Jet Surface Interaction

Scrubbing Noise from High Aspect-Ratio Rectangular Jets

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Motivation

Interaction of jet exhaust with nearby solid surfaces:
- Hybrid Wing Body (HWB) concepts
- High aspect ratio rectangular exhaust with extended beveled surfaces
- Over the wing engine mount
- Nearby structural components could provide noise shielding
- They could also produce new sources of sound
Geometry – Rectangular Exhaust

\[ a = 8b \]

\[ b = 8a \]

\[ 5.35 \times 0.67 \text{ (in}^2) \]

\[ X_{TE} / a = 18 \]

\[ M_a = 0.90, \ h = 0, \ X_{TE} = 12'' , \ \theta = \pi/2 \]

\[ \text{Trailing edge noise} \]

\[ \text{Reflected/scrubbing noise} \]

* J. Bridges, AIAA-2014-0876
Outline

- Governing Equations
- Propagation Green’s Fun (GF) in High-AR Rectangular Jets
- Sample GF - 8:1 Aspect Ratio Jet Exhaust
- Scrubbing Noise Spectra and Data Comparison
- Summary
Scrubbing Noise

- NS Equations \(\rightarrow\) (Mean Flow + Linear Fluctuations)
- Locally Parallel Mean Flow
- Compressible
- Constant Static Pressure
- Ideal Gas Law

Variable density Pridmore-Brown eq.

\[ L\pi' = \Gamma, \quad \pi' \simeq \frac{p'({\bar{x}},t)}{\gamma \bar{p}} \]

\[ L \equiv D \left( D^2 - \frac{\partial}{\partial x_j} \left( c^2 \frac{\partial}{\partial x_j} \right) \right) + 2c^2 \frac{\partial U}{\partial x_j} \frac{\partial^2}{\partial x_1 \partial x_j}, \quad D \equiv \frac{\partial}{\partial t} + U \frac{\partial}{\partial x_1} \]

\( (\text{Goldstein 2010}) \)
Green’s Function Method

\[ \pi'(\bar{x},t) = \int \int G(\bar{x},t; \bar{y},\tau) \Gamma(\bar{y},\tau) d\tau d\bar{y} \]

\[ LG(\bar{x},t; \bar{y},\tau) = \delta(\bar{x} - \bar{y}) \delta(t - \tau) \]

- **Wetted side of the plate only**
  (Trailing Edge Noise component discussed by Goldstein et al, 2013)

**Transform:**

\[ (x_1 - y_1, x_2 - y_2, t - \tau) \to (k_1, k_2, \omega) \]

\[ G(\bar{x},t; \bar{y},\tau) \to \hat{G}(\vec{k}_t, x_3; y_3, \omega) \]

\[ \vec{k}_t \equiv (k_1, k_2) \]

- **Far-field Spectrum**

\[ p^2(\bar{x},\omega) = \int \int \int_{\gamma, \xi, \tau = -\infty} G^*(\bar{x}, \bar{y} - \bar{\xi}/2; \omega) G(\bar{x}, \bar{y} + \bar{\xi}/2; \omega) q(\bar{y}, \bar{\xi}, \tau) e^{i\omega \tau} d\tau d\bar{\xi} d\bar{y} \]
GF Method (Cont’d)

- Stationary Phase solution ($\kappa_0 R \gg 1$, $\kappa_0 = \omega / c_\infty$)

$$\tilde{k}^s_t = \kappa_0 (\sin \phi^s \cos \theta^s, \cos \phi^s)$$

(Khavaran, 2014)

$$G(\bar{x}, \bar{y}; \omega) \sim -i \frac{e^{i\Theta(\tilde{k}^s_t, \bar{x}, \omega)}}{(2\pi)^3 R} \frac{\sin \theta^s \sin^2 \phi^s}{c^2 \omega^2 c(y_3)} \frac{b_2(\tilde{k}^s_t, \omega) V_1(\tilde{k}^s_t, y_3, \omega)}{W_0(\tilde{k}^s_t, \omega, \bar{Z})} \frac{1 - M_\infty \sin \phi^s \cos \theta^s}{c^2 \omega^2} \frac{1 - U(y_3)}{c_\infty} \left\{ \Im \right\}^2$$

$$\Theta(\tilde{k}^s_t, \bar{x}, \omega) = k_1(x_1 - y_1) + k_2(x_2 - y_2) - \chi_\infty x_3$$

$$V_2(\tilde{k}^s_t, x_3, \omega) = b_2(\tilde{k}^s_t, \omega) e^{-i\chi_\infty x_3} \quad x_3 \to \infty$$

- Two linearly independent solutions

$$V_j(\tilde{k}^s_t, x_3, \omega), \quad j = 1, 2$$

$$V_j'' + f(\tilde{k}^s_t, x_3, \omega)V_j = 0$$

$$0 \leq \theta \leq \pi, \quad 0 \leq \phi \leq \pi$$
Numerical Results

- SolidWorks RANS (k-ε Turb Model) – Commercial Code
- Mapping – Cloud Solution to Structured Grid
- Normalized GF  $G_N \equiv \pi c_\infty^3 \left( \frac{G}{G_{FS}} \right)$
- Strouhal Frequency  $St \equiv a f / U_j$
- Source Location  $\eta \equiv y_3 / a$

Simulation Conditions

<table>
<thead>
<tr>
<th>8:1 Aspect Ratio Rectangular Exhaust (N8Z)</th>
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</thead>
<tbody>
<tr>
<td>Set Point</td>
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<tr>
<td>---------------------</td>
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<tr>
<td>SP07 (H02XTE12)</td>
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<td>SP07 (H19XTE12)</td>
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<td>SP07 (Isolated)</td>
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<td>SP05 (H19XTE12)</td>
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<td>SP03 (H19XTE12)</td>
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</table>
SolidWorks Mesh* – N8Z

* Rick Bozak, 2013
RANS Solution (Mapped to Rectangular Grid)

Block 1: 70 171 109 \((x_1, x_2, x_3)\)
Block 2: 81 171 169

SP07-H02-XTE12, \(X_1X_3\) Plane
Mean Flow ( SP07-H02-XTE12 )

U (fps)

T (static) / T_\infty
$G_N - Above Surface$

$\text{N8Z} - SP07-H02-XTE12$

$(\theta = \pi / 4, St = 0.25)$

Section Profile ($x = 0.52\text{FT}$)

$(G_N - Analytical Profile)$

$\text{GN}$ vs source location $(D = 2 \times \eta)$

$\text{N8Z (Solid Works), Interpolation Grid}20119, \text{Profile used at (Block1, J=33, K= PlaneOfSymmetry)}$

Jan. 2015
$G_N$ – Downstream the Plate \hspace{1cm} (\theta = \pm \pi / 4, St = 0.25 )

\begin{align*}
\theta &= +45^\circ \\
\theta &= -45^\circ 
\end{align*}
Sample Results

(1/3 Octave Lossless Spectra, Arc = 100D_{eq})

N8Z – SP07-H02-XTE12

* Measured Spectra, C. Brown & J. Bridges, GRC
Sample Results (Cont’d)

N8Z – SP07-H02-XTE12

[Graphs showing 1/3 Octave SPL vs. Freq (Hz) for 120° and 140°]
Sample Results (Cont’d)

N8Z – SP07-H02-XTE12

Trailing Edge Noise

% TKE^{0.5}/U_j

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

Y

-0.2 -0.1 0 0.1 0.2

x (FT)

1 2 3 4

B1

B2

1/3 Octave SPL (dB)

60 70 80 90

10^2 10^3 10^4 10^5

Freq (Hz)

Data

B1 (Surface)

B2

B1 + B2

90°
Sample Results (Cont’d)

N8Z – SP07-H19-XTE12

![Graph showing TKE^0.5/Uj distribution and acoustic data](image)
Sample Results (Cont’d)

N8Z – SP07-Isolated

% TKE$^{0.5}/U_j$

![Graph showing % TKE$^{0.5}/U_j$ over x (FT) and y axes.]

90°

![Graph showing 1/3 Octave SPL (dB) vs. Freq (Hz).]
Sample Results (Cont’d)

N8Z – SP05-H19-XTE12

% TKE^{0.5}/Uj

\[ 1 \ 2 \ 3 \ 4 \ 5 \ 6 \ 7 \ 8 \ 9 \ 10 \ 11 \ 12 \ 13 \ 14 \ 15 \ 16 \ 17 \]

\[ 0.2 \ 0.1 \ Y \ 0 \ -0.1 \ -0.2 \]

\[ 0 \ 1 \ 2 \ x (FT) \ 3 \ 4 \]

B1

B2

TEN

\[
\frac{1}{3} \text{Octave SPL (dB)}
\]

\[
\text{Freq (Hz)}
\]

\[
10^2 \ 10^3 \ 10^4 \ 10^5
\]

- Data
- B1 (Surface)
- B2
- B1 + B2

90°
Sample Results (Cont’d)
N8Z – SP03-H19-XTE12

% $\text{TKE}^{0.5}/U_j$

$Y$

$-0.2$

$-0.1$

$0$

$0.1$

$0.2$

$x (\text{FT})$

$0$

$2$

$4$

$B1$

$B2$

$1$

$2$

$3$

$4$

$\text{Sample Results (Cont’d)}$

$\text{N8Z – SP03-H19-XTE12}$

$\text{TEN}$

$90^\circ$

$\frac{1}{3} \text{Octave SPL (dB)}$

$10^2$

$10^3$

$10^4$

$10^5$

$\text{Freq (Hz)}$

$\text{Data}$

$B1 \text{ (Surface)}$

$B2$

$B1 + B2$

$90^\circ$

$\text{Data}$

$B1 \text{ (Surface)}$

$B2$

$B1 + B2$
Summary

- The GF was evaluated using RANS input (SolidWorks).
- The mean flow was considered as locally parallel in two directions (HAR rectangular jets).
- Source calibration parameters (length- and time-scales) follow the usual method (TKE and $\varepsilon$) in a RANS-based Acoustic Analogy.
- Spectral component associated with scrubbing noise dominated at HF.
- Jet plume downstream of the TE contributed to low- to mid-frequency.
- Trailing Edge Noise (TEN) should be superimposed on present predictions.

Next Step

- Consistency across operating conditions requires mean flow and turbulence validation (data and/or alternative RANS solvers).
- Heated jets (enthalpy-related source).
QUESTIONS ?