Receptivity of Hypersonic Boundary Layers to Acoustic Disturbances

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Hypersonic Boundary-Layer Transition Prediction
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Objectives

- The physics based $e^N$ correlation method (emalik$^{3D}$, 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.
\( T_{\text{wall}} = 0.3 T_o \)
\( Pr = 0.74 \)
\( \gamma = 1.4 \)
Gas constant \( R = 297 \).

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

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

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

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

(a) $\rho / \rho_e$

(b) $\rho / \rho_e$
N-Factors (Cases 1-3)

<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

(a)

\[ f = 440 \text{ kHz} \]
\[ \frac{p_{ac}}{p_{sc}} = 6 \times 10^{-5} \cos (\alpha \cdot x - \omega t) \]

\[ \rho \]

6.0E-05
6.8E-21
-6.0E-05

(b)

(c)
**DNS**

Cases 1-3

![Graph showing PSD](image)

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

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

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

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

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

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

- $= 2.0$  $(x \sim 0)$
- $= 4.5$  $(x \sim 23 \text{ cm})$

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

- $= 2.0$  $(x \sim 0)$
- $= 5.0$  $(x \sim 9 \text{ cm})$

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

- $= 2.0$  $(x \sim 0)$
- $= 5.0$  $(x \sim 5 \text{ cm})$
**DNS**

**Cases 1-3**

<table>
<thead>
<tr>
<th>Case</th>
<th>$X_T$ (cm)</th>
<th>N</th>
<th>PSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(p_{amp})_T$</td>
<td>Expt.</td>
<td>$(p_{amp})_T$</td>
</tr>
<tr>
<td>1</td>
<td>1.4</td>
<td>81</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>84</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>3.2</td>
<td>3.6</td>
<td>4.1</td>
</tr>
<tr>
<td>3</td>
<td>5.3</td>
<td>5.7</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>6.9</td>
<td>7.0</td>
</tr>
</tbody>
</table>

$N_T = \frac{(p_{amp})_T}{C_{recpt,p_{wall}} p_{ac}}$

$p_s/p_\infty = 3.29$
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)

\[ M_\infty = 6.0 \]
\[ \text{Re} = 10.3 \times 10^6 \text{ m}^{-1} \]
\[ T_w = 52.80 \degree \text{ K} \]
\[ T_{\text{wall}} = 300.0 \degree \text{ K} \]

Leading edge radius \( r_0 = 0.16, 1.0 \text{ mm} \)

Flare is a circle with 3.0m radius

Slope is 2 degrees at the joint

\[ X = 40 \text{ cm} \]

\[ N=15 \text{ (sharp), 292 kHz} \]

\[ N=13 \text{ (Blunt), 300 kHz} \]
DNS (Flared-Sharp-Cone)

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

\[ F = 2.15 \times 10^{-4} \text{ (308 kHz)} \]

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

\[ = 1.0 \quad (x \sim 0) \]

\[ \frac{p_{wall}}{p_\infty} = 0.4 \quad (x \sim 33cm) \]

\[ = 1.0 \quad (x \sim 36cm) \]
DNS (Flared-Blunt-Cone)

(a) Slow

\[
C_{\text{recept}, p_{\text{wall}}} = \frac{(p_{\text{wall}})_n}{p_{ac}}
\]
\[
= 5 \times 10^{-3} \quad (x \sim 10cm)
\]
\[
\frac{p_{\text{wall}}}{p_\infty} = 0.0028 \quad (x \sim 40cm)
\]

(b) Fast

\[
C_{\text{recept}, p_{\text{wall}}} = \frac{(p_{\text{wall}})_n}{p_{ac}}
\]
\[
= 10 \times 10^{-3} \quad (x \sim 10cm)
\]
\[
\frac{p_{\text{wall}}}{p_\infty} = 0.0055 \quad (x \sim 40cm)
\]
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)

T = 21.5 sec
Cone half-angle = 7 deg.
Nose radius = 2.5 mm (Reₙ=33000)
Mach number = 5.3
Freestream temp. = 201.4 K
Reynolds number = 13.2 *10⁶/m
Transition onset = 0.805 m
Angle of attack = 0.0 deg
DNS (HIFiRE-1)

\[ p_{ac} / p_{∞} = 2 \times 10^{-6} \cos (\omega_{ac} + \omega t) \]

\[ f = 550 \text{ kHz} \]

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

\[ = 1 \times 10^{-1} \quad (x \sim 47 \text{ cm}) \]

\[ \frac{p_{\text{wall}}}{p_{∞}} = 2.0 \times 10^{-7} \quad (x \sim 47 \text{ cm}) \]

\[ \frac{(p_{\text{wall}})_{\text{max}}}{p_{∞}} = 0.17 \quad (x \sim 80 \text{ cm}) \]

\[ N - \text{Factor} = 13.8 \]
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 $(1.\times10^{-6})$ is 0.17. At the transition onset it should be $\sim 1.4$. 
Mean Flow (Case 1)

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

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

(a) $Y_\gamma (\text{cm})$

(b) $X (\text{cm})$

(a) $\rho / \rho_\infty$

(b) $\eta$
Mean Flow (Case 2)

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

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

\[
\eta = \frac{n}{\rho / \rho_\infty} \quad (a)
\]

\[
\eta = \frac{\rho / \rho_\infty}{X (cm)} \quad (b)
\]
**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 \( (p_{ac})_{PSD} = C \ f^{-3.5} / Hz \)

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

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

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Fig. 18 PSD from expt. (Marineu et al. AIAA 2015)
$$p_{ac}(x,t) = \tilde{p}_{ac} e^{i(\alpha_{ac} x - \omega t)} + c.c,$$

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

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)

Fig. 18 PSD from expt. (Marineu et al. AIAA 2015)
DNS (Flared-Blunt-Cone)

(a) Slow

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

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

(b) Fast

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

\[ F = 2.045 \times 10^{-4} \text{ (292.5 kHz)} \]
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) \[ p_{ac} / p_\infty = 2 \times 10^{-6} \cos (\alpha_{ac} - \omega t) \]
\[ f = 550 \text{ kHz} \]

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

\[ 550 \text{ kHz Slow} \]
\[ 575 \text{ kHz Slow} \]
\[ 525 \text{ kHz Slow} \]