Hybrid MEMS Pneumatic Proportional Control Valve

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CCEFP Summit
March 8, 2018
Overview

- What is a hybrid MEMS valve?
- What are alternatives to electromagnetic actuation?
- How does it work?
- How well did the prototype function?
- What are the plans for further development?

Microfabricated hybrid MEMS valve parts
Project Summary

• Use piezoelectric stack actuator to modulate flow
• Use MEMS fabrication techniques to micromachine an orifice array
• Leverage these two technologies to create an ultra efficient pneumatic proportional valve

Proposed Valve Benefits:
• Near zero power to hold at a fixed deflection
• Near zero heat generation
• Low cost
• Silent operation
Why Utilize of Piezoelectric Actuation?

Thorlabs PK2FVP2

L = 40 mm

$\delta_{max} = 45 \mu m$

$F_{max} = 1000 N$

- Low static valve power consumption
- Fast response speed
- Proportional flow control at high operating pressures
- Quiet operation
- Small temperature rise at low operating frequencies
- Can be used in a magnetic field
- Compact
Modern Alternatives to Electromagnetic Actuators

Motion Amplified Piezostack: $F_+ \delta^+$
  - Increased displacement
  - Lower output force
  - Low power consumption

Piezoactuator: $F \delta$
  - Large displacement
  - Large operating bandwidth
  - Low output force
  - Low power consumption

Piezobender: $F^{-} \delta^+$

http://www.dynamic-structures.com/actuators#fpa
https://www.festo.com/cms/nl-be_be/22394.htm
Hybrid MEMS Valve Concept (1 of 2)

Full flow when $\delta \approx 0.25 D$

$A_{\text{orifice}} = 0.25\pi D^2$

$A_{\text{seat}} = \pi D\delta$
Hybrid MEMS Valve Concept (2 of 2)

Single Orifice

Orifice Diameter: 1.28 mm
Actuator Displacement: 320 um
Flow Area: 1.287 mm$^2$

Orifice Array

Orifice Diameter: 160 um
Actuator Displacement: 40 um
Flow Area: 1.287 mm$^2$

Orifice array removes need for piezostack motion amplifier!
Why Fabricate Orifice Array using MEMS Fabrication Techniques?

- Small orifice size in array format allow for use of piezostack actuator
- Cost effective bulk micromachining of silicon
- Silicon is stiffer and lighter than traditional materials
- Tighter tolerances on orifice features
Hybrid MEMS Valve Architecture

Valve Cross-Section:

- Direction of Flow
- Piezostack
- Orifice Plate
- Support

Exploded Actuator Assembly View:

- Piezostack
- Seal Plate Carrier
- Seal Plate
- Orifice Plate
Assembled Hybrid MEMS Valve
Orifice Plate Flow Performance

64 X 160 μm orifices

\[ C_D = 0.89 \]
Maximum v. Minimum Flow (6.205 bar)

Maximum Flow: 0V Applied

Leakage: 75V Applied
Valve Turndown Ratio

![Graph showing Valve Turndown Ratio vs Input Pressure (bar)]
Proportional Flow Performance

- Hysteresis characteristic of open loop voltage input
- Operating Pressure: 6.205 bar

Mass Flow Rate Eqn:

\[ m = C_D \pi D \delta P^* \sqrt{\frac{\gamma}{RT^*}} \]
Piezostack v. Piezobender
Proportional Flow Performance

Piezostack Proportionality >> Piezobender Proportionality
Piezostack proportionality is independent of pressure
Valve Transient Response

DT: valve dead time
Dynamic: valve dynamic time

DT = 1 ms
Dynamic = 3.2 ms
Response Time = 4.2 ms

Pressure dynamics of test stand artificially increased measured response time
Valve Power Draw

Static Power Consumption:
- Steady State Power: 13.1 μW

Dynamic Power Consumption:
- Peak Power: 0.18W
- Average Power: 15.7, 82.2 mW
## Competing Miniature Proportional Valves

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Actuation Method</th>
<th>Max Pressure (bar)</th>
<th>Flow Rate* (SLPM)</th>
<th>Avg Power (W)</th>
<th>Response Time (ms)</th>
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<td>178.1</td>
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<td>54.8</td>
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<td>Piezobender</td>
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<td>Amplified Piezostack</td>
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<td>Piezostack</td>
<td>6.9****</td>
<td>47.2</td>
<td>1.31E-5</td>
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</tbody>
</table>

* Flow rate a 6 to 5 bar pressure difference

** Macro-scale piezoelectric bender actuator

*** Macro-scale piezoelectric stack actuator with motion amplifier

**** Limited by in house air supply
Conclusion

• 55:1 or better turndown ratio achieved across all operating pressures on concept demonstration prototype
  ◦ Will be further improved

• Proportional but non-linear flow control
  ◦ Will be improved with feedback control system

• 4 ms response time at 6.205 bar input pressure
  ◦ Biased by test chamber pressure dynamics

• 13.1 μW steady state and 0.18W peak dynamic power consumption

The efficiency, compactness and performance of hybrid MEMS valves hold the potential to revolutionize pneumatic valve technology
Questions?

Valve Benefits:
- Near zero power to hold at a fixed deflection
- Proportional control
- Fast response time
- Near zero heat generation
- Low cost
- Silent operation
- Non–magnetic