Introduction

Setup

Unforced flow

Steady blowing

Periodic Forcing

Sliding mode

Conclusions and future work
Transportation industry

**Railway industry**
- **10 000 employees**
- **1st European region for railway**
- 4 International manufacturers leaders
- 1 Billion euros sales revenue

**Automobile industry**
- **36 000 employees**
- **1st French region for car industry**
- 3 Cars Manufacturers
- 550 000 Vehicles
- 7 production plants

**Logistics**
- **41 500 employees**
- **3rd French region for logistics**
- 1st French harbor platform
  (Boulogne, Calais, Dunkerque)
Transportation industry

PROBLEM
Reduce gas consumption

Rear face

Front face 3%  
Cooling system 8%  
Front top side 5%

Car floor 30%
Car edge 2%
Wheel 2%
Rearview mirror and other similar equipments 7%
Automotive problem

- Flow configuration

PROBLEM

Reduce gas consumption

Drag reduction

$$F_D = \iint_{S_w} (P_{t\infty} - P_{t_{sw}})d\sigma + \frac{1}{2} \rho V_{\infty}^2 \iint_{S_w} \left( \frac{V_z^2}{V_{\infty}^2} + \frac{V_z^2}{V_{\infty}^2} \right) d\sigma - \frac{1}{2} \rho V_{\infty}^2 \iint_{S_w} \left( 1 - \frac{V_x}{V_{\infty}} \right)^2 d\sigma$$
Automotive problem

- Methods of flow control

✗ Passive control
   (Small variation in the geometric configuration)
   Limitations of design requirements

✓ Active control (Injection of momentum)
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Wind tunnel

Characteristics:

✓ Closed-loop wind tunnel
✓ Max. velocity 60m/s (200km/h)
✓ Optimal test section: 2m x 2m, length 10m
Physical System

Square back ahmed body

\[ h = 0.135m \quad r = 0.05m \]
\[ w = 0.170m \quad g = 0.035m \]
\[ l = 0.370m \]

\[ U_\infty = 10m/s \]
\[ Re_h = 9 \times 10^4 \]
Physical System

PIV

2000 double frame pictures
7Hz repetition rate
Interrogation window 16x16 pixels^2
50% overlapping

PIV domain
3.7h x 1.8h
Sensor and actuator characteristics

---

**Sensor**

- A force and torque balance:
  - Drag, lift and drift
  - Sensing range up to 165N
  - Error 0.03N
- 2 sub-miniature piezo-resistive Kulite sensors:
  - Nominal measurement range of 35Kpa
  - Sampling frequency 10KHz

**Actuator**

- Actuator slit (width $h_s = 0.1\,mm$ and a length $w_a = 150\,mm$)
- Pressure supplied by a compressor
- Pulsed blowing driven by a FESTO-MH2 solenoid valve
- Velocities up to 30m/s (@ 6bar)

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Jet velocity $V_j$
Steady jet velocity $V_{j0} = 16m/s$
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Unforced flow

Instantaneous flow field #265
- Velocity field
- Unforced shear-layer vortex

Time average cross-stream velocity
- Streamlines
- Forward flow probability 50%
- Recirculation length $L_r$
Unforced flow

Present study
\[ g = 0.035m \]
\[ Re_h = 9 \times 10^4 \]

Li et al. (2017)
\[ g = 0.05m \]
\[ Re_h = 3 \times 10^5 \]

Eulalie (2015)
\[ g = 0.035 - 0.07 \ m \]
\[ Re_h = 4 \times 10^5 \]
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Steady blowing

- Active flow control

Open-loop control

\[ s(t) = F_a(t) \]
Steady blowing

Control law

$$b(t) = V_{j0}$$

Experimental plant

$$U_\infty$$

$$P(t)$$

$$F_d(t)$$

Sensors
Steady blowing
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### Control law

\[
b(t) = sq(f \ast DC)
\]

### Experimental plant

<table>
<thead>
<tr>
<th>(f)</th>
<th>(S_t_A = f_a h / U_\infty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0.0675</td>
</tr>
<tr>
<td>10</td>
<td>0.15</td>
</tr>
<tr>
<td>30</td>
<td>0.405</td>
</tr>
</tbody>
</table>
Periodic blowing
Steady blowing vs Periodic forcing

\[ St_0 = 0.15 \]
Steady blowing vs Periodic forcing

\[ St_0 = 0.15 \]
Steady blowing vs Periodic forcing

\[ St_0 = 0.15 \]
Steady blowing vs Periodic forcing

\[ S_{t0} = 0.15 \]
Steady blowing vs Periodic forcing

\[ St_0 = 0.15 \]
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Future work
- **Active flow control**

**Open-loop control**

- Actuation $b(t)$ to Experimental plant
- Sensor $s(t) = F_d(t)$

**Closed-loop control**

- Actuation $b(t)$ to Experimental plant
- Controller $s(t) = F_d(t)$
- Sensor $s(t) = F_d(t)$
\[
\dot{s}(t) = f(s, t) + g(s, t) \cdot b(t)
\]
\[ b(t) = \begin{cases} 1 & \text{if } \sigma(t) - \sigma^* < 0 \\ 0 & \text{if } \sigma(t) - \sigma^* > 0 \end{cases} \]

The control law is represented by the symbol \( b(t) \) which is a function of the error between the current state \( \sigma(t) \) and the desired state \( \sigma^* \).

The experimental plant is shown with input \( U_\infty \) and output \( P(t) \).

The diagram also shows the relationship of the output variables \( F_d(t) \) and \( S^* = F_d \) to the control system.
Choose $s^*$

Reaching phase
- Wait for $s(t)$ to arrive to $s^*$

Sliding phase
- Keep $s(t)$ at $s^*$
SMC

Control law

\[ b(t) = \begin{cases} 
1 & \text{if } \sigma(t) - \sigma^* < 0 \\
0 & \text{if } \sigma(t) - \sigma^* > 0 
\end{cases} \]

Experimental plant

Sensors

\[ U_{\infty} \]

\[ P(t) \]

\[ F_d(t) \]

\[ S^* = F_d \]
Choose $s^*$

Reaching phase

- Wait for $s(t)$ to arrive to $s^*$

Sliding phase

- Keep $s(t)$ at $s^*$

$\dot{s}(t) = f(s, t) + g(s, t) \cdot b(t)$
\[ \dot{s}(t) = \alpha s(t) + \beta b(t) \]

\[ \sigma^* = s(t) \]

\[ b(t) = \begin{cases} 
1 & \text{if } \sigma(t) - \sigma^* < 0 \\
0 & \text{if } \sigma(t) - \sigma^* > 0 
\end{cases} \]

\[ \dot{s}(t) = f(s, t) + g(s, t).b(t) \rightarrow \dot{s}(t) = \alpha s(t) + \beta b(t) \]
\[ \dot{s}(t) = \alpha s(t) + \beta b(t - h) \]
\[ \sigma^* = s(t) \]

\[ b(t) = \begin{cases} 
1 & \text{if } \sigma(t) - \sigma^* < 0 \\
0 & \text{if } \sigma(t) - \sigma^* > 0 
\end{cases} \]
\[ \dot{s}(t) = \alpha s(t) + \beta b(t - h) \]

\[ \sigma^* = s(t) + \beta \int_{t-h}^{t} b(p) dp \]

\[
\begin{align*}
     b(t) = \begin{cases} 
    1 & \text{if } \sigma(t) - \sigma^* < 0 \\
    0 & \text{if } \sigma(t) - \sigma^* > 0 
\end{cases}
\end{align*}
\]
SMC Identification

Sensor without delay

$$\dot{s}(t) = \alpha_1 s(t) - \alpha_2 s(t) + (\beta - \gamma s(t - h) + \gamma (t - \tau)) b(t - h)$$

Sensor with delay

$$FIT(\%) = \left\{1 - \frac{\|S_{exp} - S_{sim}\|_{L^2}}{\|S_{exp} - S_{exp}\|_{L^2}}\right\} \times 100\% = 53\%$$

$$\alpha_1 = 27.37 \quad \alpha_2 = 32.70 \quad \beta = 1.97 \quad \gamma = 1.92 \quad \tau = 0.18 \quad h = 0.01$$

Feingesicht et al. (2017) Int. J. Robust Nonlinear Control
Sliding mode control

\[ \dot{s}(t) = \alpha s(t) + \beta b(t - h) \]
\[ \sigma^* = s(t) + \gamma \int_{t-\tau+h}^{t} s(p)dp + \int_{t-h}^{t} (\alpha_1 s(p) + (\beta - \gamma s(p) + \gamma s(p - \tau + h))b(p))dp \]

\[ b(t) = \begin{cases} 
1 & \text{if } \sigma(t) - \sigma^* < 0 \\
0 & \text{if } \sigma(t) - \sigma^* > 0 
\end{cases} \]
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Conclusion
Future work

Sliding mode for Drift and Lift
  • Andrey Polyakov, Jean-Pierre Richard, Maxime Feingesicht & Franc Kerherve

Active flow control strategies
  • LAMIH Automatic department (ARI project)

Ahmed body (SISO MLC) Drag reduction
  • Ruiying Li, Eurika Kaiser & Bernd Noack,

CROM
  • Eurika Kaiser & Bernd Noack,

Real car active flow control
Acknowledgments

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