Simple Scaling Of Multi-Stream Jet Plumes For Aeroacoustic Modeling

James Bridges
NASA Glenn Research Center


Supported by
NASA Advanced Air Vehicles Program/Commercial Supersonics Technology Project
Thanks to Mark Wernet, Brenda Henderson, Gary Podboy for data.
Challenge: Design supersonic airliner that is acceptable in range, sonic boom, airport noise, and engine emissions. Note: System optimization key—design trades are critical. Note: If you don’t give the system analysts a noise prediction model they will make one up for themselves.
Modeling jet-installation effects—shielding

- Phased array source distributions; note amplitude scales!
- $Ma = 0.9$, unheated jet with and without simple surface at significant standoff
- First order effect—line of sight blockage
Source location modeling

- Brown’s modeling approach for JSI shielding with single stream jets, simple nozzles:
  - Suppression is function of surface length relative to source location
  - Source location is related to potential core length $X_{\text{core}}= f(M_j, T_j)$
  - Suppression modeled by $L/D$ relative to $X_{\text{core}}$.

Jet Plumes—Mean Centerline Profile

- Typical centerline velocity for single stream from simple nozzle

Variation in jet conditions:
- $0.5 < Ma < 1.33$
- $0.85 < TsR < 2.27$

Scaling of Jet Plumes—2-parameter model

- Elegant model for mean velocity on centerline
  \[
  \phi = \frac{U - U_\infty}{U_j - U_\infty} = 1 - \exp \left\{ \frac{\alpha}{1 - x/D} \right\}
  \]
  - \( \alpha \) is exponential decay, \( \beta \) is potential core length
  - Parameters \( \alpha, \beta \) obtained by fitting line to
    \[
    x \ln(1 - \phi) = \beta \ln(1 - \phi) - \alpha \beta
    \]
- For single jets \( \alpha, \beta \) modeled in terms of \( M_j, TsR \)
  \[
  \alpha = \frac{-1.848(1-0.25M_j)}{TsR^{0.4}} \quad (= 1.43 \text{ for Witze})
  \]
  \[
  \beta = \frac{3.195(1+0.796M_j)}{TsR^{0.11}}
  \]
- Referred to as Simple Single-Stream (SSS) model

Witze, P.O. “Centerline Velocity Decay of Compressible Free Jets,”

Witze (1-parameter) vs SSS (2-parameter)

- Decay is not universal as assumed by Witze (Kleinstein)
- SSS model captures decay better
- 2-parameter models can be created for other effects (chevrons, non-axisymmetric nozzles, etc.)

Centerline axial velocity—Witze scaling

Centerline axial velocity—SSS scaling
Why this works for noise source distribution—Collapse of peak turbulence

- Turbulent velocity distributions collapse as well
Extension to Multiple Stream Nozzles?

- Can we model source distributions of multiple stream jets by finding equivalent potential core and decay?
  - Equivalent origin $x_0$, diameter $De$ for complex nozzles?
  - Equivalent flow conditions $Ma$, $TsR$ for multiple stream jets?
- Can proper selection of $x_0$, $De$, $Ma$, $TsR$ produce collapse of multiple stream plumes when plugged into model equations for single-stream jet?
Three-stream PIV Dataset--Nozzles

- Henderson & Wernet AIAA SciTech2016 (preceding talk)
- Axisymmetric, externally mixed, external plug nozzles
- Three combos of area ratios, $A_2/A_1 = 1.0, 2.5$; $A_3/A_1 = 0.6, 1.0$
- Note lack of clear definition of plume origin, diameter
  - Origin: First flow nozzle? Minimum jet diameter?
  - Diameter: First flow nozzle? Total area?

\[ A_2/A_1 = 2.5 \quad A_2/A_1 = 1.0 \]
### Three-stream PIV Dataset—Flow Conditions

- **Main dataset:**
  - \(NPR_1 = 1.8\), \(NTR_1 = 3.0\),
  - \(NPR_2 = 1.8\), \(NTR_2 = 1.25\)
  - \(1.0 < NPR_3 < 2.1\), \(NTR_3 = 1.25\)

<table>
<thead>
<tr>
<th>nozID</th>
<th>setpoint</th>
<th>NPR1</th>
<th>NPR2</th>
<th>NPR3</th>
<th>NTR1</th>
<th>NTR2=NTR3</th>
<th>MfFlight</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1T1</td>
<td>88033</td>
<td>1.8</td>
<td>1.8</td>
<td>1</td>
<td>3</td>
<td>1.25</td>
<td>0.3</td>
</tr>
<tr>
<td>C1T1</td>
<td>88433</td>
<td>1.8</td>
<td>1.8</td>
<td>1.4</td>
<td>3</td>
<td>1.25</td>
<td>0.3</td>
</tr>
<tr>
<td>C1T1</td>
<td>88833</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>3</td>
<td>1.25</td>
<td>0.3</td>
</tr>
<tr>
<td>C1T1</td>
<td>88133</td>
<td>1.8</td>
<td>1.8</td>
<td>2.1</td>
<td>3</td>
<td>1.25</td>
<td>0.3</td>
</tr>
<tr>
<td>C3T1</td>
<td>88033</td>
<td>1.8</td>
<td>1.8</td>
<td>1</td>
<td>3</td>
<td>1.25</td>
<td>0.3</td>
</tr>
<tr>
<td>C3T1</td>
<td>88433</td>
<td>1.8</td>
<td>1.8</td>
<td>1.4</td>
<td>3</td>
<td>1.25</td>
<td>0.3</td>
</tr>
<tr>
<td>C3T1</td>
<td>88833</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>3</td>
<td>1.25</td>
<td>0.3</td>
</tr>
<tr>
<td>C3T1</td>
<td>88133</td>
<td>1.8</td>
<td>1.8</td>
<td>2.1</td>
<td>3</td>
<td>1.25</td>
<td>0.3</td>
</tr>
<tr>
<td>C3T3</td>
<td>88033</td>
<td>1.8</td>
<td>1.8</td>
<td>1</td>
<td>3</td>
<td>1.25</td>
<td>0.3</td>
</tr>
<tr>
<td>C3T3</td>
<td>88433</td>
<td>1.8</td>
<td>1.8</td>
<td>1.4</td>
<td>3</td>
<td>1.25</td>
<td>0.3</td>
</tr>
<tr>
<td>C3T3</td>
<td>88133</td>
<td>1.8</td>
<td>1.8</td>
<td>2.1</td>
<td>3</td>
<td>1.25</td>
<td>0.3</td>
</tr>
<tr>
<td>C3T1</td>
<td>88430</td>
<td>1.8</td>
<td>1.8</td>
<td>1.4</td>
<td>3</td>
<td>1.25</td>
<td>0</td>
</tr>
<tr>
<td>C3T1</td>
<td>80010</td>
<td>1.8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1.25</td>
<td>0</td>
</tr>
<tr>
<td>C3T1</td>
<td>80030</td>
<td>1.8</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1.25</td>
<td>0</td>
</tr>
<tr>
<td>C3T1</td>
<td>86010</td>
<td>1.8</td>
<td>1.6</td>
<td>1</td>
<td>1</td>
<td>1.25</td>
<td>0</td>
</tr>
<tr>
<td>C3T1</td>
<td>86210</td>
<td>1.8</td>
<td>1.6</td>
<td>1.2</td>
<td>1</td>
<td>1.25</td>
<td>0</td>
</tr>
</tbody>
</table>

**Variations:**
- **Vary\ NPR3**
- **Static**
- **Single Stream**
- **Isothermal**
Extracting ‘centerline’ from PIV data

- Complications by presence of plug wake, experimental deviations from symmetry
- Objective is to find end of potential core and exponential decay

Typical contour plot of mean axial velocity

Extracted axial profiles of mean axial velocity, all PIV data studied
Scaling of Multi-Stream Plumes—Fitted $\alpha$, $\beta$

- Using same procedure for fitting $\alpha$, $\beta$ to transformed profiles, multi-stream plumes collapse when plotted in normalized coordinates.
- Multi-stream plumes to have same shape!
- Can appropriate equivalent jet parameters plugged into models give similar collapse?

\[
\frac{U - U_\infty}{U_j - U_\infty} = \frac{1}{a} \left( \frac{x}{\beta} - 1 \right) / a
\]
Collapse of centerline profiles—Witze model(1)

- Three area ratio combinations with several NPR \(_3\) each.
- Using **mixed flow conditions** for Witze scaling.
- Using **total flow area** for diameter and **plug tip** for origin.
- Collapse but not matching potential core length.
• Three area ratio combinations with several NPR\(_3\) each.
• Using **mixed flow** conditions for Witze scaling
• Using **total flow area** for diameter and **first flowing lip** for origin.
• Matching potential core length.
• Not matching decay rate.
Collapse of centerline profiles—SSS model

- Three area ratio combinations with several NPR$^3$ each.
- Using *relative mixed flow* conditions for Witze scaling $(M, \rho)$
  \[(U - U_\infty)/(U_j - U_\infty)\]
- Using *total flow area* for diameter and *first flowing lip* for origin.
- Matching potential core length.
- Matching decay rate.
Single-stream, complex nozzles

- Two datasets of essentially single-stream plumes from plug nozzle
  - $M = 0.9$, $TsR = 1.0, 2.0$
- Using **total flow area** for diameter and **first flowing lip** for origin.
- Not as good match as simple nozzle flows
  - Potential core ‘knee’ corrupted by wake on cold jet
  - Hot jet has longer potential core than expected
- Examination of flow record shows that some bypass flow ($NPR_2 = 1.1$, $M_2 = 0.4$) used on hot dataset.
Alternatives for ‘nearly’ single stream case

• Given the slight \((M_2 = 0.4)\) flow from the bypass nozzle of the otherwise single-stream hot case, perhaps case should be approximated differently. Two possibilities tried.
• Not really satisfactory.
• Core problem is that small annulus co-flow affects potential core more than plume decay. Calibrated two-parameter model might address this.

Approximate as single-stream jet within \(M_\infty = 0.4\) ambient flow

Approximate as static dual-stream jet with small bypass ratio
Multi-stream cold jet cases

- Cases with all cold streams
  - \( \text{NPR}_1 = 1.8 \)
  - \( \text{NPR}_2 = 1.6 \)
  - \( \text{NPR}_3 = 1.0, 1.2 \)
- Using mixed flow conditions for Witze scaling
- Using total flow area for diameter and first flowing lip for origin
- Misses core length, decay
- ???!!!
Extracting axial profiles of turbulent velocity

- Axial profiles of $uu/U_j^2$ extracted on ‘centerline’ and at radius of peak.
Scaling peak TKE amplitude

- Radial locations of peak shifts with change in flows, no pattern discernable.
- Peak amplitude $uu/U_{ref}^2$ best scales with $U_{ref} = U_1$
Axial profiles of turbulent velocity

- TKE as extracted along centerline and peak TKE line

**Centerline**

**Peak TKE line**
Collapse of axial profiles of turbulent velocity

- Using single-parameter (Witze) scaling the TKE profiles collapse on the centerline
- The TKE profiles on peak line show banding by NPR$_3$
- Adequate for noise source modeling?

![Graphs showing collapse of axial profiles of turbulent velocity](Image)

**Centerline**

**Peak TKE line**
Summary

- For simple, single-stream jets, a simple two-parameter model collapses centerline velocity profiles better than one-parameter model (e.g. Witze).
- Two parameters can be predicted using flow conditions $Ma, TsR$ for simple jets.
- Centerline profiles of multi-stream jets can similarly be fitted using two-parameter model.
- Attempts at predicting multi-stream jets using single-stream models only moderately successful.
  - Complicated by complexity of geometry.
  - Impact of secondary (tertiary, ambient) flows different on potential core, decay.
- Best efforts use mix of physical measures of nozzle system:
  - Origin at first flowing nozzle
  - Diameter of total nozzle area
  - For axial profiles, use flow conditions of mixed flow relative to ambient.
  - For peak TKE, use flow conditions of core flow
- Result is a first-order model for plume, and hopefully of noise source distribution in multi-stream jets.
- Validation of jet shielding for three-stream nozzles near surfaces coming soon.