Active flow control on a backward facing step configuration

GDR ‘Contrôle des décollements’

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1. Introduction
2. Setup
3. Unforced flow
4. Periodic forcing
5. Machine learning control
6. Conclusions and future work
Transport industry

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

Car 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)
500,000 m² Last generation warehouses
Automotive problematic

Problem: Increase base pressure

- **Flow structure**

- **Physics of control strategies**
  - Boundary layer separation (Recirculation bubble)
  - Longitudinal vortices

- **Methods of flow control**
  - Passive control (Small variation in the geometric configuration)
  - Active control (Injection of momentum)

Limitations of design requirements
**Automotive problematic**

**Problem:** Increase base pressure

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**- Flow structure**

- Flapping shear layer
- Kelvin-Helmholtz & pairing
- Oscillation of recirculation bubble

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**- Physics of control strategies**

**Boundary layer separation** (Recirculation bubble)

**Longitudinal vortices**

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**- Methods of flow control**

**Passive control** (Small variation in the geometric configuration)

- Limitations of design requirements

**Active control** (Injection of momentum)
Active control of the turbulent flow downstream of a backward facing step with dielectric barrier discharge plasma actuators. Patricia Garrido (2014) Thesis work

Previous investigations

<table>
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<th>Fence</th>
<th>3000</th>
<th>87%</th>
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<tbody>
<tr>
<td>1</td>
<td>Loudspeaker</td>
<td>32500</td>
<td>15%</td>
</tr>
<tr>
<td>2</td>
<td>DBD plasma</td>
<td>30000</td>
<td>20%</td>
</tr>
<tr>
<td>3</td>
<td>Oscillating flap</td>
<td>39000</td>
<td>-</td>
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<tr>
<td>4</td>
<td>Loudspeaker</td>
<td>13-33 $10^3$</td>
<td>65%</td>
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<tr>
<td>5</td>
<td>Synthetic jet</td>
<td>27000</td>
<td>20%</td>
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<tr>
<td>6</td>
<td>Wake generator</td>
<td>33000</td>
<td>89%</td>
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<tr>
<td>7</td>
<td>Suction/blowing</td>
<td>35000</td>
<td>31%</td>
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<tr>
<td>8</td>
<td>Flapping foil</td>
<td>12700</td>
<td>30%</td>
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<tr>
<td>9</td>
<td>Permeable surface</td>
<td>1160</td>
<td>33%</td>
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</table>
Wind tunnel

Activity fields:
- Land transport
- Aeronautics
- Civil engineering
- Environment

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

$H = 83mm$
Physical system

2000 double frame pictures
7Hz repetition rate

Quantum bigsky laser Nd-Yag 200mJ

Row of actuators

Flow

Wind tunnel floor

2 Powerview CCD cameras 2000x2000 pixels
Sensor and actuator characteristics

Sensor

- 25 static pressure sensors in parallel with
- 25 sub-miniature piezo-resistive Kulite sensors
  • Nominal measurement range of 35Kpa
  • Sampling frequency 10KHz

Actuator

- Pulsed Jet (non-zero-net-mass-flux)
- Combination of a disc-shaped piezoelectric element and a metal diaphragm (Vibrations 26 kHz).
- Air discharges up to 1 l/min.
- Low Power Consumption.
Mean reattachment length ($L_r$) is a critical parameter in studies of separated and reattaching flows, e.g., $Re_H = 64200$.

### Aspects of turbulent boundary layer separation

- Mean detachment
- Time-averaged velocity close to the wall
- Transitory detachment
- Forward flow probability (FFP) equal to 50%

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*Aspects of turbulent boundary layer separation.* (1996) *Prog. Aerospace Sci*
Unforced flow

Table 2  Mean-flow parameters for various authors

<table>
<thead>
<tr>
<th>Authors</th>
<th>$Re_H$</th>
<th>$\delta/H$</th>
<th>$ER$</th>
<th>$L_r/H$</th>
<th>Symbols</th>
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<tr>
<td>Chung and Sung, 1996 [3]</td>
<td>33000</td>
<td>0.38</td>
<td>1.50</td>
<td>7.80</td>
<td>●</td>
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<tr>
<td>Driver and Seegmiller, 1985 [13]</td>
<td>37420</td>
<td>1.50</td>
<td>1.12</td>
<td>6.10±1.00</td>
<td>■</td>
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<tr>
<td>Westphal and Johnston, 1984 [7]</td>
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<td>8.60</td>
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<tr>
<td>Durst and Tropea, 1981 [15]</td>
<td>1800-30000</td>
<td>-</td>
<td>1.06-2.05</td>
<td>5.00-11.00</td>
<td>▲</td>
</tr>
<tr>
<td>Nadge and Govardhan, 2014 [16]</td>
<td>5000-64000</td>
<td>0.18-0.76</td>
<td>1.10-2.50</td>
<td>5.00-8.80</td>
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<tr>
<td>Li and Nagib, 2005 [14]</td>
<td>4300-13000</td>
<td>-</td>
<td>1.00</td>
<td>4.33-4.88</td>
<td>▼</td>
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<tr>
<td>Heenan and Morrison, 1995 [17]</td>
<td>190000</td>
<td>0.21</td>
<td>1.10</td>
<td>5.50</td>
<td>▼</td>
</tr>
<tr>
<td>Hudy et al., 2007 [21]</td>
<td>5980-32327</td>
<td>-</td>
<td>1.00</td>
<td>4.28-4.97</td>
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<tr>
<td>Li et al., 2015 [4]</td>
<td>9100</td>
<td>0.12</td>
<td>1.08</td>
<td>5.7</td>
<td>★</td>
</tr>
</tbody>
</table>

$U_0 = 5.7m/s - 33m/s \ \ \ \delta/H = 0.68-0.47$

$Re_H = 31500 - 182600 \ \ \ ER = 1.04$
Control design

\[ b = A \cos (wt) \]
Results

\[
f^* = f \frac{H}{U_o}
\]

<table>
<thead>
<tr>
<th>f</th>
<th>(f^* = f \frac{H}{U_o})</th>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
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<tr>
<td>3</td>
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<td>0.136</td>
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<tr>
<td>30</td>
<td>0.453</td>
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</table>
Flow control strategies

![Flow control strategies diagram](image)

**Kinematics**
- Knowledge of the plant
- Time-delay coordinates
- Empirical
- Mathematical
- Physical

**Dynamics**
- Galerkin projection
- \( \dot{a} = f(a, b) \)
- \( s = m(a, b) \)

**Plant model**
- Linear
- Weakly nonlinear
- Moderately nonlinear
- Strongly nonlinear

**Action mechanisms**
- Linear control design
- Data Acquisition control design

**Control design**
- LQR, LQG (optimal)
- Parameter tuning (heuristic)
- MLC (unsupervised)
- Adaptive control (quasi-steady)
Flow control strategies

Input/output data

Flow data

Navier-Stokes equations

Knowledge of the plant

Kinematics

Time-delay coordinates

Empirical

Mathematical

Physical

Modes

Galerkin projection

Dynamics

Plant model

Black-box model based control design

Model identification

\[ \dot{a} = f(a, b) \]
\[ s = m(a, b) \]

Action mechanisms

Optimal adjoint based control

Linear

Weakly nonlinear

Moderately nonlinear

Strongly nonlinear

Control design

Linear control design

Data Acquisition control design

LQR, LQG (optimal)

Parameter tuning (heuristic)

MLC (unsupervised)

Adaptive control (quasi-steady)

Controllers

Control design

Real-time loop (fast)

Actuators → Control law $b = K(s)$ → Sensors

$S_1 \rightarrow S_2 \rightarrow \ldots \rightarrow S_n$
Control design

Real-time loop (fast)

Actuators $b$ → Sensors $s$

Control law $b = K(s)$

Tree configuration

$b = \cos(S_1) - \tanh(0.2)$

$b = \cos(S_1) - \tanh(0.2)$

Control design

Real-time loop (fast)

Actuators $b$ → Sensors $s$

Control law $b = K(s)$

Learning loop (slow)

Genetic Programming

$J_1 < J_2 < ... < J_n$

Objective: minimize $J$

Cost $J$
Control design

\[ b_1^1 = K_1^1 \rightarrow J_1^1 \]
\[ \vdots \]
\[ b_i^1 = K_i^1 \rightarrow J_i^1 \]
\[ \vdots \]
\[ b_n^1 = K_n^1 \rightarrow J_n^1 \]

Elitism

\[ b_1^1 = H(s_3 - \exp(s_9) + 0.8) \rightarrow b_1^2 = H(s_3 - \exp(s_9) + 0.8) \]

Replication

\[ b_1^1 = H(s_3 - \exp(s_9) + 0.8) \rightarrow b_2^2 = H(s_3 - \exp(s_9) + 0.8) \]

Mutation

\[ b_1^1 = H(s_3 - \exp(s_9) + 0.8) \rightarrow b_2^2 = H(s_4 + \tanh(s_9) + 0.1) \]

Crossover

\[ b_1^1 = H(s_3 - \exp(s_9) + 0.8) \]
\[ b_i^1 = H(\tanh(s_8) - 0.1) \]
\[ b_2^1 = H(s_8 + 0.8) \]
\[ b_k^2 = H(s_8 + 0.8) \]
\[ b_i^2 = H(\tanh(s_3 - \exp(s_9)) - 0.1) \]

\[ b_j^1 = H(\tanh(s_8) - 0.1) \]

\[ b_i^2 = H(\tanh(s_3 - \exp(s_9)) - 0.1) \]

\[ b_n^2 = H(s_8 + 0.8) \]

Control design

Control law

\[ b = K(h_j) \]

Genetic programming

\[ \begin{align*}
J_1^{(1)} & \quad J_2^{(1)} & \quad J_3^{(1)} & \quad J_4^{(1)} \\
\downarrow \text{copy} & \quad \times \text{cross-over} & \quad \downarrow \text{mutation} \\
J_1^{(2)} & \quad J_2^{(2)} & \quad J_3^{(2)} & \quad J_4^{(2)}
\end{align*} \]

Multi-freq. forcing

Periodic signals

\[ h_1 \quad h_2 \quad h_3 \]
Control design

Control law
\[ b = K(P_j) \]

Sensor-based feedback

Genetic programming
\[
\begin{align*}
J_1^{(1)} & \quad J_2^{(1)} & \quad J_3^{(1)} & \quad J_4^{(1)} \\
\downarrow \text{copy} & \quad \times \text{cross-over} & \quad \downarrow \text{mutation} \\
J_1^{(2)} & \quad J_2^{(2)} & \quad J_3^{(2)} & \quad J_4^{(2)}
\end{align*}
\]
Control design

Control law
\[ b = K(P_j) \]
\[ b = K(P_j, h_j) \]
\[ b = K(h_j) \]

Sensor-based feedback
Non-autonomous feedback
Multi-freq. forcing
Periodic signals

Genetic programming
\[ J_1^{(1)} \quad J_2^{(1)} \quad J_3^{(1)} \quad J_4^{(1)} \]
\[ J_1^{(2)} \quad J_2^{(2)} \quad J_3^{(2)} \quad J_4^{(2)} \]

\[ J \]

copy  \quad \times \quad \text{cross-over}  \quad \text{mutation}
\[ J = L^E_T + \gamma < b > \]

- 12 generations
- 100 individuals

**Multi-frequency forcing**

**Non-autonomous feedback**

**Optimal periodic forcing**

**Sensor-based feedback**

**Benchmark**
RESULTS

Active control

MLC

Multi-frequency forcing
\( b = k(h_j) \)

63.45 7.76 37.57

Periodic forcing
\( b = A \cos(wt) \)

38.39 4.80 19.05

Benchmark
\( b = 0 \)

0.00 0.00 0.00

Non-autonomous feedback
\( b = k(h_j, P_j) \)

70.57 8.62 40.74

Sensor-based feedback
\( b = k(P_j) \)

8.74 1.24 8.99

Recirculation area (Ar)
Internal recirculation length (Xr)
External recirculation length (Lr)
BFS: Unforced and periodic forcing flows simulation
• David Uystepruyst & François Beaubert

Cluster reduce order model (CROM)
• Eurika Kaiser

SIMO MIMO MLC (LGPC)
• Bernd Noack, Ruiying Li

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

Ahmed body (SIMO & MIMO MLC)
• Bernd Noack, Ruiying Li & Eurika Kaiser

Real car active flow control
• Bernd Noack, Ruiying Li & Eurika Kaiser

Questions? Camila.chovet@etu.univ-valenciennes.fr

Pulsed jet (coanda effect)