2F – MEMS Proportional Pneumatic Valve

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Project Summary

Project Goal: Create an efficient miniature proportional valve for controlling air flow in pneumatic systems

CCEFP Goal: The valve will contribute to the center’s goal of creating compact and efficient systems

- Widespread appeal as a general-purpose, low-power, compact valve
- Particularly appealing for human assist devices like Ankle-Foot Orthosis (AFO)
  - In the AFO, the valve is used to control the actuator for torque assistance

- Key specification
  - Power consumption (to hold the valve in the fully open state): 5 mW
  - Total volume envelope: ~4 cm$^3$

Currently used solenoid valve in CCEFP’s AFO
Overview

• Valve concept
• Meso-scale valve
• MEMS valve
  • Orifice plate
  • Actuator array
  • Assembly
• Conclusion
Arrays of micro-actuators with corresponding micro-orifices are operated in parallel to provide macro-flow (main parts are orifice plate and actuator array).

- Actuators are cantilever beams that are normally flat against the orifice.
- When actuated, the cantilevers lift off the orifice to allow air to flow through.
- Benefits of MEMS valve could also be realized for hydraulic valves, particularly pilot valves.
Why Piezoelectric Actuation?

- Use “piezobender” actuator:
  - Lead-zirconate-titanate (PZT) chosen as piezoelectric material for its large piezoelectric coefficient
- “Unimorph” piezobender: One piezoelectric layer deposited on a passive layer
- “Bimorph” piezobender: Two piezoelectric layers work against each other to achieve more force/deflection than unimorph for same voltage

Advantages:
- Low power consumption to hold at fixed deflection
- Low heat generation
- Low cost
- Silent operation
Why MEMS Valve?

- Use *micro-electro-mechanical system* (MEMS) fabrication techniques
- MEMS-scale orifice diameters ~50 μm
  - Reduces force due to pressure over orifice to manageable levels to use micro-actuators
- Small orifices produce low flow
  - Use arrays of orifice/actuator pairs in parallel to achieve macro-flow

Advantages:
- Compact
- Fast response time
- Low actuation voltage
- Low cost with batch fabrication
- Light weight
Why a MEMS Valve?...

- Advantages for flow control mainly due to power savings and compact size

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Approx. Dimensions (mm)</th>
<th>Max Pressure (bar)</th>
<th>Flow Rate* (slpm)</th>
<th>Power (W)</th>
<th>Response Time (msec)</th>
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<tr>
<td>Commercial Valve 1</td>
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<td>Φ18x15</td>
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<td>40</td>
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</tbody>
</table>

*Flow rate estimated for a pressure drop of 6 to 5 bar

** Macro-scale piezostack actuator

*** Macro-scale piezobender actuator (limited availability in US)
Meso-scale Valve (Concept Demonstration Valve)

- Meso-scale valve employs same concept as MEMS valve but uses traditional machining (~20 times larger than MEMS device) and off-the-shelf piezobender
- Testing done in custom, ISO-compatible test stand

Results:
- At low pressure, actuator displacement is fairly proportional to input voltage
- When valve is under high pressure, flow resembles an on/off valve rather than a proportional valve
- There is 8% leakage at maximum pressure (further improved by reversing actuation direction)
- Power consumption of less than 1mW (to keep valve in the fully open state)
Main components of the MEMS valve are the orifice plate (with array of through holes) and the actuator array (with array of actuators for individual through holes).
Developed process to produce orifices with aspect ratio of 20
- Developed process to prevent backside blowout
- One with 86 µm is able to withstand the target specification pressure of 7 bar (100 psi)
- 29 µm orifice plate fractured around 2.5 bar (35 psi)
- Large orifice diameters also require more actuator force, but small orifices are limited by processing and can act as cracks
- Array of small orifices and an equivalent single orifice have similar flow capacity
MEMS valve: Actuator Arrays

- Manufacturing steps are similar for both unimorph and bimorph
- Bulk micromachining approach

The process for releasing the beams in step 6 is not very controllable because it involves etching through the 500μm-thick silicon substrate to sub-micron precision.
First MEMS Valve Prototype

- Successful fabrication and assembly of first prototypes
- Bimorph piezobenders preferred for prototypes because of their large deflection, but are more fragile than unimorphs
- Piezobender deflection fairly linear with voltage
- Prototype aligned and bonded with chip bonder and adhered using photoresist and Dymax adhesive
- Adjusted test stand to house MEMS valve instead of meso-scale valve
- Unfortunately, bimorph prototypes repeatedly failed due to electrical shorting
First MEMS Valve Prototype

- Lessons from first prototype design:
  - Devices shorted when exposed to non-cleanroom environment probably due to moisture from air gathering on electrodes
  - Bimorph piezobenders are fragile with beams more than 300x longer than they are thick (1mmx0.25mmx3µm)
  - Orifice plates fractured at low pressures
  - Method for releasing cantilevers was not very controllable
  - Method for bonding components was not very controllable
  - Under pressure, the actuators act more like an on/off valve than a proportional valve
  - Packaging and electrical connections were more of an afterthought
Second MEMS Valve Prototype

- Main changes to prototype fabrication with goal to make devices more robust:
  - Alumina coating: uniform insulating layer to prevent electrical shorting
  - Unimorph: compromise some deflection/force to make a thicker and more robust piezobender
  - Support plate: a thicker orifice plate with larger orifices is bonded to the first in order to prevent fracture
  - Silicon-on-insulator (SOI) wafer: this substrate has a thin silica layer sandwiched between silicon layers providing a stop layer during beam release
  - Eutectic bond: a more controllable bonding method that takes advantage of low melting point of certain mixtures of elements based on binary phase diagram
  - Digital proportional control strategy: the actuator array is divided into blocks, each one with twice as many beams as the previous, i.e. 1, 2, 4, 8, beams
  - Printed Circuit Board (PCB): packaging looks more like it would for production as the valve was submounted and wire-bonded to a PCB
Second MEMS Valve Prototype: Orifice Plate

- Developed model of valve to aid in design
- Support plate bonded to orifice plate with eutectic bond
  - Produces less than target flow rate for AFO, but can be increased by modularly increasing number of orifices in array
  - Handles 7 bar pressure drop with aid of support plate
Second MEMS Valve Prototype: Actuator Array

- Completed actuator array produces acceptable deflection
  - Stop layer in SOI wafer allows precise control during beam release because etch stops on the silica layer after etching through 400\(\mu\)m-thick silicon substrate
  - Can achieve up to 14 micron deflection at operating voltage of 37 V
  - Acceptable deflection for prototype as they were designed conservatively with a safety factor of two based on model deflection of 20 microns at 37 V
  - Unimorph piezobenders with dimensions of 1mmx0.25mmx17.7\(\mu\)m are much more robust

Two piezobenders before applying voltage

Two piezobenders after applying 37 V showing deflection out of the screen
Actuator array

Piezobenders starting at 14 micron deflection out of screen at 37V then returning to no deflection
Second MEMS Valve Prototype: Packaging

- Completed prototype by bonding actuator array to orifice plate with photoresist
- Submounted on PCB with through-hole for air flow and contacts for wire bonding and soldering
- Wire bond adhesion could be improved by increasing thickness of contact pads on actuator array
- Entire subassembly is sealed with a gasket and fastened to downstream housing
Second MEMS Valve Prototype

- Digital control strategy allows independent operation of 4 blocks of actuators with 2, 4, 8, and 16 beams each
- Devices with alumina coating do not experience electrical shorting
- Preliminary results for deflecting piezobenders into orifice plate show reduction in flow rate
### MEMS Proportional Valves

- **Goal:** Create ultra-efficient miniature proportional pneumatic valves
- **Alignment with CCEFP Strategy:** Compactness, Efficiency
- **Test Bed:** Ankle-Foot Orthosis (TB6)
- **Original contribution:** First macro-flow MEMS valve
- **Competition:** MEMS micro-valves, piezoelectric meso-scale valves

### Major Objectives/Deliverables

- Potentially revolutionize pneumatic valve technology
- **Exploit** piezoelectric materials in pneumatic valves
- **Exploit** MEMS technology in pneumatics market
- Manage leakage in MEMS valves

### Progress

- Orifice plate, actuator array, and support plate fabricated and assembled
- Prototype packaged in test stand
- Preliminary tests on prototype

### Next Steps

- Complete final MEMS valve prototype (October 2016)
- Test final MEMS valve prototype (November 2016)
Conclusion

• Concept demonstrated on a meso-scale prototype valve
• MEMS orifice plate, actuator array, and support plate successfully fabricated and assembled
• More results to come

MEMS is a potentially revolutionary technology for pneumatic valves
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