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

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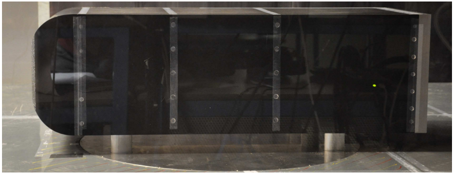
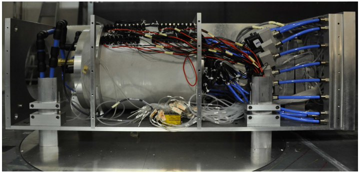
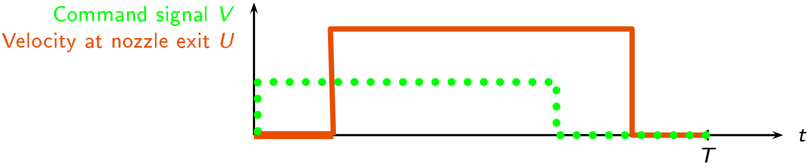
Symposium GDR 2502 *Contrôle des Décollements*
09 November 2017

- 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



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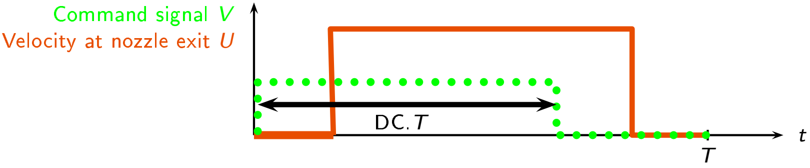

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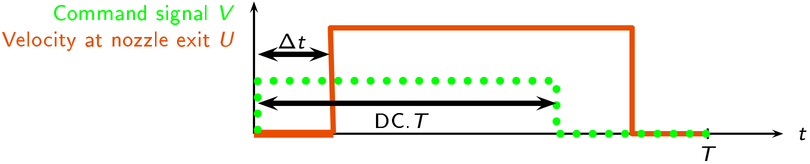

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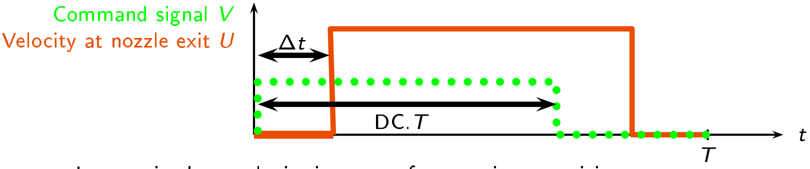


  - Interest in sharp velocity increase after opening : vorticity,
  - Fast-response actuator : high-frequency periodic or non-periodic time evolution of velocity,
  - Manageable DC : reduction of flow control cost

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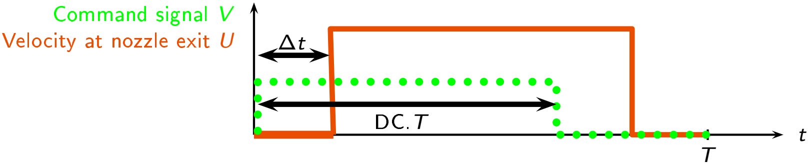


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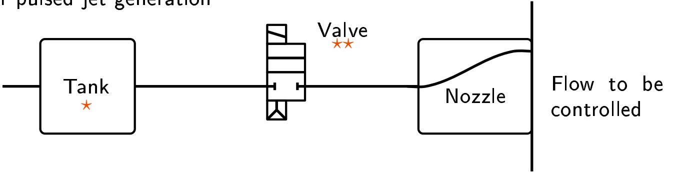
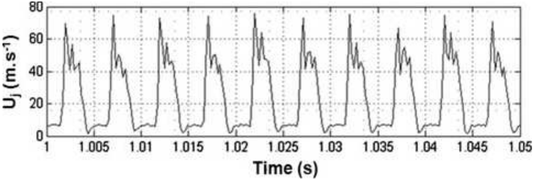
- Basic set-up for pulsed jet generation



## Some typical results obtained

• **Joseph et al.**
**Exp.in Fluids, 2012**
f=200 Hz



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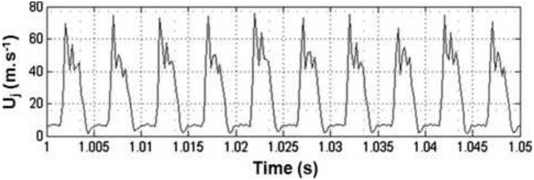


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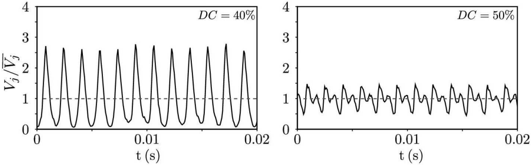

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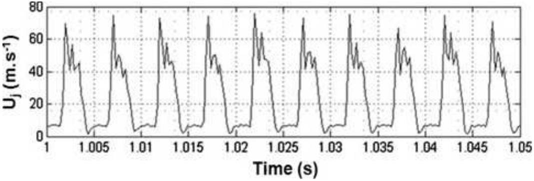


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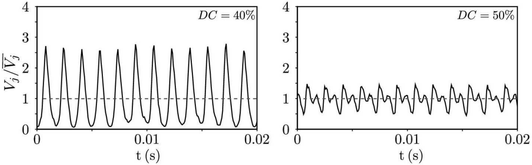


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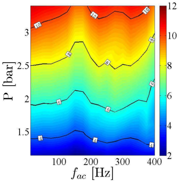

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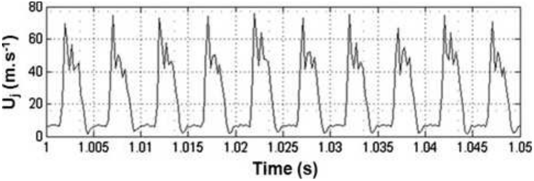


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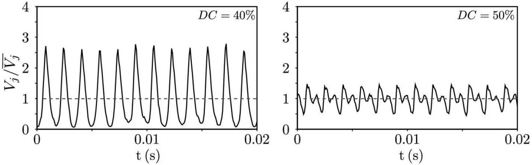


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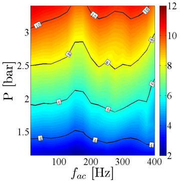
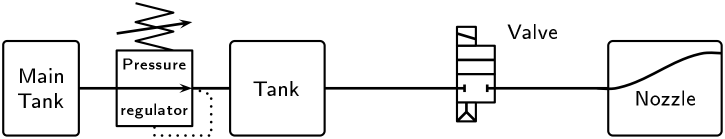



**What physical mechanism(s) may have such an influence on the pulsed jet characteristics ?**

# Outline

# Experimental set-up

- Pneumatic set-up



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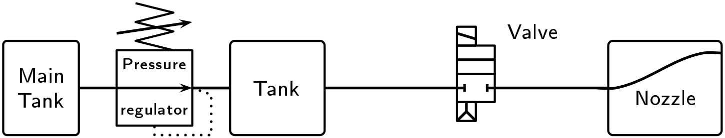


- Pneumatic valve : high speed two-port solenoid valve (SMC SX11-AJ)

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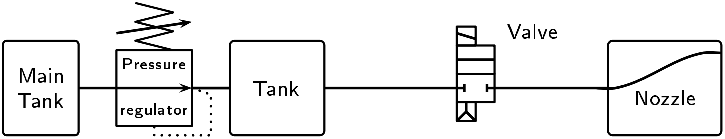


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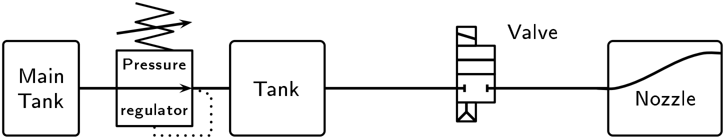
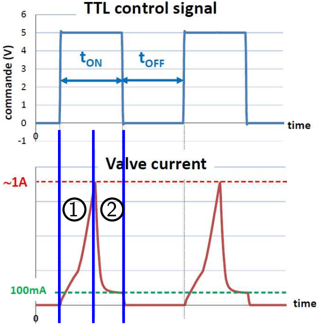



- Pneumatic valve : high speed two-port solenoid valve (SMC SX11-AJ)
- Pressure return force to close the valve instead of classical return spring.
- Control board specifically developed by Ampère




- Phase (1) : Current increase (470 $\mu$s)
- Phase (2) : Current control

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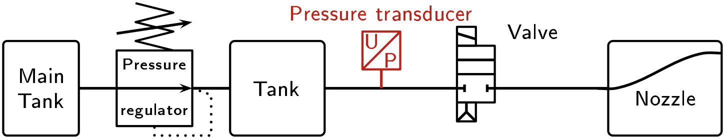


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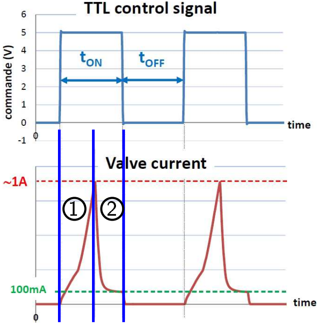


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- Pressure measurements upstream of the valve (Kulite ETL-1-140)

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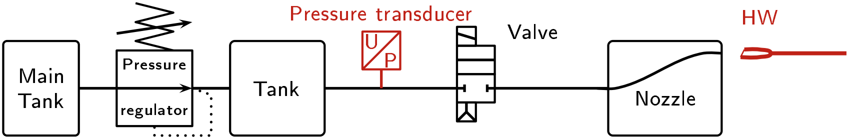


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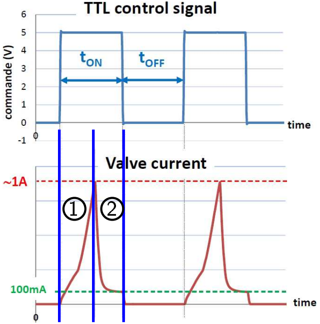


- Phase (1) : Current increase (470 $\mu$s)
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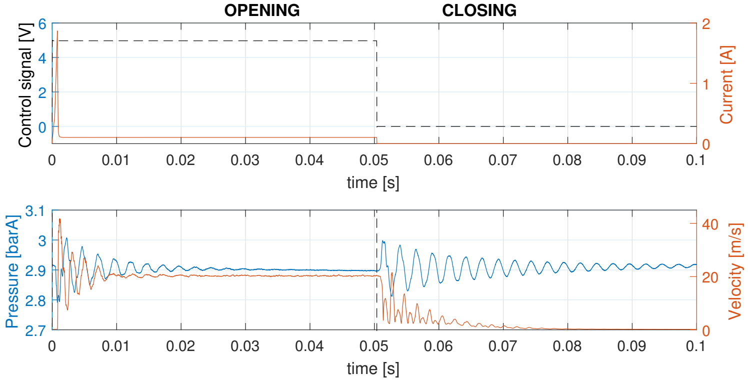
- Pressure measurements upstream of the valve (Kulite ETL-1-140)
- Velocity measurements at the nozzle exit (Dantec 55P01 probe and Dantec miniCTA)

# Typical result for an actuation frequency of 10 Hz

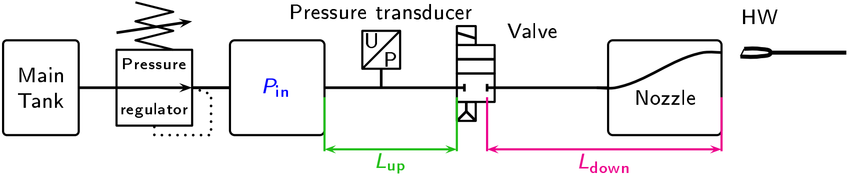



- Noticeable oscillations on pressure and velocity signals, vanishing at the end of each phase (opening or closing)
- Peculiarity of hw signal at closing : rectified waveform
- For each phase, differences in oscillation frequency between the flow upstream and downstream the valve.
- For each location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

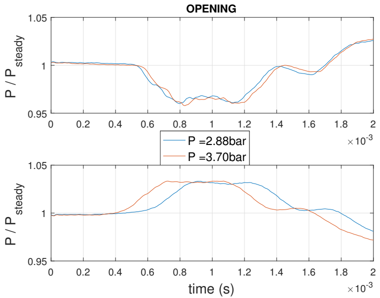



| $P_{in}$ [barA] | $L_{up}$ [mm] | $L_{down}$ [mm] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2.5 | 450 | | | | 185 | | 210 | 250 |
| 2.88 | 206 | 155 | 169 | 177 | | 200 | | |
| 3.7 | 206 | 155 | | 177 | | | | |

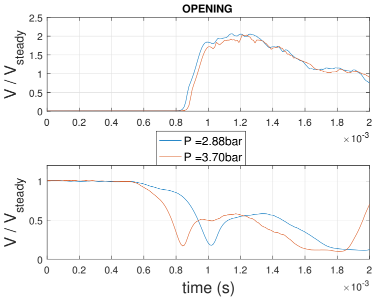
→ Normalization possible between the different results obtained by varying $P_in$, $L_{down}$ and $L_{up}$

# Identification of a time delay

Normalized upstream pressure




Normalized downstream velocity




- the time delays at opening and at closing are different,

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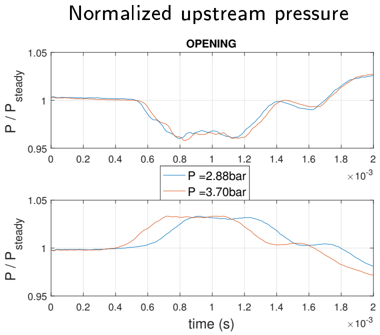


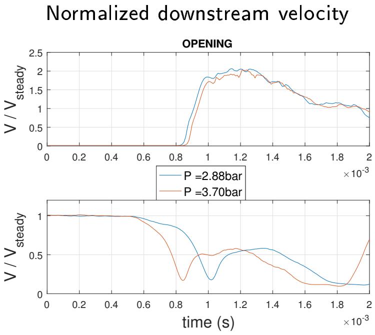


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- at closing, the time delay decreases when $P_{\text{in}}$ is increased.
  $\rightarrow$ valve working principle : closing is obtained by pressure force (pneumatic spring)

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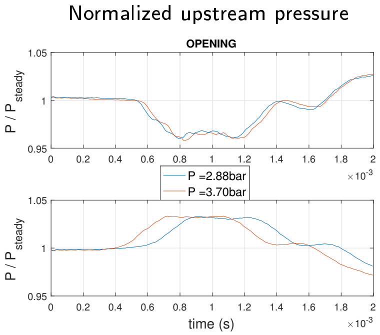
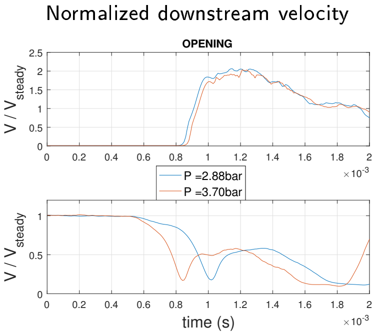
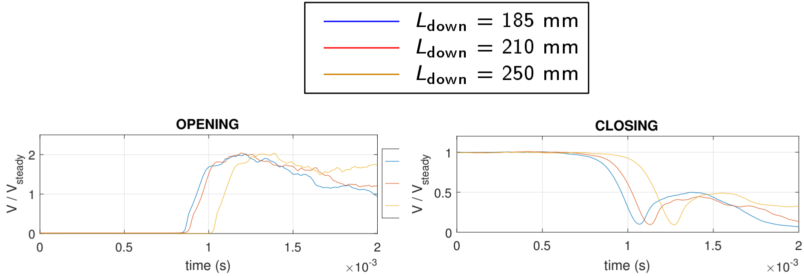



- the time delays at opening and at closing are different,
- at closing, the time delay decreases when $P_{\text{in}}$ is increased.
  → valve working principle : closing is obtained by pressure force (pneumatic spring)
- at opening, the time delay is independent of $P_{\text{in}}$,
  → Opening of the 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 $L_{down}$ for a given pressure.

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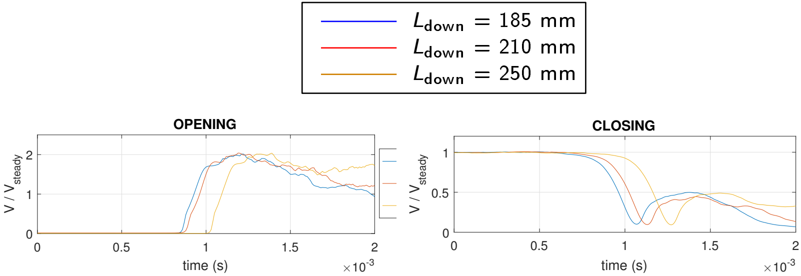


- time delay in velocity signals increases linearly with the downstream length $L_{down}$ for a given pressure.
- Movement of the mobile part of the valve is very fast, time delay assumed to result from
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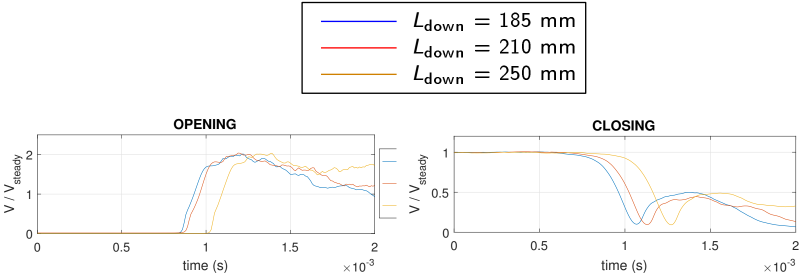


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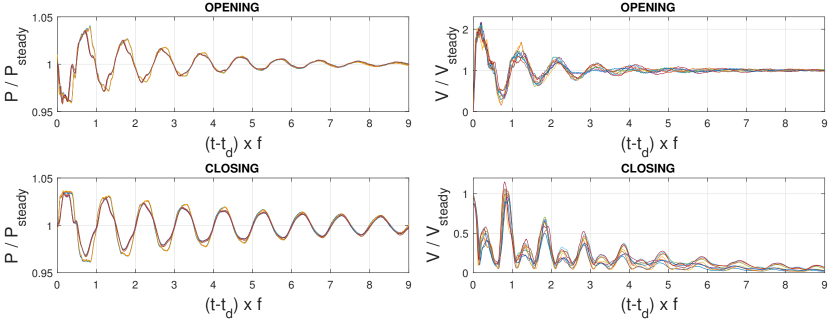
**Good match with time delays identified from experimental data**

# Normalization

Normalized results from the 9 tested configurations.

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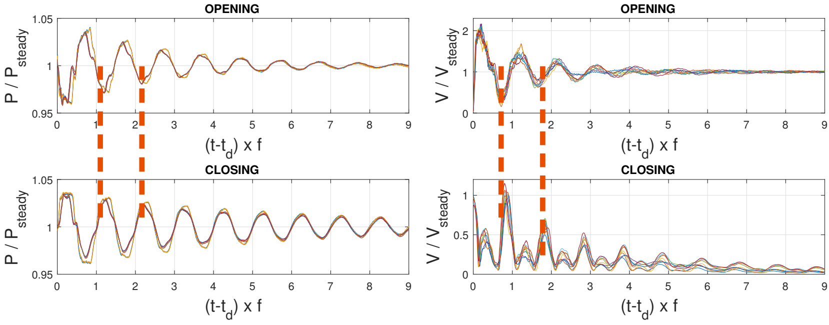


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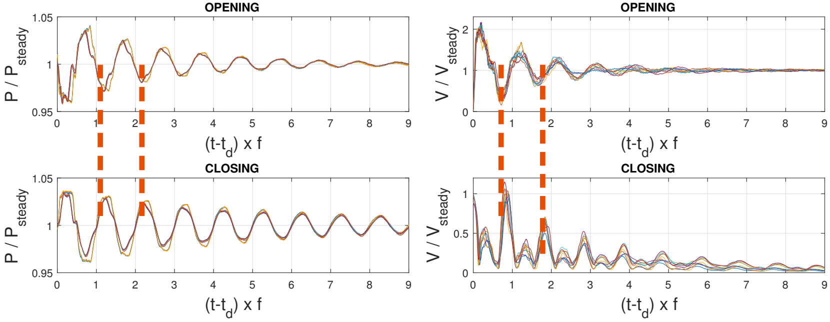


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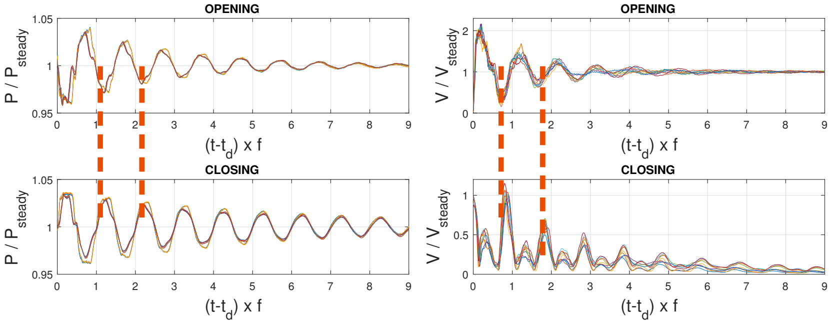


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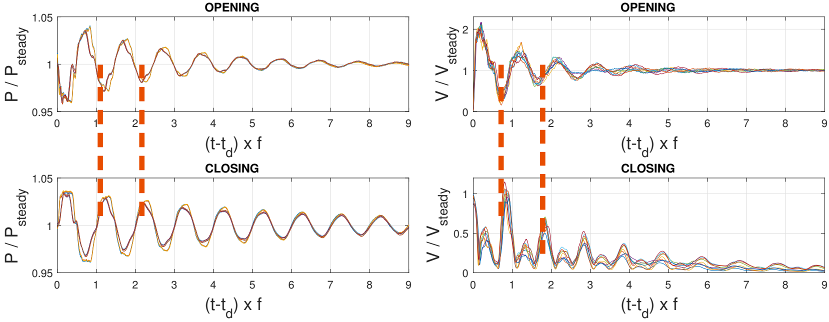


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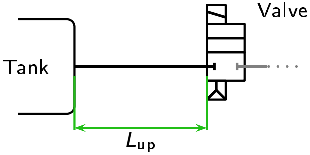
- oscillation frequencies are independent of the inlet pressure supply.
- the amplitude of the first peaks of pressure (resp. velocity) are :
  - nearly proportional to $P_{steady}$ (resp. $V_{steady}$),
  - independent of the lengths of the connecting pipes,
- the oscillation damping coefficient is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

# Pressure oscillations upstream of the valve

**After closing**



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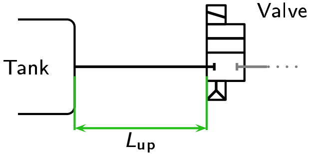


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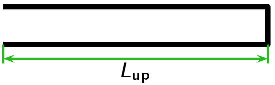


$$f_{2n+1} = (2n+1)\frac{c}{4L_{up}}\ ; \ \boxed{f_1 = \frac{c}{4L_{up}}}$$

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

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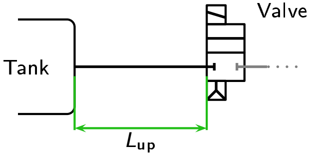


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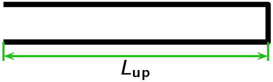


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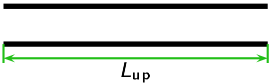


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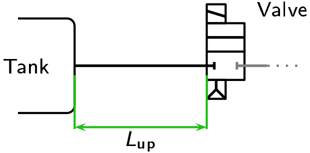


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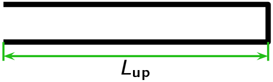


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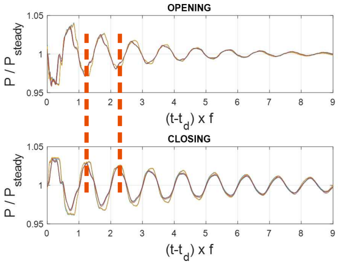


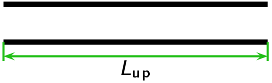


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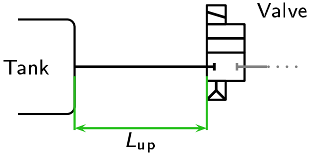


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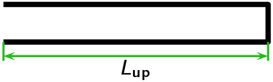
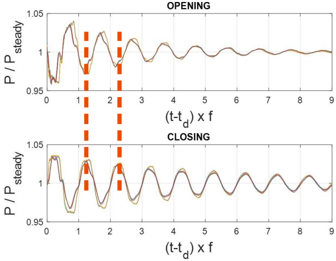
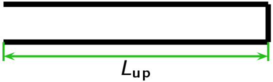



$f_{2n+1} = (2n+1)\frac{c}{4L_{up}}$ ; $\boxed{f_1 = \frac{c}{4L_{up}}}$

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

**After opening**

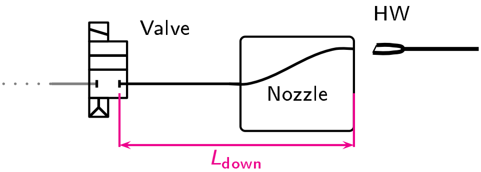



Closed-end tube model still holds

Physical interpretation : Contraction due to valve throat $\equiv$ closed termination

## Velocity oscillations downstream of the valve

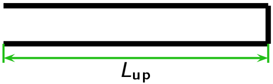



- 'Simpler' case : sonic section in the valve such that Closed-end tube model is relevant
- Estimation of equivalent pipe length taking the nozzle geometry into account not straightforward.
  Good agreement between the experiments and the closed-end tube model (max. deviation of 8% in estimation of $f_1$)

# Modelling of damping

Two possible sources of damping :

- Acoustic radiation
- Viscous effects



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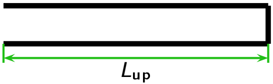


# Modelling of damping

Two possible sources of damping :

- Acoustic radiation
- Viscous effects


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

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

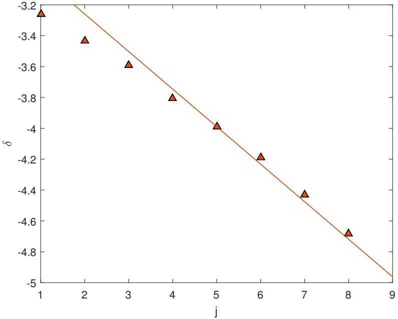
where $d$ can be seen as a 'penetration depth' for viscous effects. For zero-mean flows,

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

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

# Modelling of damping

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

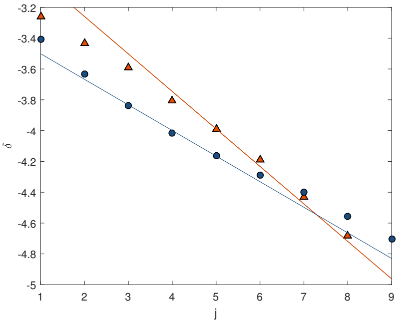



$L_{\mathrm{up}}$=450mm

Confirmation of viscous effects as predominant cause of damping

# Modelling of damping

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




$L_{up}$=450mm

$L_{up}$=206mm

Confirmation of viscous effects as predominant cause of damping

- 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.