CFD Validation Experiment of a Mach 2.5 Axisymmetric Shock-Wave/Boundary-Layer Interaction

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Background

- Experimental investigations of specific flow phenomena, e.g., Shock Wave/Boundary-Layer Interactions (SWBLI), provide great insight to the flow behavior but often lack the necessary details to be useful as CFD validation experiments.
  - Undefined Boundary Conditions
  - Inconsistent Results
  - Undocumented 3D Effects (CL only Measurements)
  - Lack of Uncertainty Analysis
Background

• The Transformational Tools & Technologies (TTT) Project under NASA’s Transformative Aeronautics Concept (TAC) Program is tasked, in part, with providing quality experiments for the purpose of validating CFD codes and turbulence models.

• Goal - Provide in-house experimental database to support inlet and nozzle CFD validation efforts.
  • Allows code/model developers to have direct input into experiment design.
  • Allows experiments to be re-visited if deemed necessary.

• A Mach 2.5 SWBLI has been identified as one of the test cases desired.
SWBLI CFD validation experiments performed in non-circular wind tunnels pose a particularly challenging problem, as streamwise and transverse pressure gradients induced by the SWBLI turn a nominally two-dimensional flow-field into a three-dimensional flow-field.

Mach 2.0 SWBLI in 15x15 cm SWT.
Background

- In order to avoid the pitfalls of a rectangular configuration, an axisymmetric configuration is proposed that is two-dimensional in the mean.
  - Circular test section.
  - Cone-cylinder located on the centerline.
  - Shock/expansion generated by cone-cylinder interacts with the naturally occurring boundary layer on the test section wall.

Region of Interest

- a) Double-Cone
- b) Cylinder-Flare
- c) Impinging-Centerbody
- d) Impinging-Duct

Axisymmetric SWBLI
FACILITY
Facility

- At the time the project was initiated, there were no supersonic axisymmetric facilities at NASA GRC.
- In order to keep costs within budget, the existing 15x15 cm Supersonic Wind Tunnel (SWT) was modified to add an axisymmetric capability.
- This required design and fabrication of three major axisymmetric components:
  - Bellmouth
  - Convergent-Divergent (C-D) Nozzle
  - Test Section
- A goal of the design was to minimize the effort required to change between the rectangular and axisymmetric configurations.
• The bellmouth is based on a Low-β ASME Long-Radius Nozzle with throat taps.
• NASA GRC has extensive experience with this type of nozzle.

With the Mach 2.5 nozzle, bellmouth throat Mach number is approximately 0.21.
Mach 2.5 C-D Nozzle

- The requirements for the C-D nozzle design included:
  - Exit Mach number of 2.5
  - Inlet and exit diameters equal (17 cm).
  - Length approximately the same as 15x15 SWT nozzles.

- The steps for designing the nozzle included:
  - Define inviscid, shock-free supersonic contour (MOC).
  - Define subsonic contour.
  - Correct supersonic contour for boundary-layer development.
  - Adjust subsonic contour to match.
Mach 2.5 C-D Nozzle

5th Order Polynomial

Constant Area

Parabolic

Wave Cancellation

Constant Area

C-D Nozzle Throat

Static Tap (8) Equally Spaced

\[ r - R_{\text{throat}} \]

\[ r', r'', r''' \]

\[ x/R_{\text{throat}} \]
The Wind-US flow solver was used to estimate the boundary-layer growth in the nozzle.
The test section is a simple circular cross-section. Two were fabricated:

- “Conventional” Test Section – static taps and two access windows.
- “Blank” Test Section - future modification for PIV system.
C-D Nozzle and Conventional Test Section
Shock Generator Assembly

- For the initial testing, two shock generator configurations were selected:

  10.0° Cone (Fully-Attached B.L.)

  13.5° Cone Incipient Separation
Shock Generator Assembly
INSTRUMENTATION

Test Entry #01
Instrumentation

Bellmouth Sta.  
PSBELL (8)

Nozzle Exit Sta.  
PSNOZ (8)

Press. Probe  
PPROBE(12)

TS #A1 Stas.  
PSTS1(156)

Exhaust Sta.  
PSEXH (6)
Test Section Static Taps
Uncertainty Considerations

- Uncertainty analysis is in progress. In addition to sensor uncertainty, the following are also being considered:
  - Geometric uncertainty
  - Static tap uncertainty
  - Total pressure probe uncertainty
    - Probe configuration
    - Near-wall effect
    - Position

<table>
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<th>i</th>
<th>Description</th>
<th>$X_i$</th>
<th>$\delta X_i$</th>
<th>N</th>
<th>$\delta X_i$</th>
<th>Units</th>
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<td>0.01</td>
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<td>C-D nozzle exit plane static pressure</td>
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<td>0.0219</td>
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<td>kPa</td>
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</table>
RESULTS

Test Entry #01
BM Flow Rate and C-D Nozzle Mach Number

- C-D nozzle Reynolds number, $Re_{D_s}$
- Mass flow rate, $w$ (kg/s)

Graphs showing:
- Mass flow rate vs. C-D nozzle Reynolds number
- C-D nozzle Mach number vs. C-D nozzle Reynolds number

CFD-based calibration

Equation:
\[ y = 1.176x - 0.039 \]
\[ R^2 = 1.000 \]
Nozzle Exit Condition

δ~0.61 cm
Clean Test Section

The diagram shows a cross-sectional view of a test section with various labels indicating different measurement points (AA, BB, CP, CS, EP, ES, DS, DP). The graph below the diagram illustrates the normalized pressure ratio $p_{\text{test}}/p_0$ as a function of $x$ (cm) in the test section. The x-axis represents the distance in centimeters, ranging from 0 to 70 cm, and the y-axis represents the normalized pressure ratio, ranging from 0.04 to 0.06. The data points correspond to different locations within the test section, as indicated by the labels on the diagram.
Test Section Exit Condition (x=66.0 cm)

<table>
<thead>
<tr>
<th></th>
<th>x (cm)</th>
<th>$M_e$</th>
<th>$\delta$ (cm)</th>
<th>$\delta^*$ (cm)</th>
<th>$\theta$ (cm)</th>
<th>$H_i$</th>
<th>$C_f$</th>
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<td>0.00152</td>
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</table>

$\delta \approx 1.47$ cm
SWBLI Interaction, $\alpha=10.0^\circ$
SWBLI Interaction, $\alpha=10.0^\circ$

The diagram illustrates the interaction between the incident shock and the reflected shock in the context of SWBLI (Sweeping Boundary Layer Interaction). The y-axis represents the distance in cm or the ratio $P_{y2}/P_{y0}$, while the x-axis represents the distance in cm. The graph shows the progression of the shock waves as they interact with the boundary layer, with annotations for the incident shock, expansion fan, and reflected shock.
SWBLI Interaction, $\alpha=13.5^\circ$
SWBLI Interaction, $\alpha=13.5^\circ$
TCFDVE Status

• A new axisymmetric facility has been assembled for investigating two-dimensional SWBLI.

• Preliminary data indicates that the facility is suitable for CFD validation studies, but some refinements are necessary:
  • Improved facility Reynolds number control.
  • Refined tunnel/shock generator alignment - fabricate fixture.
  • Upgrades to probe position encoders.
  • Source of facility debris and elimination required before hot-wire measurements commence.
TCFDVE Status

- The facility has also recently been used to checkout Surface Stress Sensitive Film (S3F) and dynamic Pressure Sensitive Paint (PSP) in collaboration with Innovative Scientific Solutions Incorporated (ISSI).

- From preliminary data, refined flowfield measurement stations and surface dynamic pressure locations will be identified.
Questions?