Unsteady pulsed jets using pneumatic valves for flow separation control: effect of internal acoustic waves on external flow structure

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Symposium GDR 2502 Contrôle des Décollements
09 November 2017
• Interest in Aerodynamics of square-back bodies
• Recent projects on flow control for drag reduction with fluidic injection → Use of synthetic or pulsed jets at 2D and 3D model rear combined with flaps.
• Definition of a new model under the framework of Activ_ROAD program (ANR) to study the effects of flow control on simplified personal cars and trucks.
• Idealized pulsed jet time-evolution

Command signal $V$
Velocity at nozzle exit $U$
- Idealized pulsed jet time-evolution

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Velocity at nozzle exit $U$

$\Delta t$

DC. $T$

$t$
• Idealized pulsed jet time-evolution

Command signal $V$

Velocity at nozzle exit $U$

- Interest in sharp velocity increase after opening: vorticity,
- Fast-response actuator: high-frequency periodic or non-periodic time evolution of velocity,
- Manageable DC: reduction of flow control cost
• Idealized pulsed jet time-evolution

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Velocity at nozzle exit $U$

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- Fast-response actuator: high-frequency periodic or non-periodic time evolution of velocity,
- Manageable DC: reduction of flow control cost

• Basic set-up for pulsed jet generation

Flow to be controlled

- Tank
- Valve
- Nozzle
Some typical results obtained

- Joseph et al.  
  Exp. in Fluids, 2012  
  $f = 200$ Hz
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  \( f = 200 \text{ Hz} \)

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  *JFM, 2016*
  \( f = 610 \text{ Hz} \)
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What physical mechanism(s) may have such an influence on the pulsed jet characteristics?
Outline

1 Experimental set-up
   1 Pneumatic setup
   2 Valve and control board
   3 Flow measurements

2 Results
   1 Illustration of typical results
   2 Processing using dimensionless parameters
   3 Basic modeling

3 Conclusions
Experimental set-up

- Pneumatic set-up

Main Tank → Pressure regulator → Tank → Valve → Nozzle
Experimental set-up

- Pneumatic set-up

- Pneumatic valve: high speed two-port solenoid valve (SMC SX11-AJ)
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• Pressure return force to close the valve instead of classical return spring.
• Control board specifically developed by Ampère

![TTL Control Signal](image)

- Phase 1: Current increase (470 μS)
- Phase 2: Current control
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- Pressure measurements upstream of the valve (Kulite ETL-1-140)

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- Pressure measurements upstream of the valve (Kulite ETL-1-140)
- Velocity measurements at the nozzle exit (Dantec 55P01 probe and Dantec miniCTA)

Phase 1: Current increase (470 μS)
Phase 2: Current control
Typical result for an actuation frequency of 10 Hz

- Noticeable oscillations on pressure and velocity signals, vanishing at the end of each phase (opening or closing)
- Peculiarity of hw signal at closing: rectified waveform
- For each phase, differences in oscillation frequency between the flow upstream and downstream the valve.
- For each location (downstream/upstream), fixed oscillation frequency.
Test-cases for identification of internal acoustic waves

Nine different configurations

- with variation in inlet pressure $P_{in}$, $L_{up}$ and $L_{down}$
- at fixed duty-cycle (50%) and actuation frequency (10 Hz)

<table>
<thead>
<tr>
<th>$P_{in}$ [barA]</th>
<th>$L_{up}$ [mm]</th>
<th>$L_{down}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>450</td>
<td>185</td>
</tr>
<tr>
<td>2.88</td>
<td>206</td>
<td>169</td>
</tr>
<tr>
<td>3.7</td>
<td>206</td>
<td>177</td>
</tr>
</tbody>
</table>

→ Normalization possible between the different results obtained by varying $P_{in}$, $L_{down}$ and $L_{up}$
Identification of a time delay

- The time delays at opening and at closing are different,
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  → valve working principle: closing is obtained by pressure force (pneumatic spring)
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- at closing, the time delay decreases when $P_{in}$ is increased.
  → valve working principle: closing is obtained by pressure force (pneumatic spring)
- at opening, the time delay is independent of $P_{in}$,
  → Opening of the valve done by the electromechanical force of the solenoid, thus delay less sensitive to pressure
Time delay modelling

- time delay in velocity signals increases linearly with the downstream length $L_{\text{down}}$ for a given pressure.
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- Movement of the mobile part of the valve is very fast, time delay assumed to result from
  - a delay due to the valve opening (or closing)
  - plus a delay due to the wave propagation from the valve to the sensor (pressure at upstream, and velocity at downstream)
**Time delay modelling**

![Graphs showing time delay modelling](image)

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**Good match with time delays identified from experimental data**
Normalization

Normalized results from the 9 tested configurations.

- upstream (resp. downstream) oscillation frequency independent of downstream (resp. upstream) length,
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- the amplitude of the first peaks of pressure (resp. velocity) are:
  - nearly proportional to $P_{\text{steady}}$ (resp. $V_{\text{steady}}$),
  - independent of the lengths of the connecting pipes,
Normalization

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- oscillation frequencies are independent of the inlet pressure supply.
- the amplitude of the first peaks of pressure (resp. velocity) are:
  - nearly proportional to $P_{\text{steady}}$ (resp. $V_{\text{steady}}$),
  - independent of the lengths of the connecting pipes,
- the oscillation damping coefficient is independent of the inlet pressure and the lengths $L_{\text{down}}$ and $L_{\text{up}}$. 
Pressure oscillations **upstream** of the valve

**After closing**

Tank

\[ L_{up} \]

Valve
Pressure oscillations upstream of the valve

After closing

![Diagram of a tank with a valve and a pipe](image)

Good agreement between the experiments and the closed-end tube model (max. deviation of 5% in estimation of $f_1$)

$$f_{2n+1} = (2n+1)\frac{c}{4L_{up}}; \quad f_1 = \frac{c}{4L_{up}}$$
**Pressure oscillations upstream of the valve**

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$$f_n = (n)\frac{c}{2L_{up}} ; \quad f_1 = \frac{c}{2L_{up}}$$
Pressure oscillations upstream of the valve

**After closing**

![Diagram of a tank, valve, and upstream length](image)

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**After opening**

![Graphs of opening and closing pressures](image)

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After opening

Closed-end tube model still holds
Physical interpretation: Contraction due to valve throat \( \equiv \) closed termination
Velocity oscillations downstream of the valve

- 'Simpler' case: sonic section in the valve such that Closed-end tube model is relevant
- Estimation of equivalent pipe length taking the nozzle geometry into account not straightforward.
  Good agreement between the experiments and the closed-end tube model (max. deviation of 8% in estimation of $f_1$)
Modelling of damping

Two possible sources of damping:

- Acoustic radiation
- Viscous effects

$L_{up}$
Modelling of damping

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Modelling of damping

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Modelling* of the damping coefficient $\alpha$ (in time) after closing:

$$\alpha = \sqrt{\frac{\omega d}{2r}} \left(1 + \sqrt{\frac{\chi}{\nu}} \left(\frac{C_p}{C_v} - 1\right)\right)$$

where $d$ can be seen as a 'penetration depth' for viscous effects. For zero-mean flows,

$$d = \sqrt{\frac{2\nu}{\omega}}$$

(*) Moloney & Hatten, American Journal of Physics, 2001
Modelling of damping

Estimation of logarithmic decrement $\delta$: experiments (symbols)/ model (solid line):

$\delta$

$L_{up}=450\,\text{mm}$

Confirmation of viscous effects as predominant cause of damping
Modelling of damping

Estimation of logarithmic decrement $\delta$ : experiments (symbols)/ model (solid line) :

Confirmation of viscous effects as predominant cause of damping

$L_{up} = 450\text{mm}$

$L_{up} = 206\text{mm}$


- **Conclusions**
  - Existence of pressure (acoustic) waves in pipes upstream and downstream of the valve in a pulsed jet system.
  - Decoupling of the pressure waves upstream and downstream of the valve.
  - Oscillation frequency well approximated by closed-end tube model.

- **Future work**
  - At high actuation frequencies, complex interactions between acoustic waves generated at opening with waves generated at closing,
  - Resonance if actuation frequency is close to the acoustic waves frequency: possible optimization for large blowing velocity peaks at constant inlet pressure.
  - Very different blowing velocity patterns at the nozzle exit can be achieved when varying DC or actuation frequency around.
• Acknowledgments
  • This work was performed within the program "Activ_ROAD" (ANR15CE220002) operated by the French National Research Agency (ANR).
  • The manufacturing by Pprime of the diffuser model used here and further employed in the program is gratefully acknowledged.