Flow control on a 3D backward facing ramp by pulsed jets

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Introduction

• FOSCO Project
  – « FOrcing for Separation COntrol »
  – Sequel of CARAVAJE project (flow control by pulsed jets applied to automotive vehicles)

  – Objective: comprehension of the physical mechanisms associated with periodic forcing
  – Test case: simple geometry but close to industrial preoccupations
Summary

• Experimental setup
  – Test case
  – Wind tunnel arrangement
  – Instrumentation

• Base flow characterization
  – Mean flow topology
  – Mean pressure distribution
  – Incoming flow characterization
  – PIV investigations

• Flow control experiments
  – Control strategy
  – Control system
  – Jets characterization
  – Parametric study
  – Mean flow modifications

• Conclusions and perspectives
Experimental setup

- Test case: the 3D backward facing ramp
  - Why not the classical Ahmed body?

- Critical, bi-stable angle
- "High drag" case unfavorable
- Underbody without moving floor
- Etc.

- Geometry well adapted for control studies related to notchback configuration
Experimental setup

• Wind tunnel arrangement
  – Automotive wind tunnel (S4) with test chamber of 5 m x 3 m, $U_0$ up to 44 m.s\(^{-1}\) and turbulence intensity $\approx 1.2\%$
  – Model installed on raised floor to deal with the natural boundary layer of the wind tunnel
  – Additional instrumented area on the raised floor due to the expected flow topology
Experimental setup

• Instrumentation
  – PIV system (2D2C – 2D3C)
  – 200 mJ, 15Hz Nd:YAG Laser
  – 4 Mpx cameras
  – Seeding with oil droplets (2µm)
  – Adaptive correlation algorithm
  – 16 x 16 pixels with 50% overlap

• Steady pressure measurements

  – Flow symmetric in the mean
  – 141 pressure taps on half of the model
  – Scanivalve pressure scanner
  – Accuracy: 0.03%
  – Results expressed as pressure coefficient:

\[ C_p = \frac{p - p_0}{\frac{1}{2} \rho U_0^2} \]
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• Conclusions and perspectives
Base flow characterization

• Mean Flow topology
  – Oil flow visualizations* at $Re_L = 1.4 \times 10^6$ ($U_0 = 20 \text{ m.s}^{-1}$)

  - Similar flow pattern with notchback car

* dodecan, silicon oil, oleic acid and titanium oxide
Base flow characterization

• Mean pressure distribution
  – Pressure coefficient ($C_p$) iso-contours ($Re_L = 1.4 \times 10^6; U_0 = 20 \text{ m.s}^{-1}$)
  
  – “Print” of the mean recirculation area
  – Lack of information regarding side regions (both for the top and the lateral edges of the slant)
Base flow characterization

• Incoming flow characterization

  – Boundary layer measurement at $X = -5 \times 10^{-2} \text{ m}$, $Y = 9.5 \times 10^{-2} \text{ m}$
  – $Re_L = 1.4 \times 10^6$ ($U_0 = 20 \text{ m.s}^{-1}$)

  \[ \begin{align*}
  \delta_{99} &= 26 \times 10^{-3} \text{ m} \\
  \delta^* &= 2.8 \times 10^{-3} \text{ m} \\
  \theta &= 2.3 \times 10^{-3} \text{ m} \\
  H &= 1.24
  \end{align*} \]

  – Similarities with the boundary layer developing on the roof of the Ahmed body
Base flow characterization

• PIV investigations
  – Longitudinal plane \((Y = 0, \text{Re}_L = 1.4 \times 10^6, U_0 = 20 \text{ m.s}^{-1})\)

  \[ L_R \approx 0.26 \text{ m, independent from Reynolds number...} \]

  \[ \ldots \text{but strongly affected by edge sharpness} \]
Base flow characterization

• PIV investigations
  – Transversal plane \((X = 0.124 \text{ m}, \text{Re}_L = 1.4 \times 10^6, U_0 = 20 \text{ m.s}^{-1})\)

  – Vortex core location independent from Reynolds number
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• Flow control experiments
  – Control strategy
  – Control system
  – Jets characterization
  – Parametric study
  – Mean flow modifications
• Conclusions and perspectives
Flow control experiments

• Control strategy
  – Objective: suppression or reduction of the mean recirculation area
  – Introduction of counter-rotating vortex pairs (CRV)

  – Momentum transfer between free flow and low velocity area
  – CRV created through **pulsed jets**
  – Dynamic vortex generators (Ortmanns et al. 2008)
Flow control experiments

• Control system
  – Pulsed jets produced by magnetic valves (see Joseph et al. 2012)
  – Valves driven by TTL (rectangular, 0 – 5V) signal with variable frequency and duty cycle
  – 89 rectangular jets located at X = - 1 x 10^{-2} m upstream of the separation point
Flow control experiments

- Jets characterization
  - Strong variations of spatio-temporal characteristics with the command parameters: supply pressure $p_s$, duty cycle $DC$ and command frequency $f_j$
  - Hot wire measurements with 1D probe at $Z = 1 \times 10^{-3} \text{ m}$

\[ f_j = 70 \text{ Hz}, \quad DC = 50\% \]

\[ f_j = 70 \text{ Hz}, \quad p_s = 6 \text{ bar} \]

\[ DC = 50\%, \quad p_s = 6 \text{ bar} \]
Flow control experiments

- Mean flow modifications
  - Parametric study ($C_\mu$, $St_J$ and $U_0$)
  - Monitoring of pressure recovery on a single point

  - Interaction with flow instabilities ?
  - Special functioning mode of the actuators ?
  - 190 Hz implies only “overshoot“ on the temporal history of the jet velocity

Addional measurements:

**Re_L = 1.4 \times 10^6 \ (U_0 = 20 \ m.s^{-1})**

- $C_\mu = 19 \times 10^{-3}$
- $C_\mu = 8.9 \times 10^{-3}$
- $C_\mu = 0.8 \times 10^{-3}$

**$p_S = 6 \ \text{bar}$**

- $U_0 = 20 \ \text{m.s}^{-1}$
- $U_0 = 30 \ \text{m.s}^{-1}$
- $U_0 = 40 \ \text{m.s}^{-1}$
Flow control experiments

- Mean flow modifications
  - PIV measurements (XZ plane, $Y = 0$, $Re_L = 1.4 \times 10^6$, $U_0 = 20 \text{ m.s}^{-1}$)
  - $C_\mu = 19 \times 10^{-3}$, $St_J = 0.89$ and $DC = 50$

- Suppression of the recirculation area
Flow control experiments

• Mean flow modifications
  – Pressure coefficient $C_p$ mapping ($Re_L = 1.4 \times 10^6$, $U_0 = 20 \text{ m.s}^{-1}$)
  – $C_{\mu} = 19 \times 10^{-3}$, $St_J = 0.89$ and DC = 50%

  - Global pressure recovery...
  - ... but lack of information on the side area (low pressure expected)
  - $C_x$ ?
Flow control experiments

- Mean flow modifications
  - PIV measurements (YZ plane, $X = 0.124$ m, $Re_L = 1.4 \times 10^6$, $U_0 = 20$ m.s$^{-1}$)
  - $C_\mu = 19 \times 10^{-3}$, $St_J = 0.89$ and DC = 50%

- Displacement of vortex cores location and increase in size
- Additional flow structures: Görtler vortices?
Flow control experiments

• Mean flow modifications
  – PIV measurements (YZ plane, $X = 0.124 \text{ m}$, $Re_L = 1.4 \times 10^6$, $U_0 = 20 \text{ m.s}^{-1}$)
  – $C_\mu = 19 \times 10^{-3}$
    \[ St_J = 0.83 \quad DC = 50\% \]
    \[ St_J = 0.28 \quad DC = 50\% \]
  – Strong influence of the actuation frequency on the additional flow structure (still under investigation)
Conclusions

- Base flow consistent with wake of a notchback automotive
- Separated bulb along with pair of longitudinal vortices
- Control action leads to reattachment
- Pressure increases globally, but effect on $C_x$ still to be addressed
- Control action mainly driven by actuator characteristics rather than by interaction with flow instabilities
- However local influence on mean flow topology
Perspectives

- Unsteady measurements
- $C_x$ evaluation through conservation of momentum
- Numerical simulation (research code developed for DNS with high order resolution)

**Instantaneous Q criterion** ($Re_L = 1.4 \times 10^6$)

**Preliminary numerical results** (isosurface $U/U_0 = 0.88$, $Re_L = 2.1 \times 10^6$)
References


