Magnetically actuated microvalve for active flow control

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Abstract. The reattachment of separated air flows can be actively controlled by blowing oscillatory air jets in the boundary layer, through submillimetric holes situated near the separation edge. To achieve such pulsed jets, a high flow rate, high actuation frequency microvalve was designed, fabricated and characterized. The microvalve is fed by a pressurized source of air, and its inner channel is alternatively pinched by a PDMS polymer membrane, modulating the air flow which is addressed towards the separated surface. Magnetostatic actuation was chosen for its high stress, high displacement, and remote actuation capabilities. The actuation consists in coupling an inductive driving coil and a NdFeB permanent magnet situated on the PDMS flexible membrane. Characterization of the resonance frequency, and vibration amplitude are achieved by interferometric means. The output flow is characterized using strioscopy visualization and hot wire anemometry methods. The design and fabrication process of the microsystem, and the results of these characterizations are presented in this paper.

Keywords: Microvalve, Active flow control, Magnetic actuation, PDMS membrane.

1. Introduction

Flow separation is generally accepted to consist in the detachment of a fluid from a solid surface. In the case of aircraft flight, this phenomenon generally happens on the front edge of the wings and is associated with loss of lift, drag increase, pressure recovery losses, …. By controlling the flow on air wings for example, one may decrease dramatically aircraft fuel consumption and/or noise. It has been proved that this separation can be managed by blowing oscillatory air jets in the boundary layer through submillimetric holes situated on the surface near the separation area [1]. For this reason, active flow control is at the intersection between the needs of the aerospace industry and the possibilities of microactuators. Two types of air blowing techniques exist: pulsed jets provide only air injection whereas synthetic jets provide successively air injection and sucking. The commonly spread method to achieve such jets consist in using bulk mechanical solutions that do not provide an independent control of each jet-generator [2]. Moreover, most of these solutions are massive and do
not suit to be placed in airfoils for aeronautical applications. Many experiments have also been conducted with the use of acoustic waves diffused through fences as jet-generators to prove the efficiency of microjets as a momentum provider for active flow control applications. Much work has recently been achieved in the development of microscale actuators for an easier integration and independent control of each actuator. Many solutions use piezoelectric moving parts for the actuation [3,4,5].

The microvalve solution developed in the LEMAC / IEMN-LML lab is based on the magnetostatic actuation principle. An internal silicon channel is fed by a pressurized source of air, providing a high speed jet at the valve exhaust. For closure, a highly deformable polymer membrane, situated over the channel, is pushed towards several silicon walls by magnetic coupling, preventing the gas from passing through the valve. The system is designed in order to provide the very high speed (150 m/s) and high frequency (400 Hz) jets needed for the aeronautical applications.

2. General layout.

The microvalve consists in a flexible Poly(dimethylsiloxane) (PDMS) membrane (4 mm*4 mm, thickness 60 μm) situated over a 3 mm wide silicon channel. A silicon “pad” (380 μm thickness, 3mm*3mm) is processed on the membrane, and bonded to a commercial cylindrical NdFeB permanent magnet (3mm diameter and 2 mm thickness) for magnetic actuation. Several walls are processed under the pad (380 μm thickness, 150 μm*3 mm), clogging the channel (cf. fig.1).

When the valve is connected to a pressurized source of air, the inner pressure increases, expanding the flexible membrane and letting the gas pass through the valve (open mode, cf. Fig.2.a). As a high force is applied normally to the membrane plane, compensating the stress induced by the inner pressure on the membrane, the silicon pad is pushed towards the walls and the valve closes down (closed mode, cf. Fig. 2.b).

3. Dimensioning

The aimed jet section is commonly situated between 500 μm² and 2 mm² for the aeronautical applications. The exhaust hole section is then set to 1 mm². The resulting force applied to the membrane by the internal gas is given by eq.(1).

\[
F_{res} = \int \int \Delta P(x,y) \, dx \, dy
\]  (1)

\(P_{int}\) is the local inner pressure, it is equal to the sum of the feeding pressure \(P_{feed}\) and the pressure drop \(\Delta P(x,y)\). \(P_{int}\) can be calculated using the equation (2):
The aimed exhaust speed is approximately 150 m/s, which gives: \( P_{\text{int}} = 11,250 \) Pa.

In order to minimize the pressure drop \( \Delta P \), the channel shape is optimized in order to avoid the appearance of dead volumes near the connection points. Moreover, the dimensioning of the system is done in order to ensure a constant fluidic section in the whole channel, and equal to the exhaust hole section (1mm²). Preliminary tests using a 60μm thick PDMS membrane situated over a linear channel showed a membrane deflection of 250 μm at the working \( P_{\text{int}} = 11,250 \) Pa. The membrane width is then fixed to 4mm in order not to modify the 1mm fluidic section under the membrane.

4. Fabrication process and realization

To achieve simultaneously large dimension objects with the compulsory high precision (wall thickness is 150 μm), silicon based microfabrication techniques were used on commonly spread 3 inches diameter, 380 μm thickness, \(<100>\) crystalline silicon wafers. Moreover, this fabrication technique allows collective processing and fabrication cost reduction of the microvalves, as packs of 15 to 30 valves are to be used for wind tunnel tests.

In order to achieve the large fluidic section channel, a specific fabrication process was successfully developed and used. The final microvalves consist in the stacking of three silicon wafers: two of them defining the silicon channel, and one defining the cover and membrane system. Each one of these two main parts are processed independently, then bonded together (cf. Fig. 3).

4.1. Channel fabrication.

Two \(<100>\) Silicon wafers are first covered with a 2000 Å Low Chemical Vapor Deposition (LPCVD) \( \text{Si}_3\text{N}_4 \) layer. It is then removed on one side of each wafer using \( \text{CF}_2/\text{CHF}_3 \), coupling Inductive Coupled Plasma (ICP) and Reactive Ion Etching (RIE) in a TRION etching machine. Both processed sides are then coated with a 2 μm thick SU-8 2002 photo resist layer, crystalline directions are then mechanically aligned using the wafer’s flat spots, before the resist layers are contacted together. The resulting system is then heated at 95 °C during 30 s, and cooled at room temperature. The resist is finally polymerized at 180 °C during 5 min (step 1.1).

Anisotropic KOH wet etching is chosen for the channel and admission/exhaust holes definition in order to benefit from the nozzle effect due to the inclined etching plans, optimize the fluidic adaptation and minimize the pressure drop. The Silicon nitride masking layer is patterned on both sides of the bonded wafer, using ICP/RIE plasma etching through a 1,5 μm thick AZ 1518 photo resist mask (step 1.2.). The substrate is then wet etched in a KOH solution at 80 °C, the bonding SU-8 resist layer acting as a stopping layer for the etching step (step 1.3.). A last step consists in removing the SU-8 layer by \( \text{O}_2 \)- plasma dry etching, then covering the walls with a 2000 Å Ti/Au layer, deposited by RF sputtering through a silicon physical mask, in order to prevent PDMS from sticking to the walls during the final bonding (cf. fig. 3, steps 1.4. and 1.5., cf. fig. 4).

4.2. Membrane, pad and cover fabrication.

The following steps aim at the fabrication of a Si square pad on a PDMS square membrane (cf. fig. 4). The resulting wafer is to be bonded to the channels, ensuring the absence of leakage and the resistance to high channel pressure.

Again, a standard \(<100>\) Silicon wafer is used for this part of the process. A first step consists in depositing a 2000 Å thick \( \text{Si}_3\text{N}_4 \) layer, as a mask for the subsequent KOH wet etching step (step 2.1.). The membrane and pad pattern is first processed on the backside of the wafer, using ICP/RIE \( \text{CF}_2/\text{CHF}_3 \) dry etching. A 60 μm thick PDMS layer is subsequently spin coated on the front side, then
cured 30s at 150 °C for polymerization (Step 2.3.). A KOH wet etching step yields the released membrane, with a silicon pad attached to it on its center (step 2.4.).

4.3. Sealing bonding
A standard PDMS on silicon nitride process is used for the valve sealing [5]. After O₂ plasma activation, both surfaces are contacted and pressed together in order to avoid the formation of leaks in the bond. Alignment is ensured using alignment holes, fabricated during the prior wet etching steps. The realized valves are then diced and bonded to feeding tubes.

5. Actuation.
As previously mentioned in paragraph 3, the minimum value of the actuation force needed for the valve closure is given by eq. (3) This stress has to be applied normally to the membrane plane, and directed towards the walls.

$$ F_{act} = -F_{res} = - \int \int (P_{int}(x,y) - P_{atm}) \, dx \, dy $$

Considering that \( P_{int}=11\,250 \) Pa and the membrane dimensions, a 4 mN force is needed for closure. Magnetic actuation was chosen for its high available stress and displacement (250 μm membrane displacement for closure).
A permanent NdFeB magnet (cylindrical, 3mm diameter, 2mm height), bonded to the pad and coupled with a 100 windings, 200 μm diameter wire coil are used to actuate the valve. When fed by the

![Figure 3: Fabrication process – Two main parts are processed independently, then bonded together.](image1)

![Figure 4: Realized microvalves – The realized valves (top), PDMS membrane and Si pad (bottom, left), channels and walls (bottom, right).](image2)
actuation current, the coil produces a magnetic field gradient on its proximity, generating a force on the permanent magnet:

\[ F_{mag} = \iiint_{\text{magnet}} (dM(r,\Theta,z) \cdot \nabla d)(\vec{B}(r,\Theta,z)) drd\Theta dz \]  

NdFeB was chosen for its high magnetization in order to yield high forces on the membrane, and a ferrite core was used in order to greatly improve the actuation field.

6. Characterization

The exhaust speed was measured using a 1 mm length, 5μm diameter DANTEC 55 P11 hot wire anemometer. Fig. 5 shows a dramatic decrease of the calculated pressure drop near 0.2 Bars, corresponding to the fact that the PDMS membrane still slightly sticks to the channel walls when the valve is not pressurized: the system acts itself as a valve, preventing the gas from passing through when the feeding pressure is inferior to this critical sticking pressure (fig.5).

A dynamical study of the actuator shows a good impermeability of the valve in closed mode up to 400 Hz, 0.5 Bars, and 0.5 A actuation current, corresponding to a maximum exhaust speed \( V_{\text{max}} = 140 \) m/s (cf.fig. 6). A leakage appears at higher pressures, deteriorating the valve characteristics. The absence of leak in closed mode was verified by stroboscopic ombroscopy, using an ultra sensitive C8484 HAMAMSU digital camera cf. fig.(7).

![Exhaust Speed Vs. Time, Dynamical Actuation](image)

Figure 5: Exhaust speed Vs. ΔP.
The hysteretic behavior at low pressure is due to the PDMS sticking to the walls.

![Exhaust Speed Vs. ΔP](image)

Figure 6: Exhaust speed Vs. ΔP.

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![Stroboscopic Strioscopy of the Exhaust Jet](image)

Figure 7: Stroboscopic strioscopy of the exhaust jet, 400Hz actuation, 0.5A, 140 m/s.
7. Conclusion

The fabricated microvalve, based on magnetic actuation, shows very good results compared to other existing bulk solutions (exhaust speed: 140 m/s, pulsed at 400Hz). Moreover, each valve can be independently actuated, improving greatly the efficiency of the active control. A wind tunnel experiment is currently being prepared in order to validate the efficiency of the valves on separated flows.

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