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Crossflow Transition on a Pitched Cone at Mach 8

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U.S. DEPARTMENT OF ENERGY
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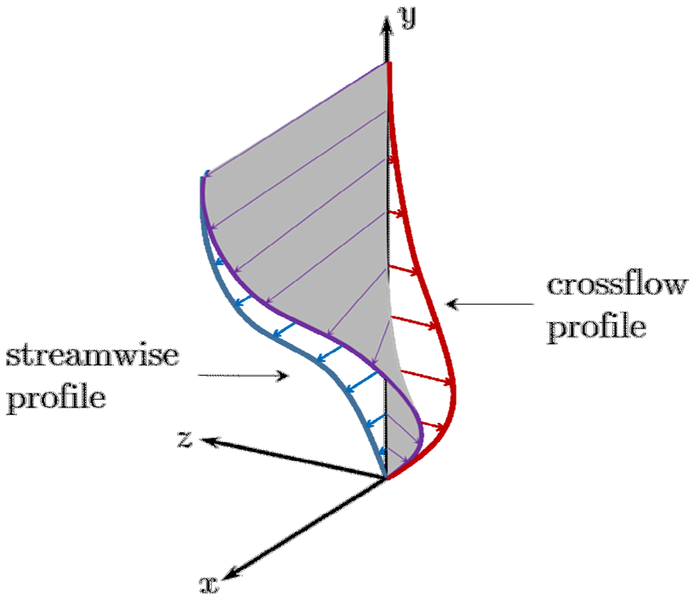
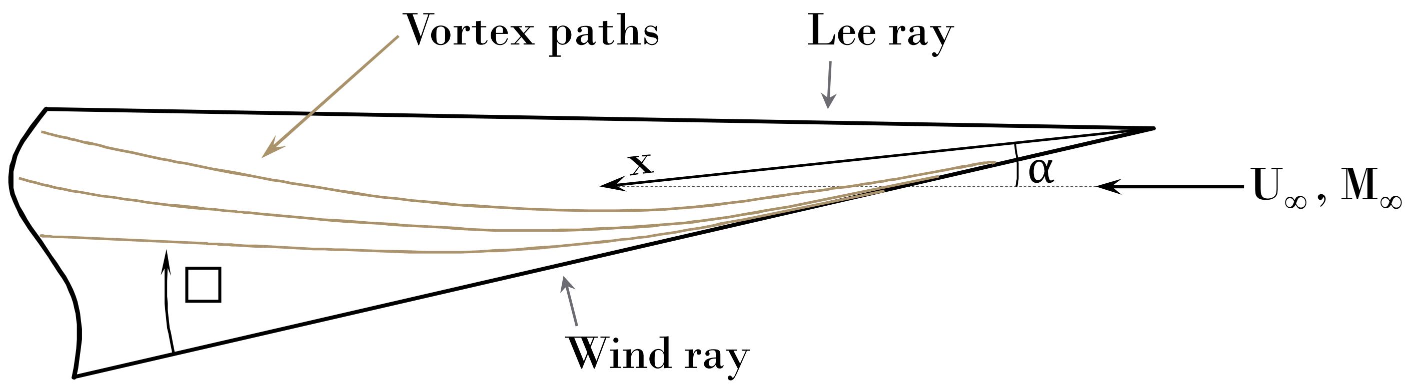
Crossflow Transition

- Boundary-layer transition can have a significant impact on hypersonic vehicle heating loads and controllability
- Crossflow results from pressure gradient ir flow
- Crossflow-dominated transition can be important in 3D flowfields
  - Cone at angle of attack
  - Elliptic cone
- Recent computations and experiments indicate that hypersonic crossflow breakdown may be due to modulated second mode
  - Acoustic wave trapped between stationary crossflow vortices and amplified



Research Motivation

- Further study of crossflow-dominated transition in conventional wind tunnels
  - What is the effect of patterned, discrete roughness elements (DREs) at several angles of attack?
  - How do trends compare between Mach numbers?



Facilities

- Hypersonic Wind Tunnel (HWT-8)
  - Sandia National Laboratories
  - Mach 8, Max $Re_\infty = 17.4 \times 10^6$ /m
  - N2 test gas, T_0 = 660 K
  - Freestream noise levels of 3 – 5%
- Boeing/AFOSR Mach-6 Quiet Tunnel (BAM6QT)
  - Purdue University
  - Mach 6, Max $Re_\infty = 12 \times 10^6$ /m
  - Air test gas, T_0 = 433 K
  - Freestream noise levels of about 2 – 3% (bleeds closed)
  - **Used in conventional (noisy) mode only for these comparisons**

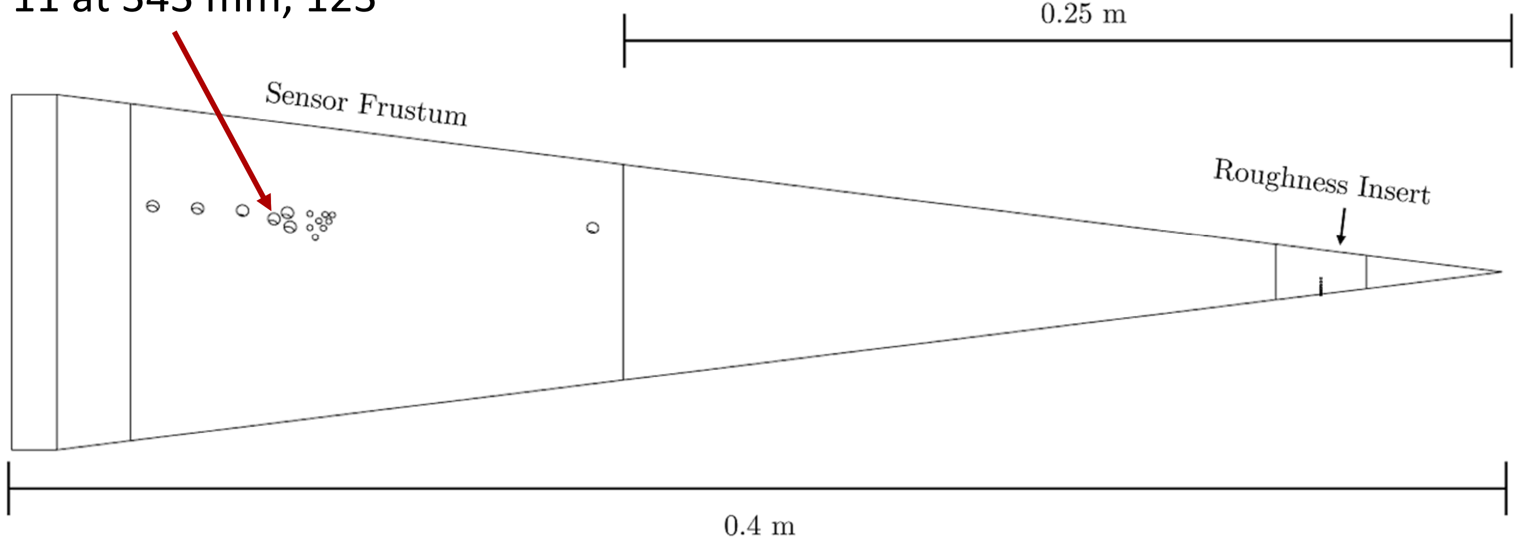
Model and Instrumentation

Sandia National Laboratories

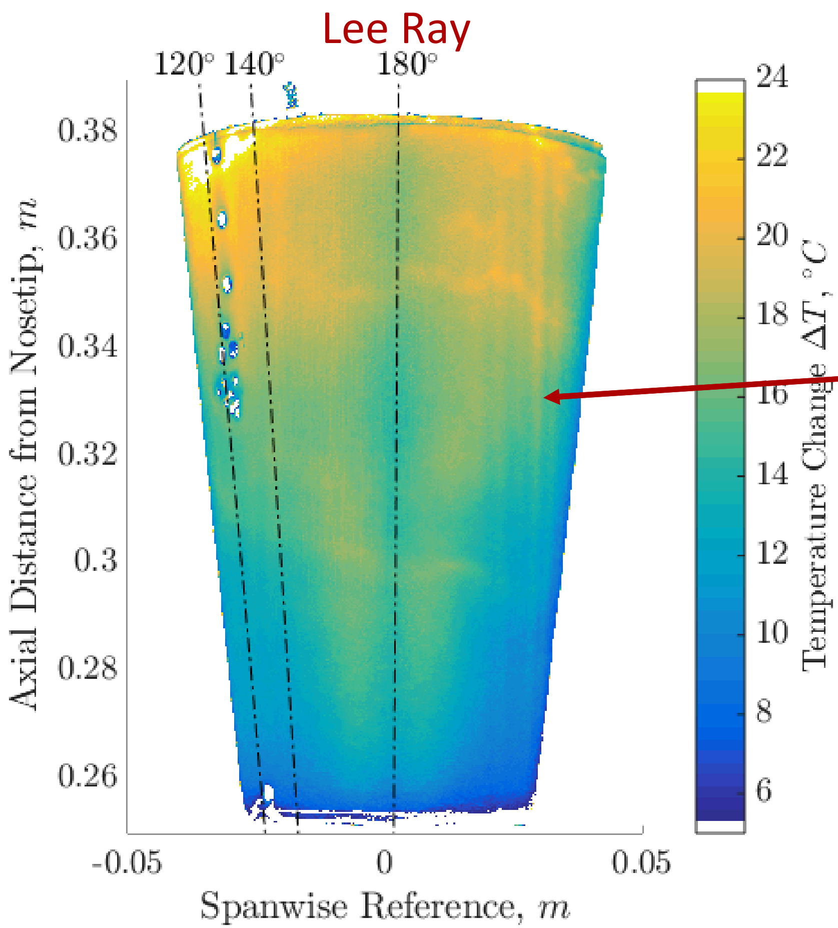
PURDUE UNIVERSITY.

- Modular cone with rotatable sensor frustum
- PCB132A31 and Kulite XCQ-062/MIC-062, Temperature Sensitive Paint
- Three roughness inserts
  - Smooth
  - 12 elements, k = 0.005”, OD = 0.022”, 9-deg spacing (RIM-12x)
  - 7 elements, k = 0.005”, OD = 0.030”, 18-deg spacing (RIM-7x)

PCB 11 at 343 mm, 123°



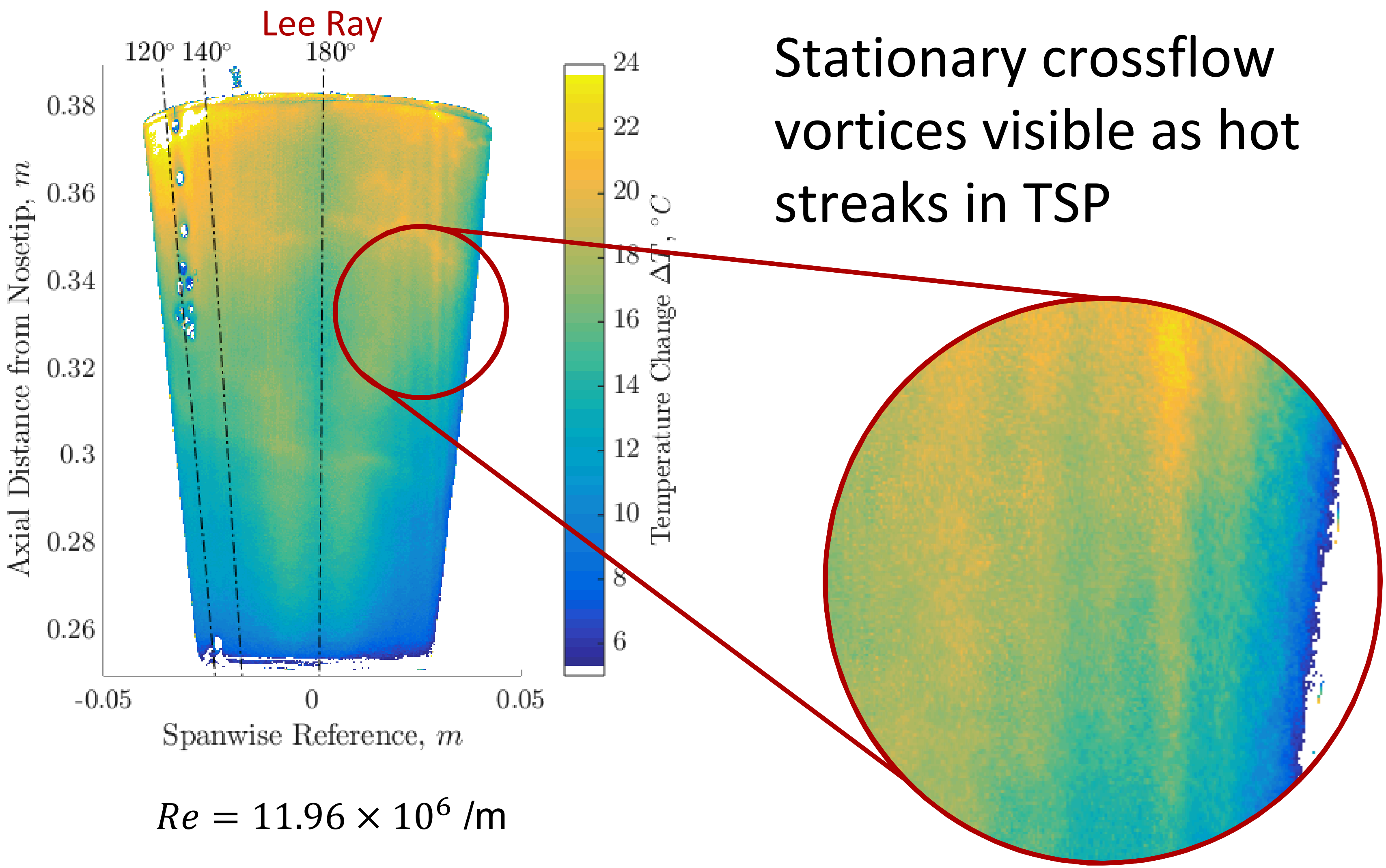
Smooth Cone Results, TSP



$Re = 11.96 \times 10^6$ /m

- 6-deg. AoA
- Smooth roughness insert (i.e., no DREs)
- Stationary crossflow vortices visible as hot streaks in TSP

Smooth Cone Results, TSP



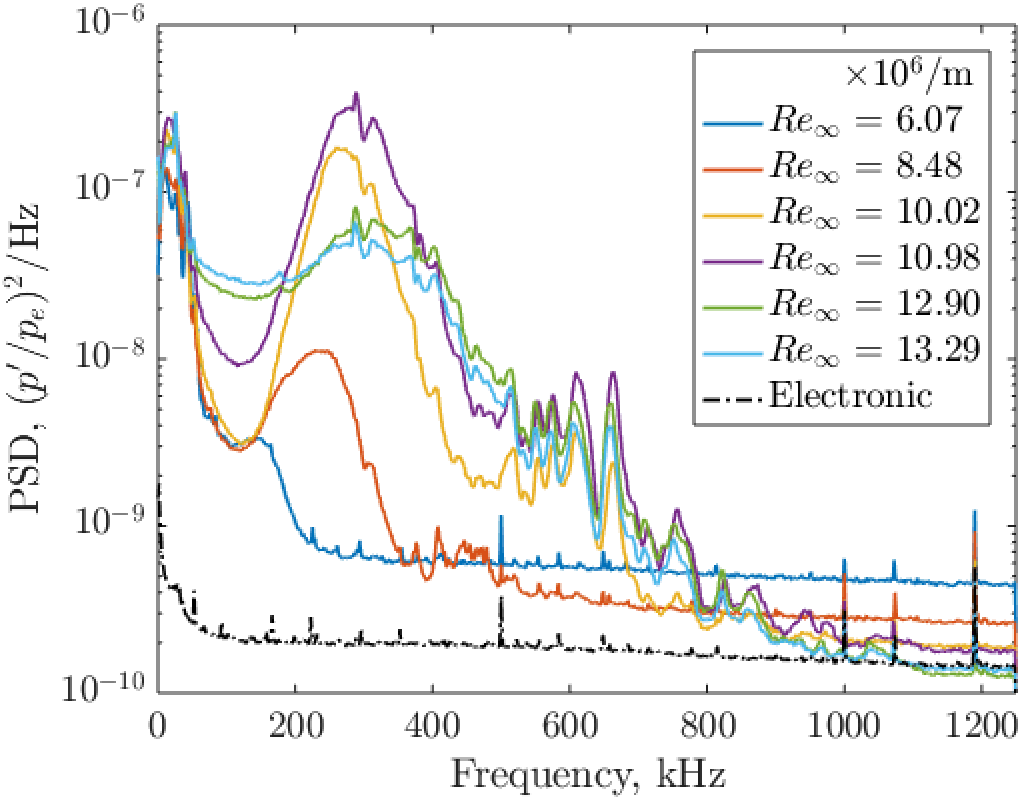
$Re = 11.96 \times 10^6$ /m

Stationary crossflow vortices visible as hot streaks in TSP

(Different temperature scale)

Smooth Cone Results, PCB132

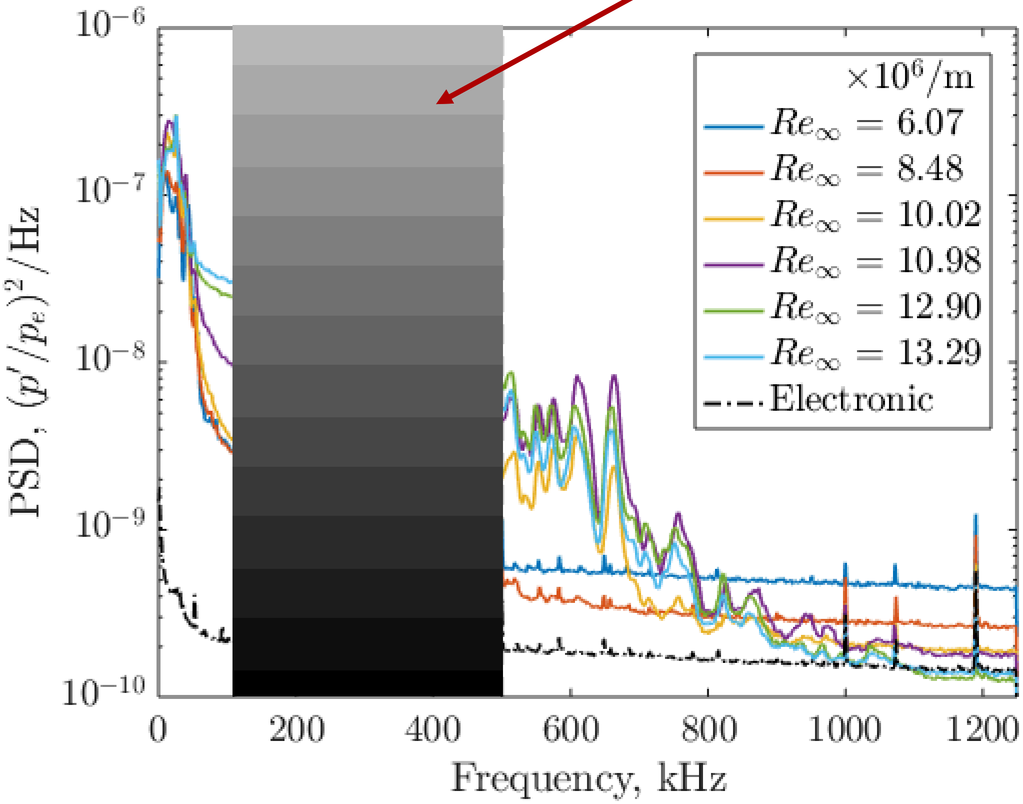
- 343 mm from nosetip
- 123° from windward



Smooth Cone Results, PCB132

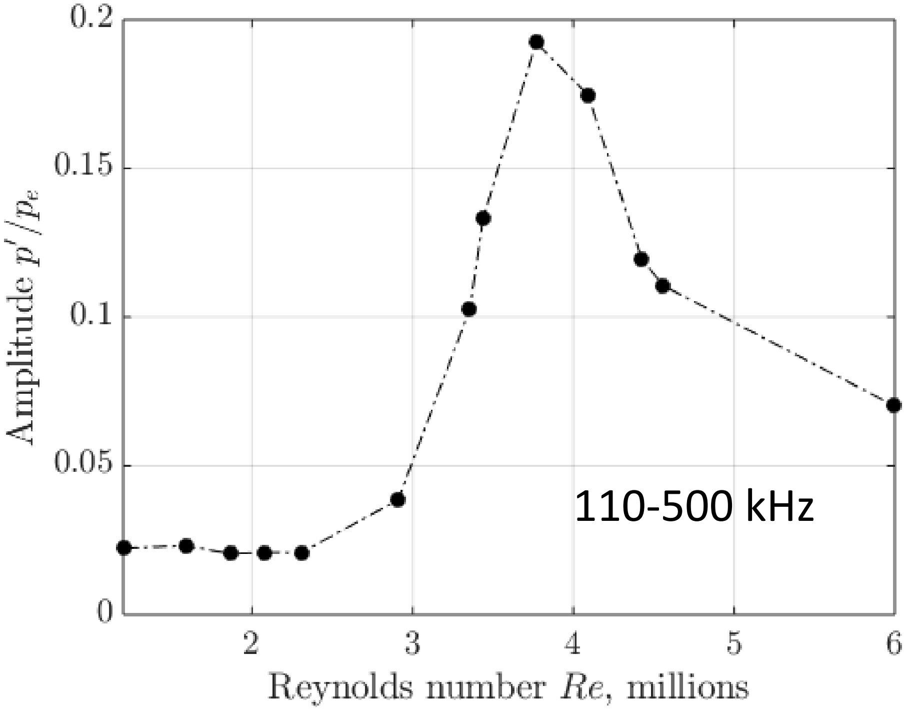
- 343 mm from nosetip
- 123° from windward

Integration band:
110-500 kHz



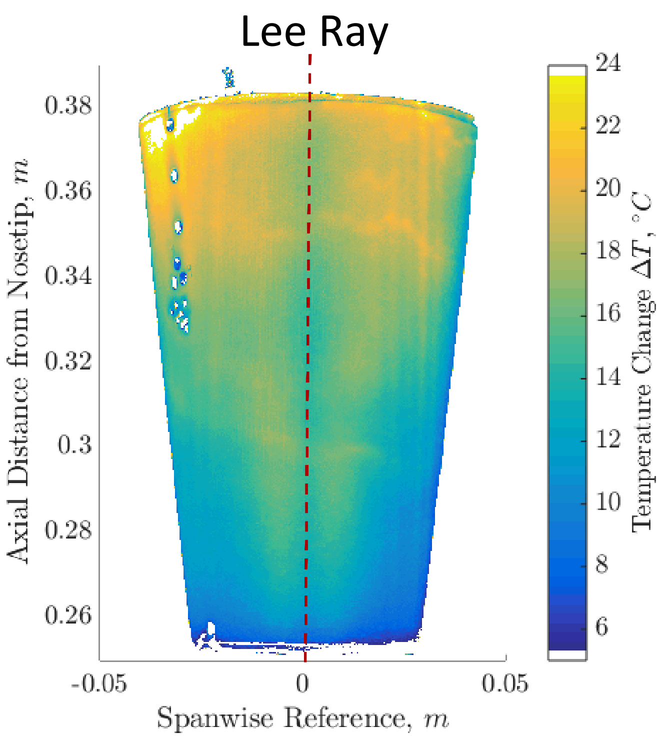
Smooth Cone Results, PCB132

- Measured second mode amplitude rises from noise floor around Re = 3 million
- Peak fluctuation amplitude of 20% edge pressure



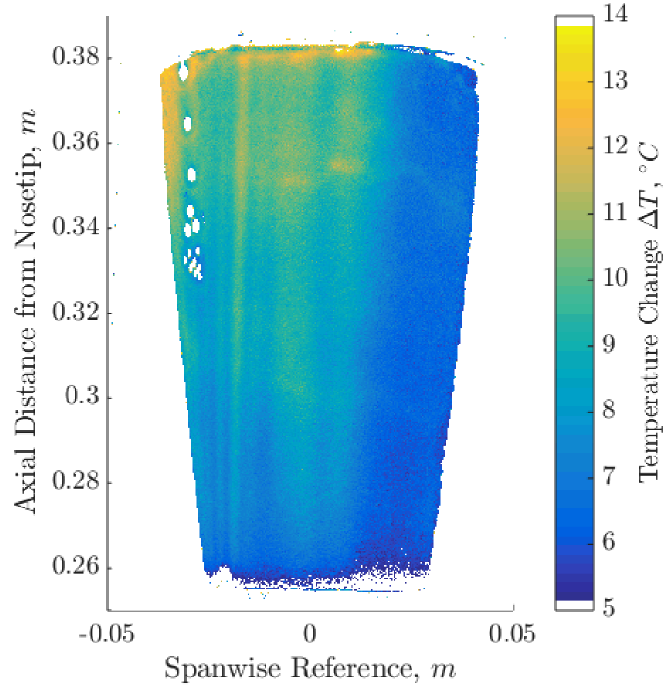
Effect of Added Roughness, TSP

Smooth



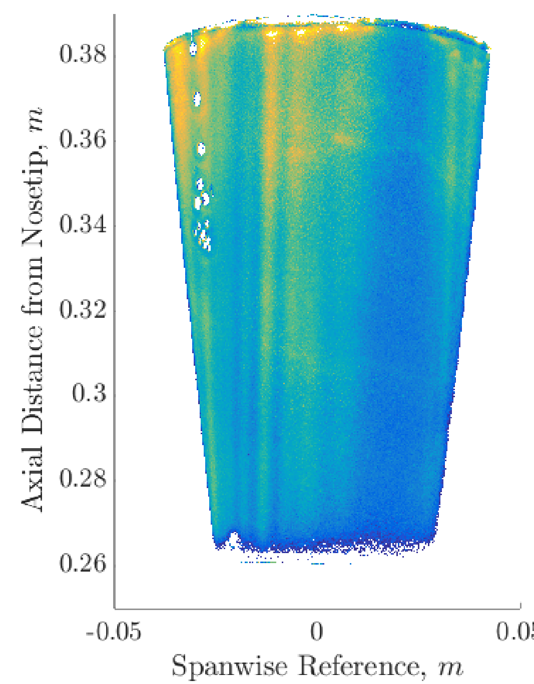
$Re = 11.96 \times 10^6$ /m

RIM-12x



$Re = 7.74 \times 10^6$ /m

RIM-7x

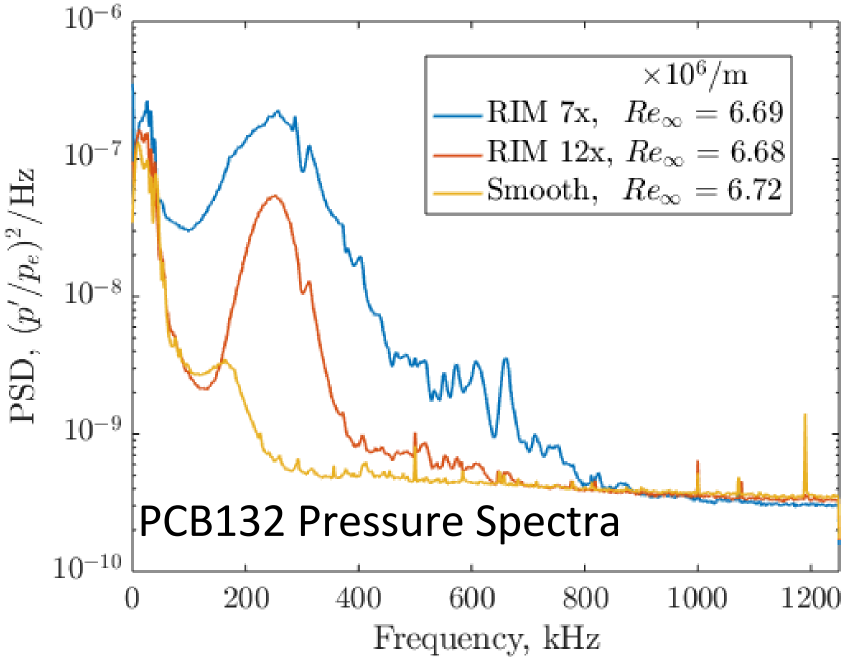


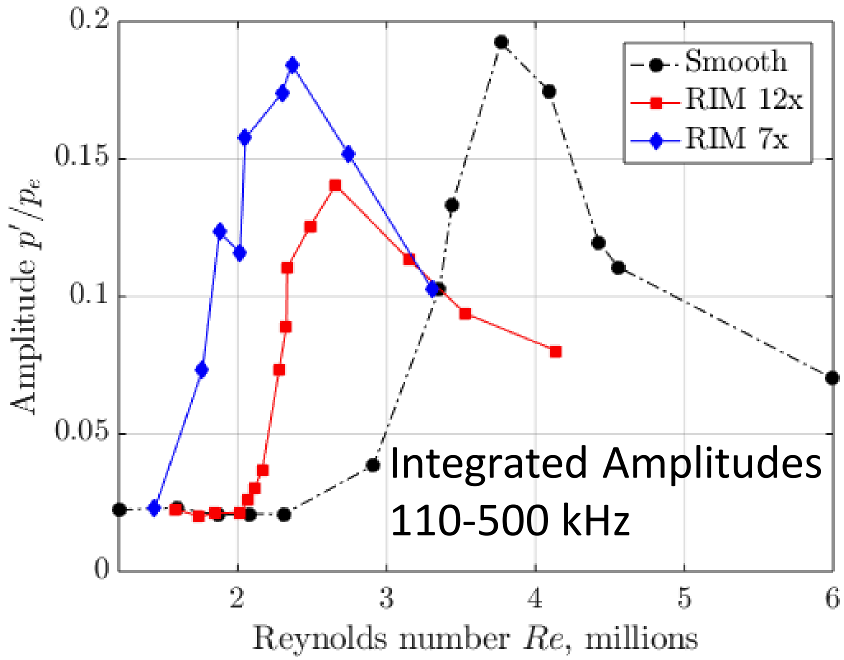
$Re = 6.69 \times 10^6$ /m

All at 6-deg. AoA

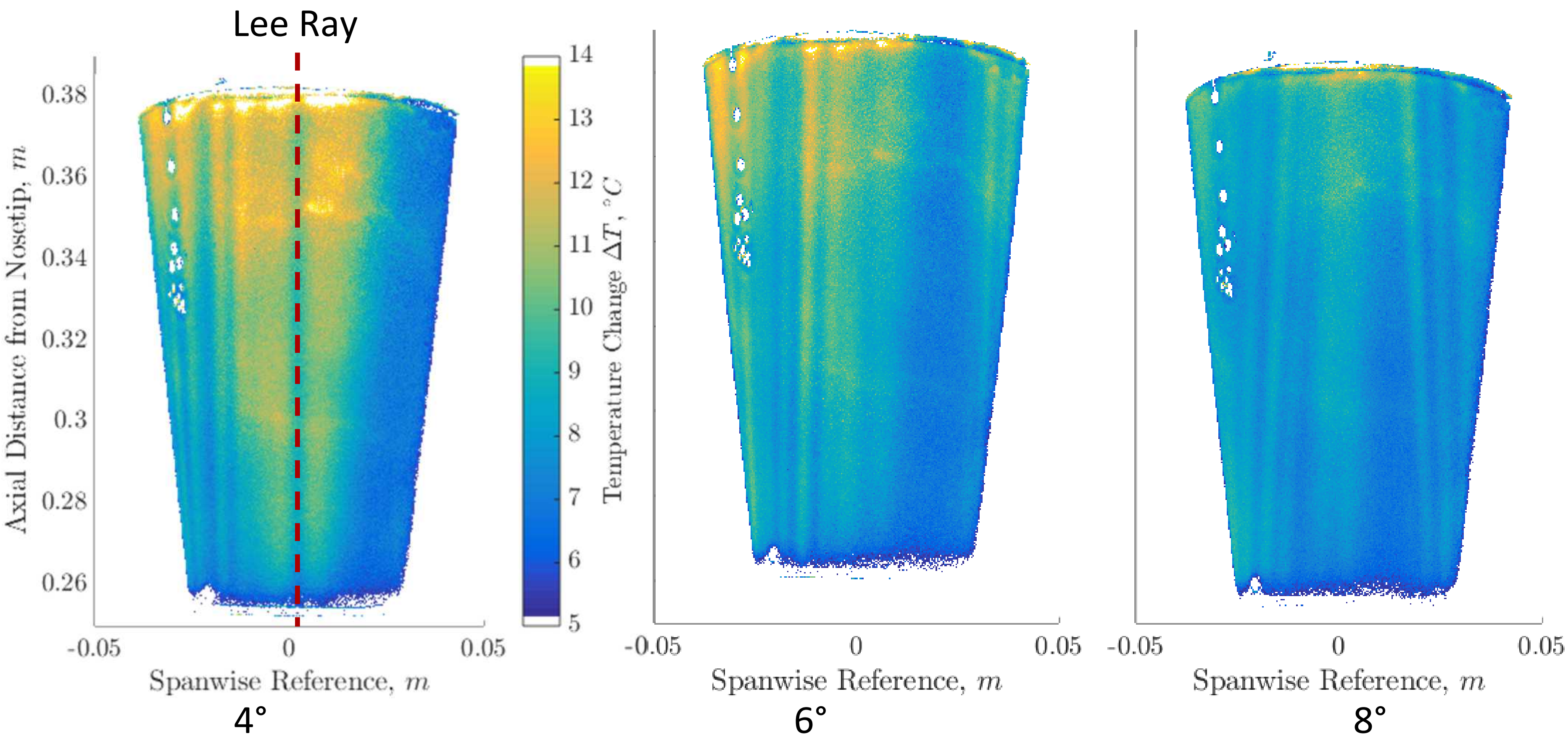
Effect of Added Roughness, PCBs

- Adding roughness causes earlier transition by Re = 2-3 million
  - Larger diameter roughness (RIM 7x) begins to increase in amplitude earlier than RIM 12x
- Peak second-mode amplitudes all similar, 15-20% edge pressure
- Roughness results in more rapid initial growth of second mode





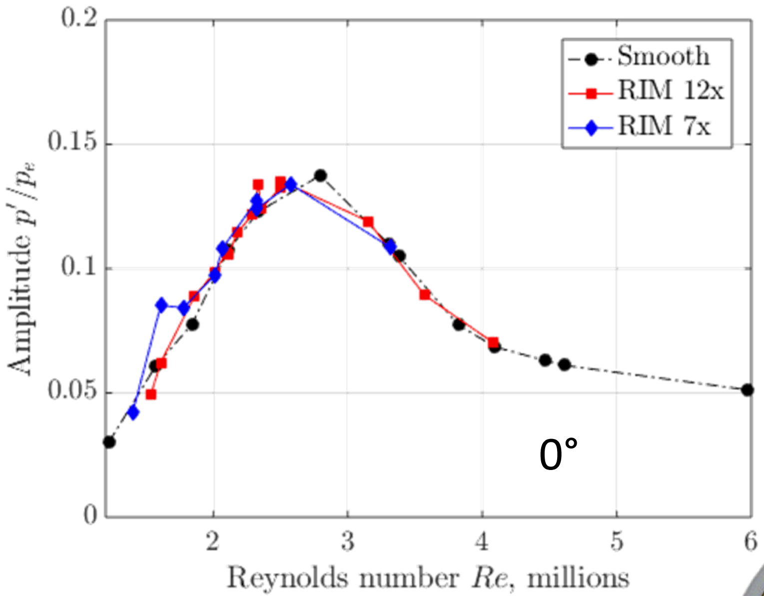
Effect of Angle of Attack, TSP

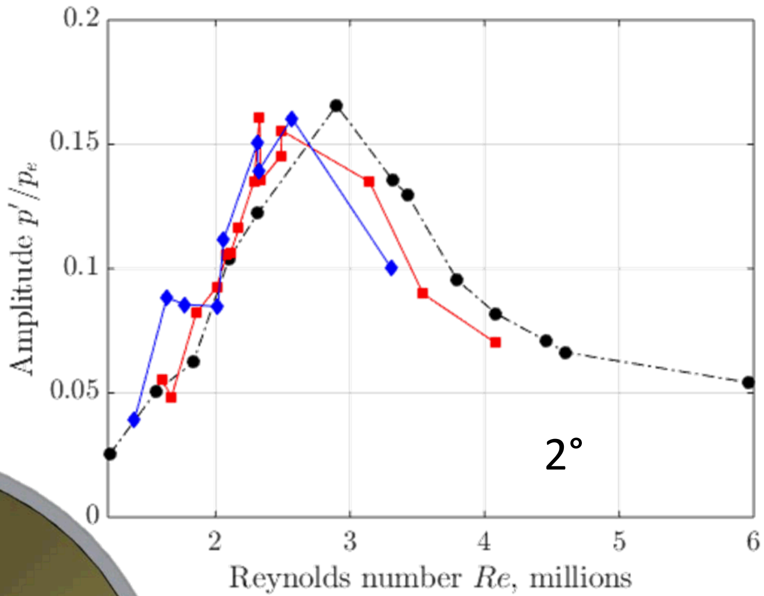


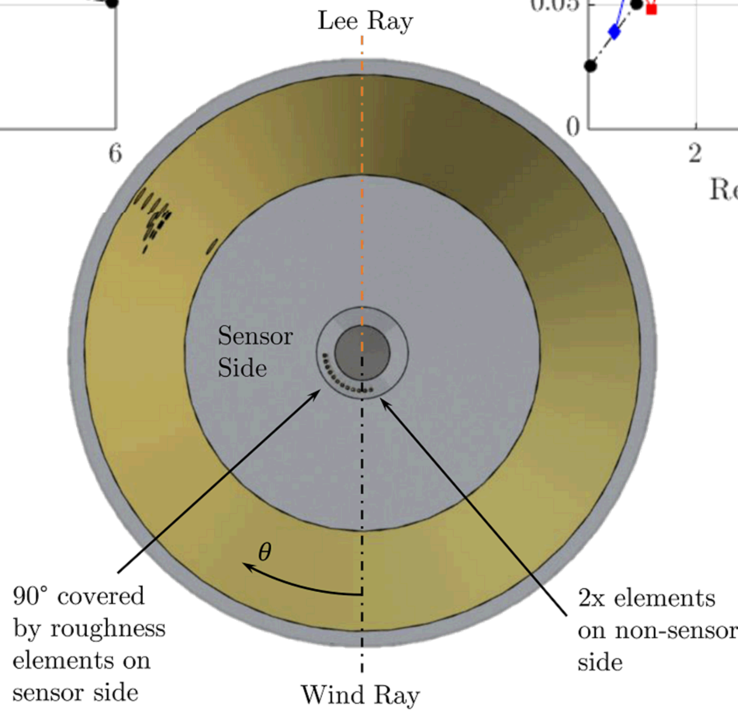
$Re \approx 6.7 \times 10^6$ /m

RIM-7x roughness

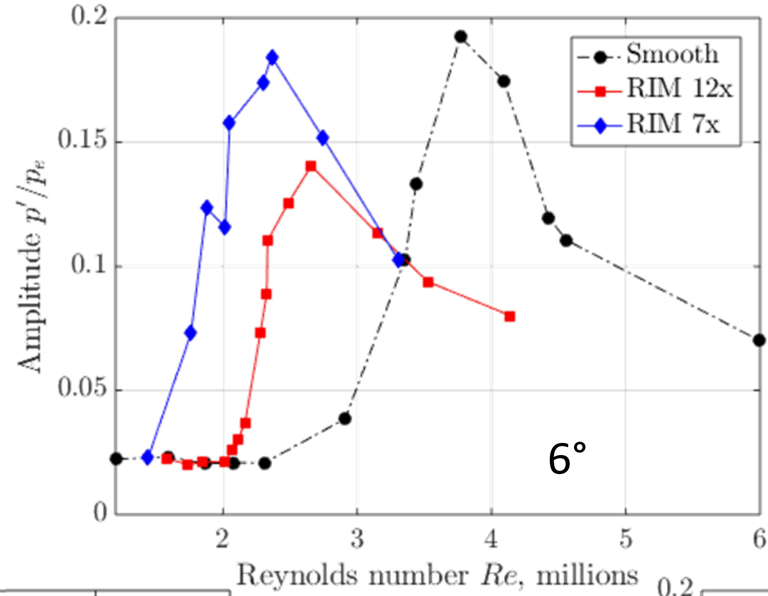
Pressure Fluctuation Amplitudes, different α

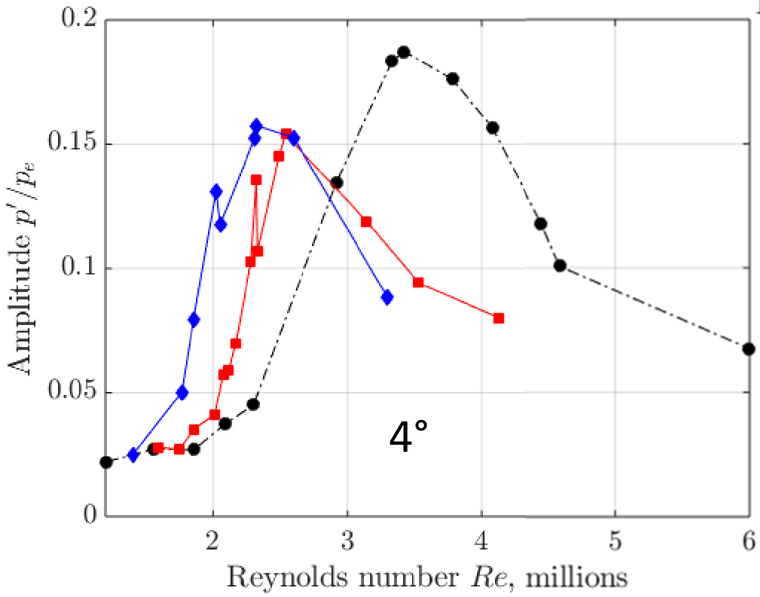


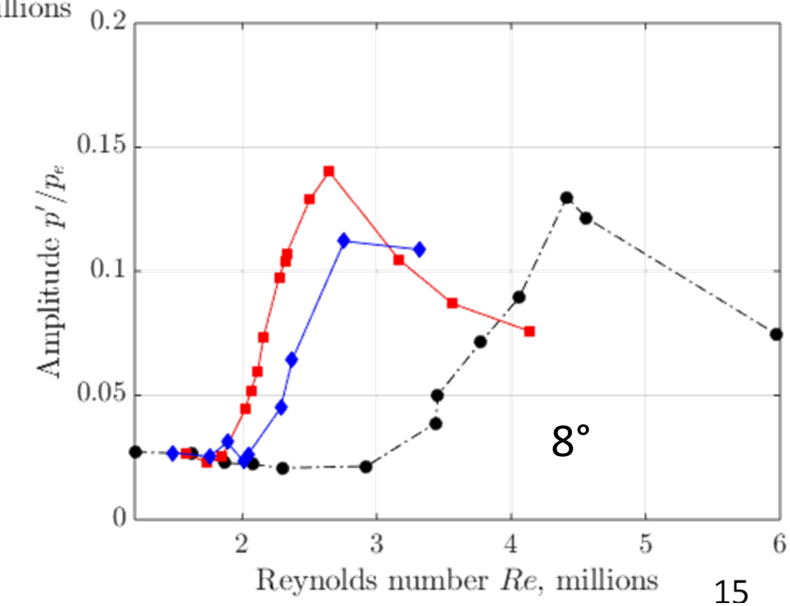




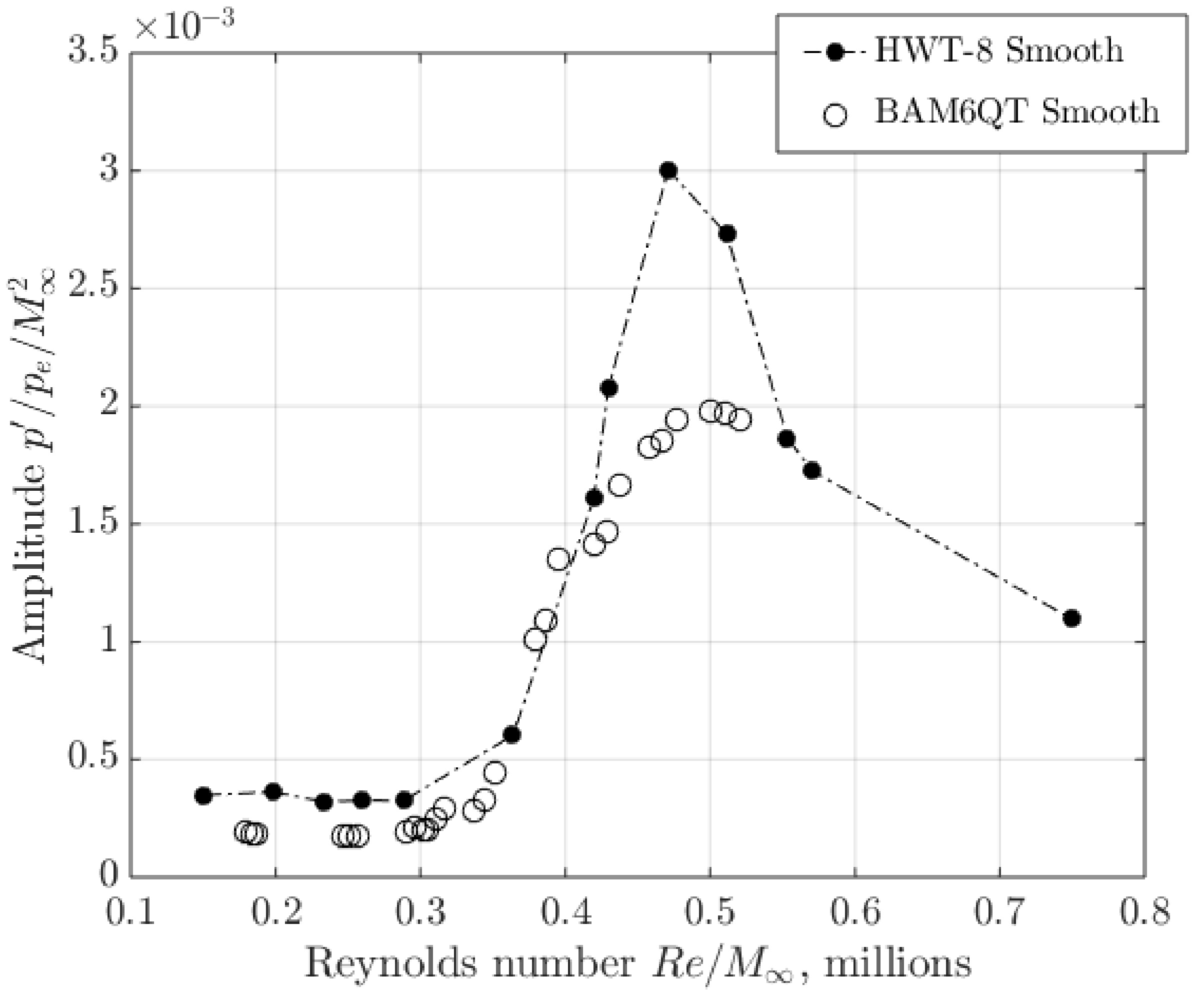
Pressure Fluctuation Amplitudes, different α





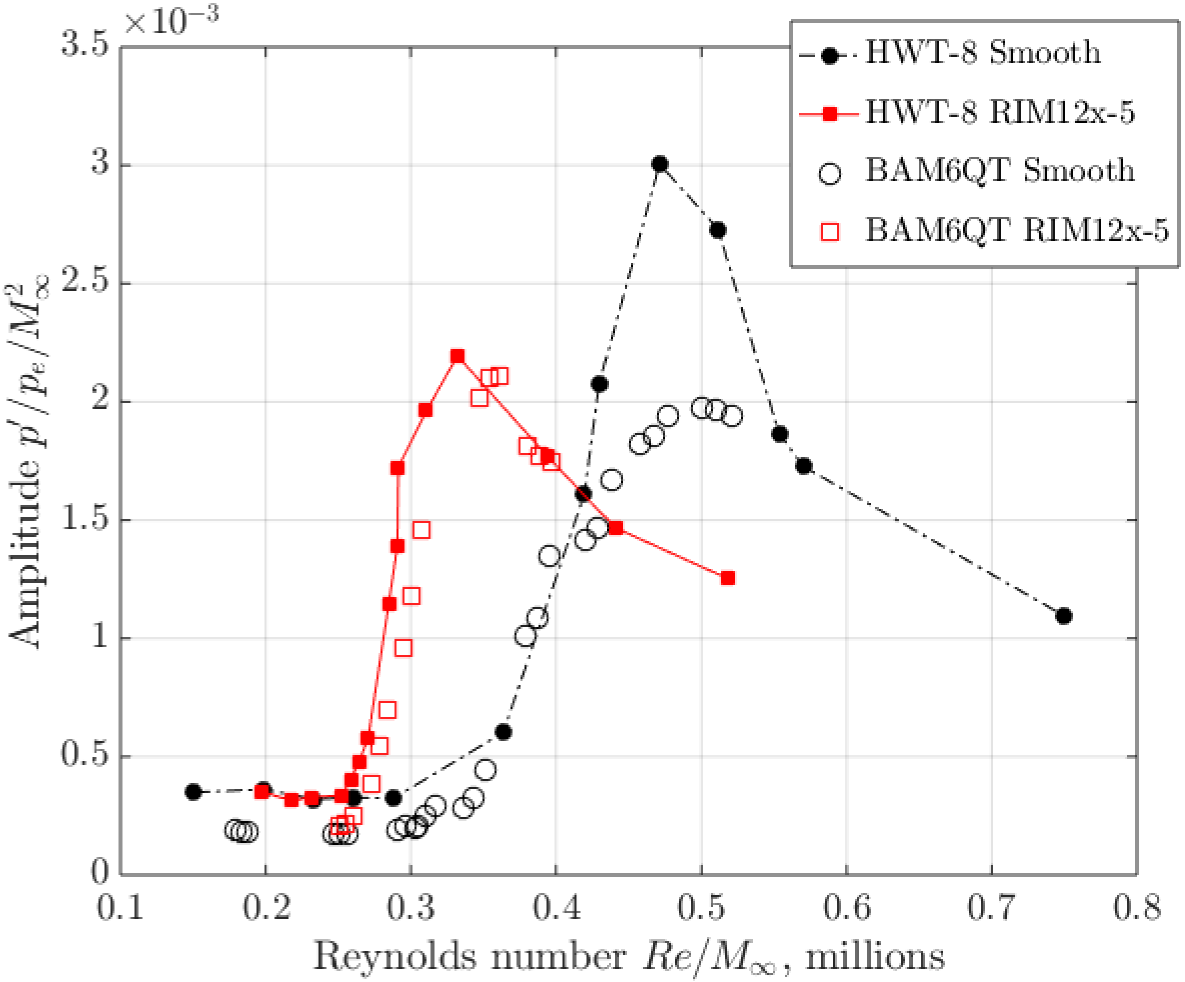


Effect of Mach Number



- 6-deg. AoA
- Modular Cone
  - 2 different sensor frusta
- BAM6QT
  - x = 341 mm
  - T0 = 430 K
- HWT-8
  - x = 343 mm
  - T0 = 660 K

Effect of Mach Number



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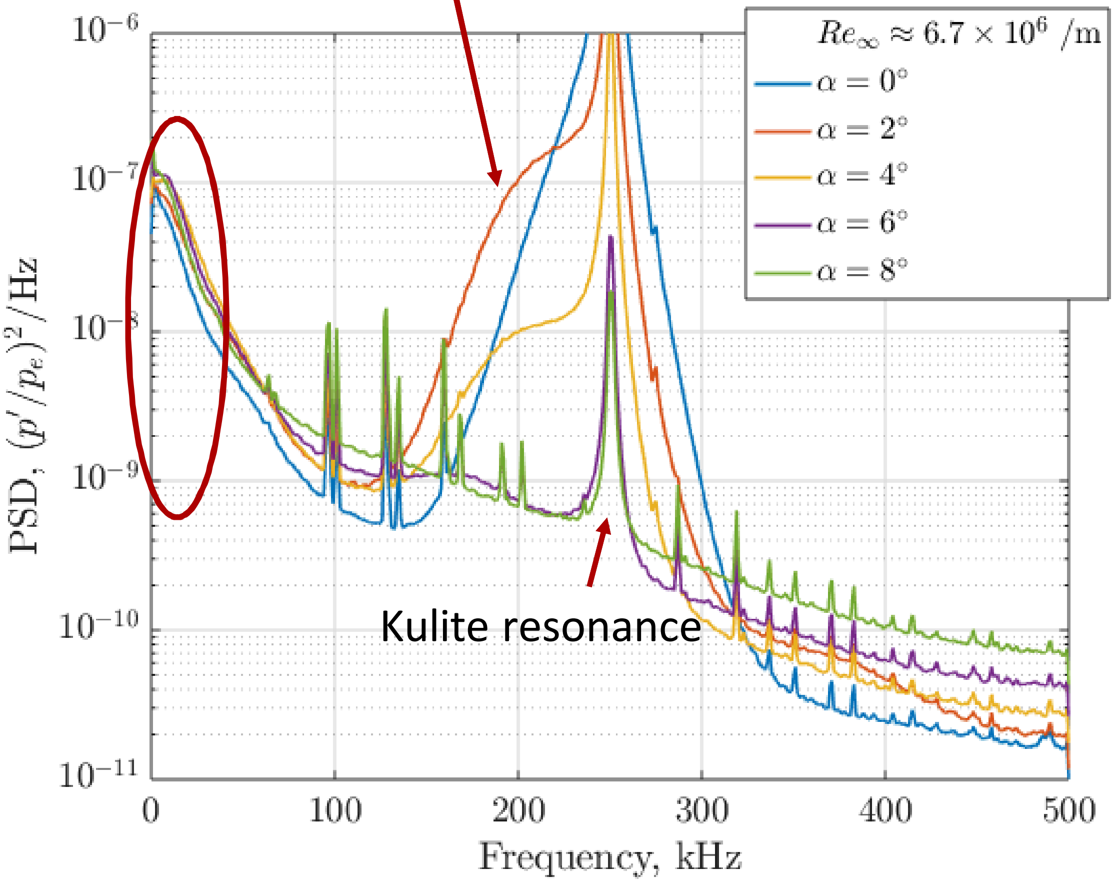
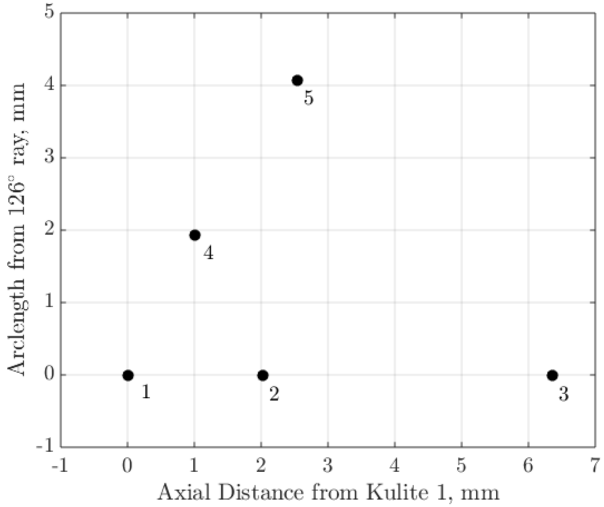
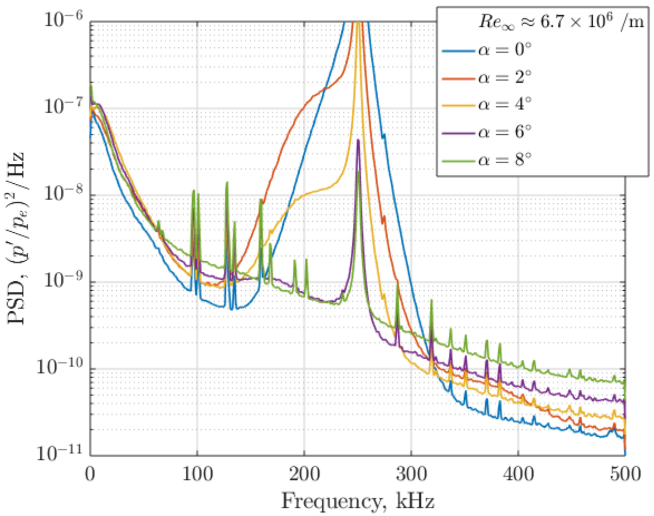
Low-Frequency Instability

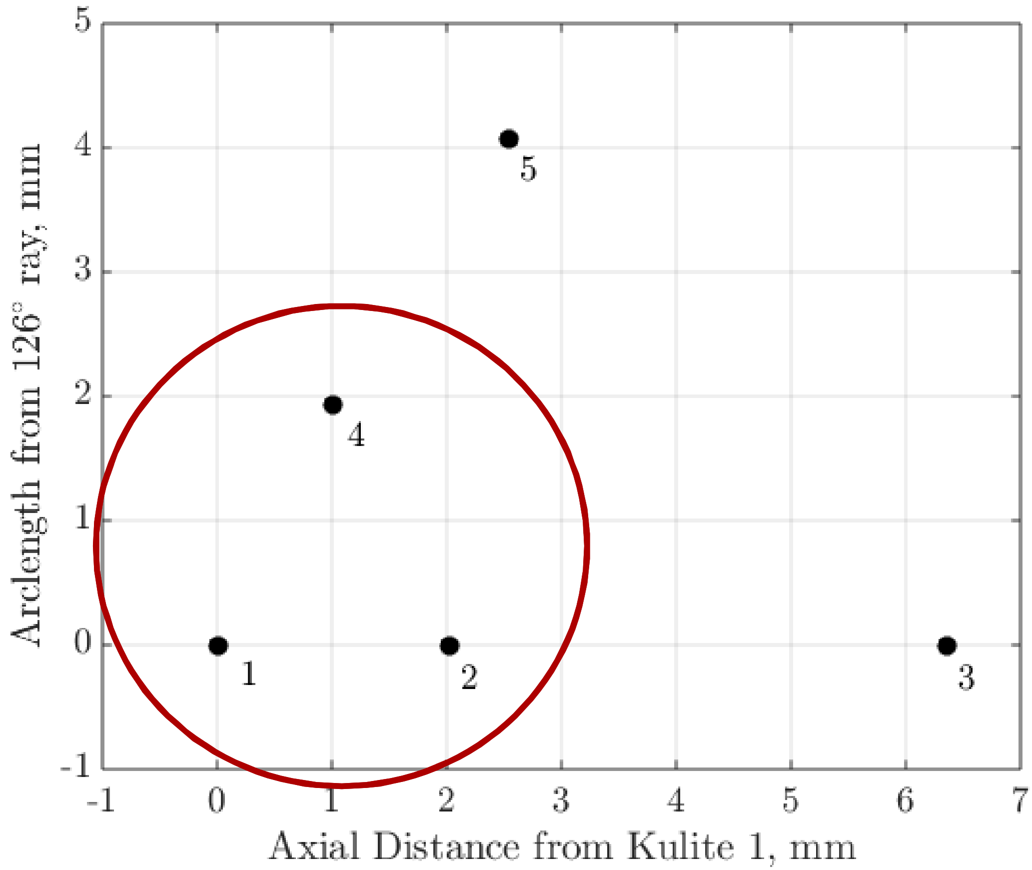




Smooth cone

Low-Frequency Instability

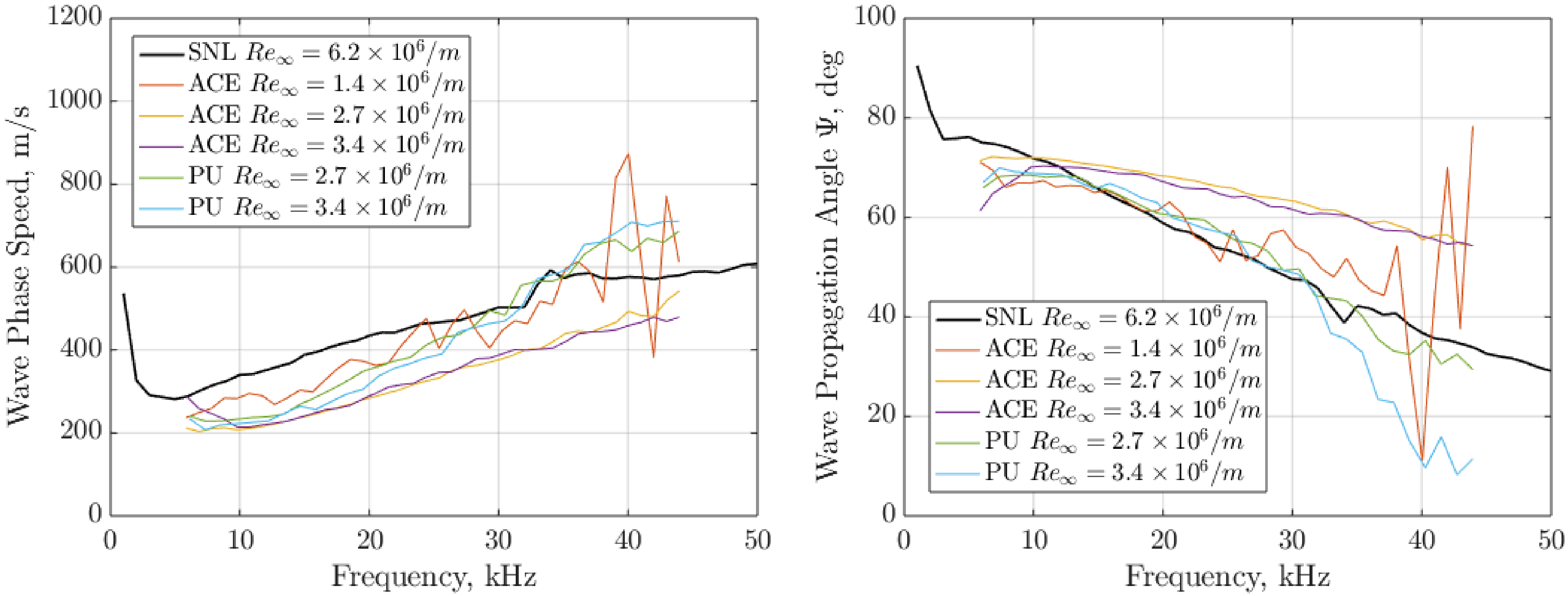




K1 at 328 mm from nosetip, 126°

Low-Frequency Instability

- Wave properties calculated using cross-power spectral density phase
- Wave properties on cone are similar to those measured on elliptic cone by Borg, et al.
  - Different geometries and Mach numbers
- Tunnel-noise driven instability?
- Very little growth with Reynolds number



SNL HWT-8: smooth cone at 6° AoA

Conclusions

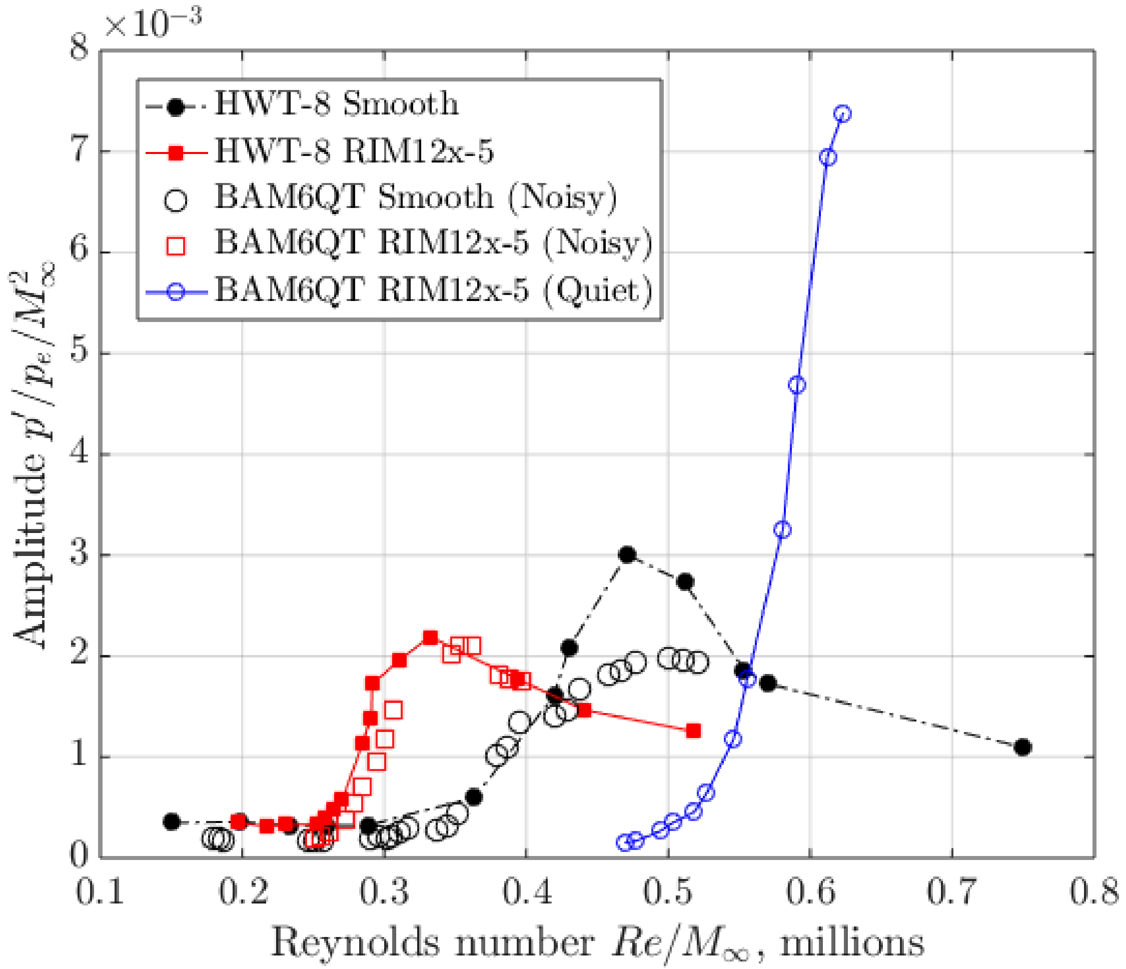
- Stationary Crossflow
  - The addition of roughness destabilizes the boundary layer
    - Transition occurs 30-40% sooner with roughness at $\alpha = 6^\circ$ than for smooth cone
    - Growth rate of second mode is higher with roughness
    - Stationary crossflow vortices modulate the second mode and amplify it
      - May not be a "true" secondary instability
  - Peak second-mode amplitudes are similar for all roughness patterns and angles of attack (except 8°), 15-20% of edge pressure
- Low-Frequency Waves
  - Phase speed and propagation angle of low-frequency waves measured using closely-spaced Kulites
  - Wave properties are similar to measurements made on elliptic cone at different Mach and Reynolds number
  - Need computations to better understand nature of instability

Conclusions

- For a hypersonic pitched cone, travelling crossflow does not seem to be important to transition ***even in noisy environment***
- Transition in this case ***may not*** be the result of "true" secondary instabilities but instead the second mode modulated and amplified by stationary crossflow vortices
- ***Computations are essential for determining transition mechanism in noisy environment***

QUESTIONS?

Mach Number Comparison – With Quiet Flow



Quiet data from x = 385 mm, 123°