Test Cases for NASA’s Revolutionary
Computational Aerosciences
Technical Challenge

Part 2: Standard Test Cases for Propulsion

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Introduction

• Revolutionary Computational Aerosciences (RCA) Technical Challenge*:
  – Identify and down-select critical turbulence, transition, and numerical method technologies for 40% reduction in predictive error against standard test cases for turbulent separated flows, evolution of free shear flows and shock-boundary layer interactions on state-of-the-art high performance computing hardware.
  – Timeframe: by 2017

• Discussions held with AIAA Turbulence Modeling Benchmark Working Group (TMBWG) and others
  – Ideas for good (representative) cases
    • Simple enough to be useful (avoid complex geometries that introduce uncertainties)
    • Possess the relevant flow physics
  – Ideas for evaluation metrics
  – By defining “common” cases and metrics, unbiased evaluation of future model improvements will be easier

* see: https://www.aeronautics.nasa.gov/fap/aeronautical_sciences.html
Introduction, cont’d

• Issue 1:
  – There are too many cases out there, and everyone has their own favorite
• Solution 1:
  – Highlight top 2-3 representative “primary” cases for each category, but list many others as optional

• Issue 2:
  – Many cases exist for which RANS “fails” but LES/DNS/hybrid “succeeds”
• Solution 2:
  – Interpret differently: For RANS, look for 40% improvement in results; for LES/DNS/hybrid, look for 40% improvement in time-to-solution for those cases where the prediction is already good

• Issue 3:
  – Impossible to agree on metrics; they are either too simplistic or too difficult to define
• Solution 3:
  – Define some relevant metrics for the primary cases, but allow some leeway and use judgment
Separated Flow Cases
2-D NASA Hump
Greenblatt et al

- Rationale for: excellent high-quality reference experimental data set; good 2-D characteristics; includes both baseline and flow control; RANS known to do poorly; eddy-resolving methods have been shown to do well; well-vetted in previous workshop

- Rationale against: endplates introduced some blockage

Baseline case: Typical RANS 35% error in bubble size (overprediction)
2-D NASA Hump (cont’d)

Baseline case: Typical RANS turbulent shear stress too small in magnitude in separated shear layer of bubble
2-D NASA Hump (cont’d)

• **General validation metrics:**
  – Separation and reattachment locations
  – Turbulent shear stress profiles
  – Velocity profiles
  – Surface pressure and skin friction coefficients

• **Specific validation metrics:**

\[
\frac{(x/c)_{sep} - 0.665}{0.665} \quad \frac{(x/c)_{reattach} - 1.1}{1.1}
\]

\[\left[ \frac{(u'v'/U^2_{ref})_{min@x/c=0.8} + 0.020}{0.020} \right] \approx -45\%
\]

– From first two, can find bubble size relative to experiment
– Current typical RANS for baseline case:

\[
\left[ \left\{ \frac{(x/c)_{reattach} - (x/c)_{sep}}{0.435} \right\} - 0.435 \right] \approx 35\%
\]

\[\left[ \frac{(u'v'/U^2_{ref})_{min@x/c=0.8} + 0.020}{0.020} \right] \approx -45\%\]
Axisymmetric Transonic Bump

Bachalo & Johnson

- Rationale for: includes shock-induced separation; widely-used dataset for many years; axisymmetry removes 2-D questions; RANS OK for some aspects but poor for others

- Rationale against: old experiment; no experience yet with eddy-resolving methods

Axisymmetric Transonic Bump (cont’d)

Typical RANS: $C_p$ can be reasonable, but 20-30% error in bubble size (overprediction)
Axisymmetric Transonic Bump (cont’d)

Typical RANS: turbulent shear stress too small in magnitude in separated shear layer of bubble
Axisymmetric Transonic Bump (cont’d)

• General validation metrics:
  – Separation and reattachment locations
  – Turbulent shear stress profiles
  – Velocity profiles
  – Surface pressure coefficients

• Specific validation metrics:

\[
\frac{((x / c)_{sep} - 0.7) / 0.7}{((x / c)_{reattach} - 1.1) / 1.1}
- \left[ \left( \frac{u'v'}{U^2_{ref}} \right)_{\text{min}@x/c=1.0} + 0.019 \right] / 0.019
\]

  – From first two, can find bubble size relative to experiment
  – Current typical RANS:

\[
\frac{\left\{ (x / c)_{reattach} - (x / c)_{sep} \right\} - 0.4}{0.4} \approx 25%
- \left[ \left( \frac{u'v'}{U^2_{ref}} \right)_{\text{min}@x/c=1.0} + 0.019 \right] / 0.019 \approx -50%
\]
Additional Optional Separated Cases

- 2-D Wake flow in APG (Driver & Mateer, 2002)
- 2-D Transonic Diffuser (Sajben, 1983)
- 2-D Ramp flow (Cuvier et al, 2014)
- 2-D Periodic Hill (Almeida et al, 1993; Frohlich et al, 2005)
- 2-D Planar Asymmetric Diffuser (Buice & Eaton, 2000)
- 2-D NACA 4412 at high AoA (Coles & Wadcock, 1979 & 1987)
- 2-D Curved Backward-Facing Step (Bentaleb et al, 2012)
- 2-D Separated Channel flow (Marquillie et al, 2008)
Additional Optional Separated Cases

- 3-D Axisymmetric Hill (Byun & Simpson, 1996)
- 3-D FAITH Hill (Bell et al, 2006)
- 3-D Cherry Diffuser (Cherry et al, 2008)
- 3-D ONERA M6 Wing (Schmitt & Charpin, 1979)
- 3-D NASA Trapezoidal Wing (Johnson et al, 2000)
- 3-D Common Research Model (Rivers et al, 2012)
- 3-D Wing-body-juncture (Devenport & Simpson, 1992)
- 3-D Prolate Spheroid (Chesnakas & Simpson, 1996)
Proposed Fundamental Experiments Investigating Separation Onset and Progression

**Axisymmetric Bump**

- **Surface skin friction**
  - Tunnel back pressure adjusted to achieve approx Ma=0.2 inflow
  - Graph showing skin friction coefficient vs. x for different wall angles

- **Turbulent shear stress**
  - Graph showing shear stress vs. y for different wall angles

**Plots showing effect of top wall shape on separation bubble behind smooth bump**

- -5 deg wall
- 5 deg wall
- 12.5 deg wall

**3-D Juncture Flow**

- Vary alpha to achieve attached, incipient, and separated side-of-body corner flow
Propulsion Cases
Compressible Mixing Layer

Schlieren Photographs

Many flow features can be qualitatively seen in the 20 ns spark schlieren photographs of case 3 shown in Fig. 2. The flow is from left to right with the primary stream on top, and three photographs are required to cover the window that is in the upstream position. The splitter plate can be seen as it extends 8 mm into the field of view from the left, and the total length of the window is approximately 267 mm. Although compression and expansion waves originating from the splitter plate are evident in the photographs, they are not strong, as to the boundary layers shed from the splitter plate. However, because of the large velocity parameter \( \lambda \) of case 4, the velocity deficit is rapidly consumed as it has essentially been eliminated by the first measurement location, which was only 10 mm downstream of the splitter plate tip. Eventually, after the velocity deficit has been eliminated, the flowfield becomes fully developed. For a mixing layer to be considered fully developed, it is required that both the mean and turbulent velocity fields be self-similar. Generally, the mean velocity field requires less streamwise distance to become self-similar.

• Goebel, Dutton, & Gruber
  Univ. of Illinois

• Two convective Mach numbers
  – Case 2, \( M_c = 0.46 \)
  – Case 4, \( M_c = 0.86 \)


*primary data source
Compressible Mixing Layer

• Objective: Improve the prediction of shear layers, including the developing region, and the effect of compressibility

• Metrics
  – Growth rate
  – Mean velocity fields
  – Reynolds stress fields

• Rationale for
  – Comprehensive data set for $M_c$’s from 0.2 to 1.0
  – 2-component LDV, with some 3-component LDV and PIV
  – Data compares well against historical measurements

• Rationale against
  – High $M_c$ case difficult to converge
  – Tunnel wall effects, blockage and shock reflections are present

• Need new experiment?
Compressible Mixing Layer

Growth Rate

$\frac{db}{dx} = \left(\frac{\partial b}{\partial x}\right)_{inc}$

$M_c$

Maydew & Reed (1963)
Ikawa & Kubota (1975)
Chinzei, et al. (1986)
Papamoschou & Roshko (1988)
Messersmith, et al. (1990)
Elliott & Samimy (1990)
Fourguette, et al. (1991)
Goebel & Dutton (1991)
Gruber, et al. (1993)
Hall, et al. (1993)
Debisschop, Chambres, & Bonnet (1994)
Clemens & Mungal (1995)
Chambres (1997)
Rossmann (2001)
Vreman, et al. (1996) DNS
Pantano & Sarkar (2002) DNS
Day, et al. (1998) LSA

Birch & Eggers (1972), "Langley Curve"
Wind-US SA
Wind-US SST
Round Jet

• Bridges & Wernet, NASA Glenn

• Three test conditions
  – Set point 3, Mach 0.5 cold
  – Set point 23, Mach 0.5 hot
  – Set point 7, Mach 0.9 cold

• Data
  – Temporally resolved PIV data
    • Mean velocities
    • Reynolds stresses
  – Farfield noise


*primary data source
Round Jet

- Objective: Improvement the prediction of jets, including the developing region, the effect of compressibility, and the effect of temperature.

- Metrics
  - Location of the end of the inviscid core flow (the point where $u/U_{jet} = 0.98$ )
  - Value and location of the peak turbulent kinetic energy on the jet centerline.
  - Mean velocity fields
  - Reynolds stress fields

- Rationale for
  - Data already widely used for validation (de facto standard jet data set)
  - Data compares against historical measurements

- Rationale against
  - Nozzle boundary layer and/or initial jet profile not defined
Round Jet

Centerline Mean Velocities

**SP 3: Mach 0.5, cold**

**SP 7: Mach 0.9, cold**

**SP 23: Mach 0.5, hot**

<table>
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<th>Set Point</th>
<th>Expt.</th>
<th>SA</th>
<th>%err</th>
<th>SST</th>
<th>%err</th>
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<td>3</td>
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<td>7</td>
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<td>9.01</td>
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<td>6.00</td>
<td>20.0</td>
<td>7.65</td>
<td>53.0</td>
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Shock Wave Boundary Layer Interaction

• J. Brown et al, NASA Ames
• Axisymmetric compression corner
• Mach 2.85
• 30 deg. conical flare
• Data
  – LDV
    • Mean velocities
    • Reynolds stresses
  – Surface static pressures
  – Interferometry
  – Schlieren


*primary data source
Shock Wave Boundary Layer Interaction

- **Objective:** Improve the prediction of shock boundary layer interaction including the extent of separation and the Reynolds stresses

- **Metrics**
  - Separation and reattachment locations, and separation length
  - Surface pressure coefficient
  - Velocity profiles
  - Reynolds stress profiles

- **Rationale for**
  - Simple geometry
  - Absence of corner flows found in many SWBLI experiments
  - Reynolds stresses available

- **Rationale against**
  - Separation onset and pressure distributions are already well predicted by some RANS models
  - Cusped nose of model not defined; effect is assumed negligible
Shock Wave Boundary Layer Interaction

Mach number contours

<table>
<thead>
<tr>
<th></th>
<th>Separation pt. (cm)</th>
<th>Reattach pt. (cm)</th>
<th>Length (cm)</th>
</tr>
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<tbody>
<tr>
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<td>0.97</td>
<td>3.70</td>
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<td>BSL</td>
<td>-2.50</td>
<td>1.38</td>
<td>3.88</td>
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<tr>
<td>SST</td>
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<tr>
<td>k-ε</td>
<td>-2.21</td>
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<tr>
<td>SA</td>
<td>-2.68</td>
<td>2.27</td>
<td>4.92</td>
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</tbody>
</table>

Surface static pressure

Expt. - BSL - SST - k-ε AKN - SA

25
Shock Wave Boundary Layer Interaction

Shear Stress Profiles

- Expt.
- BSL
- SST
- k-ε AKN
- SA

x = -4.5 cm
x = -3 cm
x = -2 cm
x = -1 cm

$\frac{<uv>}{u^2}$ vs $y$ (cm)
Additional/Optional Cases

• Shear flows
  – Numerous shear layer cases
  – Seiner’s Supersonic jet, $M_j = 2$ (Seiner et al, 1992)
  – Egger’s Supersonic jet (Eggers, 1996)

• Shock-wave/boundary-layer interaction
  – Mach 2.25 Impinging SWBLI, UFAST (DuPont et al, 2008)
  – Mach 5 Impinging SWBLI (Schulein, 2004)
  – Mach 7 Axisymmetric Compression Corner (Kussoy & Horstman, 1989)
  – NASA GRC Mach 2.5 Axisymmetric Impinging SWBLI (Davis, TBD)
Turbulence CFD Validation Experiments (TCFDVE)

PROBLEM
Very few Shock Wave/Boundary-Layer Interaction (SWBLI) experiments reported in the open literature meet the rigorous criteria required to be considered as a CFD validation dataset. This is particularly true for experiments with detailed turbulence measurements.

OBJECTIVES
Obtain mean and turbulence quantities through a M=2.5 SWBLI of sufficient quantity and quality to be considered as a CFD validation dataset. Initial efforts will focus on a Mach 2.5 2-D (in the mean) interaction with follow-on efforts investigating 3-D interactions. Both attached and separated interactions will be considered.

APPROACH
A new M=2.5 17cm axisymmetric facility is being constructed to investigate SWBLIs. The facility will be located in Test Cell W6B at NASA GRC. The SWBLI is generated by a cone located on the centerline of the facility. The strength of the interaction is varied by changing the cone angle. The measurement region of interest is where the conical shock interacts with the naturally occurring facility boundary-layer and is highlighted by the box shown in Figure 1. The new facility will be instrumented with conventional pressure instrumentation as well as hot-wire anemometry for measurement of turbulence quantities. Non-intrusive optical techniques such as PIV will be incorporated in the future. Test are also planned with dynamic surface shear film and fast response Pressure Sensitive Paint (PSP) in collaboration with Innovative Scientific Solutions, Incorporated (ISSI).

RESULTS
The new facility design is complete and delivery of the hardware is expected by the end of December 2014. Calibration of the facility is expected to commence in December. RANS and LES simulations of the facility are also underway at GRC.

SIGNIFICANCE
The data to be generated has been previously unavailable. Further, development of an in-house capability to investigate SWBLIs will allow CFD code developers and turbulence modelers to have direct input into the experiment. It will also allow the ability to revisit measurements if deemed necessary.

POC: David O. Davis (GRC)

Figure 1. 17cm Axisymmetric Supersonic Wind Tunnel
Future Validation Needs

• Most of the primary test cases are old datasets
  – There have been significant advances in measurement technology
  – New scale-resolving simulations require much more detailed boundary information
  – We have gained a better understanding of the requirements for validation experiments

• We believe there is a need for new validation data sets
  – What flows should be considered?
  – What quantities should be measured?
  – What are we missing?
Contact information

• Pleases contact us if you have any comments, or information on possible additional test cases
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This Powerpoint presentation as well as additional write-ups on the recommended test cases will be posted to the [http://turbmodels.larc.nasa.gov](http://turbmodels.larc.nasa.gov) website