Direct Numerical Simulations of Hypersonic Turbulent Boundary Layers

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Tutorial School on Fluid Dynamics: Topics in Turbulence
Center for Scientific Computation and Mathematical Modeling
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Examples
Space access and planetary entry

Shuttle – wind tunnel model

NASA Stardust
Comet Wild2

Wind Tunnels of NASA, NASA-SP-440, JAN 1, 1981

NASA CEV
Key Physical Features

High Temperature phenomena dissociation/recombination, ionization, radiation
surface catalysis and ablation

Pre-Flight

Post-Flight

ESA mission
Examples

Atmospheric hypersonic flight external and internal flows

NASA X-43A
Reusable launch vehicle

Boeing-AF X-51A
Reusable launch vehicle
Key Physical Features
Shock wave and turbulence interaction

Pratt & Whitney Generic Scramjet Engine

Flow inside a generic scramjet engine, no combustion
Courtesy of Mike Holden, CUBRC
Research Approach and Objectives

Detailed Simulations of Hypersonic Turbulent Boundary Layers (HTBL)

• HTBL competing fundamental processes
  • Mach number, heat transfer, real gas, radiation, roughness effects
  • Transpiration, blowing, surface recession, surface reactions

• Approach
  • Decouple fundamental processes
  • Validate numerical data against experimental data, as much as possible
  • Enhance experimental data
  • Understand fundamental processes

• Objective
  • Understand the fundamental physics of fully coupled problem
  • Develop a detailed simulation capability (DNS/LES) for the coupled problem
**Background: Key Relations**

- **Morkovin scaling:**  
  Any differences from incompressible turbulence can be accounted for by mean variations of fluid properties.  
  Basis for the van Driest transformation and intensity scaling, which can be used to predict the mean and fluctuation velocities

- **Strong Reynolds analogies:**  
  Relate fluctuating thermodynamic variables and velocity fluctuations  
  Give basis for the evaluation of Pr$_t$

- **Walz’s equation:**  
  Analytical result from governing equations for zero-pressure-gradient BL under negligible wall pressure and total temperature fluctuations

\[
\frac{T}{T_\delta} = \frac{T_w}{T_\delta} + \frac{T_r - T_w}{T_\delta} \left( \frac{\bar{u}}{u_\delta} \right) + \frac{T_\delta - T_r}{T_\delta} \left( \frac{\bar{u}}{u_\delta} \right)^2
\]

- **Effects of energetically dominant turbulence structure**  
  Direct connect between local flow physics and impact on the wall pressure and heat transfer
Background: Other Key Concepts

- **Intermittency**
  Gives a measure of the interaction between the irrotational fluid outside of the boundary layer and the viscous fluid within

- **Skin friction**
  Gives a measure of the viscous drag

- **Wall pressure and thermodynamic fluctuations**
  Relevant to gauge the structural and thermal design requirements

- **A priori assessment of turbulence-chemistry interaction (TCI)**
  Informs on the necessity to employ turbulence models to obtain accurate product formation and wall heating loads in design calculations

- **Accurate product formation**
  Pertains to the development of accurate scaling laws for temperature fluctuations
Mach Number Effects

Background

- Limited number of studies for boundary layers at high Mach numbers
  - Mikulla & Horstman AIAA J 1976
  - Owen & Horstman JFM 1972
  - Owen & Horstman AIAAJ 1972
  - Owen, Horstman & Kussoy JFM 1975
  - McGinley, Spina & Sheplak AIAA Paper 1994-2364
  - Sahoo & Smits AIAA Paper 2010-4471
  - Guarini, Moser, Shariff & Wray JFM 2001
  - Maeder, Adams & Kleiser JFM 2001
  - Martín AIAA 2004–2337

- Hot wire anemometry data: turbulent intensities below those in incompressible flow, not scaling according to Morkovin’s scaling
  Owen & Horstman JFM 1972; McGinley et al 1994 (possible poor frequency response)

- PIV data gave much larger turbulence intensities
  Sahoo & Smits AIAA 2010-1559 (possibly low seeding particle densities)

- Maeder et al (2001) DNS data show Reynolds stress profiles that are fuller than those for incompressible flow but computational domain sizes were suspect

- Comparisons between DNS and experiments have been at moderate Mach numbers
### Mach Number Effects

Martín 2004-2337, Beekman et al AIAA-2009-1328
Duan, Beekman & Martín AIAA 2010-0353

<table>
<thead>
<tr>
<th>Case</th>
<th>$M_\delta$</th>
<th>$\rho_\delta$ (kg/m³)</th>
<th>$T_\delta$ (K)</th>
<th>$T_w/T_\delta$</th>
<th>$Re_\theta$</th>
<th>$Re_\tau$</th>
<th>$Re_{\delta_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3</td>
<td>2.99</td>
<td>0.0891</td>
<td>218.2</td>
<td>2.60</td>
<td>2606</td>
<td>413</td>
<td>1361</td>
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<tr>
<td>M4</td>
<td>3.98</td>
<td>0.0914</td>
<td>219.2</td>
<td>3.83</td>
<td>3407</td>
<td>406</td>
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<tr>
<td>M5</td>
<td>4.97</td>
<td>0.0910</td>
<td>221.8</td>
<td>5.37</td>
<td>4086</td>
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<td>M6</td>
<td>5.93</td>
<td>0.0942</td>
<td>221.9</td>
<td>7.30</td>
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<tr>
<td>M7</td>
<td>6.94</td>
<td>0.0922</td>
<td>221.1</td>
<td>9.62</td>
<td>5574</td>
<td>358</td>
<td>1336</td>
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<tr>
<td>M8</td>
<td>7.80</td>
<td>0.0948</td>
<td>227.7</td>
<td>11.9</td>
<td>6817</td>
<td>345</td>
<td>1360</td>
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<tr>
<td>M12</td>
<td>11.93</td>
<td>0.0921</td>
<td>228.0</td>
<td>27.6</td>
<td>9842</td>
<td>328</td>
<td>1384</td>
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</tbody>
</table>

\[
Re_\theta = \frac{\rho_\delta u_\delta \theta}{\mu_\delta} \quad Re_\tau = \frac{\rho_w u_\tau \theta}{\mu_w} \quad Re_{\delta_2} = \frac{\rho_\delta u_\delta \theta}{\mu_w}
\]
Wall Temperature Effects

Background

• Limited number of detailed studies of heat transfer in HTBL
  • Gaviglio IJHMT 1987
  • Rubesin NASA CR 177556 1990
  • Huang, Coleman & Bradshaw JFM 1995
  • Maeder, Adams & Kleiser JFM 2001
  • Morinishi, Tamano & Nakabayashi JFM 2004

• Most of the work focused on the validity of the SRA
Wall Temperature Effects
Martín 2004-2337, Beekman et al AIAA-2009-1328
Duan, Beekman & Martín JFM 2010

<table>
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<th>$T_\delta$ (K)</th>
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<th>$Re_\theta$</th>
<th>$Re_T$</th>
<th>$Re_{\delta^2}$</th>
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<tbody>
<tr>
<td>M5T1</td>
<td>4.97</td>
<td>0.0890</td>
<td>228.1</td>
<td>1.00</td>
<td>1280</td>
<td>798</td>
<td>1538</td>
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<tr>
<td>M5T2</td>
<td>4.97</td>
<td>0.0890</td>
<td>228.1</td>
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<td>M5T3</td>
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<td>224.1</td>
<td>2.89</td>
<td>3010</td>
<td>522</td>
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<td>221.0</td>
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<td>4840</td>
<td>386</td>
<td>1536</td>
</tr>
</tbody>
</table>

$T_w/T_r$ varies from 1 to 0.1 with decreasing $T_w$
Turbulence Chemistry Interaction (TCI)  

**Background**

- Limited number of studies for hypersonic boundary layer applications on single binary reaction mechanisms
  - Eschenroeder Phy Flu 1964
  - Martín & Candler Phys Flu 1998
  - Martín & Candler Phys Flu 1999
  - Martín & Candler AIAA 2001-2717
  - Martín AIAA 2003-4045

- Following Martín and Candler (1998), the turbulence/chemistry interaction depends on
  - The relative time scales of turbulence and chemical production, or turbulent Damköhler number
  - The relative heat release, the ratio of energy added to the system, relative to the energy that is present locally in the flow

- When the Damköhler number approaches one, there is interaction, which is modulated by the relative heat release.

- If the relative heat release is small, the interaction is insignificant
Real Gas Effects (RGE)

Half-cone angle 32° at 24 km, 100 nose radii downstream and free stream Mach number of 21
Duan & Martín AIAAJ 2009

<table>
<thead>
<tr>
<th>Case</th>
<th>$M_0$</th>
<th>$\rho_0$ (kg/m³)</th>
<th>$T_0$ (K)</th>
<th>$T_w/T_r$</th>
<th>$Re_\theta$</th>
<th>$Re_T$</th>
<th>$Re_{\delta_2}$</th>
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</thead>
<tbody>
<tr>
<td>RGE</td>
<td>4.26</td>
<td>0.0468</td>
<td>3408.6</td>
<td>0.1</td>
<td>510</td>
<td>649</td>
<td>312</td>
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<tr>
<td>No RGE</td>
<td>4.26</td>
<td>0.0468</td>
<td>3408.6</td>
<td>0.1</td>
<td>510</td>
<td>649</td>
<td>312</td>
</tr>
</tbody>
</table>

- Five reaction mechanism for air
- Arrhenius parameters
- Equilibrium constant from Gibbs free energy functions of temperature fitted to Park (1990) expressions
- Gupta et al (1990)-Yos (1963) mixing rule for transport properties
- Multicomponent diffusion model Ramshaw (1990)
- Equilibrium catalytic binary condition
- Roe’s matrix extended for multi-species calculations
- Direct measure of TCI by comparing $w(T, cs)$ and $w(T, cs)$
## Summary of Results

<table>
<thead>
<tr>
<th></th>
<th>Mach trend with Ma ↑</th>
<th>$T_w$ trend with $T_w$ ↓</th>
<th>RGE Trend with RGE</th>
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</thead>
<tbody>
<tr>
<td>Morkovin</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SRA Huan et al JFM 1995</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Walz equation</td>
<td>✓</td>
<td>departure ↑</td>
<td>departure $T_w$ effect</td>
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<tr>
<td></td>
<td></td>
<td>up to 10%</td>
<td></td>
</tr>
<tr>
<td>Intermittency</td>
<td>↓</td>
<td>↑</td>
<td>$T_w$ effect ↑</td>
</tr>
<tr>
<td>Skin Friction</td>
<td>↓</td>
<td>↑</td>
<td>$T_w$ effect ↑</td>
</tr>
<tr>
<td>$U_{packet}$</td>
<td>↑</td>
<td>↓</td>
<td>$T_w$ effect ↓</td>
</tr>
<tr>
<td>Packet coherence</td>
<td>↓</td>
<td>↑</td>
<td>↓ RGE</td>
</tr>
<tr>
<td>$P'_{w,rms}$</td>
<td>↑ up to 15%</td>
<td>↑</td>
<td>Twofold ↑</td>
</tr>
<tr>
<td></td>
<td>&lt;1% to 9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermodynamic</td>
<td>↑</td>
<td>↓</td>
<td>↓ RGE</td>
</tr>
<tr>
<td>fluctuations</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Up to 40%</td>
<td></td>
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</table>
**Background on Performing DNS**
*Direct and Large Eddy Simulations (DNS and LES) for Compressible Turbulence*

- DNS/LES were well-developed for incompressible flows
  - NOT for compressible flow

- Require **high bandwidth** resolving efficiency and **shock capturing**
  - Attention to numerical dissipation

- **Implicit time integration** to alleviate stringent stability criteria
  - small wall-normal spacing and large speed of sound

- Starting a simulation from a laminar/random **initial condition**
  - Attention to cost
  - Control of flow conditions

- Require continuous **inflow conditions**
Initialization Procedure Development

Initial flow field resembles true flow mean, statistics, structure and spectra
Initial transient less than 10% of time required for gathering statistics

- Mean flow: Baldwin-Lomax RANS calculation (DPLR Code, NASA Ames)
  - Prescribe Mach and Reynolds numbers

- Locally transform velocity fluctuations using Morkovin’s scaling
  \[
  \left( \sqrt{\frac{\rho}{\rho_w}} \frac{u_i'}{u_\tau} \right)_{M>1} = \left( \sqrt{\frac{\rho}{\rho_w}} \frac{u_i'}{u_\tau} \right)_{M<1} \quad (\text{Spalart}1998)
  \]

- Locally compute thermodynamic fluctuations from SRA analogy
  \[
  T' = -(\gamma - 1) M^2 \frac{u'}{\bar{u}} \bar{T}
  \]
  \[
  \frac{\rho'}{\bar{\rho}} = -\frac{T'}{\bar{T}}
  \]
Inflow Condition Development

Origin: Lund et al. (1998) for incompressible flows
Xu & Martin: Phys. Flu 2004

- Generalized rescaling relations
  - Velocity
  - Thermodynamic variables
  - Mean
  - Fluctuations
Inflow Condition Development
Origin Lund et al. (1998) for incompressible flows
Xu & Martin Phys. Flu 2004

Pre-multiplied velocity energy spectrum in the freestream \((z=1.8\delta)\)

The filtering does not introduce any forcing in the flow.
Developed Numerical Methods and Simulations Methodologies for Detailed Simulations of HTBL

- Shock capturing, implicit time integration and continuous turbulence inflow data

1. Xu & Martín  *Phys Flu* 2004
2. Martín & Candler *JCP* 2006
4. Taylor & Martín *JCP* 2007
5. Taylor, Wu, & Martín *JCP* 2007
6. Wu & Martín *AIAAJ* 2007
7. Taylor & Martín *CiCP* 2008

- So far, satisfactory results for DNS and LES over flat plates
Validated Detailed Simulations

- For high-temperature phenomena
  8. Duan & Martín  AIAA J 2009

- For turbulent boundary layers against experiments at the same conditions
  9. Martín  JFM 2007
  10. Wu & Martín  AIAAJ 2007
  11. Ringuette, Wu & Martín  JFM 2008

- In the presence of shock waves against experiments and grid convergence
  10. Wu & Martín  AIAAJ 2007
  11. Ringuette, Wu & Martín  JFM 2008
  12. Duan & Martín  accepted JFM 2010
  13. Ringuette, Wu & Martín  AIAAJ 2008
  14. Duan, Beekman, & Martín  under consideration for publication in JFM
  15. Duan Beekman, Martín  AIAA 2010-0353
  16. Beekman, Priebe, Ringuette & Martín  AIAA 2009-1328
Validated DNS Data

Magnitude of Velocity Fluctuations in a Turbulent Boundary Layer

$Ma_e = 2.32, Re_\theta = 4450$ from Martín JFM 2007
Validated DNS Data
Mach 2.9, $Re_\theta$=2300 and 24° compression corner
Wu & Martin AIAAJ (2007)

Mean wall-pressure distribution
Experimental error bars at 5%

DNS data predicts experiment:
- Upstream boundary layer
- Mean and RMS wall pressure
- Size of separation bubble
- Velocity profile downstream of interaction
- Mass flux turbulent intensity
- Characteristic low and high frequencies
Low-Reynolds Number Effects
Mach 2.9, $Re_\theta=2300$ and $24^\circ$ compression corner

Dolling & Murphy AIAA J 1983 experiment
Frequencies from Selig et al., AIAAJ 1989

Ringuette & Smits AIAA 2007-4113 experiment

Wu & Martín AIAA J 2007 DNS
Validated DNS Data

Mach 2.9, $Re_\theta=2300$ and $24^\circ$ compression corner

Ringuette & Martín AIAAJ 2008

\[
\begin{align*}
\left(p'_{\text{wall}} + p'_{\text{noise}}\right)^2 & \approx p'_{\text{wall}}^2 + p'_{\text{noise}}^2 \\
p'_{\text{noise}}^2 & = \text{freestream value} \\
p'_{\text{noise}}^2 / p'_{\text{wall}}^2 & = 4\% \text{ upstream of shock} \\
& \text{16\% downstream}
\end{align*}
\]
Validated DNS Data

Temperature Profile in a Laminar Hypersonic Boundary Layer

$Ma_e = 4.0$, $Le = 1$, non-catalytic isothermal wall with $T_e = T_w = 1$, $Re_l = 1000$

$N_2 + M \rightarrow 2N + M$

from Duan & Martín AIAA J 2008

Validating real gas implementation and constitutive relations
Validated DNS Data

Local Skin Friction in a Spatially Evolving Turbulent Hypersonic Boundary Layer
SDNS compared with semi-empirical prediction and LS minimization data reduction
$Ma_e = 4.0$ from Xu & Martín  Phys. Flu. 2004
Validated DNS Data

Wall-Pressure Signal in Frequency Space from Experiments and DNS
Mach 2.9, $Re_\theta$=2300 and 24° compression corner
Ringuette, Wu & Martín AIAAJ 2008

$U_\infty/\delta$

Exp 90kHz
DNS 95kHz

$f_{\text{low}}$ (0.6 – 0.8) kHz (0.6 – 1.2) kHz

$f_{\text{high}}$ (20 – 30) kHz (17 – 95) kHz

High frequency Resolution 50kHz 950kHz

DNS data for 304 $\delta/U_\infty$
Learning from DNS data
Coherent Structures in Turbulent Boundary Layers

Background

- Hairpin vortices (horseshoes, canes, etc)

- Hairpin vortices are organized into ‘packets’
  - Adrian, Meinhart & Tomkins (JFM 2000)
  - Ganapathisubramani, Longmire & Marusic (JFM 2003)

- Very long (>10δ in the streamwise direction) low-momentum regions exist in the log layer
  - Very-large-scale motions or VSLM (Kim & Adrian, PoF 1999)
  - Superstructures (Hutchins & Marusic JFM 2007)

- It has been proposed that groups of streamwise-aligned hairpin packets induced the low-momentum regions beneath them
  - VLSM model of Kim & Adrian (PoF 1999)
Coherent Structures in Turbulent Boundary Layers

Background

- There is relatively very little data on compressible wall-bounded flows

- Ganapathisubramani et al. (JFM 2006) observed superstructures in a Mach 2 boundary layer using PIV

- Ringuette, Wu & Martin (JFM 2008) investigated the outer layer structure in DNS data of a Mach 3, $Re_0=2300$ boundary layer
  - Observed hairpin packets
  - Observed superstructures
  - Showed that packets cluster above superstructures as hypothesized by Kim & Adrian (PoF 1999)

- Van Oudheusden, Delf University of Technology, PIV studies of supersonic boundary layers
Boundary Layer Structure Analysis

Motivation

Motivation: Hairpin packets and superstructures carry a significant fraction of the Reynolds shear stress and TKE
  - Ringuette, Wu & Martin (JFM 2008) find one third of TKE in the log-layer is in the superstructures

Aims:
  - Identify ‘strong’ packets in DNS data
  - Track the hairpin packets over time
  - Develop physics-based identification and tracking technique using
    - geometric packet algorithms (Ringuette, Wu & Martin, JFM 2008)
    - enhanced correlation analyses (Brown & Thomas, PoF 1974)
    - O’Farrell & Martin JoT 2009

- Characterize packet properties, wall signatures and the relevant frequencies
  - Priebe, Beekman, Ringuette & Martin (APS DFD 2008)
  - Beekman, Priebe & Martin (APS DFD 2008, AIAA 2009-1328)
Characteristics of upstream boundary layer

Superstructures exist in DNS data

Wu & Martin AIAAJ 2007 and Ringuette, Wu & Martin JFM 2008

Rake signal from DNS data at $z_n=0.2\delta$

Contours of velocity on streamwise-spanwise planes

$x$-axis reconstruction using Taylor’s hypothesis with convection velocity of $0.76U_\infty$

Data are averaged in $x=4\delta$ intervals
Packet Identification
Part I: Geometric Analysis

- Geometric packet finding algorithm of Ringuette, Wu & Martin (JFM 2008)
  - Identifies hairpin heads using two thresholds
    - Swirling strength: \( \lambda_{ci} \geq 4.5\lambda_{ci} \)
    - Vorticity: \( \omega_y \geq \omega_y + 2\sigma(\omega_y) \)
  - Finds Ideal packets conforming to a set of geometric characteristics
    (following the hairpin packet of Adrian et al. JFM 2000)
    - Hairpin heads are closely spaced in the streamwise direction
    - Heads belonging to a packet are arranged at an acute angle to the wall (\( \leq 45^\circ \))

\[ U_c = 0.69U_\infty \]
Correlate the shear stress at the wall with the streamwise mass flux at various wall-normal locations (following Brown & Thomas PoF 1977)

\[ R_{\tau_w(\rho u)}(\Delta x) = \frac{1}{(x_2 - x_1)} \left( \frac{1}{\tau_{w,RMS}(\rho u)^{RMS}} \right) \int_{x_1}^{x_2} \tau'_w(x)(\rho u)'(x + \Delta x)dx \]

Correlation profiles peak at increasing streamwise separation, indicating the presence of a downstream-leaning coherent structure.

If, at a specified wall-normal distance, the instantaneous peak correlation exceeds the average peak value by a factor of 5, a `strong’ event is present.

Correlation profiles for DNS data of a Mach 3 turbulent boundary layer, following Brown and Thomas PoF 1977.
Packet Identification
Part III: Interpretation of Geometric Analysis

Instantaneous volume visualization connecting low-speed superstructures with “geometric” hairpin packets
Contours of velocity (for $u < \overline{U_{\text{packet}}}$)
Ticks mark location of hairpin vortices belonging to “geometric” packets

Similar to above with color contours and iso-surface of swirling strength at 3.5 times the time and volume averaged

Mach 4
Re$_0$=3400

Mach 8
Re$_0$=5700
**Analytic Tools**

*Part III: Relationship between geometric and correlation analysis*

O‘Farrell & Martin, JoT 2009

**Right:** Strong, average, and weak vortex convection velocity profiles for geometrically ideal packets, vortex convection velocity profile for all statistically strong events, and mean flow velocity profile.

**Below:** Regions of elevated Brown and Thomas correlations (gray) and ‘geometric’ events at the wall.
Analytic Tools

Part IV: Packet Tracking

Tracking a lone hairpin and the hairpins it spawns to form a packet in an incompressible channel flow (DNS). (After O’Farrell senior thesis, 2008, Princeton University; data courtesy of Green, Rowley & Haller, JFM 2007)


O’Farrell & Martin, JoT 2009
Analytic Tools
Part V: Packet Wall Signatures


A lone, synthetically generated hairpin vortex and associated wall signature in incompressible channel flow. (After O’Farrell senior thesis, Princeton University, 2008; data courtesy of Green, Rowley & Haller, JFM 2007)
Identification and Tracking of Hairpin Packets

DNS of Mach 4 turbulent boundary layer
Wall signatures

Shear stress

Pressure

Signals taken at $y/\delta = -0.35$
Identification and Tracking of Hairpin Packets
DNS of Mach 8 turbulent boundary layer
Wall signatures

Mach 8 \(Re_\theta\) 5400

shear stress wall signal

pressure wall signal

Synthetically generated hairpin in incompressible channel flow

Taken from O’Farrell, Senior Thesis, Princeton Univ. 2008
Other On-Going Work
Flow physics

- Completed reports on statistics
  - PART I: Initialization and validation, JFM 2007
  - PART II: Heat Transfer Effects, JFM 2009 with Duan & Beekman
  - PART III: March Number Effects, under consideration JFM, with Duan & Beekman
- Reporting:
  - Real gas effects, wall catalytic effects, with Duan
  - Radiation emission effects, under consideration AIAAJ, with Duan, Levin and Modest
- Studying turbulence structure origins and evolution
  Heat transfer effects, Mach number effects, with Beekman & Priebe
- Roughness and transpiration studies, joined experiments and simulations with Beekman
  experimental collaboration with A.J. Smits at Princeton
- Robust/validated large-eddy simulation methodologies for high Mach number and high temperature flow physics, with Grube
There are abundant physical phenomena that remain unexplored

Developed numerical methods and methodologies
- Accurate numerical solutions are possible
- Parametric studies are feasible
- Developing analytical tools for data interpretation

Numerical error is within experimental uncertainty

Simulation run time is of the order of the experiment turn-around time

Detailed data is a terrific playground for developing understanding and predictive capabilities for large-scale calculations

Timely opportunity to make significant advances in this area

Conclusion
Turbulent hypersonic flows