Experimental Details for the VT-NASA CFD Turbulence Model Blind Validation Challenge

Center for Research and Engineering in Aero/Hydrodynamic Technologies

K. T. Lowe, C. J. Roy, A. Borgoltz, W. J. Devenport, A. Grzyb, M. Shanmugam, A. Borole
Kevin T. Crofton Dept. of Aerospace and Ocean Engineering, Virginia Tech

A. Gargiulo
Dept. of Mechanical and Aerospace Engineering, University of Virginia
Team for Validation Challenge

Students:
(Not shown: JoJo Chen and Derek Li)

Many thanks to NASA for support under NRA Grant Nos. 80NSSC18M0146 and 80NSSC22M0061, Program Monitors Michael Kegerise and Mujeeb Malik.

Also, thanks to our assessors, Drs. Bill Oberkampf and Mory Mani

Further kind acknowledgements to Daniel MacGregor and Philippe Lavoie at UTIAS.
BeVERLI addresses 3D, smooth wall separation

- RANS and turbulence modeling workhorse in CFD
  - DNS and LES still expensive
  - CFD for high-impact decisions
- Benchmark Validation Experiments for RANS/LES Investigations (BeVERLI) hill case
  - CFD validation experiment at highest levels of completeness
  - Simple hill geometry encapsulating effects of 3D, non-equilibrium TBLs
  - Experiment and simulations

- NATO AVT-349
  - Members from academia, gov. and non-gov. labs, and industry around the globe
  - Advance accuracy and range of prediction models for high Reynolds number non-equilibrium TBLs
The BeVERLI Hill Configuration

BeVERLI = Benchmark Validation Experiment for RANS/LES Investigations

Stability Wind Tunnel

- Test section 1.85×1.85×7.3 m
- Top flow speed 85 m/s, Re=5×10^6/m
- Very low turbulence levels
- Interchangeable hard wall and acoustic test sections.
- Modular test section wall structure allows acoustic test section to also be configured as hard wall
- Serves research, education (including undergraduate courses), outreach
- Non-profit cost center

<table>
<thead>
<tr>
<th>Freestream Velocity $U_\infty$ (m/s)</th>
<th>Turbulence Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.016%</td>
</tr>
<tr>
<td>21</td>
<td>0.021%</td>
</tr>
<tr>
<td>30</td>
<td>0.024%</td>
</tr>
<tr>
<td>48</td>
<td>0.029%</td>
</tr>
<tr>
<td>57</td>
<td>0.031%</td>
</tr>
</tbody>
</table>
NATO AVT-349 Non-Equilibrium Turbulent Boundary Layers in High Reynolds Number Flow at Incompressible Conditions

- Success of gene expression programming for improving surface pressure performance
- Mesh sensitivity
- Need for geometrically asymmetric cases
- Non-uniqueness seems fundamental to three-dimensional separation

University of Melbourne
(Richard Sandberg)

École Centrale de Nantes – CNRS
(Michel Visonneau)
The BeVERLI Hill Geometry Produces a Wide Spectrum of Flow Physics

0° yaw case (bluff case)
- Asymmetric
- Unsteady/switching asymmetry
- Reduced skewing

45° yaw case (streamlined case)
- Reynolds number-dependent symmetry
- Steady asymmetry

The blind validation challenge focuses on an asymmetric yaw case, 30° orientation.
The Experiments Were an Integral Part of Undergraduate Student Labs

Stability Wind Tunnel project seeks better data for aerodynamic models

Oct 31, 2023

~200 undergraduate students participated in the validation challenge experiments
Boundary and Reference Conditions

Measurements

Reference pressures measured 2.2275 m upstream of hill center: test section geometry effects

Measured 1.93 m upstream from center of Hill

<table>
<thead>
<tr>
<th>$Re_H$</th>
<th>250,000</th>
<th>650,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{0.95}$ (mm)</td>
<td>$43.0 \pm 1.5$</td>
<td>$38.5 \pm 1.3$</td>
</tr>
<tr>
<td>$\delta^*$ (mm)</td>
<td>$8.3 \pm 0.2$</td>
<td>$6.8 \pm 0.2$</td>
</tr>
<tr>
<td>$\theta$ (mm)</td>
<td>$6.1 \pm 0.2$</td>
<td>$5.2 \pm 0.2$</td>
</tr>
</tbody>
</table>

(a)
Hill Measurements: Overview

Optical Techniques

Flow

Surface Pressure
Hill Measurements: Overview

Optical Techniques

Conformal Windows

OFI target

Flow

Surface Pressure
Pressure and Oil Flow Viz

- 135 precision taps on Hill
- Pressure scanners:
  - Esterline 9816/98RK pressure scanners
  - DTC ESP 32HD with unsteady response

Kerosene/titanium oxide/oleic acid mixture

\[ \text{Re}_H = 650 \text{k} \]
Laser-Doppler Velocimetry

- Custom, fiber-optic, embedded LDV probe
- Measurement volume of $63 \mu m \times 63 \mu m \times 50 \mu m$
- Low Stokes number, 0.2-0.3 $\mu m$ diameter smoke particles
- AUR Studio acquisition and processing software

LDV results only at $Re_H = 250k$

Stereoscopic Particle-Image Velocimetry

- LaVision, 12.6 kHz high-speed stereoscopic PIV system
- Low Stokes number, 0.2-0.3 μm diameter smoke particles

Gargiulo et al. (2023)
Oil Film Interferometry

- Silicone oil applied to cylindrical portions of hill
- Fringe processing yields Cf
Uncertainty Quantification Approach

• A priori: How well do your instruments measure what you think you are measuring?
  • Propagation of instrumentation-driven uncertainties

• A posterior: How well did the experiments and measurements reflect the reported/intended boundary conditions?
  • Geometric symmetries
  • Replicate measurements
  • Leveraging multiple diagnostics

Note: PIV uncertainty is still a work in progress, left off of plots coming up in next talk.
Wall Static Pressure

![Graph showing wall static pressure with X and X3 axes, and different pressure values for 250k and 650k.]
Wall Static Pressure

- Tap Orientation
- Centerline
- Centerspan
- Top Wake
- Top Wind
- Bottom Wake
- Bottom Wind
- Bump Outline

Graph showing $C_{p+1}$ vs. X, m with data points for 250k and 650k.
PIV Planar Results

\[ R_{eH} = 250k \]
\[ R_{eH} = 650k \]

\[ Re_H = 650k \]
Mean \( U/ U_{ref} \)
PIV Planar Results

\[ R_{eH} = 250k, \quad R_{eH} = 650k \]

\[ Re_H = 650k \]

Mean \( V/U_{ref} \)
PIV Planar Results

\[ \text{Re}_H = 650k \]

\[ \frac{\rho uu}{\rho U^2_{	ext{ref}}} \]
PIV Planar Results

\[ Re_H = 650k \]

\[ \rho v/v_{ref} \]

- LDV Profiles
- OFI Points
- PIV Planes

\[ x \times 10^{-3} \]

\[ 6 \]

\[ 5 \]

\[ 4 \]

\[ 3 \]

\[ 2 \]

\[ 1 \]

\[ 0 \]
PIV Planar Results

\[ Re_H = 650k \]

\[ \rho u v / \rho U_{ref}^2 \]

- LDV Profiles
- OFI Points
- PIV Planes

(your diagram here)
PIV Planar Results

\[ Re_H = 650k \]
PIV Planar Results

$Re_H = 650k$
LDV Mean Velocity Profiles: \( \text{Re}_H = 250k \)
LDV Reynolds Stress Profiles: $\text{Re}_H = 250k$
OFI/LDV Wall shear comparisons
Wrap up

• Measurements were the culmination of several major wind tunnel entries focused on the BeVERLI Hill
• Results covered district regimes of interest on the Hill, providing a range of possible comparisons and model validation measures
• Moving forward, the data will be archived for further validation studies by the community

Thanks so much for the attention and all the engagement throughout the BeVERLI project.