Measurements of Turbulence Convection Speeds in Multistream Jets Using Time-Resolved PIV

James Bridges and Mark P Wernet
NASA Glenn Research Center

AIAA Aviation 2016 – 5-8 June 2017

Supported by
NASA Advanced Air Vehicles Program/Commercial Supersonics Technology Project
Motivation

• **Goal**: Noise reduction concepts and prediction tools to engineer them on aircraft.

• Explore noise reduction concepts keyed to local convection speed, influenced by modifying flow profiles (*a la* Papamoschou)
  – Offset externally mixed nozzles

• Only a small part of turbulent energy couples to acoustic far-field, and convection speed one aspect of this ‘filter’.

• Convection speed of turbulent eddies play key role in acoustic analogies.
  – To create a design tool, relate $U_c$ to parameters from RANS solutions

• Important to note: convection speed of what?
  – Bulk turbulent velocity, pressure, vorticity, scalar
  – Spatial, frequency modes of these parameters?
Previous experimental work

- Older hot-wire work
  - Two probes, separate in space, measure time delay in correlation
  - Common result shown, radial profile of convection speed $U_c$, mean velocity $\langle u \rangle$
  - Usually measured in potential core region
  - $U_c$ matches $\langle u \rangle$ at $\langle u \rangle / U_{jet} \approx 0.6$
  - $U_c = 0.6U_j$ often used as simple model for convection speed at jet cross-section, including hydrodynamic near-field

Recent experimental efforts

- **Multiple-PIV tests**
  - Dual conventional PIV setups
  - Two velocity fields acquired at discrete time delays
  - Correlations of velocity fields give $R(\xi_1, \xi_2, \tau) \rightarrow Uc$
- **Time-resolved PIV tests**
  - Acquire velocity fields over contiguous time series
  - Limited spatial fields, typically looking at large $x$
- **PLIF/PDV image correlation**
  - Correlation of scalar «==» velocity?
- **Time-resolved DGV**
  - Limited spatial extent
- **Most work limited to single-stream jets**
- **Need to measure convection speed of turbulence in multi-stream, non-axisymmetric jets efficiently**
  - Limited to bulk turbulence, possibly filtered by frequency

Bridges & Wernet, “Measurements of the Aeroacoustic Sound Source in Hot Jets “ AIAA 2003-3130
Previous TRPIV Methodology

• Previous time-resolved PIV
  – CCD arrays combined in 20x300mm FoV to compliment narrow axial laser sheet
  – 25kHz dual laser rate
  – Acquire axial strips of velocity map movies along lipline and along centerline
  – Process to space-time correlations of velocities, Reynold stresses
  – Required many moves of optics to capture entire jet

New TRPIV methodology

- Lightsheet in streamwise plane, at 90° to jet axis
- Narrow (axial) sheet width
- Camera vertical FoV: 55x140mm, translated three times to acquire full 360mm cross-section of jet
- Acquire velocity maps at 25kHz.
- Process velocity map movie to get axial profile of convection velocity
Correlation processing

- Basic concept of computing convection velocity is simple:
  - Calculate space-time correlation, track peak \( x(t) \), take derivative
- Wide range of convection velocities in same measurement
  - FoV limits maximum time delay \( \tau \)
  - Acquisition rate limits temporal accuracy
  - Use fitting of single-power exponent to get subsample resolution
Axisymmetric single-stream jets

- Single-stream (internal plug), 95mm ø
- Replicate literature for cold subsonic jets
- Replicate NASA Consensus data
  - Confirm basic velocity statistics, mean $\langle u \rangle$ and variance $\langle uu \rangle$
  - Tanna matrix of velocity, temperature

<table>
<thead>
<tr>
<th>Setpoint</th>
<th>$V_j$ [m/s]</th>
<th>$V_j/c_\infty$</th>
<th>$T_{s,j}/T_\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>172</td>
<td>0.5</td>
<td>0.96</td>
</tr>
<tr>
<td>7</td>
<td>310</td>
<td>0.9</td>
<td>0.84</td>
</tr>
<tr>
<td>23</td>
<td>172</td>
<td>0.5</td>
<td>1.76</td>
</tr>
<tr>
<td>27</td>
<td>310</td>
<td>0.9</td>
<td>1.76</td>
</tr>
<tr>
<td>29</td>
<td>460</td>
<td>1.33</td>
<td>1.76</td>
</tr>
<tr>
<td>49</td>
<td>500</td>
<td>1.48</td>
<td>2.70</td>
</tr>
</tbody>
</table>
Typical result

- Single-stream jet (unheated, $Ma = 0.5$)
Comparison with historical data

- Single-stream jet (unheated, $Ma = 0.5$)
- $x/D_j = 6.5$ (TRPIV) vs $x/D_j = 5$ (hotwire)
- $U_c = \langle u \rangle$ at $\langle u \rangle = 0.6$
- TRPIV measures lower $U_c$ at outer jet edge than hotwire
Features

- Single-stream jet (unheated, $Ma = 0.5$)
- $U_c = \langle u \rangle$ where $\langle uu \rangle$ is high. $U_c$ not matching $\langle u \rangle$ where $\langle uu \rangle$ weak.
Trends with axial location

- Single-stream jet (unheated $Ma = 0.5$)
- $U_c \sim \langle u \rangle$ where $\langle uu \rangle >> 0$
- Interesting details around wake of plug on centerline and outside jet near nozzle

![Graphs showing trends at x/Dj = 2, 6.5, and 12.5](image)
Impact of heat

- Single-stream jet \((Ts/T_\infty=2.7, \ Uj/c_\infty = 1.48)\)
- Convection speed roughly same as mean velocity where \(<uu> \neq 0\)
Axisymmetric multi-stream jets

- Nozzle hardware from three-stream externally mixed experiments of Henderson
  - Axisymmetric (C1T1) with A1:A2:A3 = 1:2.5:1
- Flow conditions
  - Representative of engines
  - Chosen for variations in shear layers
  - Hope to see variations in convection speed

<table>
<thead>
<tr>
<th>Setpoint</th>
<th>NPR₁</th>
<th>NTR₁</th>
<th>NPR₂</th>
<th>NTR₂</th>
<th>NPR₃</th>
<th>Mf</th>
<th>V₁ [m/s]</th>
<th>V₂ [m/s]</th>
<th>V₃ [m/s]</th>
<th>V∞ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>58833</td>
<td>1.5</td>
<td>3</td>
<td>1.8</td>
<td>1.25</td>
<td>1.8</td>
<td>0.3</td>
<td>430</td>
<td>330</td>
<td>330</td>
<td>102</td>
</tr>
<tr>
<td>58533</td>
<td>1.5</td>
<td>3</td>
<td>1.8</td>
<td>1.25</td>
<td>1.5</td>
<td>0.3</td>
<td>430</td>
<td>330</td>
<td>275</td>
<td>102</td>
</tr>
<tr>
<td>58233</td>
<td>1.5</td>
<td>3</td>
<td>1.8</td>
<td>1.25</td>
<td>1.2</td>
<td>0.3</td>
<td>430</td>
<td>330</td>
<td>190</td>
<td>102</td>
</tr>
<tr>
<td>58033</td>
<td>1.5</td>
<td>3</td>
<td>1.8</td>
<td>1.25</td>
<td>1.06</td>
<td>0.3</td>
<td>430</td>
<td>330</td>
<td>102</td>
<td>102</td>
</tr>
<tr>
<td>58030</td>
<td>1.5</td>
<td>3</td>
<td>1.8</td>
<td>1.25</td>
<td>1</td>
<td>0</td>
<td>430</td>
<td>330</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>55833</td>
<td>1.5</td>
<td>3</td>
<td>1.5</td>
<td>1.25</td>
<td>1.8</td>
<td>0.3</td>
<td>430</td>
<td>275</td>
<td>330</td>
<td>102</td>
</tr>
<tr>
<td>85210</td>
<td>1.8</td>
<td>1.25</td>
<td>1.5</td>
<td>1.25</td>
<td>1.2</td>
<td>0</td>
<td>330</td>
<td>275</td>
<td>190</td>
<td>0</td>
</tr>
<tr>
<td>88533</td>
<td>1.8</td>
<td>3</td>
<td>1.8</td>
<td>1.25</td>
<td>1.5</td>
<td>0.3</td>
<td>510</td>
<td>330</td>
<td>275</td>
<td>102</td>
</tr>
</tbody>
</table>

Two-stream jet

- ‘Axisymmetric’ jet not so symmetric in reality.
- Where $\langle uu \rangle$ is relatively small, $U_c$ closer to nearest $\langle u \rangle$ where $\langle uu \rangle$ is large.
Three-stream jet

- Three-stream jet (Velocity ratios 430:275:330:102)
- Tertiary stream mixes out by first measurement station
  - Only two shear layers present
- Strong asymmetry grows
  - Asymmetry in $\langle uu \rangle$ much stronger than in $\langle u \rangle$
- $U_c$ still tracks $\langle u \rangle$
Source of Asymmetry?

- Due to geometric defect? Nonuniform ambient? Unstable hot core?
- Compare with and without flight stream, with and without hot core.
- Asymmetry in all, especially $\langle uu \rangle$.
- Constant in plots is geometry.
- Never assume symmetry!

![Graphs showing data points and curves for different cases with labels](image)
Non-axisymmetric multi-stream jets

- Asymmetric velocity profiles
  - Offset (SDCT) with $\Delta z = 4\text{mm}$ ($D_3 = 294\text{mm}$ φ)
  - Partial duct (PART) with $180^\circ$ tertiary stream

- Demonstrated non-axisymmetric sound fields

<table>
<thead>
<tr>
<th>Setpoint</th>
<th>NPR$_1$</th>
<th>NTR$_1$</th>
<th>NPR$_2$</th>
<th>NTR$_2$</th>
<th>NPR$_3$</th>
<th>Mf</th>
<th>$V_1$ [m/s]</th>
<th>$V_2$ [m/s]</th>
<th>$V_3$ [m/s]</th>
<th>$V_\infty$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>58833</td>
<td>1.5</td>
<td>3</td>
<td>1.8</td>
<td>1.25</td>
<td>1.8</td>
<td>0.3</td>
<td>430</td>
<td>330</td>
<td>330</td>
<td>102</td>
</tr>
<tr>
<td>58533</td>
<td>1.5</td>
<td>3</td>
<td>1.8</td>
<td>1.25</td>
<td>1.5</td>
<td>0.3</td>
<td>430</td>
<td>330</td>
<td>275</td>
<td>102</td>
</tr>
<tr>
<td>85210</td>
<td>1.8</td>
<td>1.25</td>
<td>1.5</td>
<td>1.25</td>
<td>1.2</td>
<td>0</td>
<td>330</td>
<td>275</td>
<td>190</td>
<td>0</td>
</tr>
</tbody>
</table>

Three-stream offset jets--SDCT

- Three-stream jet (Velocity ratios 430:330:275:102) with offset tertiary
- Tertiary stream evident on thick side (negative y) at x=0.29m
- Offset peak $\langle u \rangle$ by x=1.14m
- $U_\text{c}$ still tracks $\langle u \rangle$. 

$x = 0.29m$  
$x = 0.57m$  
$x = 1.14m$
Three-stream offset jets--PART

- Three-stream jet (Velocity ratios 430:330:275:102) with 180° tertiary (negative y)
- Tertiary stream reduced shear initially.
- Offset peak $\langle u \rangle$ by $x=1.14$m
- $U_c$ still tracks $\langle u \rangle$

$x = 0.29$m

$x = 0.57$m

$x = 1.14$m
Conclusion

- **Rule:** $U_c$ follows $\langle u \rangle$, where $\langle uu \rangle$ is strong. Where $\langle uu \rangle$ is not strong, $U_c$ is biased toward $U_c$ where $\langle uu \rangle$ is strong.
- Seems to be true for $U_c$ of near-field hydrodynamic pressure as well.
Summary

• For single jets, $\langle uu \rangle$ peaks around $\langle u \rangle/U_j = 0.6$, hence this value is dominant in most measurements, including local hydrodynamic pressure at jet edge.

• Applying the Rule to multi-stream jets: $U_c$ of near-field hydrodynamic wave packets will be most influenced by closest (outermost) shear layer.

• If convection speed of near-field hydrodynamic wave packet determines source strength, then sound source is controlled by outermost shear layer.

• For engineering use, $U_c = \langle u \rangle$ is a good assumption for bulk turbulence.
  – Where $U_c \neq \langle u \rangle$, then $\langle uu \rangle$ too small to matter anyway.