Characterisation of the transient dynamics of the separated boundary layer reattachment using fluidic vortex generators

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November 8th, 2013 - GDR Contrôle des Décollements
Purpose of the study

To study the transient dynamics of the separation/attachment of a thick turbulent boundary layer

- with PIV measurements of the separation bubble
- with hot-films signals from the wall

The aim is:

- to obtain temporal information on this dynamics
- to visualize the spatial organization of the flow due to the control
- to develop robust controllers for a closed-loop control
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LML wind-tunnel

Boundary Layer Wind-tunnel

- Length of the wind-tunnel \( L = 20 \text{ m} \)
- \( U_\infty \rightarrow 10 \text{ m/s} \)
- \( \delta = 30 \text{ cm} \) at the measurement zone
Characteristics of the flow

- $\alpha = -2^\circ$ and $\beta = -22^\circ$
- $U_\infty = 5 \longrightarrow 10 \, m/s$
- $H_{step} = 17.5 \, cm$
- $\delta = 0.19 \, m$ just before the flap
- $Re_\theta = 10100$ just before the flap
Actuators: description

Festo fluidic valves
- Valves MPH2-MP1H
- Max frequency of commutation: **380 Hz**

Sonic throats
- For fixing the volume flow rate
Actuators: position

**Co-rotating configuration**

- Angle $\alpha = 125^\circ$
- Angle $\beta = 35^\circ$
- Diameter $\phi = 6\text{ mm}$
- Spacing $\lambda/\phi = 13.6$

Below the ramp

Position of the jets

jets

hot-films

0.28 m

0.175 m

Flap (0.34 m)
# Parameters of actuation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR</td>
<td>Velocity ratio ($V_{jets} / V_{local}$)</td>
<td>3 and 5</td>
</tr>
<tr>
<td>Type</td>
<td>Continuous or pulsed actuation</td>
<td>Pulsed mostly</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency of actuation</td>
<td>4, 8 and 80 Hz</td>
</tr>
<tr>
<td>DC</td>
<td>Duty cycle ($T_{up} * f$)</td>
<td>50 and 80 %</td>
</tr>
</tbody>
</table>
Characteristics of the PIV setup

- $L_{PIV} = 0.95 \text{ m}$ and $H_{PIV} = 0.29 \text{ m}$
- 4 cameras $2048 \times 2048 \text{ px}^2$
- Laser : Nd-YAG - 400 mJ per pulse
Phase-averaged PIV measurements

- Each phase corresponds to a specific instant of the transition, during the separation and the attachment.
- The first PIV phase can be shifted, in order to increase the time-resolution of the PIV.
### Summary of the cases

<table>
<thead>
<tr>
<th>$U_\infty$</th>
<th>$VR$</th>
<th>$f$</th>
<th>$DC$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>4</td>
<td>50</td>
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<td></td>
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<td>8</td>
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<td>3</td>
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<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>

- $f_{PIV} = 4 \text{ Hz}$, except for
  - $f = 4 \text{ Hz}$ and $DC = 50 \%$ → 32 Hz
  - Continuous actuation → 16 Hz

(cases in grey in the table)
Position of the phases


graphical representation showing time (t) vs. position (y) with different phases indicated:
- Attach (transition)
- Attached (stable)
- Sepa (transition)

Mathematical equation:

\[
\frac{dy}{dt}(t) = -\frac{y(t)}{T_{model}} + \frac{H}{T_{model}} \cdot u(t - t_{del})
\]
Few overall results: Aera of separation

One of the overall results of the total experimental: the aera of separation.

\[ A_{sep} = \text{aera of the bubble of separation} \]
\[ A_{sep,ref} = \text{aera of the bubble of separation for the initial separated flow} \]

\[ \frac{A_{sep}}{A_{sep,ref}} \text{ is considered here} \]

See Logdberg (2008) for more details on the criteria of separation.
Few overall results: Aera of separation

Evolution in time of the aera of separation scaled with the aera of the separated flow.
(a) $\text{VR} = 3$ (b) $\text{VR} = 5$

The criteria used is $\chi > 0.5$

See Logdberg (2008) for more details on the criteria
Case presented: **Pulsed actuation**

Free-stream velocity $U_\infty = 10 \text{ m/s}$

Pulsed actuation: $f = 4 \text{ Hz}$ and $DC = 50\%$

$VR = 5$

Equivalent PIV resolution: 32 Hz

Only the transition of attachment
U10 f004 VR05 DC50 P32: Hot-films

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Model identification (1) (In progress)

Models of the hot-film signal for the closed-loop controller

\[ u(t) \rightarrow \text{Actuator} \rightarrow \text{Flow} \rightarrow \text{Sensor} \rightarrow y(t) \]

Plant

\[ y(t) \]

Modeling with time-series algorithms for the identification of parameters

examples: ARX, ARMAX, Box-Jenkins ...
For example, the ARX model:

\[ A(z).y_i = B(z).u_i + e_i \]
Evolution of the longitudinal mean velocity $U_x/U_\infty$

The separation is detected with the $\chi$ criteria
Evolution of the vorticity $\omega_z$

The separation is detected with the $\chi$ criteria
Model identification: POD

Evolution in time of the first mode of the POD functions $\phi_i$

$$u'(x, y, t_p) = \sum_{i=1}^{N_{\text{modes}}} b_i(t_p) \phi_i(x, y, t_p)$$

$\theta_p = 1.8^\circ$
Conclusion (1)

This study highlights the influence of several actuation parameters on the transient dynamics of the reattachment:

- Lower VRs tends to decrease the speed of the response
- Higher duty cycles increase the speed of the response
- Higher frequencies of actuation tends to decrease the speed of the response
Conclusion (2)

It also highlights the influence of the pulsed actuation on the spatial organization of the flow during the transition.

- Higher duty cycles tends to avoid completely the separated flow
- Higher frequencies are more efficient on the reduction of the area of separation

The instabilities of the flow during the reattachment are pulled out.

Advanced analysis of the data can be done in order to extract more information on the dynamics.
Perspectives: Closed-loop control

G(s) : Controller transfer function
H_{OL}(s) : Transfer function in open-loop of the plant (model)

Construction of robust controllers to perform a closed-loop control
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Thank you for your attention