Large Eddy Simulation of a 3D Shock Train at High Reynolds Number

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Motivation: predict aerodynamic loads and heat transfer in shock wave-turbulent boundary layer interactions

Reason for WMLES:
- Improve predictions over methods known to be deficient for such flows
- Reduce cost to enable comparison at high Reynolds numbers from experiments
Carroll & Dutton STCAD Experiment

- Carroll & Dutton (1988) STCAD data includes:
  - Wall-pressure measurements
  - Laser Doppler Velocimetry (LDV)
  - Schlieren images and oil flow visualizations

- Measurement data taken along spanwise center plane of duct
  - No data along sidewalls
  - Limited data upstream of initial shock

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Mach Number</td>
<td>1.61</td>
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<tr>
<td>Reynolds Number, $Re_\delta$</td>
<td>162,000</td>
</tr>
<tr>
<td>Reynolds Number, $Re_\theta$</td>
<td>15,000</td>
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<tr>
<td>Stagnation Temperature</td>
<td>295 K</td>
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<tr>
<td>Stagnation Pressure</td>
<td>$206 \times 10^3$ Pa</td>
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<tr>
<td>Pressure Ratio</td>
<td>2.23085</td>
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<tr>
<td>Tunnel Aspect Ratio</td>
<td>2.26</td>
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</tbody>
</table>
Three-Dimensional WMLES Calculation
Wall-Model LES Methodology

LES Solver:
- CharLESX code developed by Center for Turbulence Research at Stanford
- Unstructured, finite volume solver for compressible Navier-Stokes equations
- Uses a sub-grid scale model and digital filtering for inflow turbulence generation

Wall-Model:
- Solves equilibrium boundary layer equations on a separate, embedded grid using information from LES calculation
- Based on model of Kawai & Larsson
- Implementation due to Bodart & Larsson
Wall-Model LES Methodology

\[ h_{wm} \approx 0.15 \delta_{ref} \]
Three-Dimensional Simulations of Full Duct

Experimental unknowns:
- Properties of sidewall boundary layers
- Measurements upstream of STCAD interaction

Tactics to address simulation uncertainties:
- Information regarding sidewall boundary layers:
  1. Use RANS calculations to simulate full duct geometry from throat through test section
  2. Conduct parameter study using WMLES while matching available data
- Information upstream of STCAD:
  1. Use growth rates from preliminary calculations to inform inflow profiles
  2. Compare with experiment at locations relative to initial shock
Purpose: obtain estimates of sidewall boundary layers through simulating full duct

Aspects of Simulations:
• Used an unstructured RANS solver JOE developed at Stanford under PSAAP
• Domain extended from nozzle throat through test section and modeled using ¼ of cross-section and symmetry boundary conditions
• Simulations incorporated multiple:
  - levels of grid resolution
  - turbulence models: Spalart Allmaras, $k$-$\omega$, Menter SST
  - inflow profiles
Conclusions:

- Boundary layers ahead of STCAD are roughly equivalent between top-bottom and sidewalls.
- Downstream of STCAD interaction, boundary layer parameter growth rates larger for sidewalls than top-bottom walls.
- Thicker sidewall BL trend seen for all models, though choice affects magnitude of growth rate.
**WMLES Parameter Study**

**Constant Simulation Parameters:**
- Cross-Sectional geometry
- Grid resolutions
- Wall-model exchange location

**Varied Simulation Parameters:**
- Domain length
- Pressure ratio across STCAD (\(P_{out}/P_1\))
- Relative thickness of sidewall to top-bottom walls for incoming boundary layer parameters (e.g. \(\delta, \theta, \delta^*\))
Full Duct WMLES Comparison with Experiment

Shock-Shifted Centerline Mach Number

Normalized Wall Pressure, $\frac{P_{wall}}{P_{ref}}$

- Baseline $\delta_{side}$
- Baseline $\delta_{side}$ Long
- Double $\delta_{side}$
- Double $\delta_{side}$ Long
- Data
Full Duct WMLES Comparison with Experiment

Boundary Layer Confinement, $\delta_{99}/h$

Displacement Thickness Confinement, $\delta^*/h$

- Baseline $\delta_{side}$
- Baseline $\delta_{side}$ Long
- Double $\delta_{side}$
- Double $\delta_{side}$ Long
- Data
"Best Match" from WMLES with Experiment
Summary & Conclusions

Summary of Investigations
I. RANS simulations used to provide information about sidewall boundary layers relative to those on top-bottom walls
II. WMLES parameter study used to address additional experimental unknowns

Conclusions from Simulations
I. Both RANS and WMLES significant asymmetry downstream of initial shock for boundary layer quantities
II. Highly non-linear behavior of STCAD governed by centerline Mach number upstream of initial shock, pressure ratio across interaction, and three-dimensional boundary layer confinement (most notably for $\theta$ and $\delta^*$)

Future Work
I. Further study of confinement effects for a three-dimensional shock train
II. Attempt to quantify STCAD behavior using parameters ($M$, $(P_{out}/ P_1)$, $\theta$, and $\delta^*$) identified from existing simulations
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