VELOCITY STATISTICS AND SPECTRA IN THREE-STREAM JETS

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AIAA SciTech 2016
Overview

- Background
- Time-resolved Doppler Global Velocimetry
- Facility and experiment
- Turbulence results
- Conclusions and next steps

Acknowledgements:
This work supported by Commercial Supersonic Technology Project in the Advanced Air Vehicles Program and the US Office of Naval Research (ONR) through the Hot Jet Noise Basic Research Challenge
Mark Wernet for PIV data and support in planning and setup
Motivation

Persistent Jet Noise Challenge

- Supersonic transport unique jet noise problems
- Substantial impact on health of service persons

Instrument development goals

- New tools for turbulent plume details
- Data for development of models for jet noise prediction

Noise levels on carrier decks can exceed 145 dB

<table>
<thead>
<tr>
<th>Continuous dB</th>
<th>Permissible Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>85 dB</td>
<td>8 Hours</td>
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<tr>
<td>88 dB</td>
<td>4 Hours</td>
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<tr>
<td>91 dB</td>
<td>2 Hours</td>
</tr>
<tr>
<td>94 dB</td>
<td>1 hour</td>
</tr>
<tr>
<td>97 dB</td>
<td>30 minutes</td>
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<tr>
<td>100 dB</td>
<td>15 minutes</td>
</tr>
<tr>
<td>103 dB</td>
<td>7.5 minutes</td>
</tr>
<tr>
<td>106 dB</td>
<td>3.75 minutes (&lt; 4 min)</td>
</tr>
<tr>
<td>109 dB</td>
<td>1.875 minutes (&lt; 2 min)</td>
</tr>
<tr>
<td>112 dB</td>
<td>.9375 min (~ 1 min)</td>
</tr>
<tr>
<td>115 dB</td>
<td>.46875 min (~ 30 sec)</td>
</tr>
</tbody>
</table>
Background

Henderson (2012): Axisymmetric third stream:
- High frequency noise reduction
- Reduced impact with forward flight

Papamoschou et al. (2016): Even more creative third streams:
- RANS shows redistribution of TKE
- Dramatic noise downstream reduction

Henderson, Leib and Wernet (2015): Asymmetric third stream
- Dramatic reductions downstream
- Redistribution of TKE
High speed jet instrumentation & measurements

High-data rate, non-intrusive measurements in **cold supersonic jets/ hot subsonic jets:**

- **LDV, Kerhervé et al. (EIF 2004)**
  - 2-point LDV in cold supersonic jet
  - Space-time correlations
- **TR-PIV, Wernet and Bridges (2007)**
  - Up to 50 kHz in subsonic hot jets
  - Spectral development
  - Space-time correlations
- **Megahertz rate DGV (Thurow et al., 2005):**
  - max. 1 MHz camera sampling rate (presented results up to 250 kHz), 1-comp
  - Supersonic cold jet
  - Convective velocities

Doppler Global Velocimetry

Basics:

• First developed by Komine (Northrop Co) in 1990, refined by Meyers and Komine (1991)

• Mie scattered light is sent through a molecular gas cell (e.g. Iodine) and its frequency transduced to intensity (24 “optical frequency-to-intensity converter”)

• Using a reference or calibration the Doppler frequency shift can be determined:

\[ f_D = \frac{\bar{\delta} - \bar{i}}{\lambda} \cdot \vec{V} \]

• Considered to be optimal for high speed flow due to absolute error

• Conventional systems have (mean) uncertainties in the range ±0.5 m/s to ±3 m/s

*Iodine cell transmission scan

Three-velocity component operation by velocity multiplexing:

2 laser beam directions + 2 collection directions = 3 linearly independent Doppler directions + 1 redundant measurement

\[ f_D = \frac{\bar{\delta} - \bar{i}}{\lambda} \cdot \bar{V} \]
Previous TR-DGV

Thurow et al. (2005)
• High-Speed camera based

Ecker et al. (2014)
• Single point 3 component TR-DGV (PMT based)
• First approach to laser beam multiplexing
• Mean velocity, Reynolds shear stresses and velocity spectra

Ecker et al. (2015a,b,c)
• Multi-channel PMT cameras
• Convective velocities for heated supersonic jet
• Intermittency factor distribution
• Frequency dependent convective velocities
Key Development: PMT camera

Newly developed PMT camera based on:

- Hamamatsu H8500C/H10660 64 CH PMT array
- Custom 16 CH instrument amplifier boards
- FPGA based DAQ backend allows recording at 50MHz sampling rate. Preprocessing on the FPGA reduces actual streaming bandwidth to 10MS/s per channel
Time-resolved Doppler Global Velocimetry

- **Lens focal length**: 200 mm
- **Magnification**: 1.257
- **Sensor area (effective)**: 24.12 x 48.7 mm²
- **Measurement area**: 30.32 x 61.22 mm²
- **(horizontal) spatial resolution on measurement plane**: 7.58 mm

- 250 kHz flow sampling
- 3-velocity component capability
- 32-points simultaneously sampled
Tests in Nozzle Acoustics Test Rig (NATR) and High Flow Jet Exit Rig (HFJER) at the NASA GRC Aero-Acoustics Propulsion Laboratory

- 65 feet high, 130 feet diameter AAPL dome
  - Anechoic testing environment
  - Engine component R&D
- NATR:, 53 inch diameter, free-jet acoustic wind tunnel
- HFJER to mount test nozzle hardware within NATR

http://facilities.grc.nasa.gov/aapl/
**Installation:**
- Used NASA facility traverse
- All optics, electronics on traverse
- Acoustic box for acoustic and thermal shielding of Laser and reference gas cell

**Notes:**
- Operation robust over $25^\circ C$ temperature changes (and freezing temps)
- More seeding than PIV
- Laser frequency stabilization

**Configuration instantaneous velocity uncertainty** $\pm 9 \text{ m/s}$
Three-stream experiments

<table>
<thead>
<tr>
<th>Area ratio:</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>$A_t / A_c$</td>
<td>1.0</td>
</tr>
<tr>
<td>$A_b / A_c$</td>
<td>2.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nozzle pressure ratio:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NPR: core and bypass</td>
<td>1.8</td>
</tr>
<tr>
<td>NPR: tertiary</td>
<td>1.4</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Nozzle temperature ratio:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NTR: core</td>
<td>3.0</td>
</tr>
</tbody>
</table>

All experiments at 0 free jet Mach number

**Flow seeding:**
- 0.5 μm diameter alumina powder.
- Seeding colloid prepared using a pH stabilization technique (Wernet and Wernet 1994)
Velocity results: Validation

Comparison PIV data: Henderson and Wernet (2016)

- Laser frequency fluctuations
- Mean velocity comparison reasonable
- Turbulence results show some differences
  - Instrument variance
  - “Missing” samples
Velocity spectra: Axisymmetric nozzle on centerline

Stream-wise development of velocity spectra

- Consistent increase at all frequencies
- Spectral estimator important
  - Drop-out
  - Spectral variance
- Consistent instrumentation noise floor
- Spectral uncertainties still being quantified
Convection velocity: Axisymmetric

Convection velocity from time/space correlation across stream-wise-spaced sensors (e.g., Ecker et al. AIAA J. 2015, ±6.5% RMS uncertainties)

Comparison of convection and mean velocity
Convection velocity: Axisymmetric vs Offset

Offset clearly thickened for \(x/\text{DeqA}<3\)
Diminishes as flow develops
Convection velocity

Axisymmetric configuration

Development of profiles throughout this region

Profiles all similar to downstream axisymmetric

Offset configuration

Virtually no change in profiles for outer portions of shear layer
Regarding TR-DGV

- Discussed more instrumentation aspects in AIAA-2016-0029
- Laser frequency fluctuations
  - On-going work for signal processing
- Current results first for scaled-up arrangement
  - 250 kHz velocimetry
- Shows strength of method for time-resolved data
- Work confirms complementary role for TR-DGV in conjunction with PIV
Conclusions and next steps

- Measurements using time-resolved velocimetry in 3-stream jet
- Good agreement of mean velocity data with PIV comparison data
  - Turbulent intensity problematic due to noise influence, signal estimation
- Used time-resolved data to begin analysis of statistical turbulence characteristics
- Next steps
  - Continue refinement of velocity estimation
  - Use spectral and correlation data to update source models for three-stream jet predictions
  - Analyze physics using both PIV and TR-DGV insights
  - Process more data: two more configurations, one additional condition
Questions ?
Background

Review 3-stream work

NASA results previously reported

Turbulence information in 3-stream jet noise predictions


Convection velocity: Offset

Convection velocity offset configuration (TR-DGV)

Mean stream-wise velocity axisymmetric (PIV)

Offset configuration convection velocity compared to mean velocity of axisymmetric case (reference)
TR-DGV geometry

- 45 deg. arrangement
- Uncertainty (inst) 9.2 / 6.5 / 6.2 m/s
- Uncertainty (mean) 1.5 / 1.5 / 1.5 m/s

\[ u_{optical} = -\frac{\sqrt{2}}{2} u + \frac{\sqrt{2}}{2} v + w \]

\[
\delta u_i = \frac{c}{f_0} \sqrt{\left(\frac{df}{dT}\right)_i^2 (\delta T_i)^2 + T_i^2 \left[\delta \left(\frac{df}{dT}\right)_i\right]^2 + \frac{f_i^2}{f_0^2} \left(\frac{df}{dT}\right)_0^2 (\delta T_0)^2 + T_0^2 \left[\delta \left(\frac{df}{dT}\right)_0\right]^2} \]

\[
\Delta U = \begin{bmatrix} \delta u_x \\ \delta u_y \\ \delta u_z \end{bmatrix} = \sqrt{\left(\begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix}\right)^2 \begin{bmatrix} \delta u_1 \\ \delta u_2 \\ \delta u_3 \end{bmatrix}^2 + \left(\begin{bmatrix} \delta R_{11} & \delta R_{12} & \delta R_{13} \\ \delta R_{21} & \delta R_{22} & \delta R_{23} \\ \delta R_{31} & \delta R_{32} & \delta R_{33} \end{bmatrix}\right)^2 \begin{bmatrix} \delta u_1 \\ \delta u_2 \\ \delta u_3 \end{bmatrix}^2} \]