Micro-systèmes et contrôle d'écoulements

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Résumé :

Les micro-systèmes magnéto-mécaniques présentent des possibilités intéressantes en matière de contrôle d'écoulements. Ils permettent de remplir les cahiers des charges des constructeurs aéronautiques ou automobiles. Ils sont également plus facilement intégrables sur les prototypes que les MEMS issus de microtechnologies entièrement intégrées. On présentera quelques tests en soufflerie. Les effets sur les écoulements seront discutés et les perspectives tracées.

Abstract :

Micro-magnetical mechanical Systems are potential solutions for flow control actuation. They are compatible with the requirements of aeronautic and automobile industries. Their implementation is easier than for the MEMS fabricated in totally integrated micro-technologies. Some wind tunnel tests are commented. The effects on flowsand some perspectives are evocated.

Mots clefs : contrôle d'écoulements. Micro-technologies

1 Introduction

In a context of environmental constraints and fuel consumption reduction, flow control is becoming an important topic for aeronautic and automobile industries. Increase of performances or drag reduction are the main issue where flow control can bring a substantial contribution. Recently, two flow properties focussed the research efforts: separation and wall friction. Controlling the first one means increase in lift or press*ure* drag reduction while controlling the second one reduces the viscous drag. In these kind of applications, the control needed is localized and must be reactive according to the definition of Gad-el-Hak. [1]. Obviously, the control must need less energy than it saves. For this reason and because the uncertainty on the localization leads to distributed control devices, MEMS technology quickly appeared as a potential solution. It has been shown for example that a control can be realized by blowing oscillatory air jets in a boundary layer through submillimetric holes situated on the wall surface just up-stream of a separation area [2,3,4,5]. For friction control one of the most elaborated works by Kasagi et al [6] demonstrated the possibility of controlling a turbulent boundary layer in a channel. Pulsed jets are considered as a good candidate for most of the situations not only because they reduce the flow rate relatively to equivalent continuous jets but also because they are selective: they can be used to *fin*d a specific sensitive frequency instead of acting blindly on the whole flow. This is particularly important for aeroacoustic problems or for turbulence control. This is obviously the consequence of the non linearity for Navier-Stokes equations where small scale perturbation*s* at high frequency may have global consequences at low frequency as suggested for example by Wiltse-Glezer [7] or Stanek [8]. As Navier-Stokes equations are the expression of the conservation of momentum for fluids, it is natural to think that the control must modulate sources of momentum. This idea dominates all the numerical simulation on flow control. Nevertheless going from the concept to real actuation is not a small challenge. It supposes at least an open loop control with a distributed sensors and actuators arrays. Wall deformations or fluidic actuators can be considered for this task and pulsed jets stand out because of their potential high momentum.

On the technological point of view the production of a localized source of high momentum with small energy expenses needs a mode of actuation that enables quick and large displacements of a small quantity of fluid. Two types of air blowing techniques exist: pulsed jets, providing only air injection and synthetic jets, providing alternating air injection and suction capabilities. The wide-spread method to achieve such jets relies on bulk mechanical systems that do not provide an independent control of each microjets. Moreover, well known actuation are massive and are not suited for the available space on airfoils for aeronautical applications. Much work has been achieved recently in the development of microscale actuators for easier integration and independent jet control [9]. Existing solutions, based on electrostatic [10] or piezoelectric [11] actuation techniques, currently provide acceptable pulsation frequency or outlet speed. We present in this paper a novel architecture of silicon based, micromachined microvalves specifically dedicated for active air flow control. The microvalves actuation will be made on electromagnetic method which has attracted a high level of interest, since it provides an extended working range, a short response time, a high field energy density, and a low actuating voltage. A specific fabrication process involving high cross section silicon microchannels is described, as well as the setup of the electromagnetic actuation technique which allows to satisfy requirements in terms of performances (e.g. bandwidth, time response, closed-loop controllability, output force and displacement amplitudes). The microvalves can provide high speed (150 m/s) microjets for actuation frequencies between DC and 400 Hz.

2 Valve architecture

The MEMS architecture consists of a silicon microchannel covered with a flexible PolyDimethylSiloxane (PDMS) membrane (60 µm thickness). The architecture of the microvalve is shown in fig.1. The silicon block processed over the PDMS membrane allows to increase the robustness, to set the resonance frequency higher to obtain a large actuation bandwidth, it's also allows to enhance the closed mode, all the while preserving the elasticity of the membrane. The silicon pad, is free to move upwards along the y axis and/or rotate around the z axis under the effect of the pressure distribution introduced by a series of silicon walls processed in the microchannel under the pad.

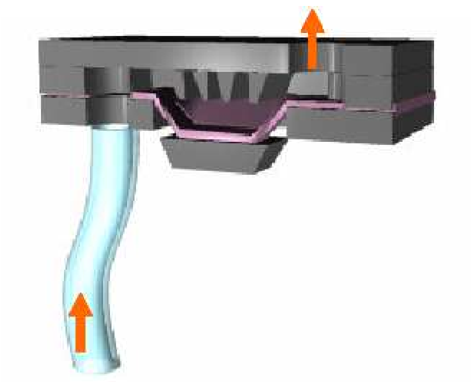

FIG. 1. Microvalve architecture. A silicon pad, processed over the membrane, pinches the microchannel when pushed towards the walls

Pressurization of the inlet induces an increase of the static pressure in the microchannel and the expansion of the flexible membrane. The inlet gas is then free to pass through the microsystem, and a static equilibrium is reached between the resulting pressure forces and the tensile stress induced in the membrane (200 µm vertical displacement, 0.6 rad rotation around the z axis due to the pressure drop under the membrane in open mode, nominal inlet pressure of 1.5 Bars). Actuation is obtained by applying a force on the rigid pad normal to the channel plane, overcoming the inner pressure forces and resulting in the mechanical pinching of the silicon microchannel. Such a system is represented in Fig.2. Electromagnetic actuation was chosen for the high strain and displacements achievable and the ease of integration of coil-magnet systems. 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 actuation current, the coil produces a magnetic field gradient on its proximity, generating a force on the permanent magnet directed normally to the membrane plane. Electromagnetic actuation means provide the compulsory high force and displacement needed for the aimed high flow rate, low frequency applications.

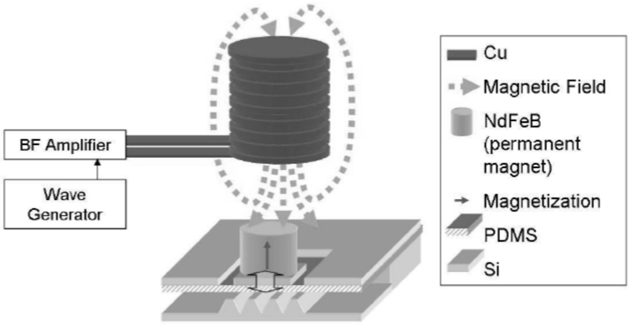

FIG. 2. Electromagnetic actuation principle: the magnetic field gradient induces the closure force on the permanent magnet bonded to the mobile silicon pad.

Critical dimensions for the microvalve arise from the tradeoff between the targeted high flow rate and the nominal inlet pressure P_{in}. As high deformation of the polymer membrane induces risks of tearing and fatigue, the nominal inlet pressure is fixed to 1.5 Bar, corresponding to a stready-state displacement of the rigid pad of 200 µm in the direction normal to the channel plane. The outlet flow rate is then maximized by minimizing the total pressure drop in the microsystem. For this reason, the microchannel cross section is set to 380 µm height and 3 mm width in order to reach the 1mm hydraulic diameter of the outlet hole. Silicon pad dimensions are set to 3mm*3mm and the inlet nominal pressure is set to 1.5 Bars, inducing 200µm vertical displacement of the pad and an acceptable 30% elongation of the PDMS membrane.

3 Characterization

The outlet speed is measured thanks to a 1mm long 55P11 DANTEC hot wire anemometer. The measure is made 500µm away form the outlet hole, in a direction parallel to the exit microjet. Independently, a shadowgraph system permits the monitoring of the microjet shape, and leakage diagnosis on the measured microvalves. Figure 3 shows cartographies of the measured outlet speed obtained using a 30° inclined vectoring plate. The maximum outlet speed reaches 150 m/s in the case of a perpendicular vectoring plate.

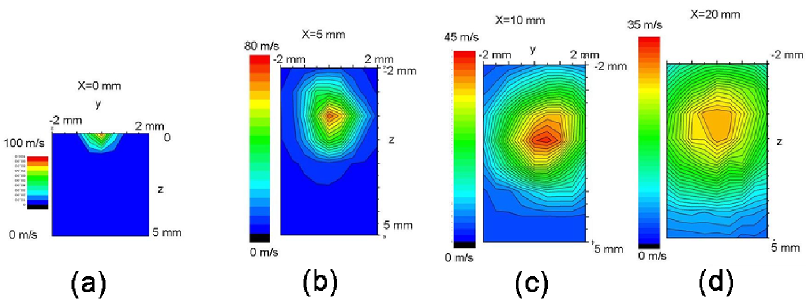

Fig. 3. Cartographies of the measured outlet speed, 30° vectoring plate, 1mm diameter outlet hole. Figures (a),(b),(c), and (d) represent perpendicular cuts of the microjet at a distance respectively equal to 500µm, 5mm, 10mm and 20 mm of the outlet hole.

As the measured value is an integration of the speed along the wire length, the presented values are slightly underestimated. Fig. 4 shows very weak leakage in closed mode during dynamical actuation (400 Hz, 0.5 A).

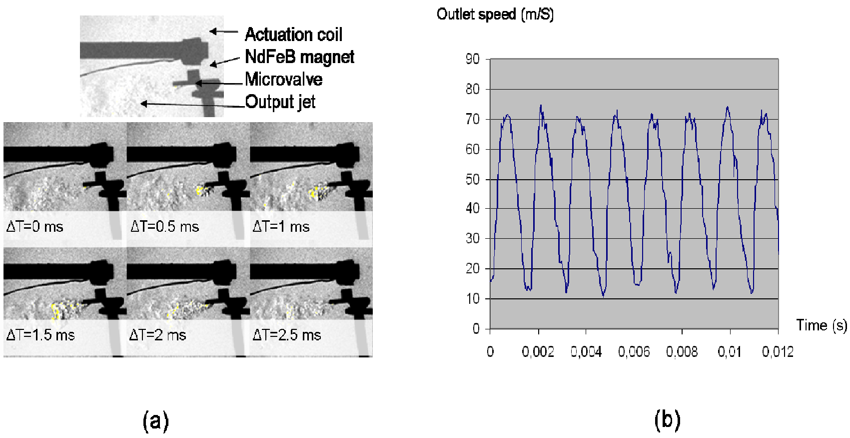

Fig. 4. Exhaust speed vs. time (4 wall valve, 550Hz actuation frequency, 0,5A coil current, 75 m/s max. outlet speed, b). Stroboscopic shadowgraph of the exhaust jet (a). The high actuation current can be reduced by increasing the coil winding number.

Figure 5 shows measured maximum exit velocities versus the inlet pressure. It can be seen that the valve performances are relatively similar.

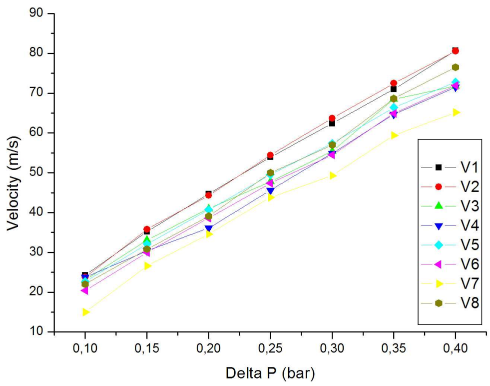

Fig.5 Maximum exit velocity versus inlet pressure for 8 valves

4 Basic flow control experiment

The general idea is to generate a pressure gradient on a boundary layer on flat wall by a modification of the opposite wall curvature (diffuser) in a low velocity Eiffel-type wind tunnel. The diffuser has an expansion ratio of about 2 (0.29/0.14). It is equipped with perforated suction holes to prevent separation. Consequently, the flow separates on the flat plate. RANS computations have shown that the plate being flat there is nothing promoting the reattachment and the separation length could have been as long as 80 cm. A NACA 23012 airfoil was then positioned at about 7 cm from the flat plate side to cause the reattachment. It was found that a chord of 18 cm, an angle of attack of 7 degrees and a distance of the trailing edge to the flat plate equal to 58 mm were adequate to fix the separation length to a reasonable value. The idea was to avoid obtaining a separation length larger that the wind tunnel span (0.3 m) in order to limit 3D effects. The sketch of the experimental set-up is represented in figure 6 which includes all the useful dimensions.

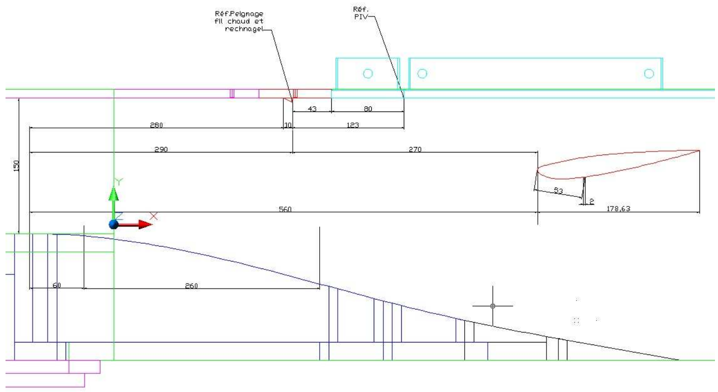

Fig 6. Sketch of the Wind tunnel experiment at ONERA Lille.

The inflow velocity was 31 m/s. The boundary layer was fully turbulent at the actuator location and its height was δ_0=1.5 cm. The Reynolds number based on the boundary layer displacement thickness was about 4000 at the actuator location. The stagnation pressure and temperature corresponded to atmospheric conditions. The suction velocity through the diffuser porous wall deduced from the measured flow rate was about 0.6 m/s. It represents about 2% of the main flow rate. The microjets have been disposed at about 14 δ_0 upstream of the separation point. Figure 7 shows the array of microvalves.

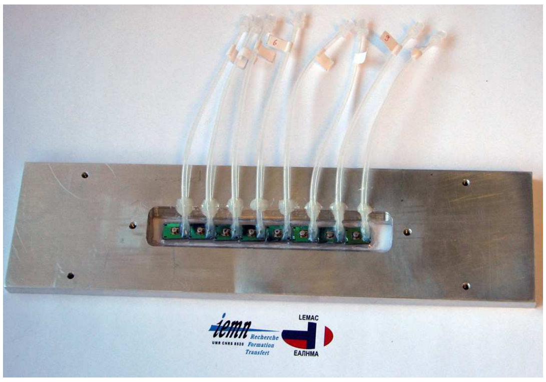

Fig 7. Array of microvalves monted on the backside of the flat plate (without the coils) The spacing between each actuator is 15 mm (1 δ_0). The squared hole edge dimension is 1 mm and the jet direction is oriented with the pitch and skew angles both equal to 45 degrees.

5 Results and conclusion

The first results shows that the pulsed jets are able to reattached the flow (Figure 8 and 9) for a maximum exit velocity of 50 to 60m/s. This result is similar for continuous jets and doesn't seem to depend on the frequency (35Hz, 70Hz, 140 Hz have been tested, 70hz corresponding to F^+=1). Nevertheless, since the injected momentum is lower with pulsed jets than with continuous jets (the inflow pressure being the same), one can conclude to a better overall efficiency of the pulsed jets which gives the same results than the continuous ones at a lower energetic cost (the electric cost being negligible). It is clear that controlling turbulent structure will require a more sophisticated control (like a close loop) and in that perspective, pulsed or synthetic jets are far more promising that continuous jets or VG. In this work we just demonstrated that such fluid device without any optimization and close loop control is as efficient as VG or continuous jets. But another important results is the demonstration of the technical possibility to implement microsystems in a model and to achieve successfully wind tunnel tests without damaging the microvalves.

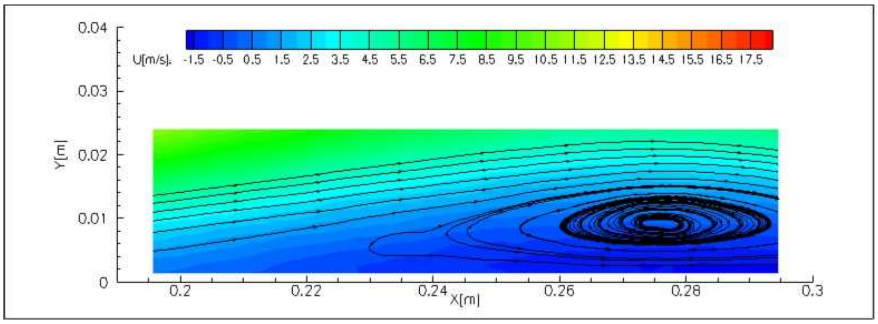

Fig 8. Longitudinal velocity field of the uncontrolled flow in the symmetry plane (2D PIV)

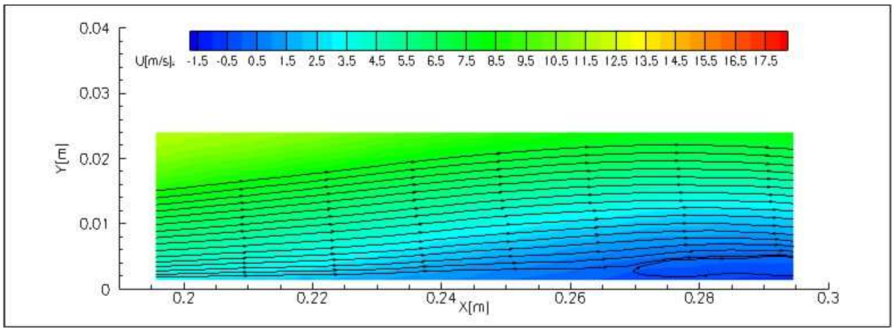

Fig 9. Longitudinal velocity with micro-jets (P=1.2 bars, F=70 Hz)

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