Simulation of Acoustic Radiation from Turbulent Boundary Layers at High Mach Numbers

Lian Duan and Chao Zhang
Missouri University of Science and Technology
Rolla, MO 65409

Meelan Choudhari
NASA Langley Research Center
Hampton, VA 23693

NATO STO AVT-240 & RTG-082
Hypersonic Boundary-Layer Transition Prediction
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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 $M > 1$

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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**
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**Harvey, 1978**

- 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 $M > 1$
In a conventional ("noisy") tunnel, tunnel disturbances are dominated by acoustic radiation from tunnel wall turbulent boundary layers for $M > 2.5$ (Laufer, 1964).
Methodology

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 & Maidenik 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 only amplitude, 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
- $M_\infty = 14, T_w/T_r = 0.18$, Flat Plate (preliminary analysis)
  
  • Freestream condition representative of AEDC Tunnel 9 at $p_0 = 1,023$ psi
  • Comparison with Boundary-layer measurements at AEDC Tunnel 9 (Expected)
Outline

- DNS methodology
- Validation & Comparison with Experiments
- Effects of freestream Mach number and wall cooling on freestream p’ fluctuations
  - Intensity
  - Frequency spectrum
  - Space-time correlation
  - Wave-front orientation
- Effect of geometric confinement on acoustic radiation
- Concluding remarks
DNS Setup
Case M14Tw18

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

- Uniform grid in streamwise-spanwise directions
  - $\Delta x^+ \approx 9.9$, $\Delta y^+ \approx 4.9$
  - $\Delta z_w^+ \approx 0.5$, $N_z = 19$ for $z^+ < 10$,
  - $\Delta z_\delta^+ \approx 5.2$, $N_z = 186$ for $z < \delta$
  - $N_x \times N_y \times N_z = 2500 \times 460 \times 540$ (Total: 621 M)

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

- $M_\infty = 14$, $Re_\theta \approx 9540$, $Re_T \approx 461$, $T_w/T_r \approx 0.18$
Freestream Disturbance Field

- Freestream disturbance field is **acoustic** in nature
  - Small amplitude
  - Isentropic conditions hold
  - Sound mode >> vorticity mode

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_w/T_r$</th>
<th>$u'_{\text{rms}}/\bar{u}$</th>
<th>$v'_{\text{rms}}/\bar{u}$</th>
<th>$w'_{\text{rms}}/\bar{u}$</th>
<th>$p'_{\text{rms}}/\bar{p}$</th>
<th>$\rho'_{\text{rms}}/\bar{\rho}$</th>
<th>$T'_{\text{rms}}/\bar{T}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 2.5</td>
<td>1.0</td>
<td>0.00076</td>
<td>0.0005</td>
<td>0.0008</td>
<td>0.004</td>
<td>0.0028</td>
<td>0.0011</td>
</tr>
<tr>
<td>M6Tw025</td>
<td>0.25</td>
<td>0.0025</td>
<td>0.0016</td>
<td>0.0033</td>
<td>0.035</td>
<td>0.025</td>
<td>0.010</td>
</tr>
<tr>
<td>M6Tw076</td>
<td>0.76</td>
<td>0.0013</td>
<td>0.0010</td>
<td>0.0021</td>
<td>0.020</td>
<td>0.015</td>
<td>0.0059</td>
</tr>
<tr>
<td>M 14</td>
<td>0.18</td>
<td>0.0016</td>
<td>0.0015</td>
<td>0.0028</td>
<td>0.065</td>
<td>0.046</td>
<td>0.0185</td>
</tr>
</tbody>
</table>

\[ \frac{p'_{\text{rms}}}{\bar{p}} \approx \gamma \frac{\rho'_{\text{rms}}}{\bar{\rho}} \]

\[ \frac{\theta' \theta' / \omega_i \omega_i}{\infty} > 1000 \]

Contours of Dilatation

Contours of Vorticity
## Domain/Grid Sensitivity Assessment

### Case M6Tw076

<table>
<thead>
<tr>
<th>Case</th>
<th>$N_x \times N_y \times N_z$</th>
<th>$L_x/\delta_i$</th>
<th>$L_y/\delta_i$</th>
<th>$L_z/\delta_i$</th>
<th>$\Delta x^+$</th>
<th>$\Delta y^+$</th>
<th>$(\Delta z^+)_\text{min}$</th>
<th>$(\Delta z^+)_\text{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>$1600 \times 800 \times 500$</td>
<td>58.7</td>
<td>15.7</td>
<td>39.7</td>
<td>9.64</td>
<td>5.14</td>
<td>0.51</td>
<td>5.33</td>
</tr>
<tr>
<td>AI</td>
<td>$1920 \times 320 \times 500$</td>
<td>70.4</td>
<td>6.26</td>
<td>39.7</td>
<td>9.64</td>
<td>5.14</td>
<td>0.51</td>
<td>5.33</td>
</tr>
<tr>
<td>All</td>
<td>$2400 \times 480 \times 500$</td>
<td>58.7</td>
<td>6.26</td>
<td>39.7</td>
<td>6.43</td>
<td>3.43</td>
<td>0.51</td>
<td>3.55</td>
</tr>
</tbody>
</table>

Good agreement is achieved up to $\omega \delta / U_\infty \approx 25$ or $\omega v_w / u_t^2 \approx 1$
Comparison with Experiment (M6Tw076)

Mean flow predictions and \textbf{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 $p'$

$\Phi(\omega)/U_\infty^2 \rho_{rms}^2$

$\omega \delta/U_\infty$

$\omega^2$, $\omega^{-1}$, $\omega^{-7/3}$, $\omega^{-5}$

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

$\Phi(\omega)/U_\infty^2 \rho_{rms}^2$

$\omega \delta/U_\infty$

$\omega^{-1}$, $\omega^{-7/3}$, $\omega^{-5}$

DNS, M6Tw076
DNS, $M_\infty=2.5$
Exp. Laufer, $M_\infty=2.0, Re_\infty=30000$
Exp. Laufer, $M_\infty=4.5, Re_\infty=30000$
Random

Finite spatial coherence

Preferred range of orientation for eddy Mach waves
  ➢ Higher inclination than Mach wave direction
Effects of Freestream Mach number and Wall temperature on Free-stream $p'$ fluctuations
Pressure Fluctuation Intensity

\[ \frac{p'}{\tau_w} \] near the wall shows a strong wall-temperature dependence. \[ \frac{p'}{\tau_w} \] in the free stream increases with Mach number and is insensitive to wall temperature.
Pressure Fluctuation Intensity

Free stream

\[ p'_{\text{rms}} / \tau_w \]

In the free stream shows a strong Mach-number dependence, but is insensitive to wall temperature.
Wall $p'$ Frequency Spectra

**Outer scale**

- $\Phi(\omega)u_\infty^2/p_{rms}^2$ versus $\omega\delta/U_\infty$
- Lines for different $M$ and $T_w/T_r$ values:
  - M2.5, $T_w/T_r=1$
  - M6, $T_w/T_r=0.25$
  - M6, $T_w/T_r=0.76$
  - M14, $T_w/T_r=0.18$

**Inner scale**

- $\Phi(\omega)u_\infty^2/p_{rms}^2$ versus $\omega\nu_{\infty}/u_\infty^2$
- Lines for different $M$ and $T_w/T_r$ values:
  - M2.5, $T_w/T_r=1$
  - M6, $T_w/T_r=0.25$
  - M6, $T_w/T_r=0.76$
  - M14, $T_w/T_r=0.18$
Freestream $p'$ Frequency Spectra

**Outer scale**

\[ \frac{\Phi(\omega)}{\omega^5} \]

**Inner scale**

\[ \frac{\Phi(\omega)}{\omega^{11/3}} \]

- M2.5, $T_w/T_r=1$
- M6, $T_w/T_r=0.25$
- M6, $T_w/T_r=0.76$
- M14, $T_w/T_r=0.18$
Pre-multiplied $p'$ Frequency Spectra

Wall

Free stream

$\omega \langle \phi (\omega) \rangle / \rho'_{rms}$

$\omega \delta / U_\infty$

M2.5, $T_w / T_r = 1$
M6, $T_w / T_r = 0.25$
M6, $T_w / T_r = 0.76$
M14, $T_w / T_r = 0.18$

$M_\infty$
Wall Temperature has subtle influence on the propagation speed of freestream fluctuations as Mach number increases.
Wall Temperature has subtle influence on the propagation of freestream fluctuations
Preferred Orientation of Eddy Mach Waves

\[ \frac{U_b}{U_\infty} = 1 - \frac{1}{M_\infty \sin \theta} \]

\( M_\infty = 5.86, \frac{T_w}{T_r} = 0.76 \) (Purdue Quiet Tunnel, noisy run)

\( \theta = 30 \text{ Deg} \)

\( M_\infty = 14, \frac{T_w}{T_r} = 0.18 \) (AEDC Tunnel 9)

\( \theta = 28 \text{ Deg} \)
Summary and Conclusion

- Freestream acoustic radiation due to (nominally) high-speed turbulent boundary layers was investigated using DNS
  - \( M_\infty = 2.5, \ Re_\tau \approx 510, T_w/T_r = 1.0 \)
  - \( M_\infty = 5.86, \ Re_\tau \approx 465, T_w/T_r = 0.25, 0.76 \) (Purdue Quiet Tunnel, noisy run)
  - \( M_\infty = 14, \ Re_\tau \approx 461, T_w/T_r = 0.18 \) (AEDC Tunnel 9)

- Simulation results (mean flow prediction, wall \( p' \) frequency spectrum) in good agreement with existing data in literature

- Effects of \( M_\infty \) and \( T_w \) on freestream \( p' \)
  - Strong Mach number dependence
    \[
    M_\infty \uparrow \implies p'_{rms}/\tau_w \uparrow, \ \theta \text{ (wave orientation)} \downarrow, \ \frac{U_b}{U_\infty} \uparrow
    \]
  - Appears to be relatively insensitive to \( T_w \) (including \( p'_{rms}/\tau_w, \ U_b/U_\infty, \ \theta \))

- Computations provide additional details of the **anisotropic random** field that will be useful for modeling receptivity in conventional tunnels
Outlook
Facility Disturbance + Receptivity

Freestream acoustic disturbances radiated from tunnel-wall turbulent boundary layers

Stochastic Acoustic disturbance field

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

Stochastic variables (\(U_c, \theta, \phi, \omega,\) etc)

Frequency spectrum

Propagation Speed

Inclination angle

External Forcing

Laminar Oscillator

Freestream acoustic disturbances radiated from tunnel-wall turbulent boundary layers

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

(Choudhari et al. 2003)
Outlook

Facility Disturbance + Receptivity

Mimic the transition process in the tunnel-like environment

Potential contributions:
• Generate improved knowledge of receptivity process in facility-disturbance environment
• Investigate differences between receptivity to natural broadband disturbance and monochromatic plane-wave disturbances
• provide the initial disturbances in hypersonic boundary layers required for conducting stability analysis.

Ongoing collaborations with NATO STO AVT-240 group on Hypersonic Boundary-Layer Transition Prediction
• experimental and numerical studies on the second-mode wave of 7° sharp cone at zero angle of attack
Acknowledgment

• Drs. Steve Schneider and Katya Casper
  – For providing wind-tunnel measurements for comparison with DNS

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