Wall-pressure-based observers to assess separation control techniques

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November, 8th – 9th 2017

Orléans, France
Control of separating/reattaching flows (diffuser, road vehicle, airfoil ...)

Issues:
From lab (well resolved) to real life (sparse information)
Matching between the collected information and the control objective
Find candidates to describe the flow state with as less as possible sensors?

Outlines

Experimental set-up
Results
Conclusion
The experimental model

Data shown today

\[ h = 100 \text{ mm} \]

\[ Re_h = \frac{U_{ref} h}{\nu} = 1.3 \times 10^5 \]

Kinematic viscosity of air
The incoming boundary layer

\[ \frac{\delta}{h} = 0.19 \]

\[ Re_\theta = \frac{U_\infty \theta}{v} = 2550 \] (≈ fully turbulent according to Song & Eaton (2004))
### Characteristics of PIV system

<table>
<thead>
<tr>
<th><strong>Laser</strong></th>
<th>Model</th>
<th>Quantel Evergreen 200-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Nd:YAG (532 nm)</td>
<td></td>
</tr>
<tr>
<td>Maximum energy</td>
<td>200 mJ</td>
<td></td>
</tr>
<tr>
<td>Maximum frequency</td>
<td>15 Hz</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Cameras</strong></th>
<th>Model</th>
<th>LaVision Imager LX 11M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>CCD cameras</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>4032 x 2688 pixels</td>
<td></td>
</tr>
<tr>
<td>Maximum frequency</td>
<td>( \approx 2.5 ) Hz</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Seeding</strong></th>
<th>Type</th>
<th>Olive oil droplets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean diameter</td>
<td>1 ( \mu )m</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Calculation parameters</strong></th>
<th>Correlation window</th>
<th>32 x 32 pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overlap</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>Combined FOV</td>
<td>628 mm x 319 mm</td>
</tr>
<tr>
<td></td>
<td>Spatial resolution</td>
<td>1.89 mm</td>
</tr>
</tbody>
</table>

- **Experimental set-up**

Velocity measurements

- **Backflow probability**

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Wall pressure measurements

Characteristics of pressure measurements systems

<table>
<thead>
<tr>
<th>Model</th>
<th>3 x 32 channels Chell μDAQ-32C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>93 pressure taps</td>
</tr>
<tr>
<td>Acquisition frequency</td>
<td>500 Hz</td>
</tr>
<tr>
<td>Number of samples</td>
<td>30 000</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 0.25%</td>
</tr>
</tbody>
</table>

Experimental set-up

Wall pressure measurements

\[ C_p = \frac{P - P_\infty}{\frac{1}{2} \rho U_\infty^2} \]

Reynolds stresses

\[ \frac{\partial C_p}{\partial x_i} \approx \frac{2}{U_\infty^2} \frac{\partial}{\partial x_j} \left( U_i U_j + \langle u'_i u'_j \rangle \right) \]

PIV data
Experimental set-up

Synthetic jet actuator

Technical characteristics
- 3 x 380 mm / 600 W loudspeakers
- Audio amplifier 4 x 490 W
- Slot width $b = 1$ mm
- Singleton sine excitation
- Excitation frequency $f_E \in 5 - 200$ Hz
- Excitation voltage $V_E \in 0.5 - 2.5$ V
Experimental set-up

**Synthetic jet actuator**

Technical characteristics
- 3 x 380 mm / 600 W loudspeakers
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Experimental set-up

Synthetic jet actuator

Momentum coefficient

\[ C_\mu = \frac{bU_{j,max}^2}{hU_\infty^2} \]

Strouhal number

\[ F^+ = \frac{f_E h}{U_\infty} \]
Find candidates to describe the flow state with as less as possible sensors?

2 objectives: drag & recirculation length

State observers based on wall pressure measurements
The pressure drag

\[ C_{Dp} = \frac{1}{h} \int_0^h C_p \, dy \]
The pressure drag

$$\Delta C_{Dp} = 1 - \frac{C_{DpC}}{C_{Dp0}}$$

**NB:** lowest drag ≠ smallest recirculation
The pressure drag

Model fitted (dashed lines): 2nd order polynomial $\Rightarrow$ 3 sensors needed
The recirculation length

\[ \frac{L_R}{h} = 5.5 \]

Link between \( L_R \) and wall pressure?

Intensity of the turbulent shear stresses

\[ \Delta C_p \sim -2R_{uv} \frac{L_R}{h} \]

Mean streamwise momentum equation along the separation line

\[ \frac{\partial P}{\partial x} \approx -\rho \left( \frac{\partial \langle u'v' \rangle}{\partial y} \right)_{L_R} \]

The recirculation length

\[ L_R \]

Pressure sensor at the foot of the ramp

C_{Pf}

\[ \Delta C_{pf} = 1 - \frac{C_{pfC}}{C_{pf0}} \]

\[ \Delta L_R = 1 - \frac{L_{RC}}{L_{R0}} \]
The recirculation length

NB: no matching between change in drag and recirculation length
Active control of a separating/reattaching flow

**Goal:** identify candidate suited to represent the flow state with a limited number of sensors

Objectives: drag and recirculation length

State observers only based on wall pressure sensors only

Results emphasize relevant surrogates with a maximum of 3 sensors

Issues to be addressed:

Bring physics within the process of selection

Dynamics of the mechanisms

Extension to other flows
Figure 7.4: GDR reference boundary layer profile at $Re_\theta = 2547$ ($Re_\tau = 1090$), normalised in external units. (a) $U/U_\infty$; (b) $\sqrt{\langle (u')^2 \rangle}/U_\infty$. + hotwire measurements at $x/h = -9$; ● composite boundary layer profile (Chauhan et al. (2009)); ◇ data from the PIV auxiliary field. --- DNS at $Re_\theta = 2537$ ($Re_\tau = 830$) as given in Schlatter & Örlü (2010).