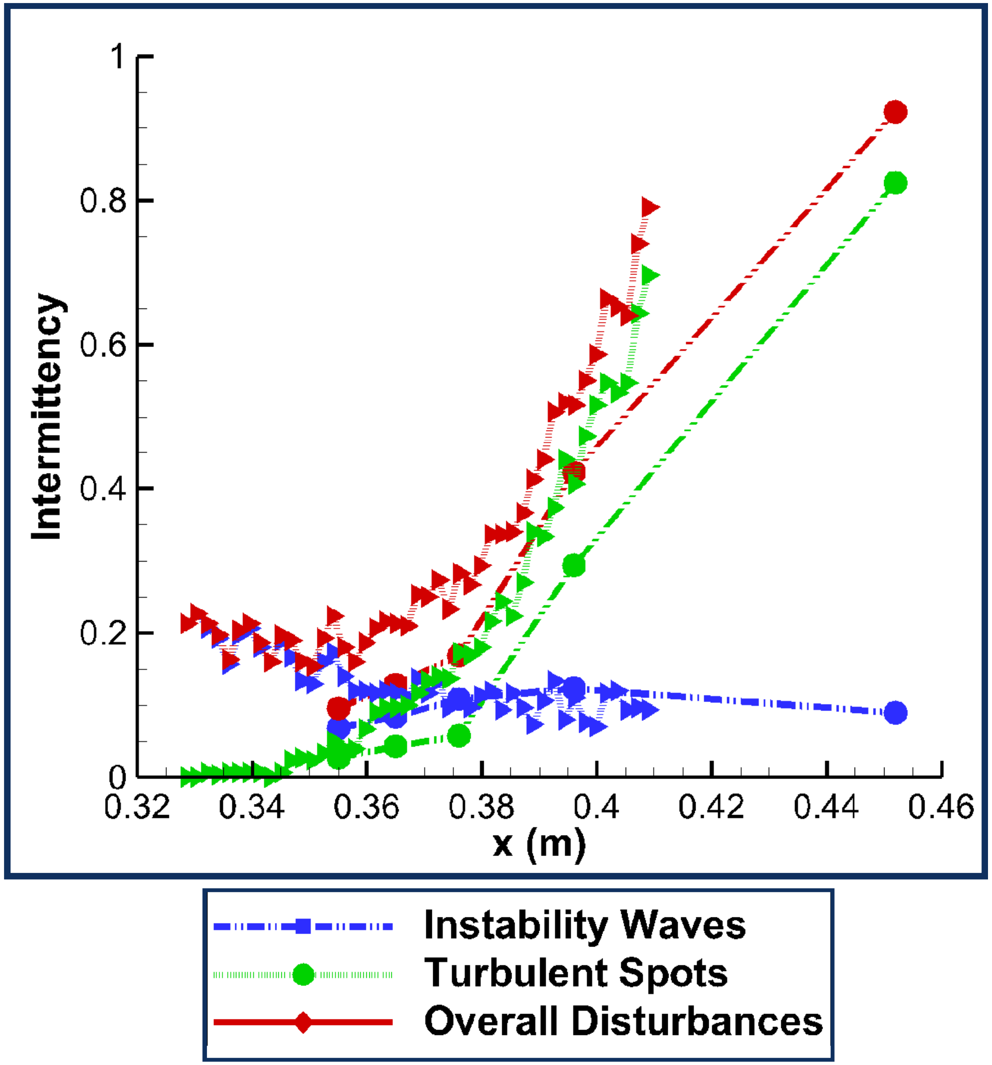
Mach 5 Transition Statistics, Re = 9.75 x 10^6/m

Pressure measurement indicator signals used to compute transition statistics.

Compute separate statistics for:

- Instability waves
- Turbulent spots
- Overall disturbances (waves or turbulence are both included without distinction).

Intermittency results show reasonable agreement with schlieren measurements.



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

Instability waves

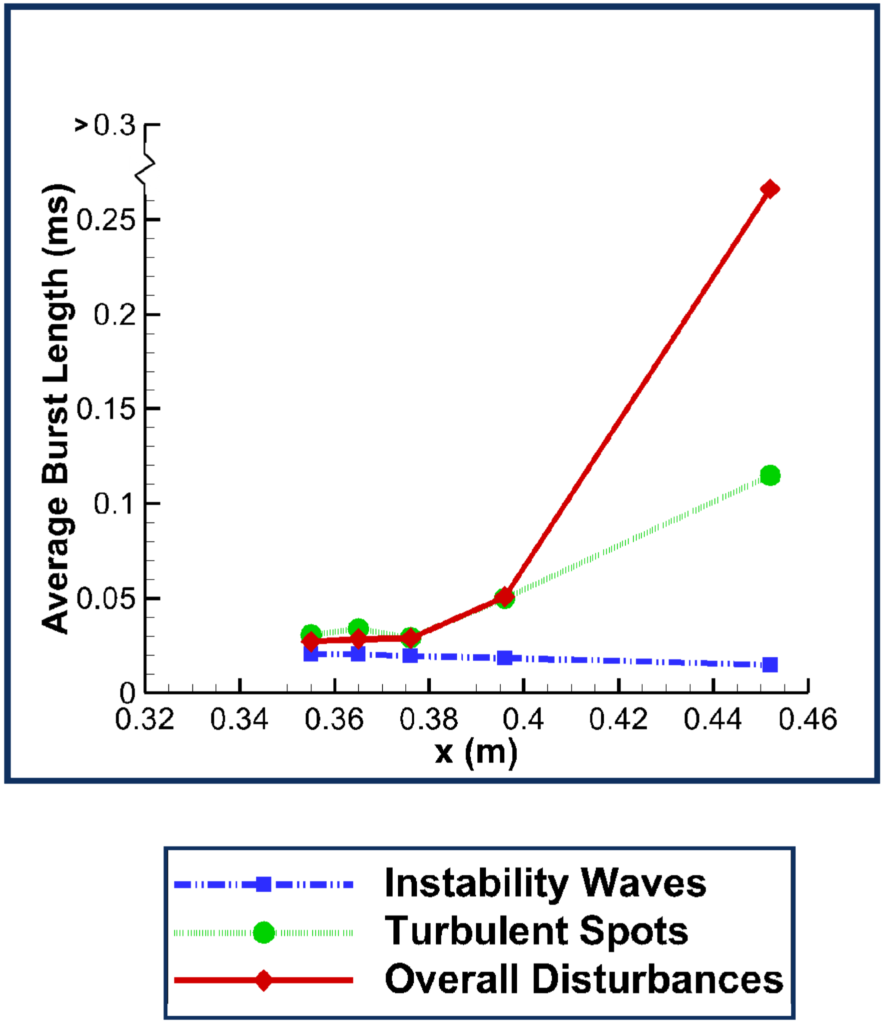
- Remain small portion of flow.

Turbulent spots

- Intermittency rises, burst rate peaks, and burst length increases as transition progresses.

Overall disturbances

- Statistics track turbulent spot behavior.



Mach 5 Transition Statistics, Re = 11.8 x 10^6/m

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Instability waves

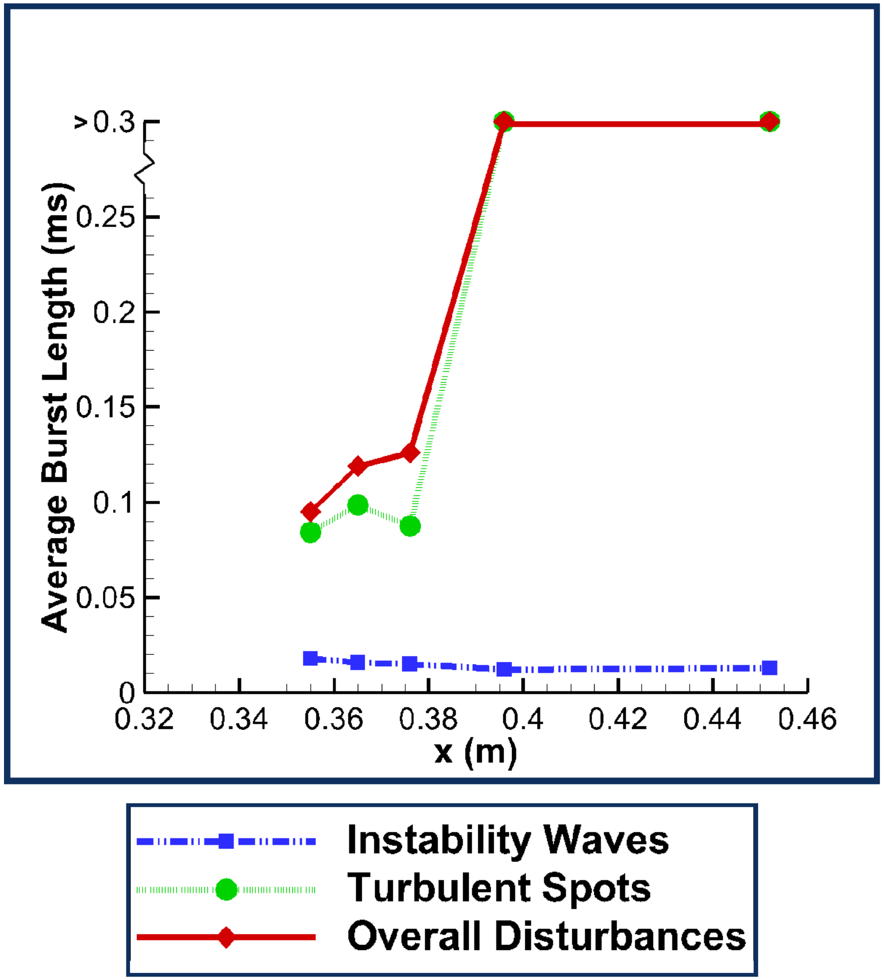
- Again remain a small portion of flow.
- Intermittency decreases, as does the average burst length.

Turbulent spots

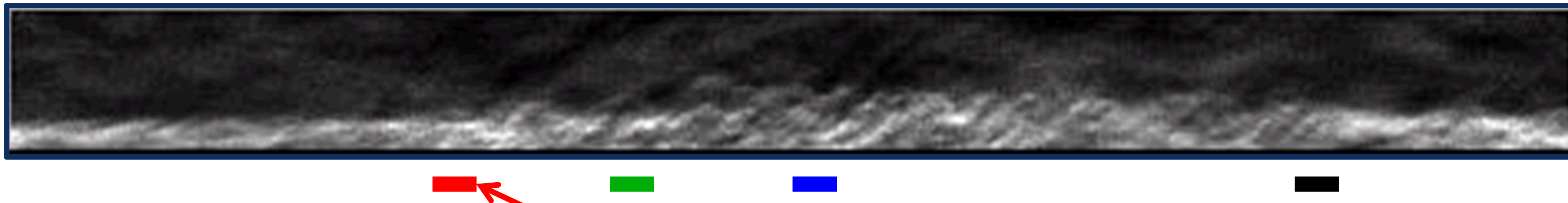
- Begin to dominate flow.
- Turbulent intermittency rises to one.
- Burst rate decreases as the flow becomes mostly turbulent.
- Average burst length increases until flow is primarily turbulent.

Overall disturbances

- Statistics again track turbulent spot behavior.



Mach 8 Measurements, Re = 9.74×10^6/m

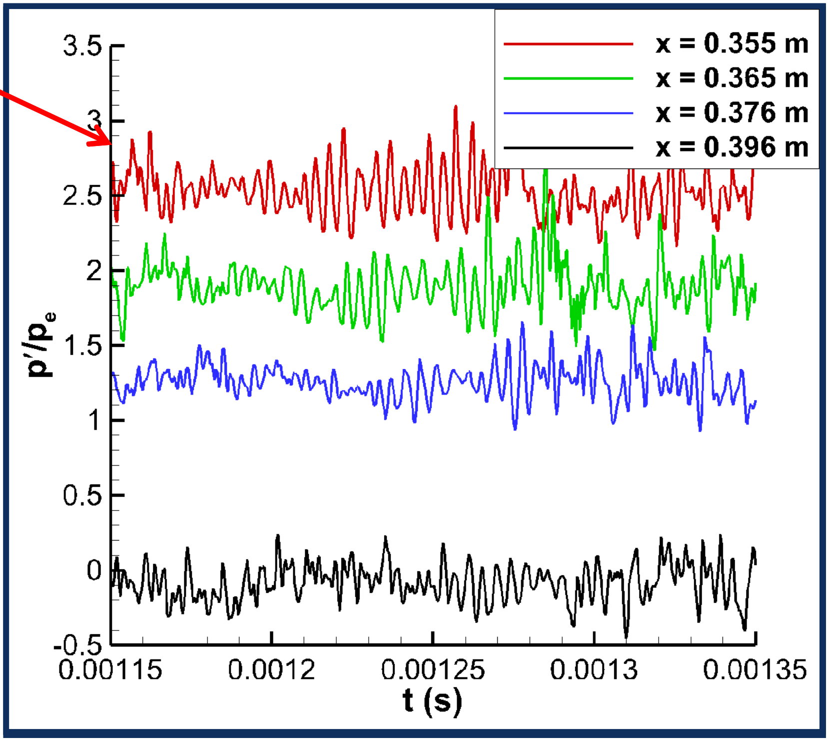


Schlieren Videos

Flow alternates between second-mode waves and turbulence.

- Smooth, laminar boundary layer not observed in transitional region.
- Different behavior than at Mach 5.

Especially important to separate waves from turbulence in this case.

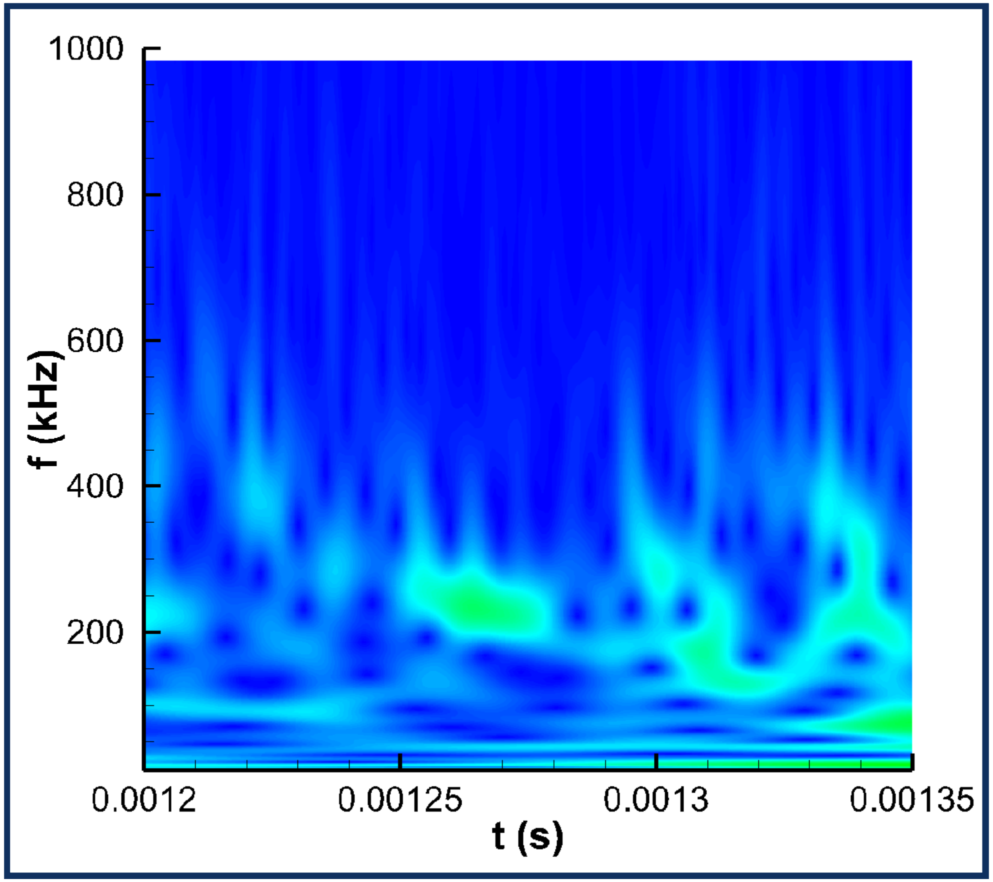


Pressure Traces

Mach 8, Pressure Measurement Technique

Wavelet transform technique again used to separate waves from turbulence at Mach 8.

- Low frequency region can again be used to define turbulent regions.
- High-frequency region then used to identify waves.

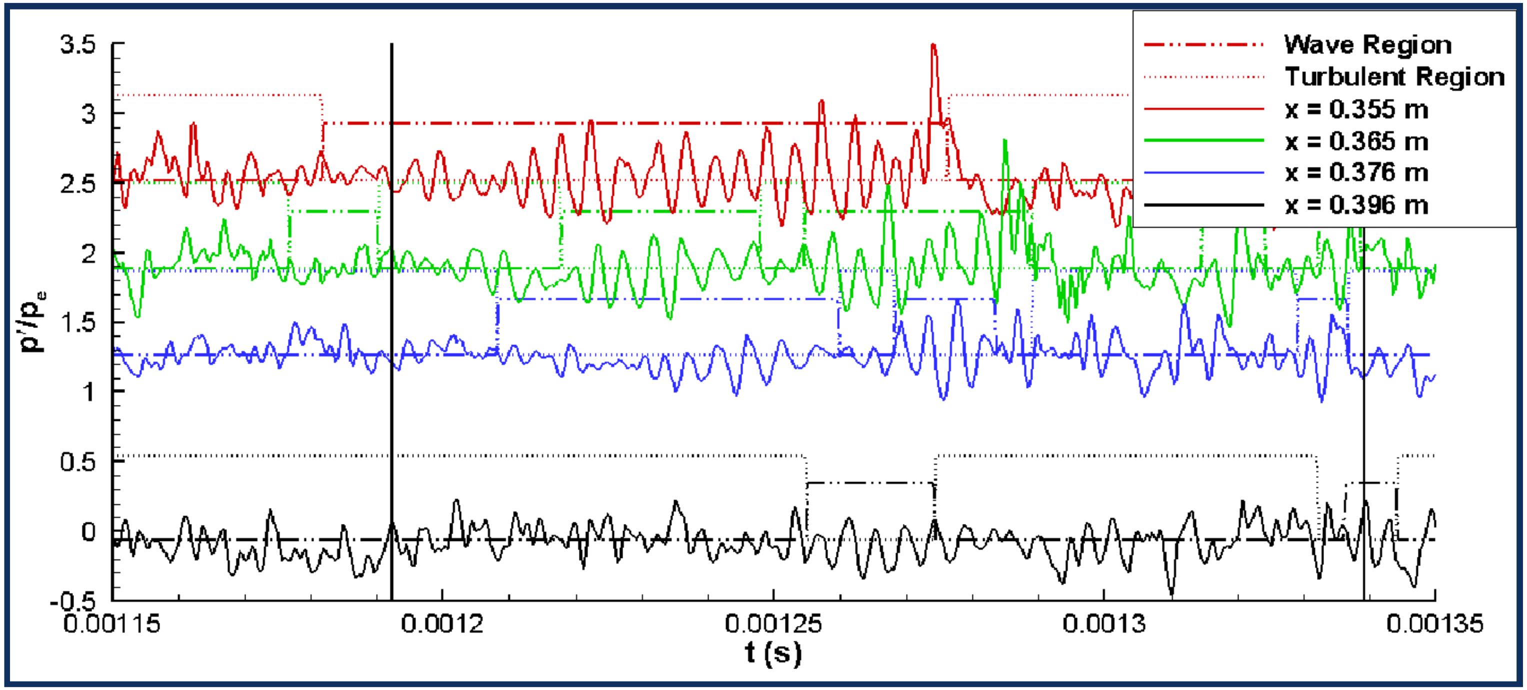


Wavelet transform of pressure traces

Mach 8, Pressure Measurement Technique

Indicator signals again computed for both instability wave and turbulent regions.

- Technique does a reasonable job separating the two regions.
- Still need to refine technique and threshold levels.



Mach 8 Transition Statistics, Re = 9.74 x 10^6/m

Instability waves

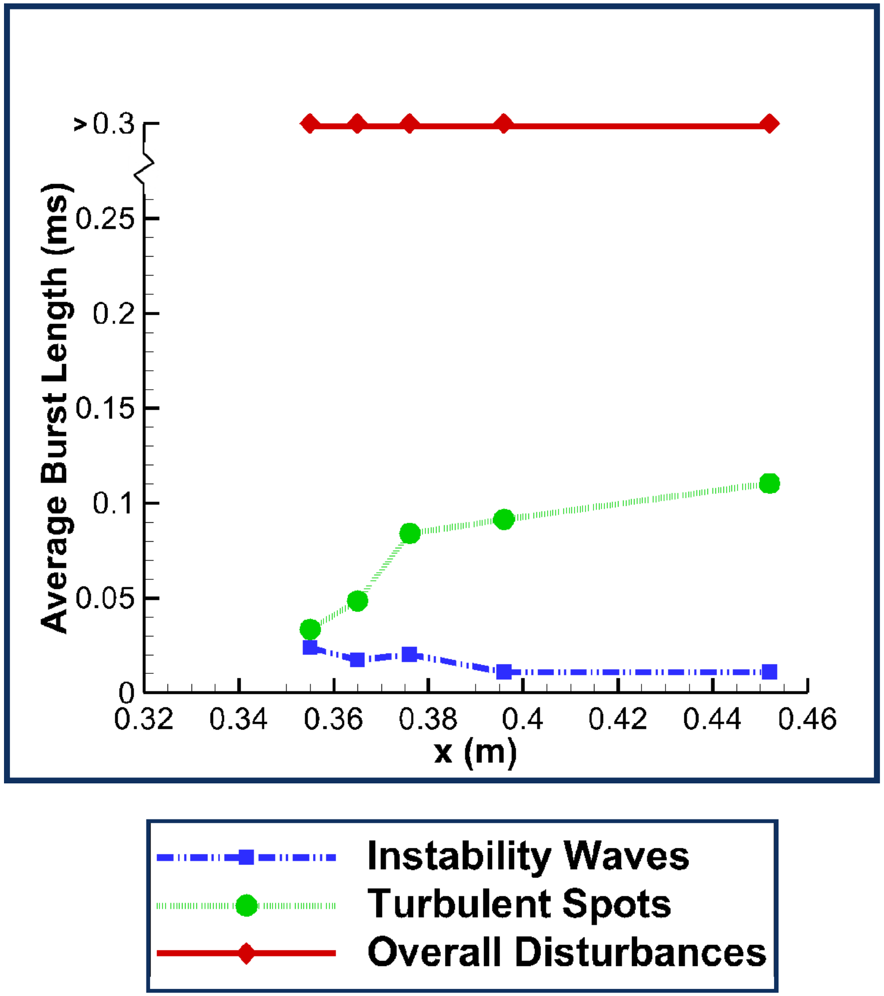
- Significant part of the flow prior to development of turbulent spots.

Turbulent spots

- Gradually begin to dominate flow.
- Turbulent intermittency rises as instability wave intermittency decreases.
- Burst rate decreases as the flow become more turbulent.
- Average spot length increases through the transition region.

Overall disturbances

- Statistics no longer track turbulent spot behavior because instability wave are a significant part of the transition region.



Conclusions: Part 1

Thick nozzle-wall boundary layer allows resolution of boundary-layer disturbances with pressure instrumentation.

Wave packets:

- Smaller wave packets are ordered and concentrated near the centerline.
- Larger wave packets become distorted.
- Weaker second-mode disturbances extend in spanwise direction.

Turbulent spots:

- At higher *Re*, wave packets break down to turbulence in center of spots.
- See characteristic arrowhead shape of turbulent spots.
- At edges, front, and rear of spots, second-mode waves are still observed and dominate the spectra.

Development of turbulent-spot model:

- Experiments provide convection velocity, spreading angle, and pressure-fluctuation field of disturbances.

Conclusions: Part 2

Simultaneous pressure and schlieren measurements were used to study transitional boundary layer at Mach 5 and 8.

- **Mach 5:** Transitional flow is characterized by isolated disturbances within a smooth laminar boundary layer. The presence of small wave packets does not have a large influence on transition.
- **Mach 8:** Wave packets dominate the boundary layer when transition occurs. Regions of turbulence break down within the waves and then grow and merge together.

Developing techniques to separate instability waves from turbulence in both measurements.

- Provisionally calculated intermittency, burst rate, and average burst length through transition.
- Transition statistics successfully capture the changing character of boundary layer with Mach number.

Future Work

Still additional effort required to understand individual disturbances.

- Need to address spot merging effects.
- Need to better define lateral spreading angle.

A significant effort remains to refine the techniques to separate instability waves from turbulence.

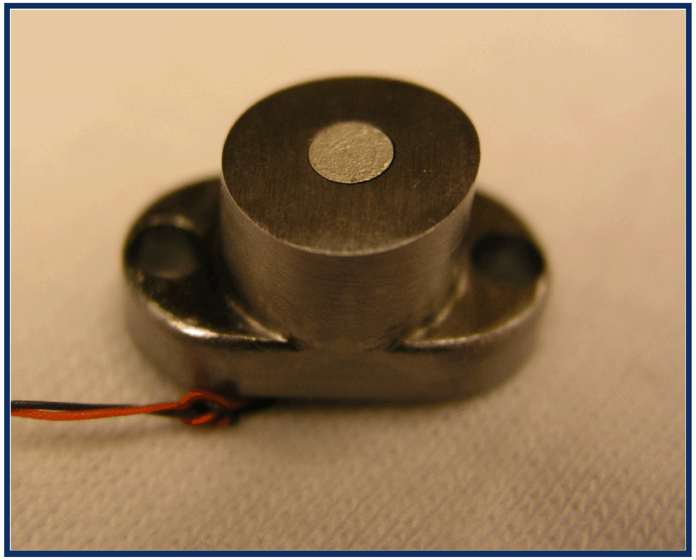
- The sensitivity of the results to the algorithms needs to be studied.
- Need to apply methods to additional Re to better study transitional behavior and generate sufficient statistics for modeling.

Backup Slides

Pressure Instrumentation

PCB132 high-frequency pressure transducer

- Piezoelectric-type sensor.
  - Resonant frequency above 1 MHz
  - Signal high-pass filtered at 11 kHz.
- Designed as time-of-arrival sensors.
  - Have not yet been sufficiently dynamically calibrated.
- Successfully used to measure high-frequency second-mode instability waves.

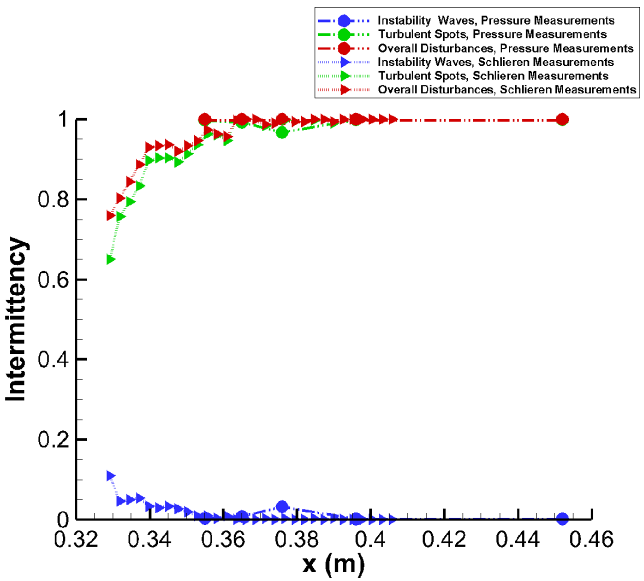


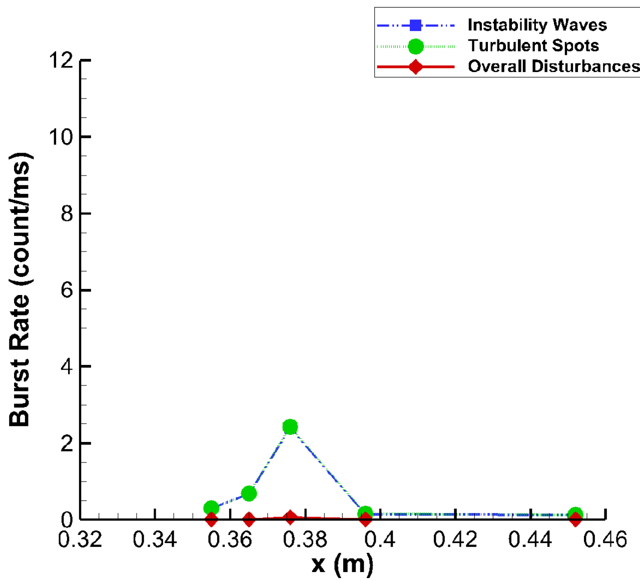
PCB132 installed in cone insert

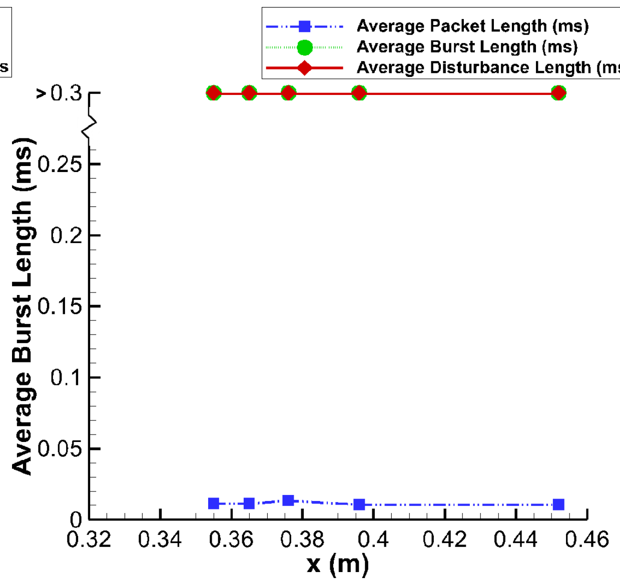
Mach 5 Transition Statistics, Re = 15.4 x 10^6/m

Flow is mostly turbulent at this higher Re.

- Instability waves occur at a very small rate, for only brief periods of time.
- Turbulent spots dominate the flow
  - Turbulent intermittency rises to one,
  - Burst rate remains low since the flow is mostly turbulent.
- Overall disturbance statistics again track turbulent spot behavior.







Mach 8 Transition Statistics, Re = 7.1×10^6/m

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Transition begins to occurs at this lower Re.

- Instability waves again dominate the flow prior to the development of turbulent spots.
- Turbulent spots gradually begin to dominate flow through transition.
  - Turbulent intermittency rises as instability wave intermittency decreases.
  - Burst rate increases as the flow begins to fluctuate between instability waves and turbulence.
  - Average spot length begins to increase as incipient turbulent spots begin to grow.
- Overall disturbance statistics once again do not follow the turbulent spot behavior.