Dynamics of Fluidic Oscillators and Their Synchronization for Active Flow Control

Shiqi WANG

Supervisors: Lucien Baldas, Azeddine Kourta

Participants: Stéphane Colin, Stéphane Orieux

Nicolas Mazellier, Ahmad Batikh

1 ICA(Institut Clément Ader); INSA-Toulouse; Université de Toulouse; France
2 PRISME Laboratory, INSA-CVL; Université d’Orléans, France
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2-- Measured frequency response profile analysis
3-- Simulated internal flow pattern analysis
4-- Controlling factors verification
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Background and general context

1: Periodic injection by fluidic oscillators

Jet-Interaction Fluidic Oscillators
Pulsed-jet wall attachment fluidic oscillator

Sweeping-jet wall attachment fluidic oscillator

Reliability Robustness
Background and general context

1: Periodic injection by fluidic oscillators
2: Key parameters for controlling the separation

A, Actuation position, injection orientation

B, Momentum addition

\[ C_\mu = \frac{\rho_j U_j^2 G}{\sqrt{2} \rho_\infty U_\infty^2 L} \]

for steady blowing:

\[ C_\mu = \frac{2G}{L} \left( \frac{U_j}{U_\infty} \right)^2 + \frac{2G}{L} \left( \frac{U_j}{U_\infty} \right)^2 \]

for oscillation exiting:

C, Excitation frequency: \( F^+ = \frac{f_e X_{te}}{U_\infty} \)

For a given case, there exists both an optimal frequency \( F_{opt}^+ \) and momentum coefficient \( C_\mu \) where the best separation control results can be achieved.
## State of the art: main recent publications

<table>
<thead>
<tr>
<th>Research group</th>
<th>Institute</th>
<th>Year</th>
<th>Research content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simoes et al</td>
<td>University of San Paulo, Brazil</td>
<td>2005</td>
<td>Bistable wall attachment fluidic oscillator</td>
</tr>
<tr>
<td>Ciro Cerretelli et al.</td>
<td>GE global research Europe, Germany</td>
<td>2010</td>
<td>Bistable wall attachment fluidic oscillator</td>
</tr>
<tr>
<td>Khelfaoui et al</td>
<td>INSA-Toulouse, France</td>
<td>2011</td>
<td>Monostable wall attachment fluidic oscillator</td>
</tr>
<tr>
<td>Tesař, V., et al.</td>
<td>Academy of Sciences of the Czech Republic, Czech</td>
<td>2011</td>
<td>Bistable wall attachment fluidic oscillator</td>
</tr>
<tr>
<td>R. Woszidlo, et al</td>
<td>University of Kansas, US</td>
<td>2015</td>
<td>Sweeping fluidic oscillator</td>
</tr>
</tbody>
</table>

× proposed function by Simoes et al: $T = 2(\tau_t + \tau_s) = 2\left(\frac{l}{c} + \frac{\xi L}{u}\right)$

× proposed control factor by Khelfaoui et al: feedback loop volume
Prototypes for experiments

**Oscillator N° 1**: totally two dimensional, depth of channel of 10 mm, loop length 391 mm

**Oscillator N° 2**: identical central part as No. 1 oscillator, while tubes of 4 mm in diameter and different lengths (200 mm, 300 mm, 400 mm, 500 mm, 600 mm, and 766 mm) have been used to realize the feedback loops by connecting parts \( a_1 \) et \( a_2 \). The cross-section area of the feedback loops is the same for both devices (12.6 mm\(^2\)).
Experimental results and analysis

when the inlet total pressure is higher than 1.7 bar, the frequency $f$ can be approximated by the equation $f \approx \frac{C_0}{4L_f}$, where $C_0$ is the sound velocity at the nozzle ($\approx 340$ m/s) and $L_f$ is the feedback loop length.

<table>
<thead>
<tr>
<th></th>
<th>$L_f$ (mm)</th>
<th>$C/4L_f$ (s$^{-1}$)</th>
<th>$F$ (Hz)</th>
<th>deviation</th>
</tr>
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<tbody>
<tr>
<td>Design 2</td>
<td>286</td>
<td>297</td>
<td>263</td>
<td>13%</td>
</tr>
<tr>
<td>Design 2</td>
<td>386</td>
<td>220</td>
<td>208</td>
<td>5.8%</td>
</tr>
<tr>
<td>Design 2</td>
<td>486</td>
<td>175</td>
<td>174</td>
<td>0.6%</td>
</tr>
<tr>
<td>Design 2</td>
<td>586</td>
<td>145</td>
<td>150</td>
<td>-3.3%</td>
</tr>
<tr>
<td>Design 2</td>
<td>686</td>
<td>124</td>
<td>132</td>
<td>-6.1%</td>
</tr>
<tr>
<td>Design 2</td>
<td>852</td>
<td>100</td>
<td>110</td>
<td>-9.1%</td>
</tr>
<tr>
<td>Design 1</td>
<td>391</td>
<td>217</td>
<td>231</td>
<td>-6.1%</td>
</tr>
</tbody>
</table>
Numerical simulation of the 2D fluidic oscillator

- OpenFOAM, sonicFoam solver
- Realizable k-epsilon turbulence model
- 2\textsuperscript{nd} order upwind spatial discretization schemes
- 2\textsuperscript{nd} order backward temporal discretization scheme
- $Co < 0.3$, $\Delta t = 4\ ns$
- $y+ \sim 10$
- Inlet total pressure 2.5 bar, outlet pressure 1.0 bar
- Simulated frequency of 231 Hz and corresponding measured frequency of 226 Hz for the 1\textsuperscript{st} design model
Switching process inside the oscillator -1

\[ a) \ t = 0 \quad \text{b) } t = 0.03 \ T \]
Switching process inside the oscillator -2

\[
a) \ t = 0.225 \ T \\
b) \ t = 0.258 \ T
\]
Switching process inside the oscillator -3

a) $t = 0.49 \, T$

b) $t = 0.5 \, T$
Isolated effect of pressure difference between the Control ports

All outlet pressures equal to 1 bar for case 0, with pressures at two control ports also equal to 0.9 bar. For case 1-(1-5), the left control port pressure is 0.9 bar, while right control port pressures are 1.25 bar, 1.5 bar, 1.6 bar, 1.8 bar and 2.0 bar respectively.

The pressure difference between the control ports can not provoke the switching, even for values as high as 1.1 bar.
### Isolated effect of pressure difference between the Two Branches

<table>
<thead>
<tr>
<th>Case 2-x</th>
<th>P&lt;sub&gt;or&lt;/sub&gt; /bar</th>
<th>Switching Time/ms</th>
<th>Scaled Switching Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2-1</td>
<td>1.1</td>
<td>No switching</td>
<td>No switching</td>
</tr>
<tr>
<td>Case 2-2</td>
<td>1.2</td>
<td>No switching</td>
<td>No switching</td>
</tr>
<tr>
<td>Case 2-3</td>
<td>1.25</td>
<td>0.78</td>
<td>0.18 T</td>
</tr>
<tr>
<td>Case 2-4</td>
<td>1.35</td>
<td>0.58</td>
<td>0.13 T</td>
</tr>
<tr>
<td>Case 2-5</td>
<td>1.45</td>
<td>0.22</td>
<td>0.05 T</td>
</tr>
<tr>
<td>Case 2-6</td>
<td>1.6</td>
<td>0.22</td>
<td>0.05 T</td>
</tr>
<tr>
<td>Case 2-7</td>
<td>1.8</td>
<td>0.06</td>
<td>0.01 T</td>
</tr>
<tr>
<td>Case 2-8</td>
<td>2.0</td>
<td>0.06</td>
<td>0.01 T</td>
</tr>
</tbody>
</table>
Combined effect of two pressure differences

<table>
<thead>
<tr>
<th></th>
<th>$P_{cr}$/bar</th>
<th>$P_{or}$/bar</th>
<th>Switching Time /ms</th>
<th>Scaled Switching Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 3-1</td>
<td>1.25</td>
<td>1.1</td>
<td>0.53</td>
<td>0.12 T</td>
</tr>
<tr>
<td>Case 3-2</td>
<td>1.25</td>
<td>1.2</td>
<td>0.16</td>
<td>0.04 T</td>
</tr>
<tr>
<td>Case 3-3</td>
<td>1.25</td>
<td>1.3</td>
<td>0.13</td>
<td>0.03 T</td>
</tr>
<tr>
<td>Case 3-4</td>
<td>1.25</td>
<td>1.4</td>
<td>0.10</td>
<td>0.02 T</td>
</tr>
</tbody>
</table>

- Pressure difference between the two branches<br>Pressure difference of 0.35 bar between the control port:<br>Jet switches to the other branch in a very short time<br>When the right outlet pressure increases, the time needed to complete the switching decreases quickly to reach a minimum value for pressure differences between the branches higher than 1.4 bar.
Synchronization of oscillators

A series of fluidic oscillators needed in application

Different frequencies due to machining error or/and assemblage error

Output jets operate independently, random and unpredictable phase difference

Predictable results are preferable for an efficient active flow control application

Identical frequency and known phase discrepancy
Synchronization of two oscillators

Method 1

Method 2
Synchronization of two oscillators

Method 3

Method 4
Synchronization of two oscillators

Method 2

Method 3
Design of an array of synchronized oscillators

Method 3
Conclusion and Perspectives

Conclusion

• The feedback loop length is the controlling factor
• The jet switching is due to the combined effect of:
  • the pressure difference between the two control ports
  • the pressure difference between the two branches
• Oscillators can be well synchronized in two ways

Perspectives

• An array of fluidic oscillators is under fabrication and will be tested in a ramp flow soon
• Methods to control the phase difference between oscillators
• Numerical study the effect of various internal geometrical parameters on the oscillator’s performance
Thanks for your attention

Questions?
References