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# Magnetostatic Microvalve for High Momentum Rate Pulsed Jet Generation

R. Viard<sup>1</sup>, A. Talbi<sup>1</sup>, P. Pernod<sup>1</sup>, V. Preobrazhensky<sup>1</sup>, A. Merlen<sup>2</sup>

*Joint International Laboratory LEMAC / Institute of Electronics, Microelectronics and Nanotechnologies : Villeneuve d'Ascq, France*

<sup>1</sup>*Ecole Centrale de Lille, B.P.48, 59651 Villeneuve d'Ascq, France*

<sup>2</sup>*USTL, 59655 Villeneuve d'Ascq, France*

## Abstract

A fully integrated magnetic driven MEMS Micro-valve providing pulsed jets was developed and characterized for active aerodynamic control. The device is composed of a microvalve, a magnetostatic actuator and a packaging allowing accurate positioning on the models or prototypes. The microvalve is a resonator actuated by a specific coupling between an inductive driving coil and a NdFeB permanent magnet. The generated force was optimized to provide 250mN at 0.5A. High momentum rate, fully modulated pulsed jets have been obtained in the frequency range [0 – 500Hz] with velocities up to 150m/s. The actuation method allowed a good control over the pulsed jets characteristics that reached the required values for real scale automotive and aeronautic flow control experiments.

Keywords: Pulsed jet, magnetic actuator, Microvalve, active aerodynamic control

## 1. Introduction

In a context of environmental constraints and fuel consumption reduction, flow control is becoming a key topic for aeronautic and automobile industries. Generally, the research efforts focus on separation and wall friction. For these kinds of flows, a localized control by pulsed jets is a good candidate relatively to equivalent continuous jets mainly because they can monitor sensitive frequencies of the flow. MEMS technology quickly appeared as a potential solution to develop distributed network of easily integrated microactuators providing independent jet control [1]. But, from a technological point of view, the production of a high-momentum localized source with small energy expenses needs an actuation mode that enables quick and large displacements of small quantities of fluid. The MEMS solutions proposed in the literature for pulsed jets are based on electrostatic [3] or piezoelectric [4,5] actuation techniques and provide momentum rate lower than  $6 \cdot 10^{-3}$  N.

## 2. Electromagnetic micro valve description

The microactuator device developed in this study (see Fig. 1) is composed of a silicon micro channel, an input orifice having a nominal area of  $2\text{mm}^2$  with a pressure reservoir on one side and venting to the atmosphere on the other via an orifice area of  $1\text{mm}^2$ . The opening and closing of the device is controlled by a flexible membrane equipped with a rigid silicon square that moves normal to the series of walls processed in the micro-channel. The membrane is normally held in the open position. Full details of the fabrication process are given by Pernod et al. [1, 2]. The membrane rigid element is equipped with an NdFeB Permanent magnet. Therefore, when the coil is excited

with a current, the membrane is pulled to the closed position by a magnetic force.

The pictures of one of the micro-valves chosen for characterization study are shown in Figure 1. The final dimensions of a fully developed device (packaging included) is of the order of 15 mm long  $\times$  10 mm wide  $\times$  8 mm thickness.

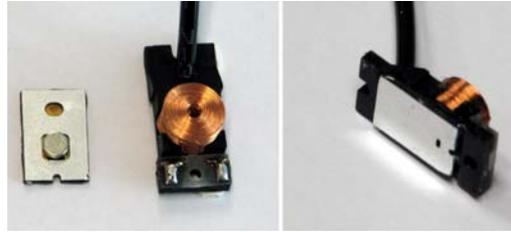


Figure 1: Pictures of the micro-valve and the assembled actuator

### 3. Results and discussion

#### 3.1. Static test

Micro-valve flow static tests were conducted on free open configurations with no electromagnetic actuation force applied on the flexible membrane and for various inlet pressures. The flow rate was measured upstream the valve inlet by a flow meter, and the exit jet velocity was measured by a hot-wire anemometry probe operated in constant temperature. The pressure/flow rate and jet velocity behavior of the micro-valve were characterized for two hydraulic diameters of 1mm and 0.5mm of the inner micro-channel. Figure 7 shows the flow rate and jet velocity characteristics of the micro-valve as a function of the inlet pressure. It can be seen that for a micro-channel of 1mm the flow rate obtained for an inlet pressure of 500kPa can reach 8.5L/min and the jet velocity 140m/s. The static characteristic of the microvalve can be easily adjusted for a given flow experiment by changing the depth of the silicon micro channel.

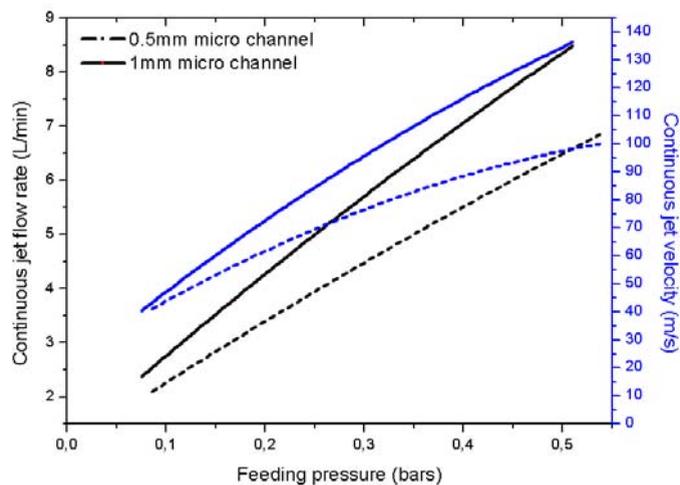


Figure 2: Characterization of the flow rate and jet velocity for micro channels with hydraulic section of 0.5 and 1 mm.

### 3.2. Dynamic test

The micro-valve was submitted to a series of tests to study its dynamic performances over a wide range of actuation modes and driving frequencies. Figure 3 shows the pulsed jet velocity evolution for an inlet pressure of 500kPa. The dynamic responses show that the actuation is strong enough to close almost completely the valve periodically (see Fig. 3). As shown in Figure 3b, we measured the dynamic response of the micro-valve at various duty ratios of the coils driving current signal. Good control over the jet duty cycle was obtained up to the lower resonant frequency of the membrane resonator ([0-200Hz]).

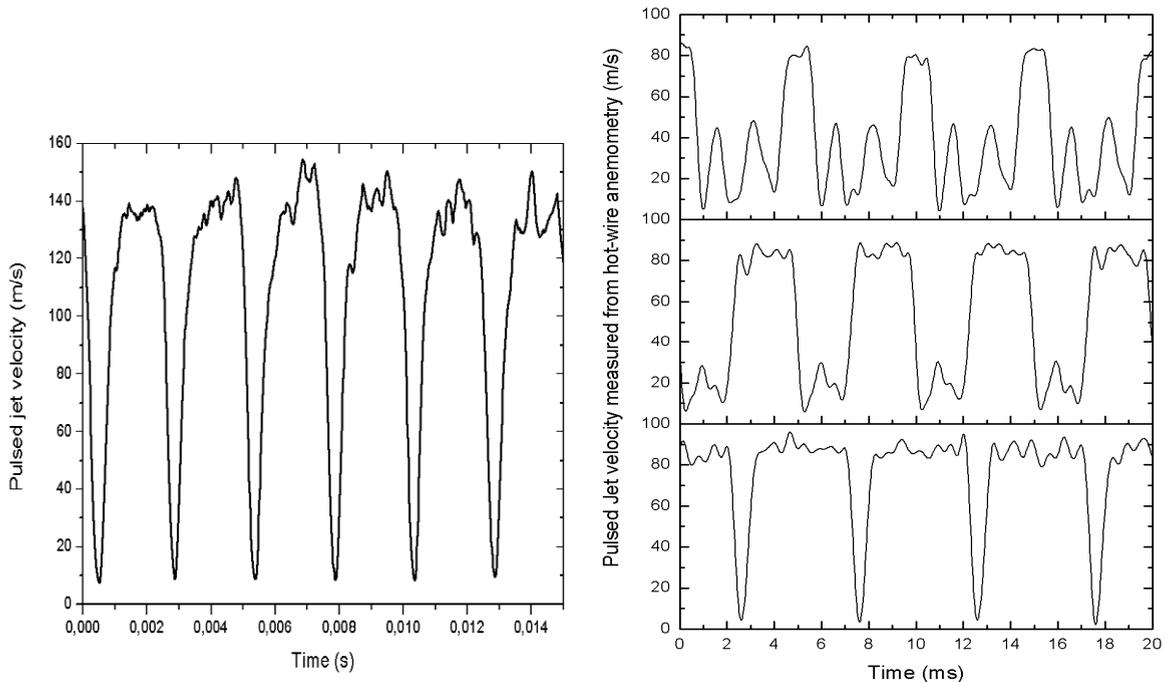


Figure 3: (a) Pulsed jet velocity evolution for an inlet pressure of 500kPa and a frequency of 400Hz (1mm micro channel - 2W electrical power)  
 (b) Effect of duty cycle on the jet velocity at the frequency of 200Hz (0.5mm micro channel - 0.5bars - 2W electrical power).  
 Up: duty cycle 20%, middle 50%, down 80%.

A more elaborated driving of the device was investigated using the mixing of the square signal with a positive and negative offset. Three configurations have been tested. The first one gave an output signal totally positive which corresponded to a pure push mode, the second and the third one corresponded to a push-pull mode with different intensities.

Figure 4 shows that the micro-valve is able to provide jet pulses over a wide range of frequency. A clear correlation between the frequency band pass of the device and the actuation mode can be observed. To explain this behaviour, we have focused our interest on the dynamic response of the micro-valve membrane. The displacement of the membrane is induced by the antagonist effects of the flow pressure and the magnetic actuation. First we have measured the time response to a current step required to move the membrane from the entire open position to the closed one, this time is close to 0.5ms. On the other hand, we have measured the duration necessary to open the micro-valve using only the internal pressure load; this duration is close to 1.5ms. The device minimum time response when push only actuation mode is used is about 2ms, corresponding to the 500Hz frequency limit seen on figure 4. However in the push pull case, the measured high frequency limit was still 500Hz instead of the 1kHz expected. We determined that a parasitic mode of vibration is excited at upper frequency, through non axial driving excitation. This is a consequence of the pressure distribution in the micro channel and of the micro-actuator non ideal assembly.

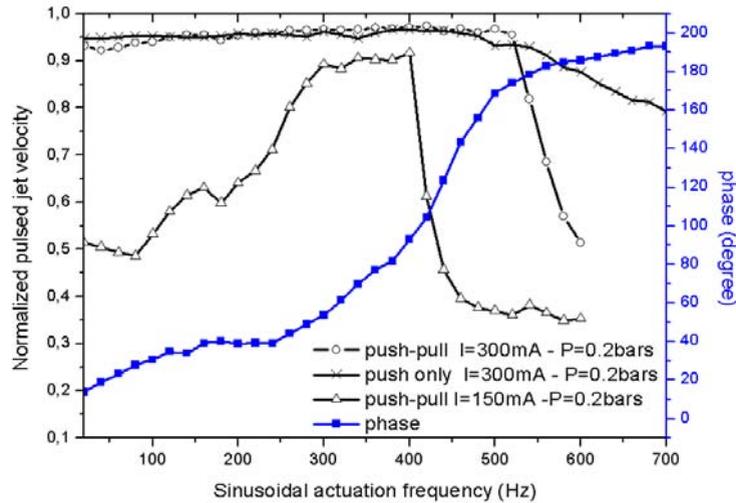


Figure 4: Frequency response of the micro valve at midrange operating pressure of 0.2 bars (0.5W electrical power)

#### 4. Conclusions

The fully functional magnetic driven MEMS microvalves presented in this paper reached a higher momentum rate of about  $3 \cdot 10^{-2}$  N compatible with real flow manipulation. The high flow rate was achieved through a magnetostatic actuation technique which allowed high frequency pulsation up to 500Hz and high pulsed fluid velocities (up to 150m/s). Easy integration and long term resistance is obtained by a plastic packaging fabricated by rapid prototyping. The device dimensions are approximately 15mm x 10mm x 8mm, the maximum power consumption level is about 2W. Arrays of these microvalves demonstrated successful control effects on real 3D flows in wind tunnel experiments.

#### Acknowledgements

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