Acoustic Radiation from a Mach 14 Turbulent Boundary Layer

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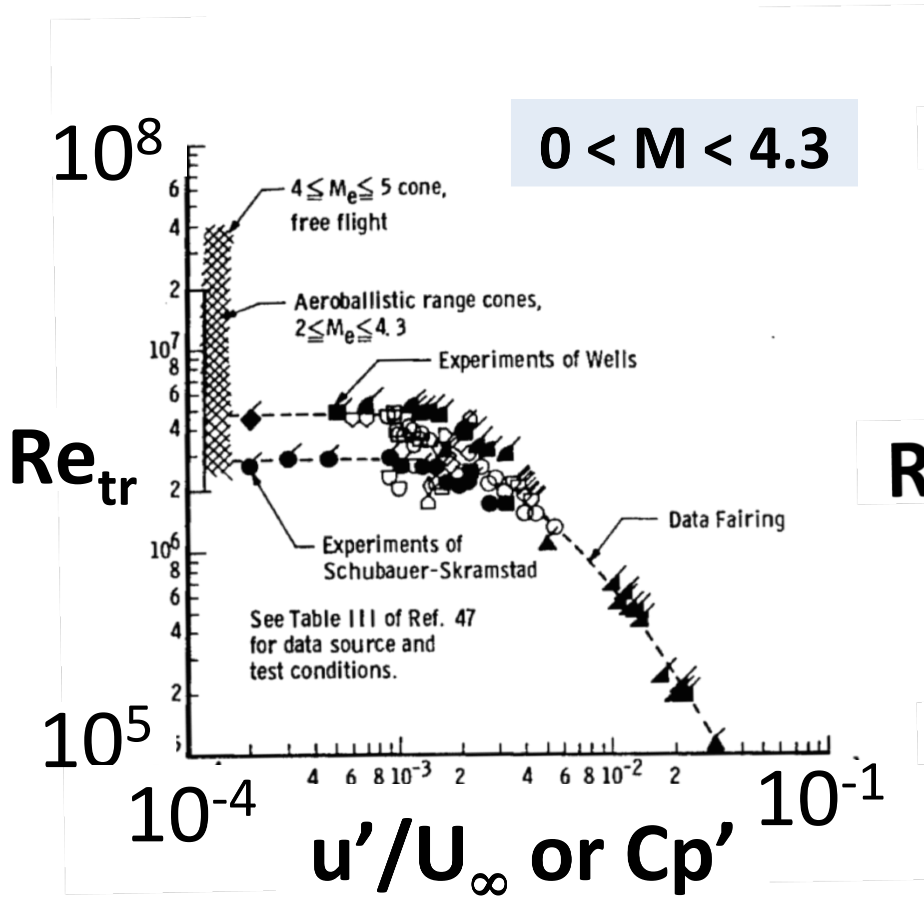
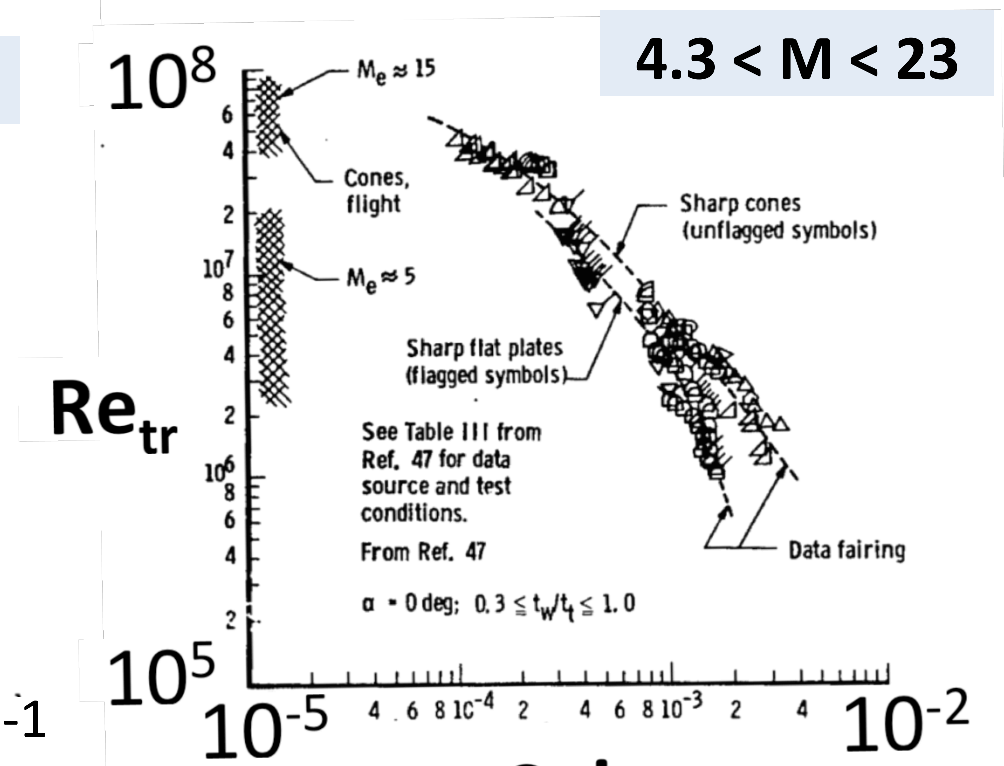
- Transition testing in hypersonic ground facilities
    - an important avenue to understanding the laminar-turbulent transition behavior of hypersonic vehicles
- Most hypersonic wind tunnels have elevated freestream disturbances
- **Tunnel Disturbances** have a large impact on Transition at M > 1

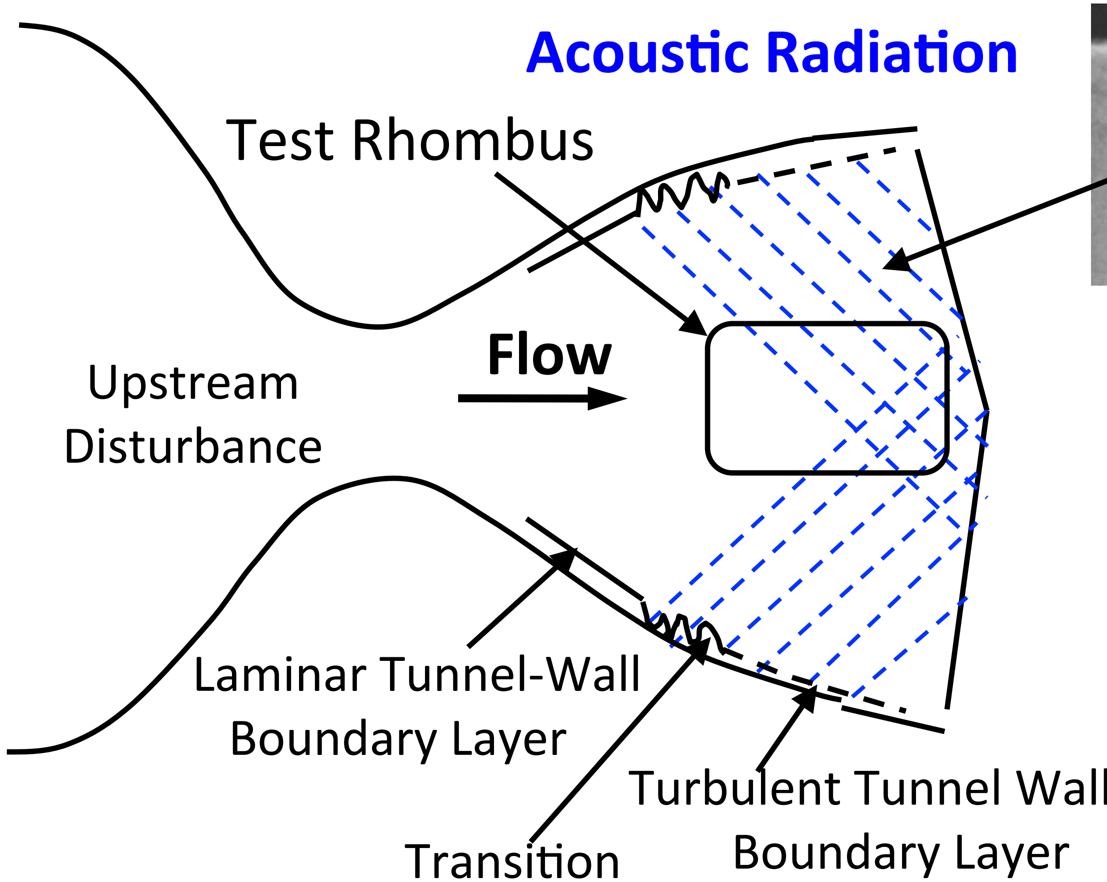


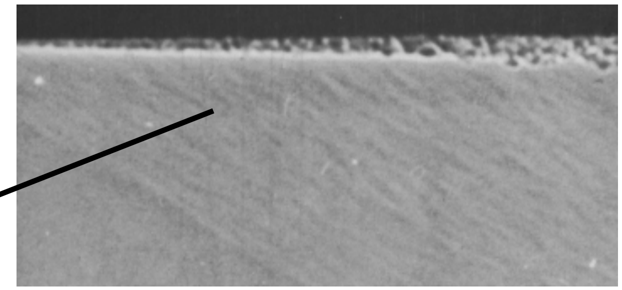


Harvey, 1978

Background

Disturbance Environment for Wind-Tunnel Facilities (Blanchard et al. 1997)





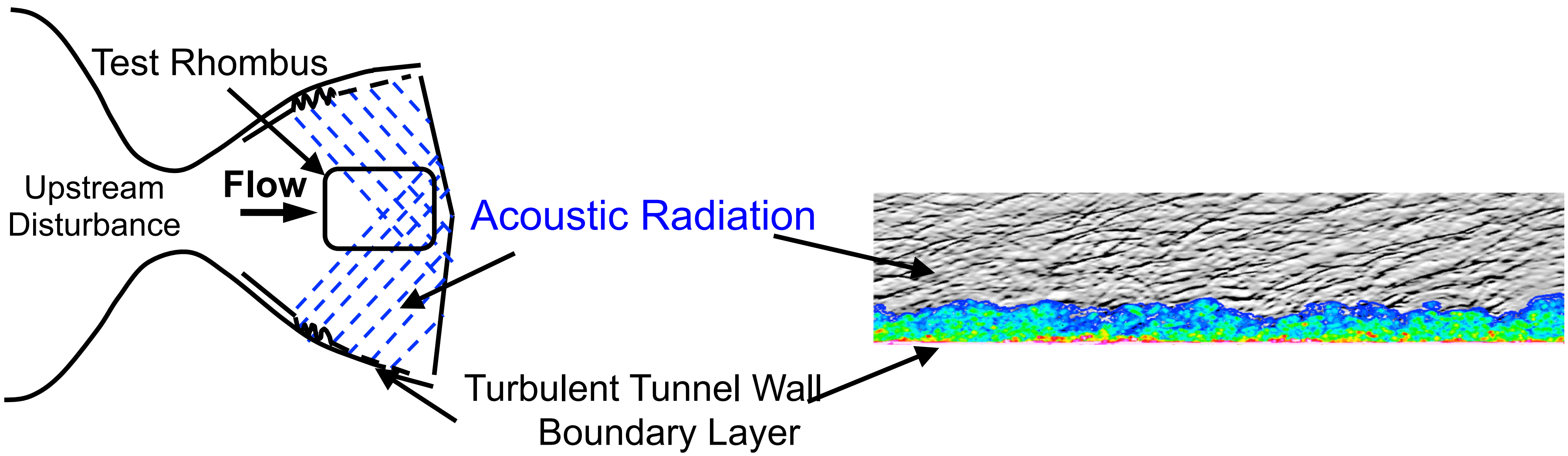
Shadowgraph of the radiated noise from a Mach 3.5 tunnel-wall turbulent boundary layer (courtesy of NASA Langley)

In a conventional ("noisy") tunnel, tunnel disturbances dominated by acoustic radiation from tunnel wall turbulent boundary layers for M > 2.5 (Laufer, 1964)

Methodology

Approach

High-fidelity simulation of acoustic radiation from tunnel-wall turbulent boundary layers



Impact: Understanding the acoustic fluctuations in wind tunnels and their influence on boundary layer transition would enable

- Better use of transition data
- Meaningful application of receptivity theory (Fedorov and Khokhlov, 1991)
- Potential reconciliation of differences in transition onset across multiple facilities

Acoustic Radiation from High-Speed Turbulent BLs

Theory

- Eddy Mach wave convecting supersonically with respect to free stream (Phillips, 1960; Ffowcs-Williams & Maidanik 1963)
- Restricted to prediction of intensity of the freestream fluctuation

Experiments

- Laufer (1961, 1964); Kendall (1970); Rufer (2000); Bounitch et al. (2011); Masutti et al. (2013); Radespiel et al. (2013)
- Mostly limited to amplitude and spectra with limited bandwidth; no multi-point statistics

Acoustic Radiation from High-Speed Turbulent BLS

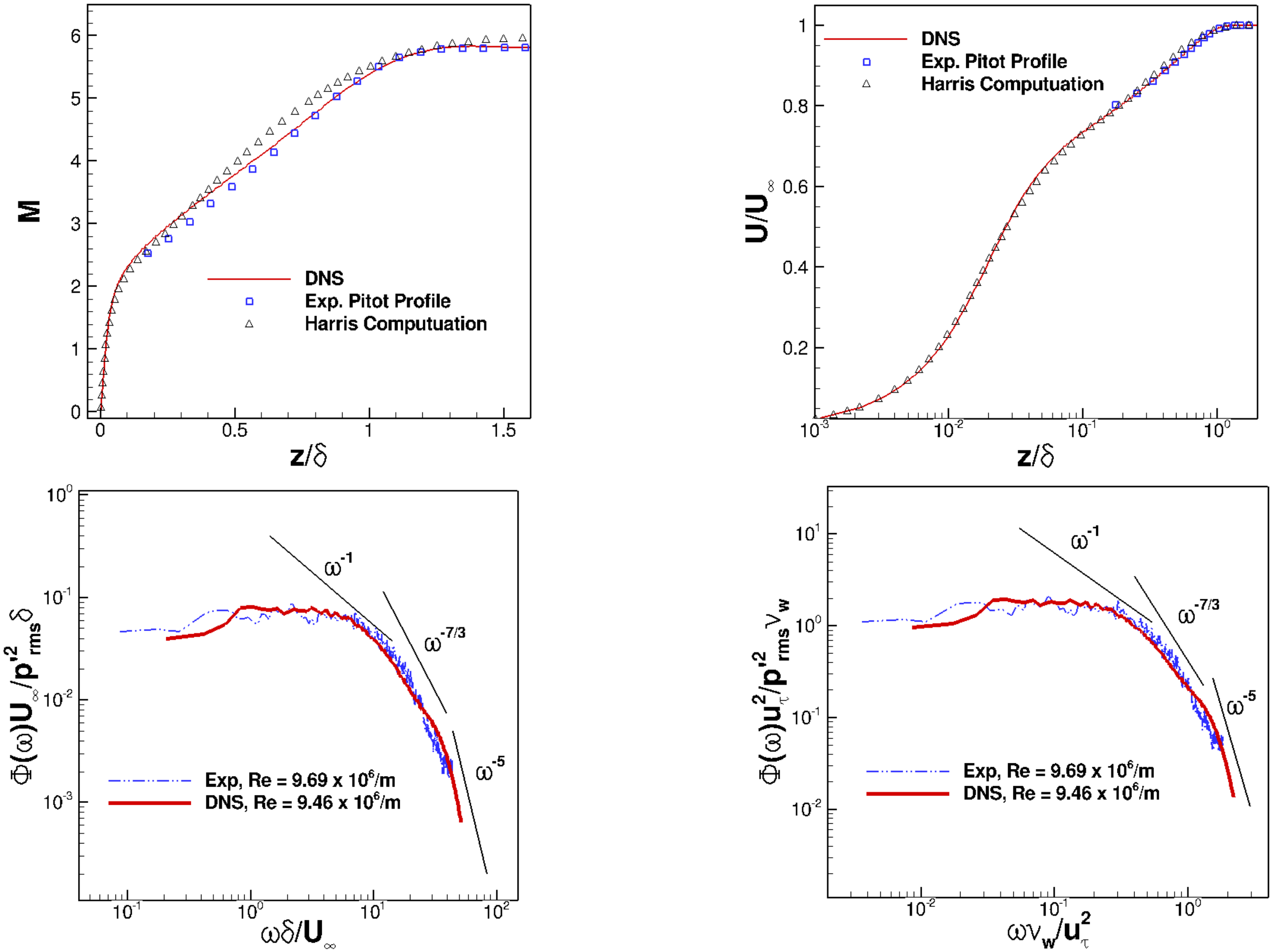
Direct Numerical Simulations (*Duan et al., AIAA 2012-3070, AIAA 2013-0532, AIAA 2014-2912, JFM vol. 746, pp 165-192, 2014*)

- include both the flow field and near-acoustic field
- isolate a purely acoustic freestream disturbance field above a single tunnel wall
- Identify generic statistical and spectral features of freestream disturbances
- Open doors to further simulations of receptivity in a tunnel-like environment

DNS datasets:

- M_∞ = 2.5, T_w/T_r = 1.0, Flat Plate
- M_∞ = 5.86, T_w/T_r = 0.76, Flat Plate (M6Tw076) & T_w/T_r = 0.25, Flat Plate (M6Tw025)
    - Freestream condition representative of Purdue Quiet Tunnel under noisy condition with p_0 = 132 psi, T_0 = 432 K
- **M_∞ = 14, T_w/T_r = 0.18** (M14Tw018) Flat Plate
    - Freestream condition representative of AEDC Tunnel 9 at p_0 = 1,023 psi
    - Comparison with Boundary-layer measurements at AEDC Tunnel 9 (Expected)

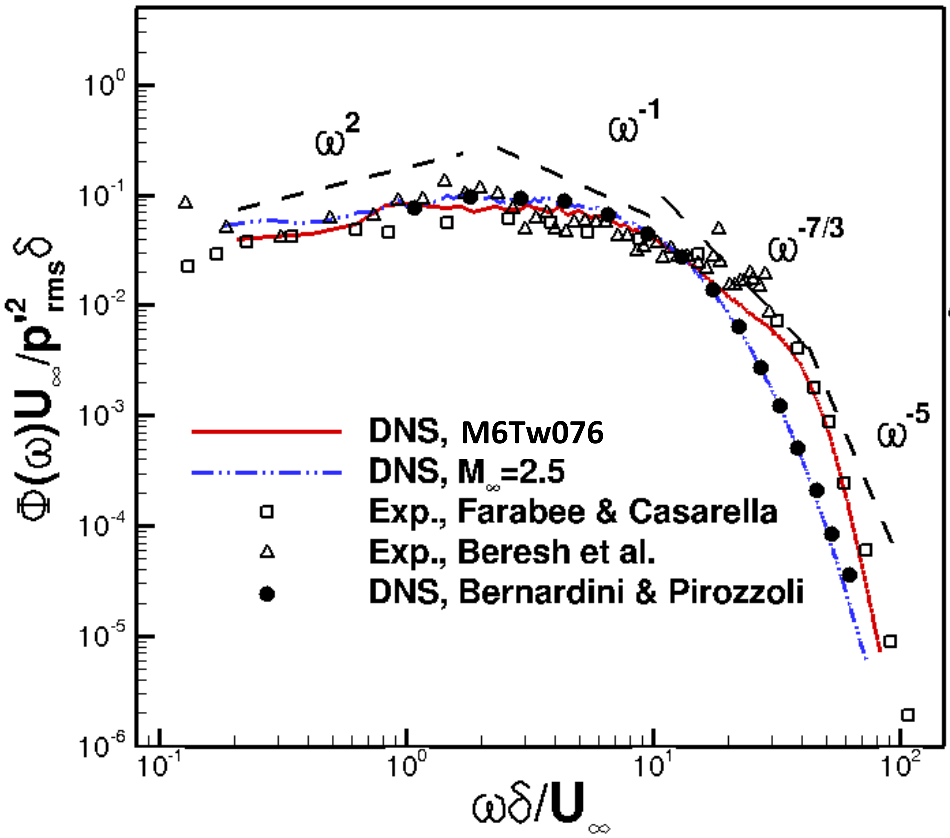
Comparison with Experiment (M6Tw076)



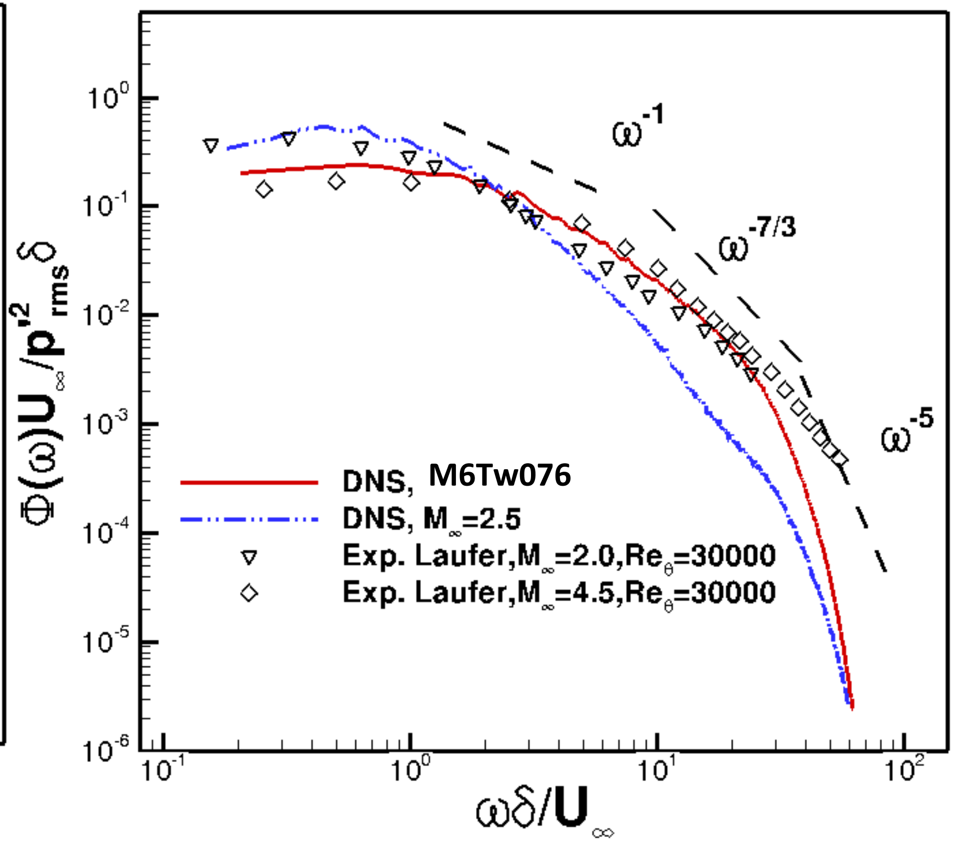
Mean flow predictions and **wall-p'** frequency spectrum are in good agreement with the measurements in the Boeing/AFOSR Mach 6 Quiet Tunnel under noisy condition

Normalized Frequency Spectra

Wall p’

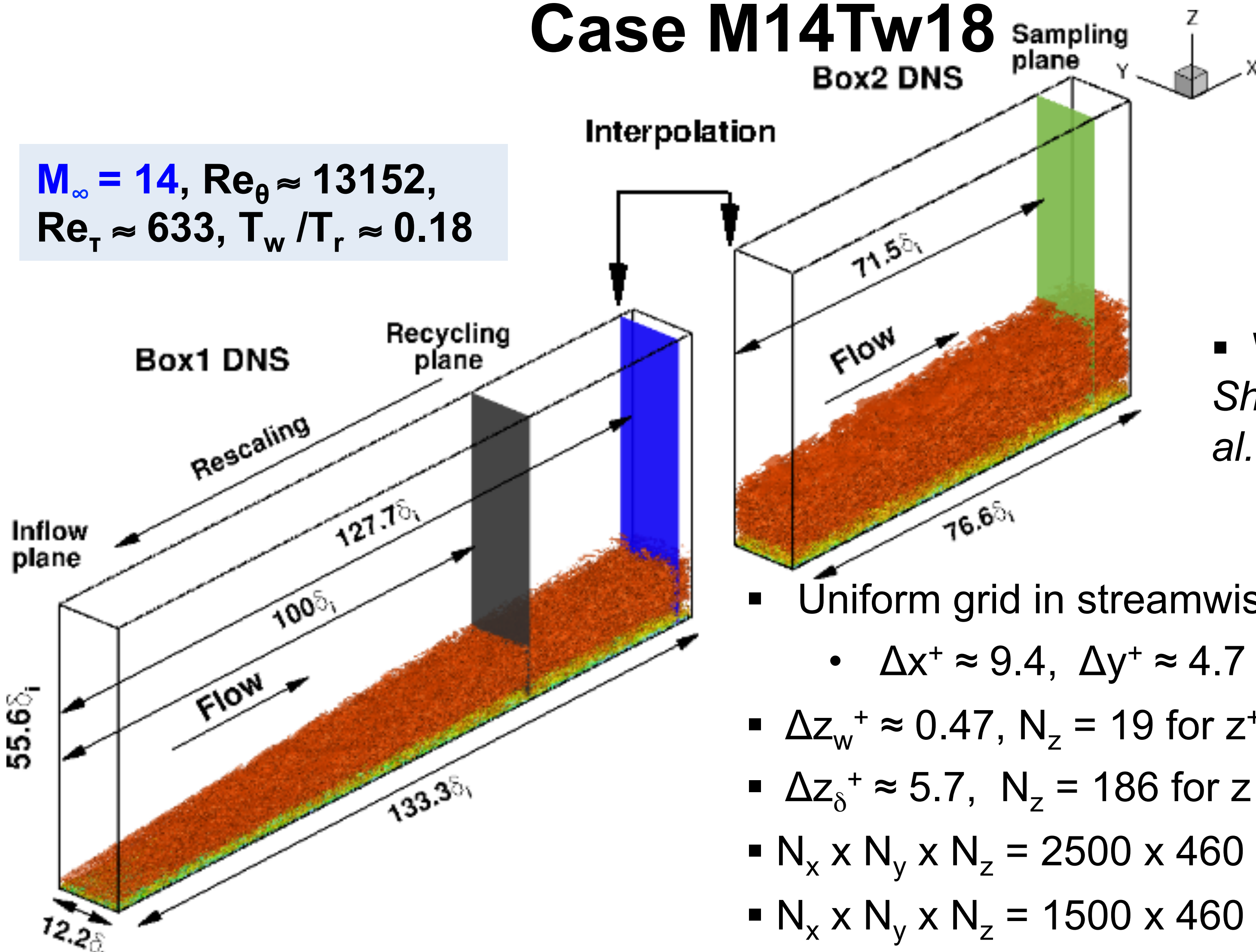


Freestream p’



DNS Setup
Case M14Tw18

$M_\infty = 14$, $Re_\theta \approx 13152$,
$Re_\tau \approx 633$, $T_w / T_r \approx 0.18$



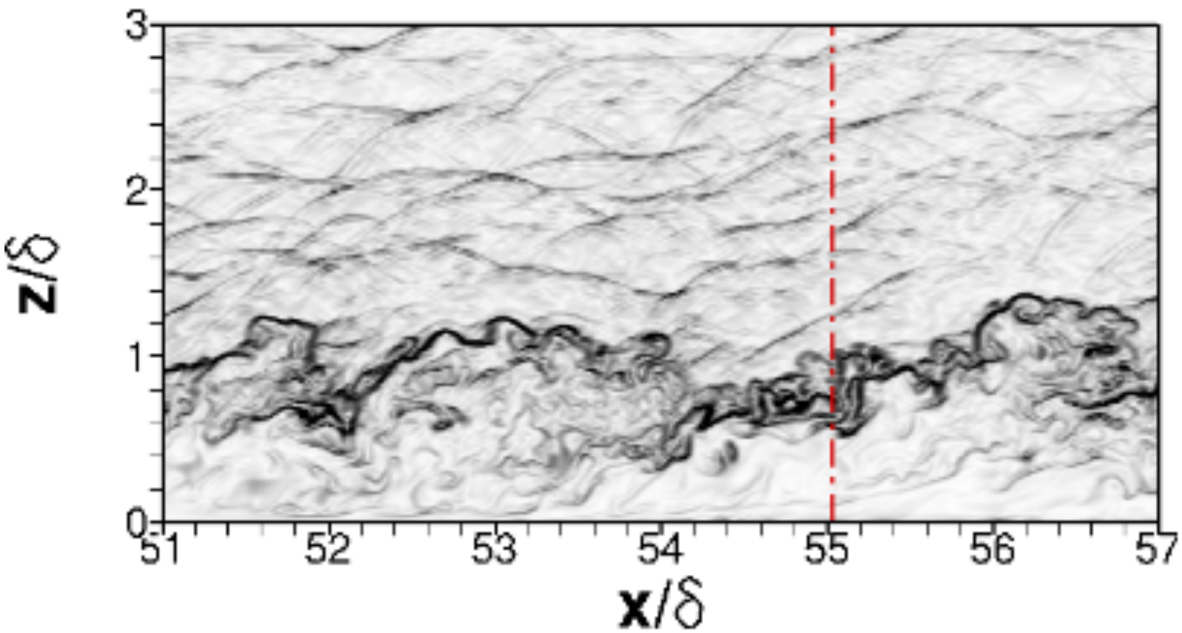
- **WENO** *(Jiang & Shu 1996, Martin et al. 2007)*

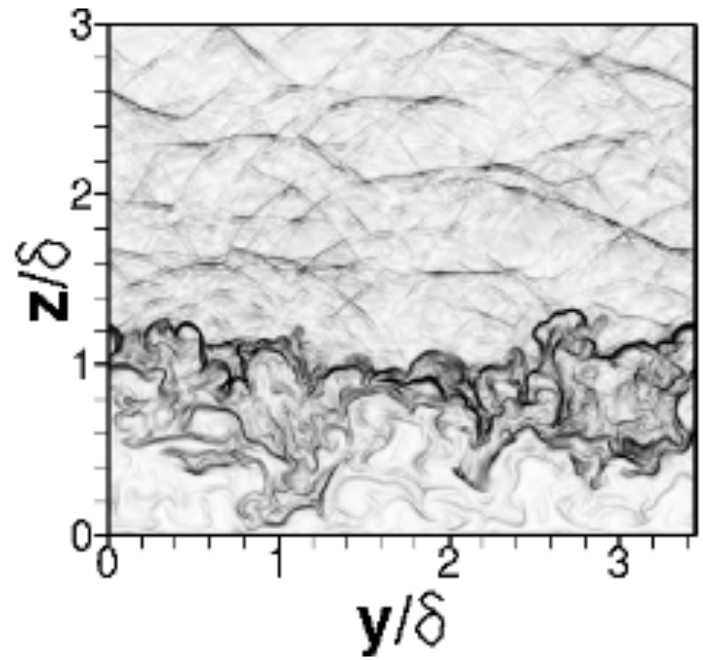
- Uniform grid in streamwise-spanwise directions
  - $\Delta x^+ \approx 9.4$, $\Delta y^+ \approx 4.7$
- $\Delta z_w^+ \approx 0.47$, $N_z = 19$ for $z^+ < 10$,
- $\Delta z_\delta^+ \approx 5.7$, $N_z = 186$ for $z < \delta$
- $N_x \times N_y \times N_z = 2500 \times 460 \times 540$ (Box 1 DNS)
- $N_x \times N_y \times N_z = 1500 \times 460 \times 786$ (Box 2 DNS)

- Grids designed to simultaneously resolve both the **hydrodynamic disturbances** and **near-acoustic field**

Numerical Schlieren Visualization

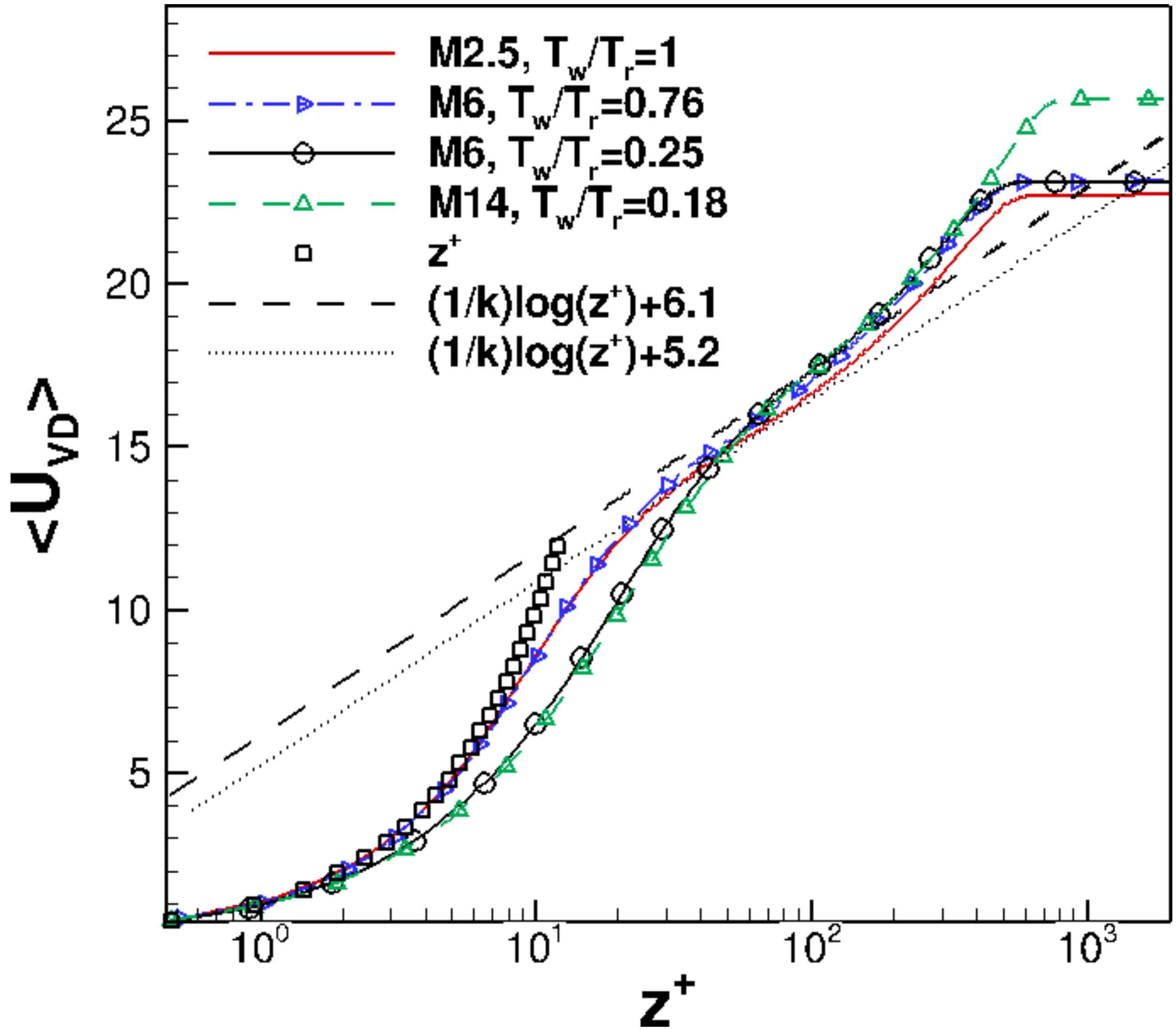
M14Tw18



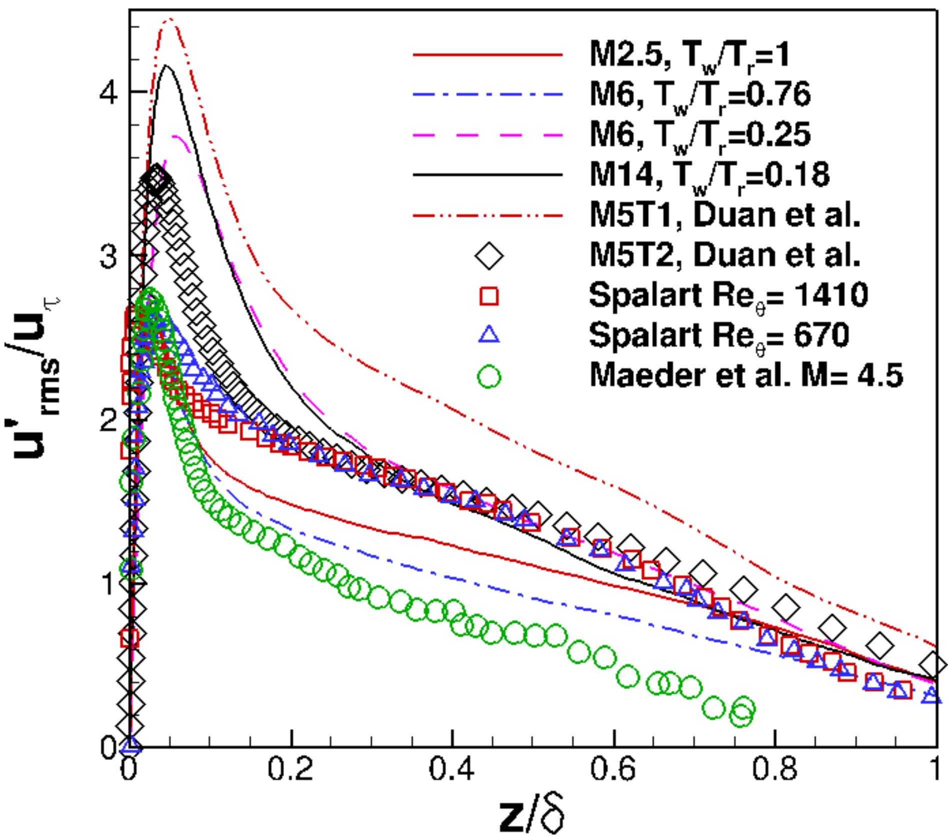


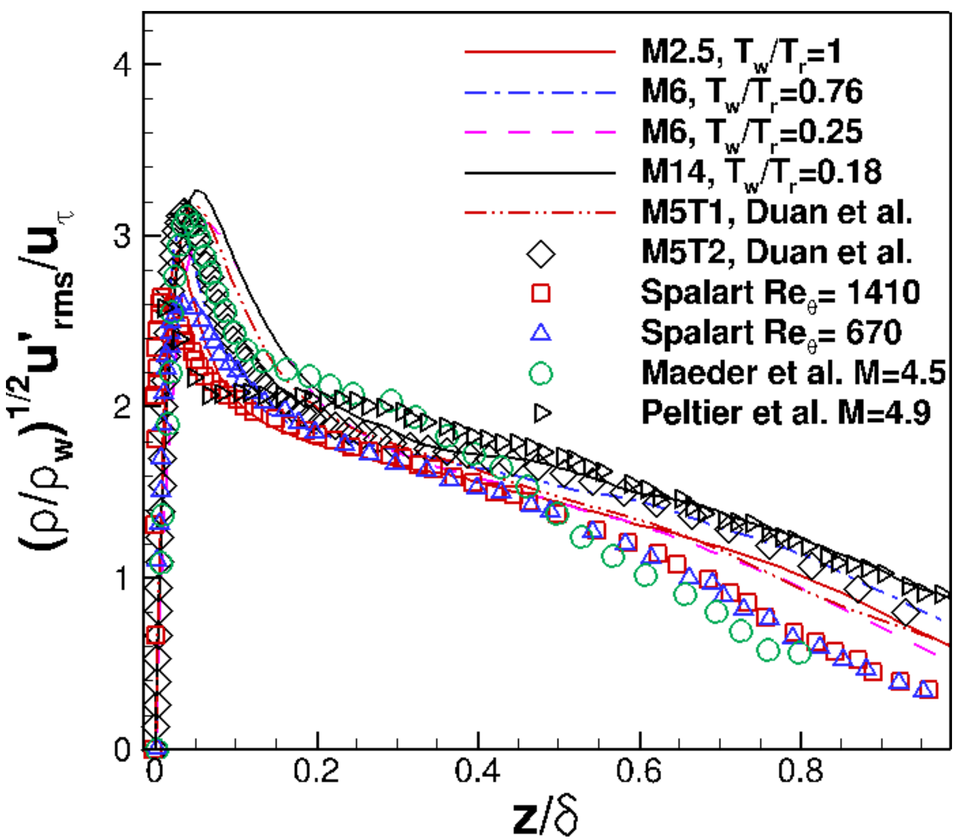
- Large scale motions cause incursions of the freestream irrotational flow into the boundary layer
- Distributed regions of strong density gradient can be seen within the boundary layer
  - Existence of 'shocklets'???

van Driest Transformed Mean Velocity Profile



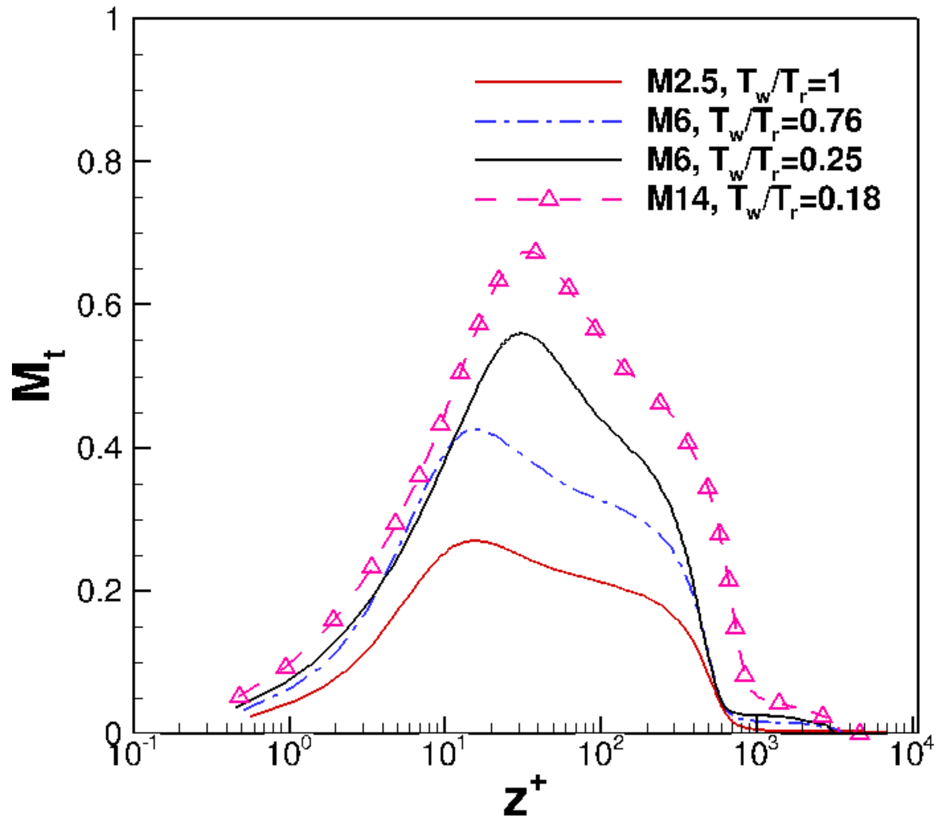
Turbulence Intensities

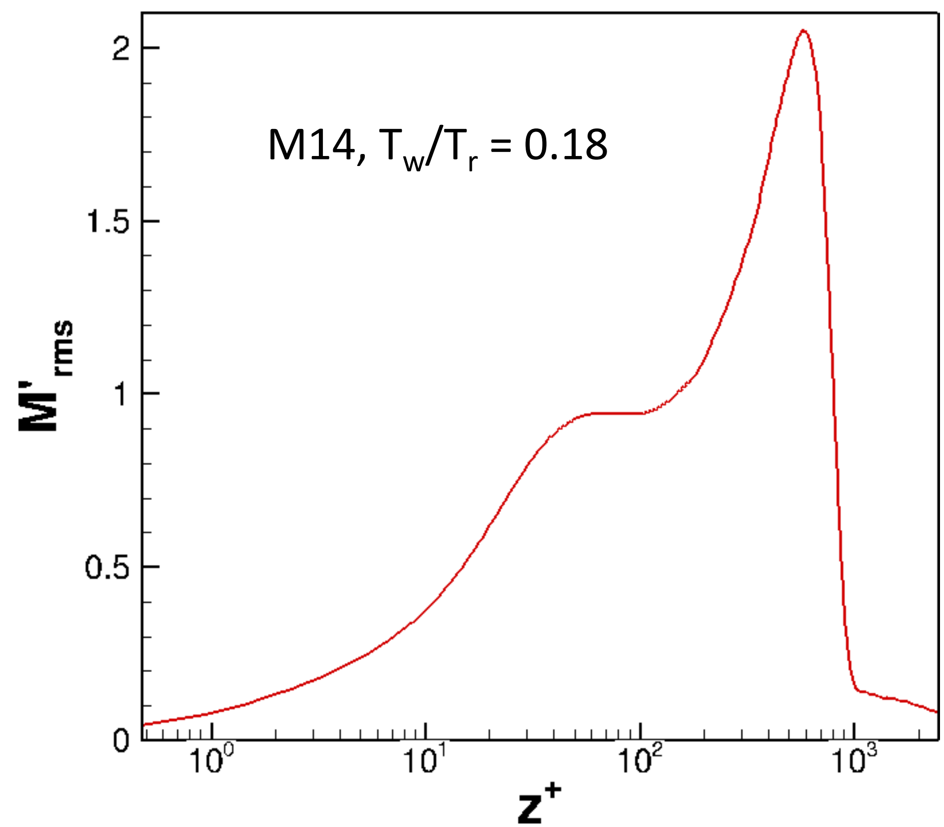




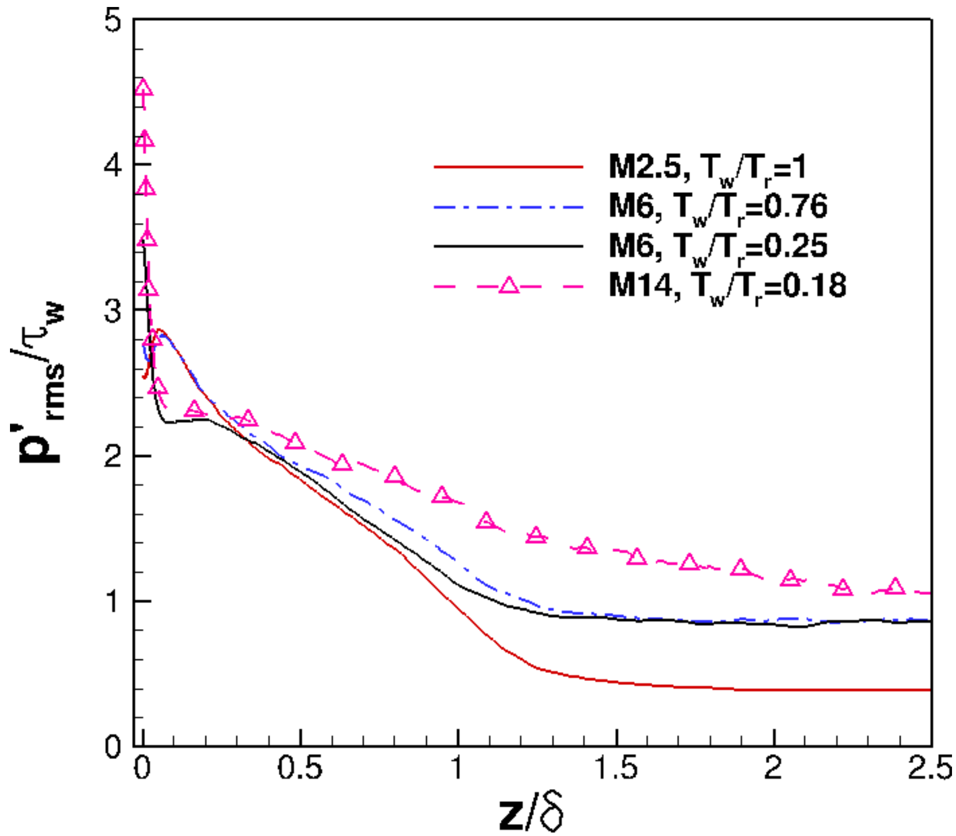
Significantly improved collapse of data is achieved by Morkovin's scaling

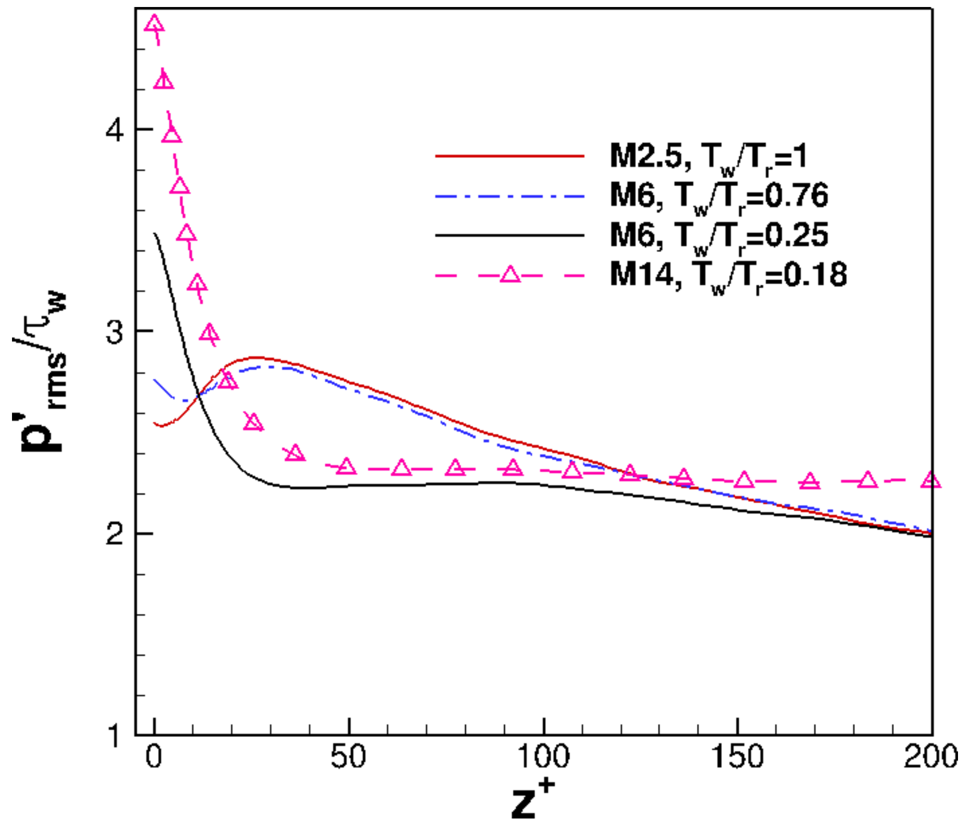
Turbulent Mach Number and Fluctuating Mach Number





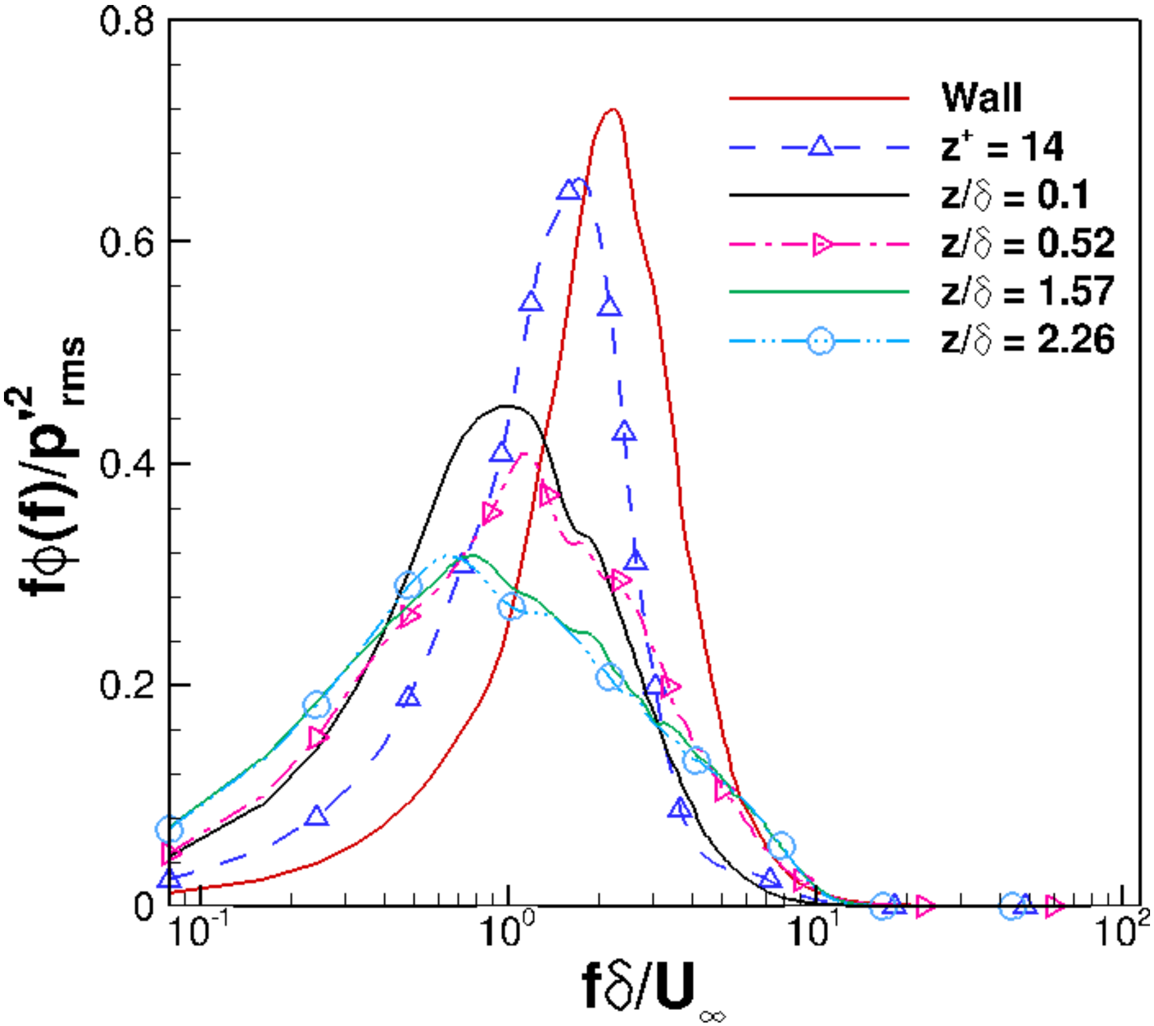
Pressure Fluctuation Intensity





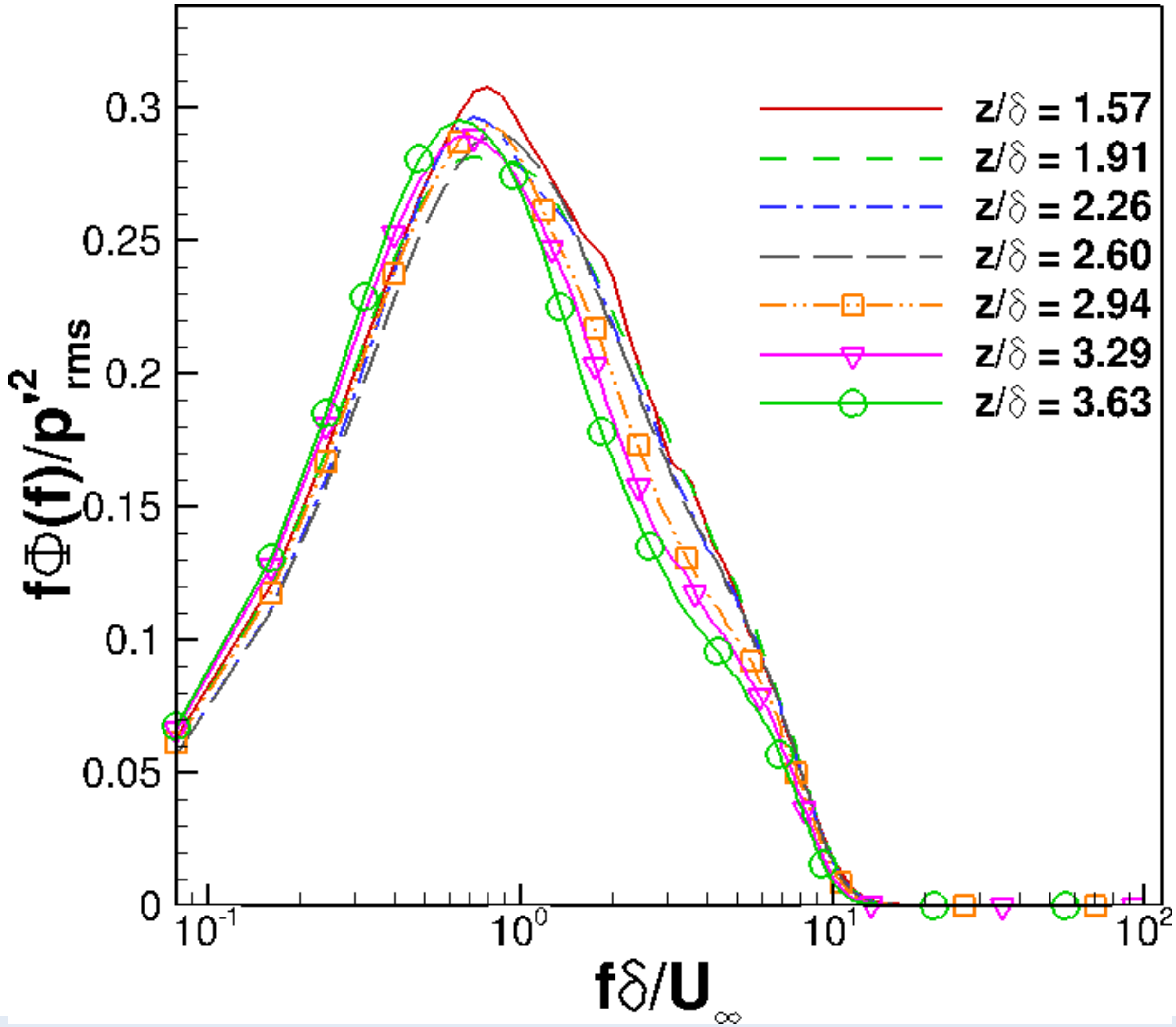
p'_{rms}/τ_w near the **wall** shows a strong wall-temperature dependence
p'_{rms}/τ_w in the **free stream** increases with Mach number and is insensitive to wall temperature

Pre-multiplied p' Frequency Spectra



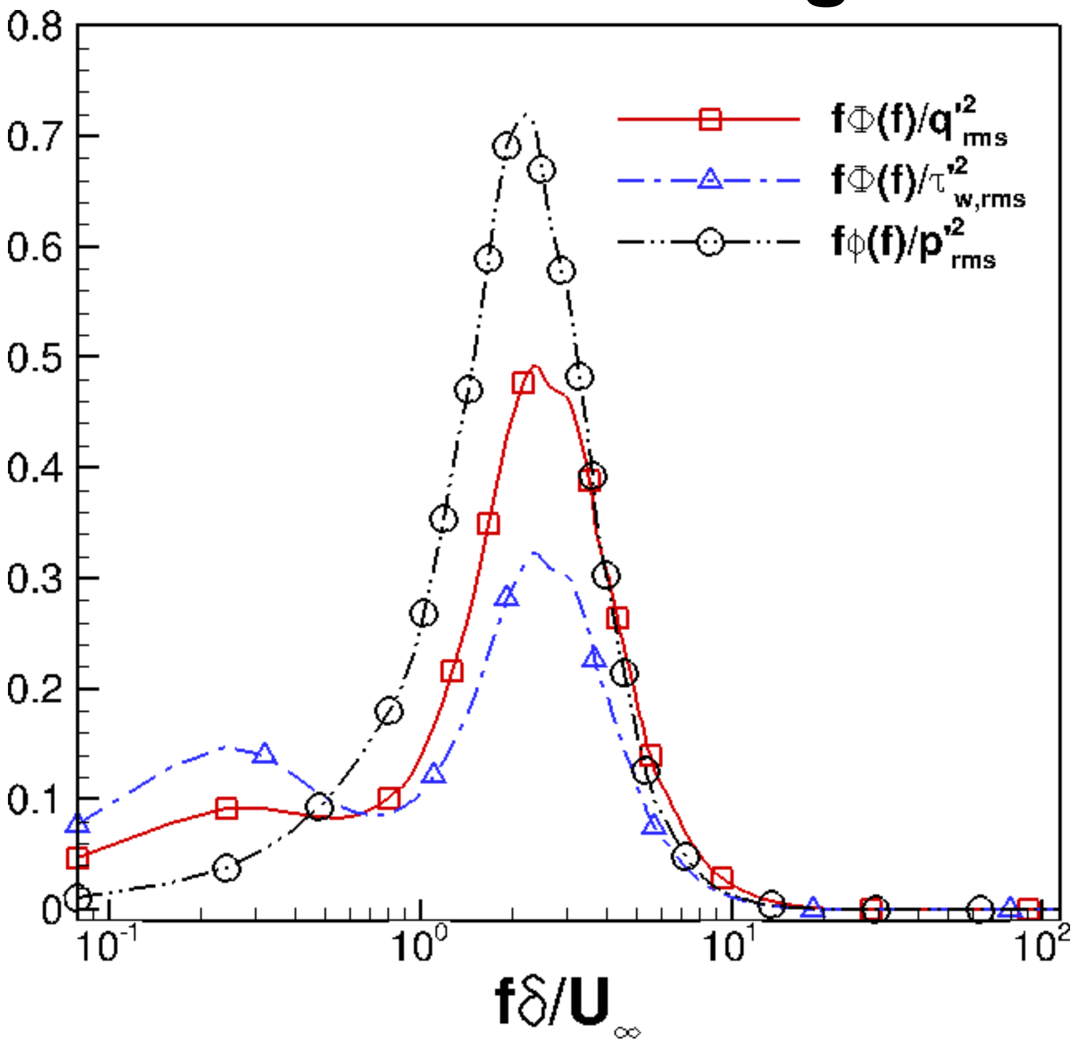
p' spectrum peak shifts to lower frequencies as the location of interest moves away from the wall

Pre-multiplied p' Frequency Spectra



Good convergence of p' spectra in the free stream
Freestream p' spectrum centered at $f\delta/U_\infty \approx 0.7$

Fluctuating Wall Quantities



$$\frac{\tau'_{w,rms}}{\tau_w} = 53\% \qquad \frac{q'_{w,rms}}{\bar{q}_w} = 67\%$$

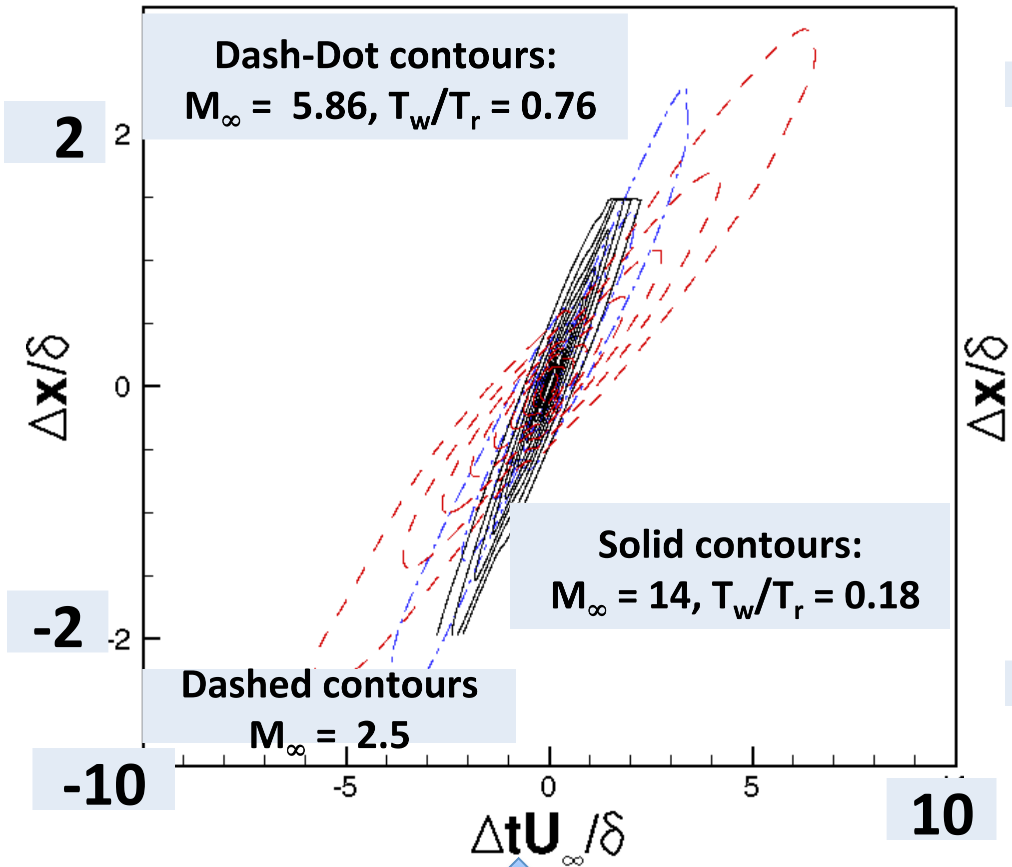
$$\frac{p'_{w,rms}}{\bar{p}_w} = 24\% \qquad \frac{p'_{w,rms}}{\tau_w} = 4.41$$

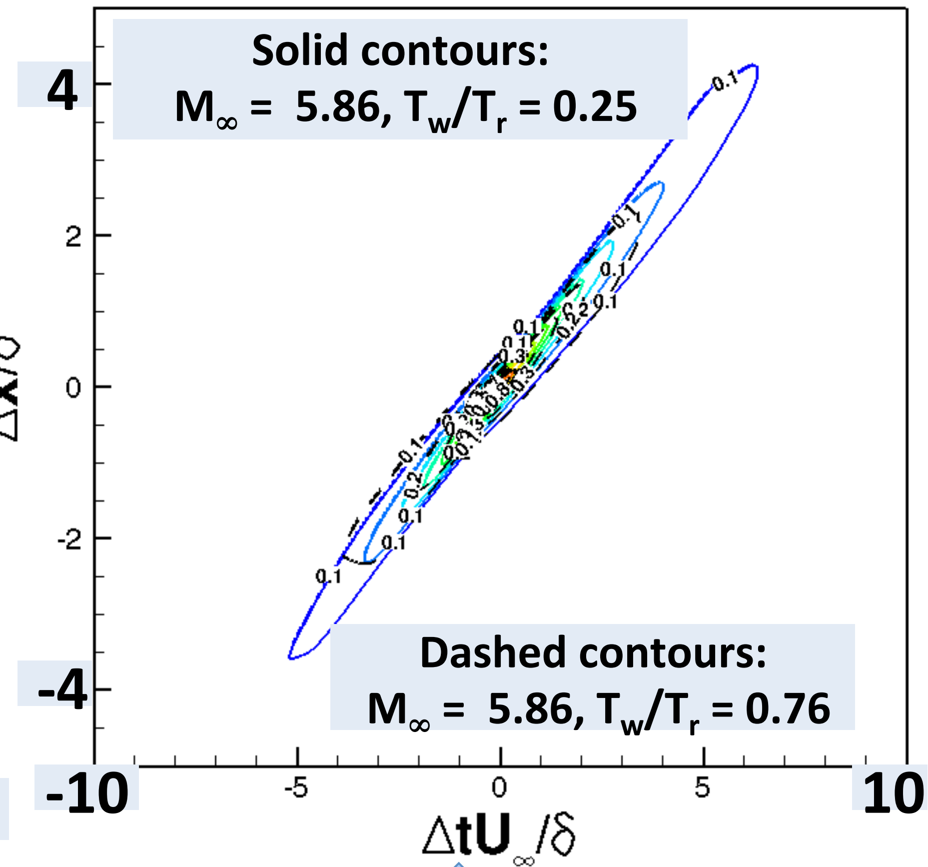
$$\frac{2C_h}{C_f} = 1.47$$

p_w, τ_w, *and* q_w show large fluctuations relative to the mean value

p'_w, τ'_w, *and* q'_w spectra peak at the same frequency of $f\delta/U_\infty \approx 2$

Propagation Speed of Acoustic Disturbance



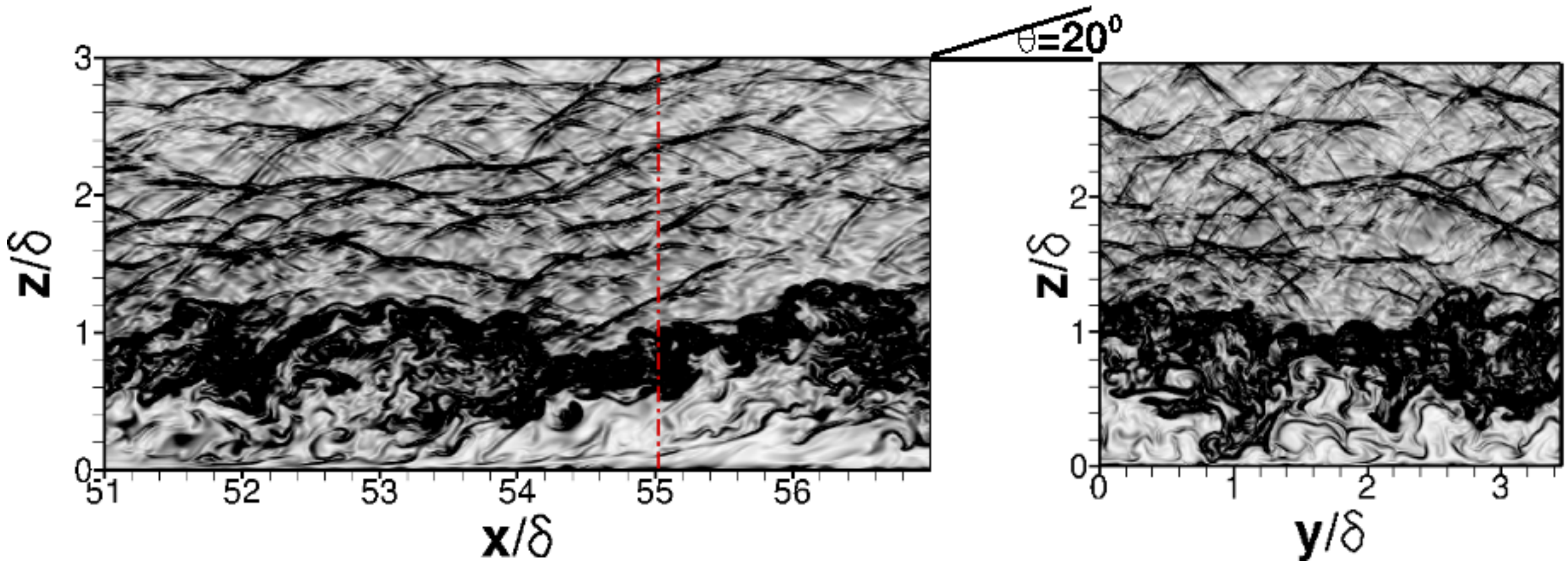


Faster propagation speed of freestream fluctuations as Mach number increases

Wall Temperature has subtle influence on the propagation speed of freestream fluctuations

Numerical Schlieren Visualization

$M_\infty = 14, T_w/T_r = 0.18$



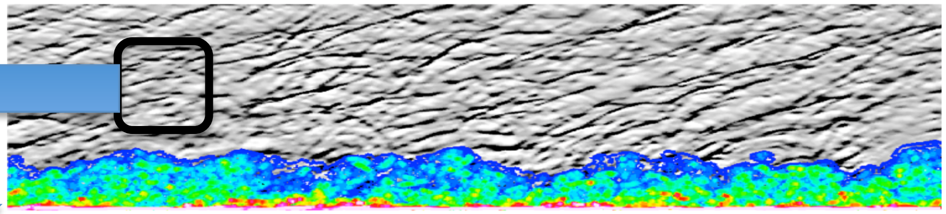
- Random
- Finite spatial coherence
- Preferred range of orientation for eddy Mach waves
  - Higher inclination than Mach wave direction

Summary and Conclusion

- Turbulence statistics and pressure fluctuations induced by a Mach 14 turbulent boundary layer were investigated
  - $M_\infty = 14$, $Re_\tau \approx 633$, $T_w/T_r = 0.18$ (a condition of AEDC Tunnel 9)
- Velocity fluctuations scales according to the Morkovin's scaling
- Property of pressure fluctuations varies dramatically as a function of wall-normal distance within the inner layer ($z/\delta < 0.08$ or $z^+ < 50$)
  - fluctuation magnitude p'_{rms}/τ_w
  - dominant frequency f_{pk} associate with pressure spectrum
- Fluctuating wall quantities (p'_w, τ'_w, q'_w)
  - Large fluctuation amplitude relative to the mean values (p'_{rm}/p_w =24%, $\tau'_{w,rms}/\tau_w$ = 53%, $q'_{w,rms}/q_w$ = 67%)
  - A match in dominant frequency among p'_w, τ'_w, q'_w with $f\delta/U_\infty \approx 2$
- Freestream pressure fluctuations involves a broadband peak centered at $f\delta/U_\infty \approx 0.7$

Outlook

Facility Disturbance + Receptivity



Freestream acoustic disturbances radiated from tunnel-wall turbulent boundary layers

Stochastic Acoustic disturbance field

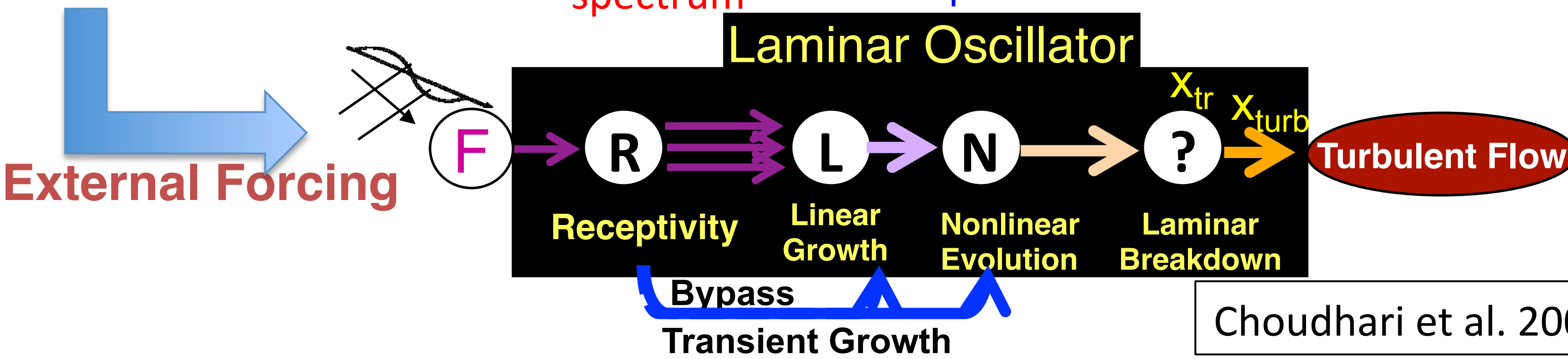
stochastic variables (Uc, θ, ϕ, ω, etc)

$$\begin{Bmatrix} u' \\ v' \\ w' \\ p' \end{Bmatrix} = \mathrm{Exp}\left[-i\omega t - i\omega/U_c \{x + \tan(\theta)\, z \pm \tan(\phi)\, y\} \right]$$

Frequency spectrum

Propagation Speed

Inclination angle



Choudhari et al. 2003

Provide “practical” input data regarding **disturbance environment** for conducting stability analysis in the context of actual wind-tunnel experiments

Enable holistic prediction of transition in High-Speed Boundary Layers

Acknowledgment

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  - for providing wind-tunnel measurements for comparison with DNS
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