Modern CFD Validation for Turbulent Flow Separation on Axisymmetric Afterbodies

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Outline

1. Test Case Motivation
2. A Priori RANS Guidance
3. Risk-Reduction Test Setup
4. Summary and Future Work
5. Questions and Answers
**Motivation: NASA CFD Vision 2030**

- Need for improved CFD modeling/validation of smooth-body turbulent flow separation
- Need for fundamental experiments designed specifically for CFD validation
- Support range of cases:
  - attached flow $\rightarrow$ partially separated $\rightarrow$ large separation

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Axisymmetric Converging Flow with APG\(^2\)

- Example of higher-\(Re\) test case
- Analogy to **cambered delta wing**
- Turbulence modeling issues in “waist” region
- Mainly considered attached flow
- RAE 8 × 8 ft Wind Tunnel:
  \[0.6 < M < 2.8; \ 5 \times 10^6 < Re_L < 2 \times 10^7\]

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Test Case Concept: NASA Axisymmetric Afterbody

- **Axisymmetric:** no intersection with sidewall corner flows
- **Wider validation domain:** sting-mount to access higher Reynolds number facilities

- **Parametric body:**
  - Analytical shape; continuous second derivative
  - Extendable forebody
  - Interchangeable afterbody *(cf. Presz and Pitkin [3]*)

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Family of Afterbodies

Decreasing Aft Cylinder Radius
“Slip-Ons”

cf. NASA TN D-4504 (1968)

“Attached Flow”

“Incipient Separation”

“Fully Separated”

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Axisymmetric Afterbody: Industry-Relevant Configuration

“Hammerhead” Launch Vehicle Buffeting (NASA Ames)

Helicopter Aft-Fuselage Drag Reduction (Allan and Schaeffler [4])

Aeropropulsion: Nozzle Afterbodies

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5. Questions and Answers
• Determine boattail angle where turb. model results are ambiguous
  – Searching for a discriminating test case

• Compute risk-reduction configuration with tunnel walls
  – NASA Langley 15-Inch Low-Speed Wind Tunnel (15x15 inch cross-section)
  – Approximate square test section by circle that inscribes it
  – Steady RANS
  – Fully turbulent

• Assess sensitivity of afterbody flow to:
  1. Body nose (with/without)
  2. Tunnel boundary layer (with/without)
Representative Flowfields: SA-RC Turbulence Model

\[ M_{\text{inflow}} \sim 0.12 \]
\[ Re_{R_{\text{max}}} \sim 180k \]

No separation on outer wall

Similar Flow Behavior
Pressure Distribution: *Turbulence Model Differences*

\[ N = \text{Nose Body} \]

- Fully converged + residuals below $10^{-15}$
- Peak $C_p$ agreement, followed by boattail discrepancies
Pressure Distribution: *Turb. Model + Nose Effects*

\[ \frac{\sigma(C_{p,peak})}{\langle C_{p,peak} \rangle} < 1\% \]

Full Reynolds Stress Models (RSM): Computed on \( \frac{1}{4} \)-plane nose-less domains
Boattail Skin Friction: *Turbulence Model Differences*

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**Graph:**

- **Axes:**
  - $R(x)$ vs. $x/L_B$
  - $C_f$ vs. $x/L_B$

- **Legend:**
  - SA-neg (N)
  - SA-RC (N)
  - SST (N)
  - Wilcox2006 (N)
  - k-kL-MEAH2015 (N)

- **Note:**
  - $[N = \text{Nose Body}]$

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**Text:**

- Attached
- Separated

- **Key Points:**
  - SA vs. SA-RC
  - SA-RC indicates barely-reversed flow, while SST barely **fails** to show reversed flow
Boattail Skin Friction: \textit{Turb. Model + Nose Effects}

\[ R(x) \]

$C_f$ vs $x/L_B$

- Attached
- Reversed

\[ [N = \text{Nose Body}] \]
\[ [NL = \text{Nose-Less Body}] \]

- SA-neg (NL)
- SA-neg (N)
- SA-RC (NL)
- SA-RC (N)
- SST (NL)
- SST (N)
- Wilcox2006 (NL)
- Wilcox2006 (N)
- k-kL-MEAH2015 (NL)
- k-kL-MEAH2015 (N)
- SSG-LRR-RSM-w2012 (NL)
- WilcoxRSM-w2006 (NL)

- \textit{RSM differences}
Boattail Skin Friction: *Effect of Tunnel Boundary Condition*

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![Graph showing skin friction coefficients for various tunnel boundary conditions.](image)

- **$R(x)$**
- **$C_f$**
- **$x/L_B$**

Legend:
- SA-neg (slip tunnel)
- SA-neg (no-slip tunnel)
- SA-RC (slip tunnel)
- SA-RC (no-slip tunnel)
- SST (slip tunnel)
- SST (no-slip tunnel)
- Wilcox2006 (slip tunnel)
- Wilcox2006 (no-slip tunnel)
- $k$-$kL$-MEAH2015 (slip tunnel)
- $k$-$kL$-MEAH2015 (no-slip tunnel)

[Note: Body Only]

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Risk-Reduction Experimental Setup: NASA Langley 15-Inch LSWT

Test Model

Sting Support

Undercarriage (Pitch & Yaw Adjustments)

Flow

1 ft (30.48 cm)
Risk-Reduction Test Model Assembly  
(Courtesy: Vincent LeBoffe, NASA LaRC)

- Integrated Sting Connection
- Sting Support
- Model Roll Indexer
- Undercarriage (Pitch & Yaw Adjustments)
- Floor Plate

(Useful for rotating point-sensors around circumference)
Summary and Future Work

- Development of new CFD validation test case for smooth-body turbulent separation based on parametric body-of-revolution.
- Design guided by *a priori* RANS studies searching for critical disagreement among turbulence models.
- Assessment of sensitivity to:
  1. body nose (with/without)
  2. tunnel wall boundary layer (with/without)

  in which effects were smaller than overall disagreement among models.

- Must now pursue “truth case”: Appear to be twin paths for experiment (nose-body) and LES/DNS (nose-less body).