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

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


- 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:

- $M_\infty = 2.5, T_w/T_r = 1.0$, Flat Plate
- $M_\infty = 5.86, T_w/T_r = 0.76$, 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
- $M_\infty = 14, T_w/T_r = 0.18$ ($M14Tw018$) 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 $p'$

\[ \Phi(\omega) = \frac{\Phi_w(\omega)}{p_{rms}^2} \]

\[ \frac{\omega \delta}{U_\infty} \]

- DNS, M6Tw076
- DNS, $M_\infty=2.5$
- Exp., Farabee & Casarella
- Exp., Beresh et al.
- DNS, Bernardini & Pirozzoli

\[ \frac{\omega \delta}{U_\infty} \]

- DNS, M6Tw076
- DNS, $M_\infty=2.5$
- Exp. Laufer, $M_\infty=2.0, \text{Re}_\infty=30000$
- Exp. Laufer, $M_\infty=4.5, \text{Re}_\infty=30000$
DNS Setup
Case M14Tw18

- **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*
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

\[
\begin{align*}
\langle U_{VD} \rangle &= (1/k) \log(z^+) + 6.1 \\
\langle U_{VD} \rangle &= (1/k) \log(z^+) + 5.2
\end{align*}
\]
Significantly improved collapse of data is achieved by Morkovin’s scaling.
Turbulent Mach Number and Fluctuating Mach Number

M14, \( T_w/T_r = 0.18 \)
Pressure Fluctuation Intensity

$p'_{\text{rms}}/\tau_w$ near the wall shows a strong wall-temperature dependence. $p'_{\text{rms}}/\tau_w$ 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.
Good convergence of p’ spectra in the free stream
Freestream p’ spectrum centered at $f\delta/U_\infty \approx 0.7$
Fluctuating Wall Quantities

\[ \tau'_{w,\text{rms}} = 53\% \quad \frac{q'_{w,\text{rms}}}{q_w} = 67\% \]

\[ \frac{p'_{w,\text{rms}}}{p_w} = 24\% \quad \frac{p'_{w,\text{rms}}}{\tau_w} = 4.41 \]

\[ \frac{2C_h}{C_f} = 1.47 \]

\[ p_w, \tau_w, \text{and } q_w \text{ show large fluctuations relative to the mean value} \]

\[ p'_w, \tau'_w, \text{and } q'_w \text{ spectra peak at the same frequency of } f\delta/U_\infty \approx 2 \]
The propagation speed of acoustic disturbance is influenced by wall temperature and Mach number. Faster propagation speed of freestream fluctuations as Mach number increases, while wall temperature has a subtle influence on the propagation speed of freestream fluctuations.

- **Solid contours:**
  - $M_\infty = 5.86, \frac{T_w}{T_r} = 0.25$
  - $M_\infty = 14, \frac{T_w}{T_r} = 0.18$

- **Dash-Dot contours:**
  - $M_\infty = 5.86, \frac{T_w}{T_r} = 0.76$

- **Dashed contours:**
  - $M_\infty = 2.5$
Numerical Schlieren Visualization

\[ M_\infty = 14, \frac{T_w}{T_r} = 0.18 \]

- 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 \((z/\delta < 0.08 \text{ or } z^+ < 50)\)
  
  - fluctuation magnitude \( p'_{\text{rms}}/\tau_w \)
  
  - dominant frequency \( f_{pk} \) associate with pressure spectrum

• Fluctuating wall quantities \( (p'_w, \tau'_w, q'_w) \)
  
  - Large fluctuation amplitude relative to the mean values \( (p'_{\text{rm}}/p_w = 24\%, \; \tau'_{w,\text{rms}}/\tau_w = 53\%, \; q'_{w,\text{rms}}/q_w = 67\%) \)
  
  - A match in dominant frequency among \( p'_w, \tau'_w, q'_w \) 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

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

External Forcing

Laminar Oscillator

Receptivity  Linear Growth  Nonlinear Evolution  Laminar Breakdown

Bypass  Transient Growth

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
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