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IEMN/LEMAC-LICS Magneto-mechanical micro-actuators and active flow control: review of the last 15 years results

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Abstract

In this paper, we present an overview of the microjet solutions developed by IEMN/LEMAC-LICS during these last ten years for active flow control in the framework of the GDR "Control of separations", the European FP6 "ADVACT" program, and different projects from DGA, the aeronautic foundation, EADS foundation, and CNRT-R2A. The work within these different research projects has been made in collaboration with the major French and European aeronautic and automobile industrials. The IEMN/LEMAC-LICS solutions are based on Micro-Magneto-Mechanical Systems (MMMS) and concern integrated devices delivering pulsed microjets, continuous microjets with bistable « ON-OFF » actuation, and synthetic microjets. These devices were combined in arrays of 8 to 30 elements distributed near the leading edge of a physical model of air wing, within an engine blade, inside a S-duct, around an engine exhaust and at the rear end of a Ahmed car model. Several wind tunnel experiments were made for separation control, and aero-acoustic control. It was demonstrated that the microjets satisfied the functional specifications defined by the industrial partners. Efficient flow control was obtained. MMMS actuators have demonstrated a good robustness in severe wind tunnel environments (temperature, compressibility, humidity, structural vibrations…).

Introduction

Active aerodynamic flow control is an important topic for aeronautic and automobile industries, because it can provide reduction of fuel consumption, vibrations, noise, or improvements of the lift and manoeuvrability. Separation control, wall-friction control, or fluidic vectoring are some examples of the main concerns in this field. Good results have been obtained these last years by fluid mechanicians using simulations, or experiments in wind tunnels. For this reason, the demand for actuators fulfiling the specifications for flow control on real airplanes or cars increased dramatically. It is generally desired to have robust actuators, of small sizes, providing length- and time-scales matching with the flows to be controlled. But the actuators also need to be low cost, have a low-energy consumption, and to be simple to fabricate in large numbers because a spatial distribution of the devices is often required. Therefore, Micro-Electro-Mechanical Systems (MEMS) quickly appeared as an interesting potential solution. First appeared in the late 80s at Berkeley University (USA), MEMS now refer to micrometric-millimetric devices, integrating electronics with mechanical components and fabricated using integrated circuit batch-processing techniques. They usually combine sensors, actuators, and processing electronics, providing a high functionality, highperformance, low-cost integrated microsystem. Some achievements in MEMS actuators for flow control were obtained in a few research groups using electrostatic, piezoelectric, pneumatic, or magnetic actuating solutions (for more information, see review in [1]).

IEMN/LEMAC-LICS proposed some original and efficient solutions of microjet devices based on Micro-Magneto-Mechanical Systems (MMMS), which refers to Micro-System devices based on coupled magnetic and mechanical phenomena. Developed more recently than Micro-Electro-Mechanical Systems (MEMS), MMMS provide now efficient solutions in particular in the field of micro-actuators when high forces and/or large displacements are required. In the following sections we will present a review of the MMMS microjet devices developed by IEMN/LEMAC-LICS and tested in several wind tunnel experiments for aeronautic or automobile applications within the GDR program and several additional projects and contracts (DGA projects, FP6 European ADVACT project, Aeronautic foundation project, EADS foundation & CNRT-R2A projects). Results from experiments are discussed.

1. Overview of the MMMS IEMN/LEMAC-LICS microjet devices

IEMN/LEMAC-LICS designed and fabricated several arrays of microvalves, each being specifically dedicated to a particular flow control application tested in a wind tunnel experiment. Three types of microvalves were elaborated (Figure 1) : 1) Microvalves for pulsed microjets with magnetostatic or auto-oscillating actuating modes, 2) Microvalves for continuous microjets with a bistable (on-off) magnetostatic mode of actuation, and very recently 3) Microvalves for Synthetic Microjets.

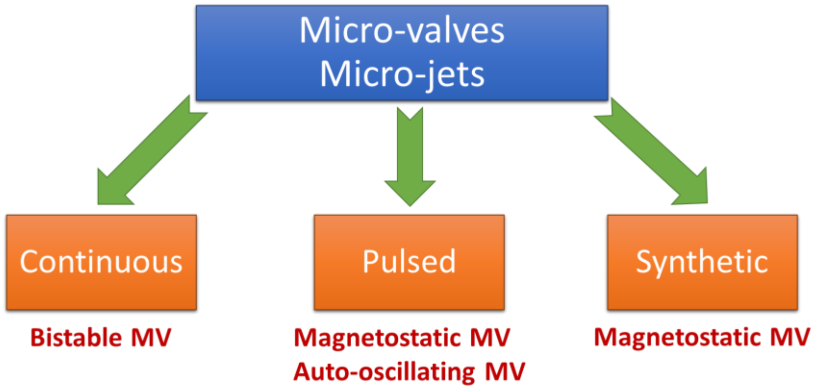

Figure 1: The 3 types of MMMS IEMN/LEMAC-LICS Microvalves dedicated to microjets for active aerodynamic flow control

2. Pulsed micro-jets

Pulsed micro jets were historically the first devices to be developed in IEMN/LEMAC-LICS. The general scheme of the micro valve is presented on figure 2. The micro valve is based on a PolyDimethylSiloxane (PDMS) flexible membrane (typical size: 4 mm x 4 mm x 60 µm) opening and closing a microchannel (typical size: 3 mm wide x 360 µm high) fabricated using silicon microfabrication technology. The membrane is locally rigidified by a silicon pad. The internal structure of the microchannel presents a series (typically 2, 4 or 6) of silicon walls (3 mm x 360 µm x 150 µm) allowing hermetic closure of the valve as well as a controlled pressure drop in the fluid flowing under the membrane. 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. Two types of actuating techniques for the opening and closing of the micro valves were developed. The first one uses magneto static interaction between a magnet fixed on the pad and an external mini-coil. The second one uses an auto-oscillating mode of the micro valve due to fluid-structure interaction between the PDMS membrane and the fluid flowing within the microchannel.

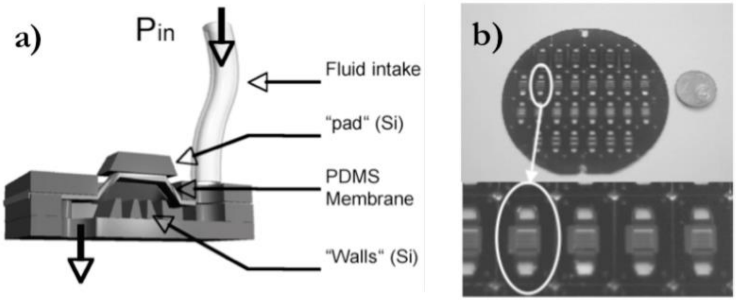

Figure 2 : a) Architecture of the pulsed micro valve; (b) Wafer with 28 elements showing the inner part of the micro valve.

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2.1 Pulsed micro jets with magneto static control

2.1.1 General design

In this configuration, the actuation of the micro valve is obtained by applying a force on the rigid pad normal to the channel plane using coil-magnet interaction. This force overcomes the inner pressure forces and results in the mechanical pinching of the silicon microchannel. Such a system is represented in figure 3. Electromagnetic actuation has the advantage of high strain and displacements achievable and the ease of integration of coil-magnet systems. The typical frequency range of such an actuation is [0, 700 Hz] but can be extended up to 1 kHz. Technological details are provided in ref. [2-4].

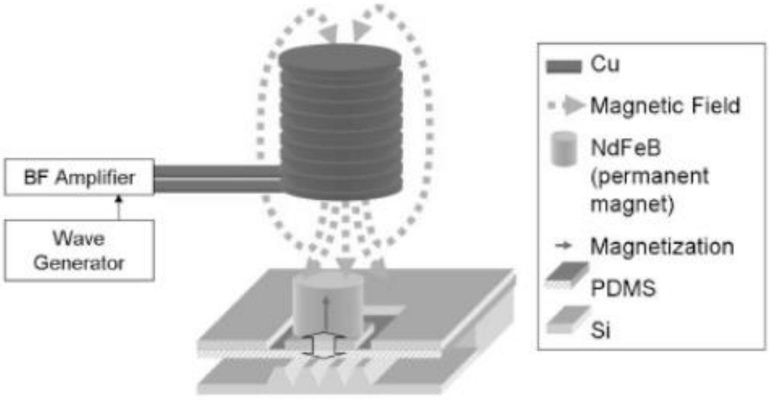

Figure 3: Magneto static actuation principle: the magnetic field gradient induces the closure force on the permanent magnet bonded to the mobile silicon pad.

2.1.2 Control of a flow separation only due to a pressure gradient

The first wind tunnel test of the pulsed micro valves was made in the framework of the European STREP ADVACT project [5]. An array of 8 magneto static Micro valves (1cmx1.5cm) for pulsed micro jets has been elaborated and integrated in the ONERA Lille wind tunnel (Figure 4). The experiment was dedicated to the active control of a flow separation only due to a pressure gradient. The inflow velocity was about 30 m/s. The boundary layer was fully turbulent at the actuator location and its thickness was d0=1.5 cm. The Reynolds number based on the boundary layer displacement thickness was about 4000 at the actuator location. Results presented in figure 5 show that the pulsed micro jets, with velocities about 50-60 m/s and 70 Hz actuating frequency, provide an effective control of the separation (see ref. [6,7] for complete set of results). In this first version of implementation in array the micro valves were glued on an insert plate and the coils were assembled all together within a metallic bar fixed on the backside of the micro valves. This system has shown many disadvantages like the impossibility to change a valve when it was altered or difficult alignments of the coils with the magnets. This leaded later to consider valves with individual packaging.

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Figure 4: (a) Metallic bar supporting the coils; (b) Array of micro valves glued to the insert plate; (c) Photograph of the array integrated in the wind tunnel and view of the pressure distribution system.

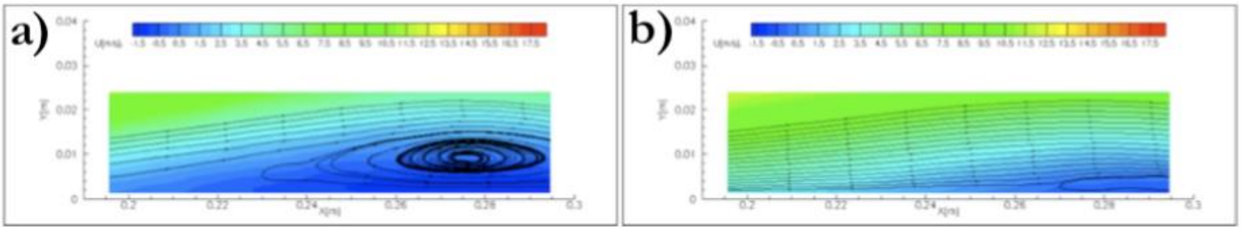

Figure 5: (a) Longitudinal velocity field of the uncontrolled flow in the symmetry plane of the flow (2D PIV); (b) Longitudinal velocity with pulsed micro-jets activated (P=1.2 bars, f=70 Hz). Flow is re-attached.

2.1.3 Control of a flow separation in a S-duct

A second wind tunnel experiment has been made in ONERA Modane for separation control within an S-duct in the framework of a DGA project. An array of 14 pulsed smaller micro valves (0.7 cm x 1.5 cm) with improved micro jets velocities (> 100 m/s), stable characteristics over an extended frequency range [50 Hz, 700 Hz], and specific packaging for easy individual mounting on non-conformal geometries has been designed and fabricated (figure 6). The results, which cannot be detailed here for confidential reasons, generally show that the micro jets are effective for the re-attachment of the flow and that efficiency of the control is particularly effective at some particular frequency pulsations. In addition, the experiment has shown an excellent robustness of the micro valves which were used in harsh conditions of temperature, compressibility, humidity, structural vibrations…

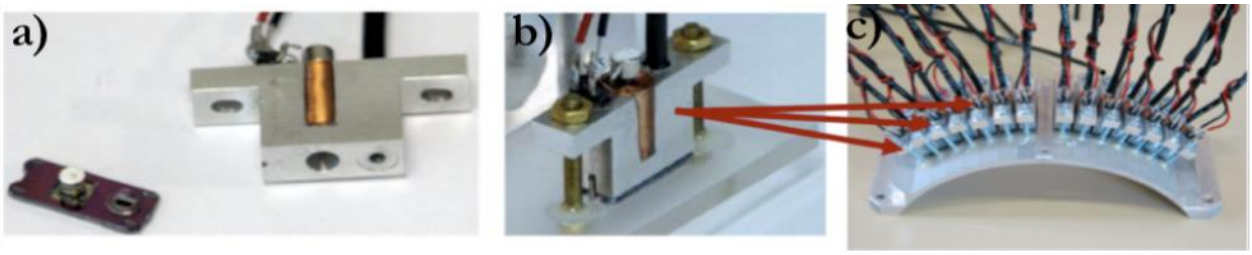

Figure 6: Magneto static pulsed micro valves with packaging allowing easy individual mounting on no conformal Geometries for separation control. Micro jet velocities>100m/s, frequency range [50 Hz, 700 Hz].

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3.1.4 Control of a flow separation on the rear end of a Ahmed car model

Similar micro valves with improved internal design were also tested in the wind tunnel of the PRISME Institute of Orléans in the framework of a CNRT-R2A contract. The goal was the control of a flow separation on the rear end of an Ahmed body (scale 0.7, angle of the rear window relatively to the roof 25°).
The packaging of the micro valves and the actuating system were improved in order to decrease the total thickness of the device, and increase the actuation force. Simultaneously the design and fabrication process were changed to simplify the production, increase the reproducibility and decrease the cost for large scale fabrication. The quick prototyping and the plastic moulding technique, have been used (figure 7). A linear array of 19 such micro valves has been implemented along the width of the rear window of the model. The exit holes were localized 2 mm downstream the edge with an angle of 45° relatively to the window surface. Flow velocities between 10 m/s and 40 m/s were considered, and jet velocities in the range [40 m/s and 110 m/s]. Diameter of the exit hole of the micro valves was 1 mm. The results obtained in the wind tunnel show that pulsed micro jets are able to reduce the separation on the rear window with a total suppression for a sufficient injected flow rate. A reduction of 5% to 6% of the Cx coefficient was achieved (figure 8). Higher injection does not provide any further reduction of Cx. It was found that there is no effect of the actuating frequency in the tested range [0, 400 Hz], except within a very narrow band near the Strouhal of the pseudo Von Karman street. The latter develops two alternated vortex of horizontal axis parallel to the width of the car at the rear end. Out of this resonant frequency the effect of the pulsed jet is comparable to the effect of the continuous ones, pulsation resulting only in a reduction of the flow rate to be injected by the micro jets. At the resonant frequency, the pulsed injection increases the energy of the street and affects the drag reduction. Nevertheless, this shows a sensitivity of the flow to this frequency and may be used in the future to improve the efficiency of the control. For example it is expected that it is possible to reduce the intensity of the Karman street by a better positioning of the micro valves on the Ahmed car model and by a proper adjustment of the pulsation phases in order to be in opposition with the natural oscillation of the street.

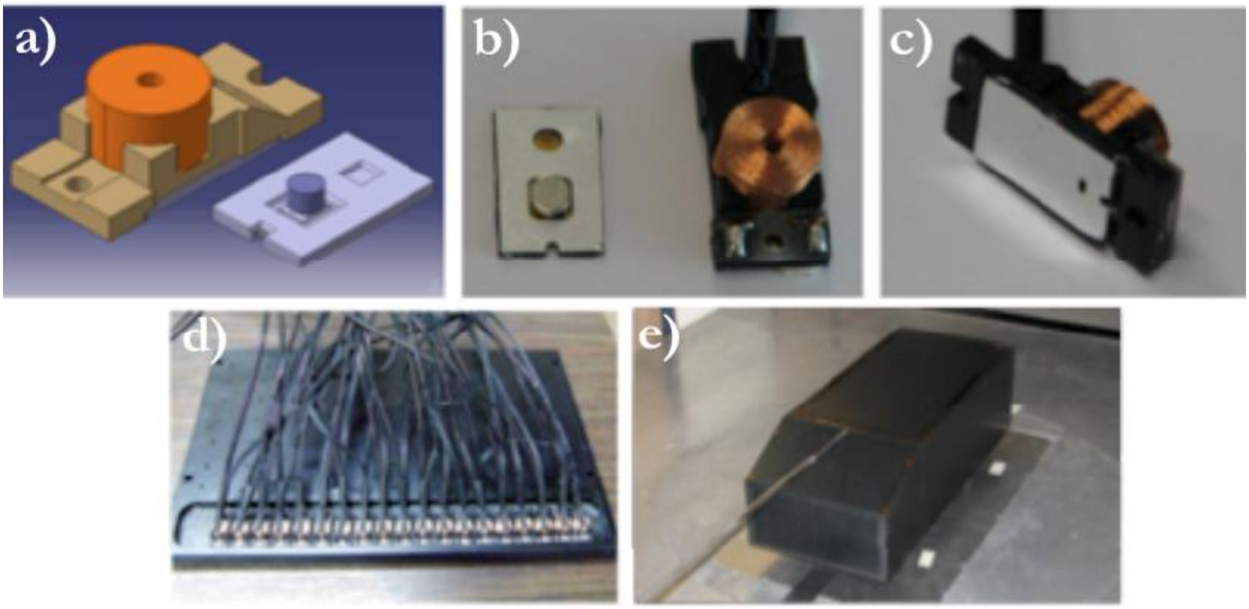

Figure 7: (a-c) new packaging of the micro valves fabricated by plastic moulding; (d) Photograph of the array of micro valves implanted within the insert modelling the rear window of the car; (e) Photograph of the rear end of the Ahmed car model in the wind tunnel of PRISME Institute (Orléans).

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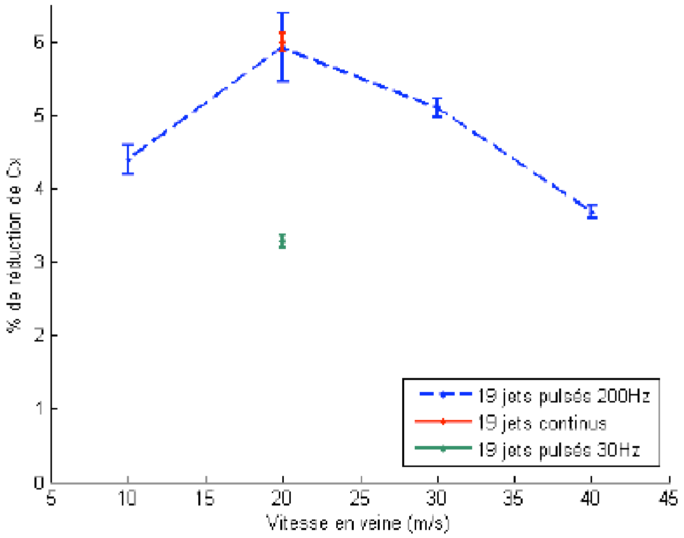

Figure 8: Comparison of the Cx between a generic pulsed case (200 Hz), continuous jets and the resonant configuration (30 Hz)

2.2 Pulsed micro jets with magneto static control

A second original mode of actuation, based on a natural instability within the micro valve has been developed. Auto-oscillation of the micro valve was obtained by inducing a desired fluid-membrane instability, which was obtained by a proper design of the internal channels, number and size of the internal walls, and a correct choice of the input pressure range. This mechanism was analysed theoretically and experimentally in the reference [8]. The mode presents several advantages: 1) no actuating elements, and therefore no electrical connections, no electrical consumption, and a smaller thickness of the device which can be inserted if necessary in thin slits (like some blades for example) 2) higher frequency of pulsation of the micro jets, which can easily be tuned from a few hundred hertz to 3 kHz by small changes on the device. A circular array of 12 high frequency (2.5 kHz) auto-oscillating micro valves has been implemented around the exhaust of an airplane engine model (axisymmetric jet) in the Laboratory of Fluid Mechanics and Acoustics (LMFA) of Ecole Centrale de Lyon in the framework of the OSCAR project supported by the Aeronautic Foundation (Figure 9). The goal of the work was the aero-acoustic noise control of the main jet. A specific packaging has been designed in order to be compatible with the ring support of the installation. The Mach numbers considered for the main jet were in the range going from Ma=0.3 to Ma=0.9, and the self-oscillating micro jet velocities in the range 60 m/s to 100 m/s. The obtained results presented in figure 10 show that in the tested configuration the micro jets provide no modification of the noise. Nevertheless, an analyse made by numerical simulations in ONERA shows that the actuation has to be synchronized with the spatio-temporal modes of the flow (spatial distribution, frequency, and phase) to obtain an effect. As a consequence, such kind of control must be reactive and needs the integration of micro sensors within the control device and a means of control of the self-oscillations. This kind of improvement is now under development in IEMN/LEMAC.

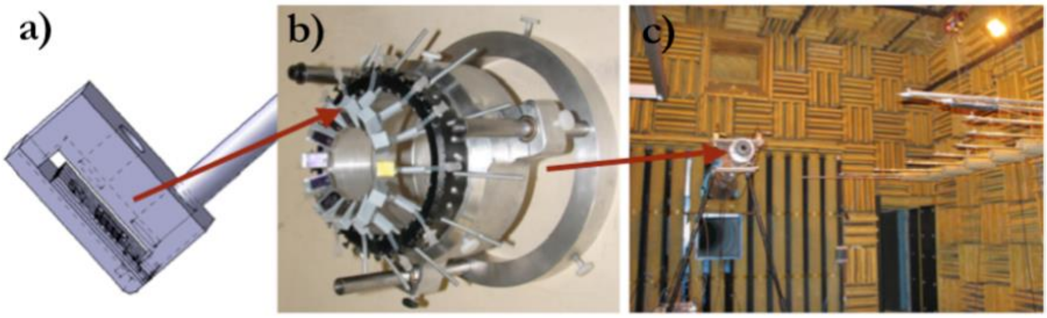

Figure 9: (a) Self-oscillating pulsed micro valve inserted in its packaging; (b) The 12 valves mounted on the ring support; (c) Airplane engine exit instrumented with the ring of micro valves for acoustic noise control. Frequency 2.5 kHz, micro jet velocity from 60 m/s to 90 m/s

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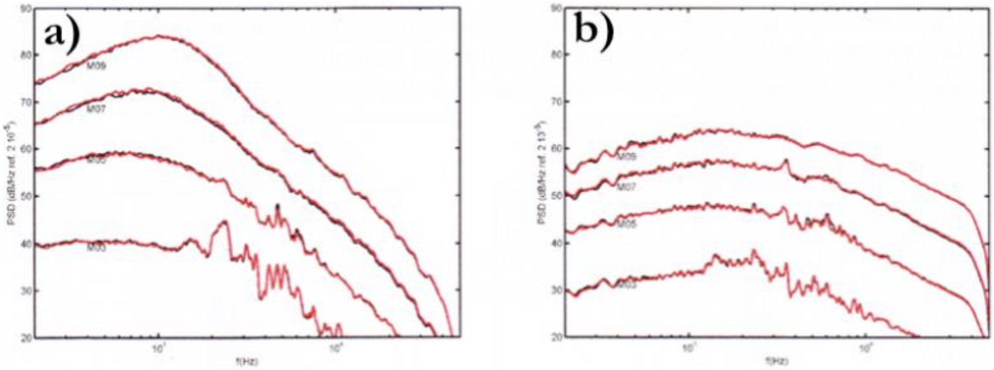

Figure 10: Pressure spectral density of the flow measured at angles: (a) 20° and (b) 90° for different Mach. Black curve: without control. Red curve: with control by the auto-oscillating micro jets.

3. Continuous micro jets with bi-static « ON-OFF » magneto static actuation mode

In the framework of another DGA contract, some new micro valves with a high flow rate and a high momentum have been elaborated. A new internal design of the microchannel allowed to minimize the pressure drops and to increase the micro jet velocities higher than 250 m/s.

Possible self-oscillations of the membrane described earlier were also supressed by a change in the channel design. Finally, a bi-stable magnetic actuator was combined with the micro valve in order to provide an « ON-OFF » control. An array of 32 such continuous high velocity micro jets have been implemented in a 3 m long airplane wing model (figure 11) and tested for separation control in the wind tunnel of the Laboratory of Aerodynamic Control (LEA) in Poitiers. The results illustrated in figure 12 show that the micro jets allow the reattachment of the flow.

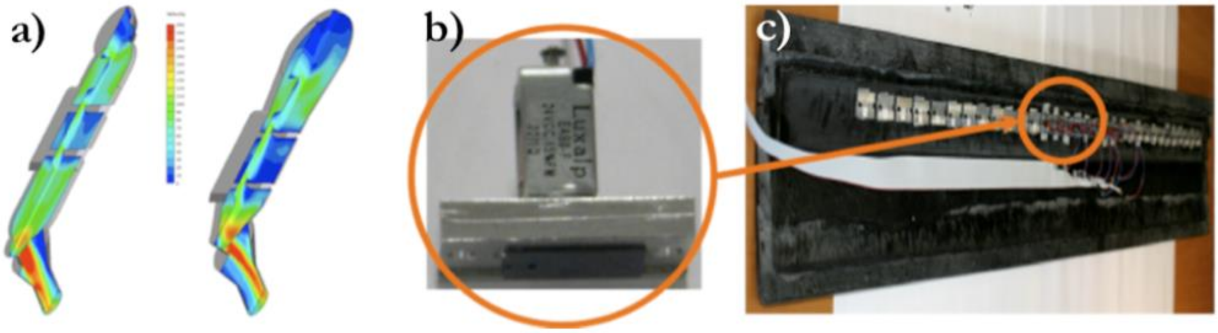

Figure 11: (a) Simulations showing increase of 30 m/s of max micro jet velocity by improvement of internal design of the micro valve. (b) and (c) Micro valves for continuous micro jets with their packaging and bi-static actuators mounted of inside an airplane wing model. Jet velocities > 250 m/s.

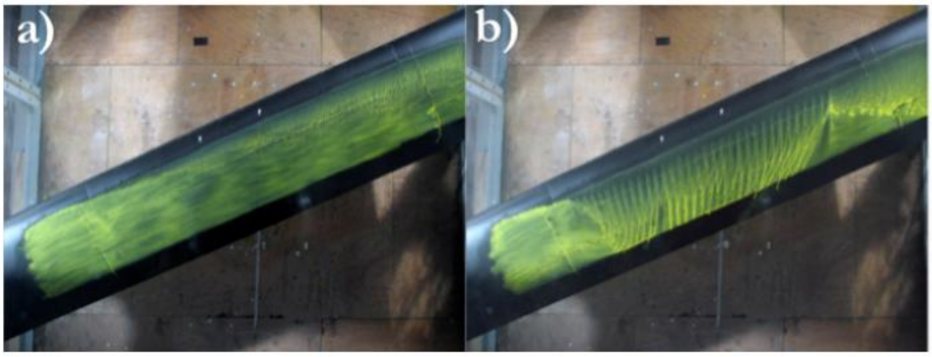

Figure 12: Visualization of the flow on a NACA profile (a) Result without control; (b) Result with control;

4 Synthetic micro jets

More recently an axisymmetric synthetic micro jet generator based on MMMS concepts was also elaborated (in the framework of an EADS foundation contract). Synthetic (or zero net mass flux) jets are a particular case of pulsed jets generated by creating volume variations in a cavity. The main interest of synthetic (or zero net mass flux) jets compared to conventional pulsed ones is the absence of fluidic connections, which simplifies the system for active flow control. The developed prototype consists of a circular flexible membrane locally rigidified by a silicon pad, situated over a silicon cavity (18, 8 mm3 in volume). The membrane is driven by an electromagnetic control system based on a miniature NdFeB magnet coupled with a coil. The cavity presents an orifice (600µm diameter) through which air is alternatively sucked and ejected. The size of the fabricated device including actuation means does not exceed 1 cm3 (figure 13 (a)), and its maximum consumption reaches 600 mW. The optimum frequency range is located between 400 Hz and 700 Hz for the chosen configuration. In this range, a 600 µm diameter outlet micro jet reaches maximum velocities ranging from 25 m/s to 55 m/s (figure 13 (b)).

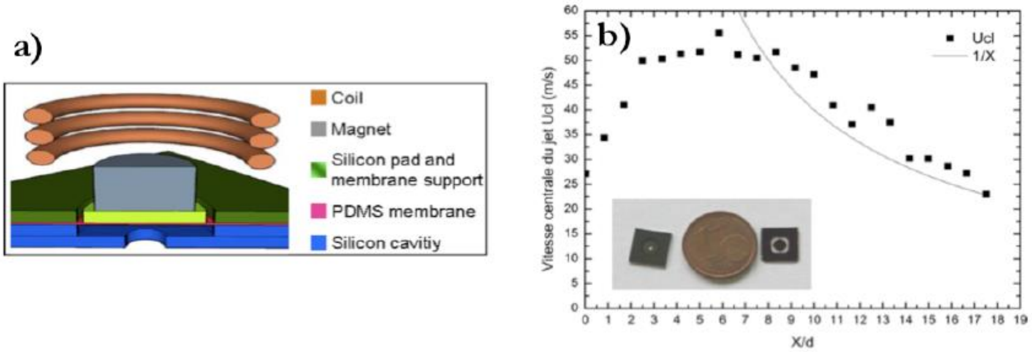

Figure 13: (a) Schematic section of the micro valve (b) Evolution of centreline velocity.

Conclusion

IEMN/LEMAC-LICS MMMS solutions cover a large panel of devices able to deliver continuous, pulsed or synthetic micro jets, arranged in linear or non-conformal arrays, and with various collective or individual packaging. It was demonstrated that the developed micro jets are able to satisfy the aerodynamic specifications of the real configurations interesting for aeronautic and automobile industries with several successful results in the field of separation control. It was also shown that their robustness is compatible with wind tunnel harsh environments. Generally speaking developed MMMS technology is flexible and can be adapted to various kinds of flow control applications. In the more complex studied configurations, the wind tunnel experiments emphasized the need of a reactive control with an actuation synchronized with the spatio-temporal modes of the flow. In addition to the adaptation of the micro valves to the real applicative environment, the present developments in IEMN/LEMAC-LICS are focused on the elaboration of flow micro sensors and micro jets with integrated micro sensitive elements. Further progress in flow control will need a strong coordination between simulations, experiments and theoretical approaches. The MMMS micro jets provide now real performance and geometrical data that can be used for simulations compatible with realistic or generic experiments.

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