LES of a Compressible Mixing Layer and the Significance of Inflow Turbulence

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Objectives

- Develop an improved prediction capability for turbulent shear flows
- Analyze the effects of inflow turbulence on the shear layer
- Apply the Synthetic Eddy Method (SEM) to model inflow turbulence
- Compare SEM-LES to a Fixed-LES with no inflow turbulence
- Access sensitivity to spanwise width
- Compare turbulence intensity profiles with experiments
- Apply best practices developed for $M_c = 0.46$ to a high convective Mach number case, $M_c = 0.87$. 
Motivation

Pervious Work(s)
LES was used by Georgiadis et al.\(^1\) and Mankbadi et al.\(^2\) that pointed to the need to account for inflow turbulence.

New Work
SEM is utilized as a means to simulate the effects of inflow turbulence on compressible mixing layers.

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Introduction

Compressible mixing layers
- Examples: supersonic combustion, exhaust nozzles, and internal flows present in jet engines and scramjets
- Experimental studies investigating compressibility effects: Chinzei et al., Papamoschou & Roshko, Goebel and Dutton, Samimy & Elliot, Hall et al., and Clemens & Mungal.

Turbulent Inflow Conditions
(1) full LES of upstream boundary layers
(2) Recycling/Rescaling
(3) Hybrid RANS/LES
(4) synthetic turbulence inflow boundaries
Description of the Flow

**Primary Flow:** $M=1.91$, $U=700\text{m/s}$, $P=49\text{kPa}$

**Secondary Flow:** $M=1.36$, $U=399\text{m/s}$, $P=49\text{kPa}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Primary Flow</th>
<th>Secondary Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>1.91</td>
<td>1.36</td>
</tr>
<tr>
<td>$U$ (m/s)</td>
<td>700</td>
<td>399</td>
</tr>
<tr>
<td>$T_\infty$ (K)</td>
<td>578</td>
<td>295</td>
</tr>
<tr>
<td>$P$ (kPa)</td>
<td>49</td>
<td>49</td>
</tr>
<tr>
<td>$\delta^+$ (mm)</td>
<td>0.90</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Case 2 $M=0.46$

Case 4 $M=0.87$

The Synthetic Eddy Method

Jarrin et al. is applied to the mixing layer under consideration to simulate the effects of inflow turbulence.

**Inputs:**

1. A Reynolds stress tensor and mean flow
2. A length scale
3. A convective velocity

SEM succeeded in replicating the Reynolds stress tensor when the length scale was approximately $1/10$ of the boundary layer thickness.

Digital Filtering requires three input length scales.
Computational Approach

Tenth-Order NASA GRC Wave-Resolving LES (WRLES) code solves the discretized Favre-Filtered Navier-Stokes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline Grid</th>
<th>Axially Refined Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of points</td>
<td>1025 425 138</td>
<td>2049 425 138</td>
</tr>
<tr>
<td>Length of domain (mm)</td>
<td>500 48 24</td>
<td>250 48 24</td>
</tr>
<tr>
<td>Minimum spacing (mm)</td>
<td>0.0125 0.0125 0.1875</td>
<td>0.00625 0.0125 0.1875</td>
</tr>
<tr>
<td>Maximum spacing (mm)</td>
<td>5 0.2 0.1875</td>
<td>5 0.2 0.1875</td>
</tr>
</tbody>
</table>

Results

SEM delivers turbulent boundary layer to splitter-tip which enhances downstream mixing.

Structures are Turbulent not Laminar
Fixed-LES: Spanwise width Grid Study

Case Methodology Grid Size Width Grid Pts
A Fixed-LES 1025 x 425 x 33 6mm 14.4 M
B Fixed-LES 1025 x 425 x 65 12mm 28.3 M
C Fixed-LES 1025 x 425 x 129 24mm 56.2 M
D Fixed-LES 1025 x 425 x 257 48mm 112 M
E SEM-LES 2049 x 425 x 42 6mm 36.6 M
F SEM-LES 2049 x 425 x 74 12mm 64.4 M
G SEM-LES 2049 x 425 x 138 24mm 120.2 M
H SEM-LES[QUAD] 2049 x 425 x 138 24mm 120.2 M

A wake-like region

Compare these two cases to prove span independence at 24mm.

Spanwise Independent at 24mm
Fixed-LES: Spanwise width Grid Study

- EXP - Case 2
- Fixed - LES - 48mm
- Fixed - LES - 24mm
- Fixed - LES - 12mm
- Fixed - LES - 6mm

Spanwise Independent thickness at 24mm.

SEM-LES: Grid Study

- wake-like region is significantly reduced

SEM-LES is in better agreement with exp.
SEM-LES: Grid Study

plots show agreement between the numerical results and experiment.

$W_{\text{rms}}$ suppression for a span of 6mm is eliminated when the span is extended to 24mm.

Effect of Inflow Turbulence

SEM reproduces the EASM input stress

projection error:

1. the Reynolds tensor specified at the inflow satisfies the RANS equations instead of the Favre-filtered Navier Stokes
2. the inability of the numerical scheme to represent the prescribed flow field on the grid
3. the synthetic eddies are not real turbulence and therefore undergo a process whereby they adjust to the Navier-Stokes equations.
Effect of Inflow Turbulence

No noticeable difference

Peak Reynolds stresses are unchanged
Effect of Inflow Turbulence

Key Finding: Variations in Reynolds tensor supplied to SEM do not affect the solution.

Transition to Turbulent Mixing

Clemens and Mungal's schlieren concurs with the quick transition to turbulent mixing of SEM-LES.
SEM-LES’s inclusion of inflow turbulence makes a dramatic difference in the transition process.
- The specified turbulence quickly destroys the organized structures and transition occurs immediately downstream of the splitter tip.
- The entire shear layer exhibits a broader range of structures which closely resemble the schlieren images of the experiment.

Fixed-LES transitions to turbulent mixing at $x = 50$mm upward change in slope.
- SEM-LES transitions earlier than Fixed-LES.
- Both SEM-LES and Fixed-LES eventually have the same slope downstream, after the Fixed-LES fully transitions to turbulent mixing.
Leveraging the practices developed for the low convective Mach number, we subsequently investigated the high convective Mach number case.

<table>
<thead>
<tr>
<th>Case</th>
<th>Methodology</th>
<th>Grid Size</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>SEM-LES</td>
<td>2049 x 425 x 42</td>
<td>6mm</td>
</tr>
<tr>
<td>K</td>
<td>SEM-LES</td>
<td>2049 x 425 x 74</td>
<td>12mm</td>
</tr>
<tr>
<td>L</td>
<td>SEM-LES</td>
<td>2049 x 425 x 138</td>
<td>24mm</td>
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<td>616</td>
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<tr>
<td>$P$ (kPa)</td>
<td>578</td>
<td>360</td>
</tr>
<tr>
<td>$\delta^*$ (mm)</td>
<td>49</td>
<td>36</td>
</tr>
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Increase in spanwise width has no effect on the flow.

RMS amplitudes are converging with increasing spanwise width.
Compressibility Effects at High Convective Mach Number

**Graph (C)**
- RMS amplitudes are converging with increasing spanwise width.

**Graph (D)**
- Trend is consistent with previous findings.
- Linear growth means self-similar very early on.
- It was hoped that the higher accuracy methods offered by LES would outperform RANS.

SEM-LES assuming (1) periodic flow in z-direction; (2) neglected upper and lower viscous walls; (3) inexact approximation of the inflows and outflow (due to limited experimental measurements).
Conclusions

- LES of a compressible shear layer for: $M_c = 0.46$ (case 2), and $M_c = 0.87$ (case 4).
- Spanwise turbulent stresses and mixing layer thickness were suppressed if the domain is too narrow (6mm).
  1. Fixed inflow neglects inflow turbulence
  2. SEM inflow accounts for inflow turbulence.
- For $M_c = 0.46$, Fixed-LES showed large laminar structures in the initial portion of the shear layer and a delayed transition to turbulent mixing.
- SEM-LES eliminated the organized vortical structures and transition to turbulent mixing occurred immediately following the splitter tip.
- SEM-LES better replicated the experimental trends in turbulent stresses.
- For $M_c = 0.87$, similar trends were found when investigating spanwise width.
- The experimentally observed mixing rate was overpredicted by LES which agreed with RANS-EASM. Neither RANS nor LES have yet to capture the reduced growth rate trend with increasing convective Mach number.
- The key finding was that accounting for inflow turbulence through SEM-LES is a viable option alongside recycling/rescaling LES.

Future Work: Flow Separation

WR-LES and WM-LES

Wall Resolved LES

Backstep $Re_H=36,000$

$M=0.128$

Diffuser $Re_H=20,000$

$M=0.06$

$Y^+ = 1$

$Y^+ = 1$