Receptivity of Hypersonic Boundary Layers to Acoustic Disturbances

P. Balakumar and Amanda Chou
NASA Langley Research Center
Hampton, VA 23681

NATO STO AVT-240 & RTG-082:
Hypersonic Boundary-Layer Transition Prediction
March 26, 2015
Objectives

- The physics based e^N correlation method (emaili3D, LASTRAC, STABLE etc.) is easy to implement and yields satisfactory results if appropriate N-Factors are used to fix the transition onset. This factor depends on several parameters including geometry, tunnel noise and surface roughness. However, the N-Factors vary broadly and it becomes difficult to predict the onset accurately.

- Can we improve it? How can we achieve this?
- We have
  - To include the effects of freestream disturbances on the transition process in the transition prediction methods
  - To identify a criterion to determine the transition onset point
Results

• Show the results for
  • Flow over a 7-deg cone at Mach 10. Experiments were performed recently in the T9 Tunnel.
  • Flow over a sharp and a blunt flared-cones at Mach 6. Experiments were performed in the Purdue Tunnel.
  • HIFiRE-1 Flight Experiment.
Flow over a Cone at M=10 (Expts. Performed at T9, Marineau et al. AIAA 2014-3108)

### Parameters

<table>
<thead>
<tr>
<th>Case</th>
<th>$R_n$ (mm)</th>
<th>$P_o$ (MPa)</th>
<th>$T_o$ (K)</th>
<th>$M_\infty$</th>
<th>$p_\infty$ (kPa)</th>
<th>$T_\infty$ (K)</th>
<th>Re/m (1E6/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (3745)</td>
<td>0.152</td>
<td>2.3</td>
<td>982</td>
<td>9.39</td>
<td>82.34</td>
<td>52.69</td>
<td>2.03</td>
</tr>
<tr>
<td>2 (3743)</td>
<td>0.152</td>
<td>8.9</td>
<td>1018</td>
<td>9.60</td>
<td>275.15</td>
<td>52.38</td>
<td>7.03</td>
</tr>
<tr>
<td>3 (3742)</td>
<td>0.152</td>
<td>22.6</td>
<td>1035</td>
<td>9.86</td>
<td>584.97</td>
<td>50.62</td>
<td>16.25</td>
</tr>
</tbody>
</table>

Cone half-angle = 7 deg.

- $T_{wall} = 0.3*T_o$
- $Pr = 0.74$
- $\gamma = 1.4$
- Gas constant $R = 297.$

Sutherland viscosity law = $1.458*10^{-6} \ T^{1.5} / (T+102.7 \ K)$

Leading edge of the cone: Sphere with radius, $R_n$
Mean Flow (Case 3)

(a) Re = 16.25 \times 10^6 \text{ m}^{-1}

\begin{align*}
\rho &
\begin{array}{cccc}
2.65 & 2.25 & 1.85 & 1.45 & 1.05 \\
\end{array}
\end{align*}

(b) Re = 16.25 \times 10^6 \text{ m}^{-1}

\begin{align*}
\rho &
\begin{array}{cccc}
13 & 13.1 & 11 & 11.1 & 9 & 9.1 & 7 & 7.1 & 5 & 5.1 & 3 & 3.1 & 1 & 1.1 \\
\end{array}
\end{align*}

(a)

\begin{align*}
X (\text{cm}) &
\begin{array}{cccc}
0.5 & 4.0 & 10.0 & 20.0 & 60.0 & 100.0 & 150.0 \\
\end{array}
\end{align*}

(b)

\begin{align*}
X (\text{cm}) &
\begin{array}{cccc}
0.5 & 4.0 & 10.0 & 20.0 & 60.0 & 100.0 & 150.0 \\
\end{array}
\end{align*}
N-Factors (Cases 1-3)

Transition Parameters

<table>
<thead>
<tr>
<th>Case</th>
<th>$R_n$ (mm)</th>
<th>$Re/m$ (1E6/m)</th>
<th>$S_T$ (m)</th>
<th>N</th>
<th>f (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (3745)</td>
<td>0.152</td>
<td>2.03</td>
<td>0.84</td>
<td>4.1</td>
<td>90</td>
</tr>
<tr>
<td>2 (3743)</td>
<td>0.152</td>
<td>7.03</td>
<td>0.36</td>
<td>5.1</td>
<td>240</td>
</tr>
<tr>
<td>3 (3742)</td>
<td>0.152</td>
<td>16.25</td>
<td>0.25</td>
<td>7.0</td>
<td>440</td>
</tr>
</tbody>
</table>
DNS
$p_{ac}(x,t) = \tilde{p}_{ac} e^{i(\alpha_{ac} x - \omega t)} + c.c,$

$$\langle p_{ac}\rangle_{PSD} = 2\left(\bar{p}_{ac}\right)^2$$

Measured spectrum  $\langle p_{ac}\rangle_{PSD} = C \quad f^{-3.5} / \text{Hz}$

$$2\left(\bar{p}_{ac}\right)^2 = C \quad f^{-3.5} \Delta f$$

$\Delta f \sim 10 \quad \text{to} \quad 100 \text{ kHZ} \quad \text{(need to investigate more)}$

Fig. 18 PSD from expt. (Marineu et al. AIAA 2015)
\[ C_{\text{recept}, \text{wall}} = \frac{(p_{\text{wall}})_n}{p_{ac}} \]

\[ = 2.0 \, \, (x \sim 0) \]

\[ = 4.5 \, \, (x \sim 23 \, \text{cm}) \]

\[ C_{\text{recept}, \text{wall}} = \frac{(p_{\text{wall}})_n}{p_{ac}} \]

\[ = 2.0 \, \, (x \sim 0) \]

\[ = 5.0 \, \, (x \sim 9 \, \text{cm}) \]

\[ C_{\text{recept}, \text{wall}} = \frac{(p_{\text{wall}})_n}{p_{ac}} \]

\[ = 2.0 \, \, (x \sim 0) \]

\[ = 5.0 \, \, (x \sim 5 \, \text{cm}) \]
DNS

Cases 1-3

\[ \frac{p_s}{p_\infty} = 3.29 \]

Transition Onset

<table>
<thead>
<tr>
<th>Case</th>
<th>( X_T ) (cm)</th>
<th>( N )</th>
<th>( N_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( (p_{\text{amp}})_T )</td>
<td>Expt.</td>
<td>( (p_{\text{amp}})_T )</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>1.8</td>
<td>1.4</td>
</tr>
<tr>
<td>1</td>
<td>81</td>
<td>84</td>
<td>3.2</td>
</tr>
<tr>
<td>2</td>
<td>33</td>
<td>34</td>
<td>5.3</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>23</td>
<td>6.5</td>
</tr>
</tbody>
</table>

\[ N_T = \frac{(p_{\text{amp}})_T}{C_{\text{recept},p_{\text{wall}}}p_{ac}} \]
Conclusions

• Transition onset points are predicted using the receptivity and a criteria based on the surface pressure.
• The criteria on the pressure has to be validated for other cases.
• The bandwidth for the amplitude calculations also has to be verified.
• Whether single frequency with equivalent amplitude or the multiple frequencies with small amplitudes is the right approach?
Mean Flow and Stability (Purdue Flared-Cones)

$p_{ac} = a \exp(i(\alpha_{ac}x - \omega t)) + c.c$

M = 6.0
Re = 10.3 \times 10^6 \text{ m}^{-1}
T_\infty = 52.80 \text{ °K}
T_{wall} = 300.0 \text{ °K}
Leading edge radius $r_e = 0.16, 1.0 \text{ mm}$
Flare is a circle with 3.0m radius
Slope is 2 degrees at the joint

$X = 40 \text{ cm}$
N=15 (sharp), 292 kHz
N=13 (Blunt), 300 kHz
DNS (Flared-Sharp-Cone)

\[ \frac{p_{ac}}{p_{\infty}} = 2 \times 10^{0} \cos \left( \alpha_{ac} x - \omega t \right) \]
\[ F = 2.15E-4 \ (308 \text{ kHz}) \]

\[ C_{\text{recept}, \text{wall}} = \left( \frac{p_{\text{wall}}}{p_{\infty}} \right) \frac{n}{p_{ac}} \]
\[ = 1.0 \ (x \sim 0) \]
\[ \frac{p_{\text{wall}}}{p_{\infty}} = 0.4 \ (x \sim 33 \text{ cm}) \]
\[ = 1.0 \ (x \sim 36 \text{ cm}) \]
DNS (Flared-Blunt-Cone)

(a) Slow

\[ F = 2.045 \times 10^{-4} \text{ 292.5 kHz} \]

\[ C_{\text{recpt,wall}} = \frac{(p_{\text{wall}})_n}{p_{ac}} \]

\[ = 5 \times 10^{-3} \quad (x \sim 10\text{cm}) \]

\[ \frac{p_{\text{wall}}}{p_{\infty}} = 0.0028 \quad (x \sim 40\text{cm}) \]

(b) Fast

\[ F = 2.045 \times 10^{-4} \text{ 292.5 kHz} \]

\[ C_{\text{recpt,wall}} = \frac{(p_{\text{wall}})_n}{p_{ac}} \]

\[ = 10 \times 10^{-3} \quad (x \sim 10\text{cm}) \]

\[ \frac{p_{\text{wall}}}{p_{\infty}} = 0.0055 \quad (x \sim 40\text{cm}) \]
DNS (Flared-Blunt-Cone)

X ~ 22 cm (Slow)
X ~ 30 cm (Fast)

Straight sharp cone
Expts. (Flared-Sharp and Blunt-Cones)

Blunt Flared-Cone

Sharp Flared-Cone

Amanda et al. AIAA-2015-1734
Conclusions

- A small bluntness affected the receptivity process over flared cones. Compared to the sharp flared-cone case, the receptivity coefficient is about 200 times smaller for the blunt flared-cone.
- These conclusions agree with the experimental data.
HIFiRE-1 (Kimmel et al. 2010) (t=21.5 sec)

(a) Re = 13.2 * 10^6 m^-1

(b) Re = 13.2 * 10^6 m^-1

T = 21.5 sec
Cone half-angle = 7 deg.
Nose radius = 2.5 mm (Re_n = 33000)
Mach number = 5.3
Freestream temp. = 201.4 K
Reynolds number = 13.2 * 10^6/m
Transition onset = 0.805 m
Angle of attack = 0.0 deg
DNS (HIFiRE-1)

\[ p_{ac} / p_{\infty} = 2 \times 10^{-6} \cos (\omega_{ac} \cdot t) \]
\[ f = 550 \text{ kHz} \]

\[ C_{recept,p_{wall}} = \frac{(p_{wall})_n}{p_{ac}} \]
\[ = 1 \times 10^{-1} \quad (x \sim 47 \text{ cm}) \]
\[ \frac{p_{wall}}{p_{\infty}} = 2.0 \times 10^{-7} \quad (x \sim 47 \text{ cm}) \]
\[ \frac{(p_{wall})_{\text{max}}}{p_{\infty}} = 0.17 \quad (x \sim 80 \text{ cm}) \]

\[ N - \text{Factor} = 13.8 \]
Conclusions

• Cooling and bluntness stabilized the first mode. The disturbances started to grow from $x \sim 50$ cm.

• Maximum amplitude reached with the free stream acoustic level of $(1. \times 10^{-6})$ is 0.17. At the transition onset it should be $\sim 1.4$. 
Mean Flow (Case 1)

(a) $Re = 2.03 \times 10^6 \ m^{-1}$

(b) $Re = 2.03 \times 10^6 \ m^{-1}$

(a) $\rho/ho_\infty$

(b) $\eta$

$\rho$

13 13.1
11 11.1
9 9.1
7 7.1
5 5.1
3 3.1
1 1.1
Mean Flow (Case 2)

(a) $Re = 7.03 \times 10^6 \text{ m}^{-1}$

(b) $Re = 7.03 \times 10^6 \text{ m}^{-1}$

$\eta \rho / \rho_e$

$\rho$

13 13.1
11 11.1
9 9.1
7 7.1
5 5.1
3 3.1
1 1.1
DNS

\[ p_{ac}(x,t) = \tilde{p}_{ac} e^{i(\alpha_{ac} x - \omega t)} + c.c, \]

\[ (p_{ac})_{PSD} = 2\left( \tilde{p}_{ac} \right)^2 \]

Measured spectrum \( (p_{ac})_{PSD} = C \ f^{-3.5} / \text{Hz} \)

\[ 2\left( \tilde{p}_{ac} \right)^2 = C \ f^{-3.5} \ \Delta f \]

\( \Delta f \sim 10 \ \text{to} \ 100 \ \text{kHz} \) (need to investigate more)

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\[ \Delta f \sim 10 \text{ to } 100 \text{ kHz} \] (need to investigate more)
DNS (Flared-Blunt-Cone)

(a) Slow

\[ \frac{p_{ac}}{p_{ac}} = 2 \times 10^6 \cos (\alpha_{ac} x - \omega t) \]

\[ F = 2.045 \times 10^{-4} \ (292.5 \text{ kHz}) \]

(b) Fast

\[ \frac{p_{ac}}{p_{ac}} = 2 \times 10^6 \cos (\alpha_{ac} x - \omega t) \]

\[ F = 2.045 \times 10^{-4} \ (292.5 \text{ kHz}) \]
Expts. (Flared-Blunt and –Sharp Cones)

(a) $r_n = 1\ \text{mm}$. Computation: $p_0 = 600\ \text{kPa}$, $T_0 = 411\ \text{K}$, $\rho_\infty = 0.026\ \text{kg/m}^3$. Experiment: $p_0 = 605.5\ \text{kPa}$, $T_0 = 412.3\ \text{K}$, $\rho_\infty = 0.026\ \text{kg/m}^3$.

(b) $r_n = 0.16\ \text{mm}$. Computation: $p_0 = 535\ \text{kPa}$, $T_0 = 428\ \text{K}$, $\rho_\infty = 0.023\ \text{kg/m}^3$. Experiment: $p_0 = 537.6\ \text{kPa}$, $T_0 = 429.0\ \text{K}$, $\rho_\infty = 0.023\ \text{kg/m}^3$. 
DNS (HIFiRE-1)

(a) $p_{ac} / p_v = 2 \times 10^{-6} \cos (\omega_{ac} - \omega t)$
f = 550 kHz

(b) $p_{ac} / p_v = 2 \times 10^{-6} \cos (\omega_{ac} - \omega t)$
550 kHz Slow
575 kHz Slow
525 kHz Slow