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Open-loop cavity flow control with Micro-Magneto-Mechanical Systems (MMMS) microvalves

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Abstract

A design of Micro-Magneto-Mechanical microvalves is proposed in this paper to perform open-loop flow control experiments on an open-cavity flow. The unstable flow developing over the open-cavity is sensitive to the velocity fluctuations induced by a forcing. Consequently, a linear array of microvalves has been integrated on the upstream wall of an open-cavity. Both quasi-steady and pulsed jets effects of the actuators on the flow were studied. Microvalves jets reduced the open-cavity oscillations. A reduction of 20 dB in the cavity fundamental amplitude sound pressure level was measured. Depending on the forcing frequency, pulsed jets could further reduce this amplitude.

1. Introduction

The cavity is a commonly studied geometry in fluid dynamics, as it has many practical applications. In the aeronautical domain, airplanes landing gear doors or weapon bays have cavity shapes [1]. These shapes can also be found on vehicles such as cars or trucks, considering wheel wells, trains between two carriages or even regarding telescope bays [2]. Therefore, cavity flows which have been under considerations for a long time constitute a convenient geometry to test new flow control technologies such as the Micro-Magneto-Mechanical Systems (MMMS) microvalves presented here. Flow over cavities have been extensively studied by Roshko [3], Krishnamurty [4], Plumblee *et al* [5], Rossiter [6], East [7], Tam and Block [8] or Rockwell and Naudascher [9]. As depicted in Figure 1, the laminar or turbulent boundary layer developing upstream the cavity, characterized by a thickness δ and a momentum thickness θ , separates at the cavity upstream border. It results in a shear layer developing over the cavity of length L, depth D and span W. This shear layer undergoes hydrodynamic instabilities over the cavity, reattaches near the cavity downstream corner. The shear layer impacting the trailing edge, generates acoustic waves, which propagate upstream and excite the shear layer instabilities at the upstream corner. This flow description was proposed by Rossiter [6] and corresponds to an aeroacoustic feedback mechanism, for which oscillations are self-sustained. Rossiter proposed an empirical expression for the prediction of oscillation frequency f such that:

$$f = \frac{U_\infty}{L} \frac{(m-\gamma)}{(\frac{1}{\kappa}+M)} \tag{1}$$

where U_∞, L and M respectively denote the freestream velocity, the cavity length and the flow Mach number. The mode number, the ratio between the convection speed of the vortices and the freestream velocity and the time delay are respectively denoted m, γ and κ. For deep cavities, this mechanism can be coupled with an acoustic resonance mechanism due to the cavity normal acoustic modes. This particular mechanism was investigated by East [7], who proposed the following equation to predict the resonance frequency f:

$$f = \frac{a}{D} \frac{0.25}{1+A({}^{L}/_{D})^{B}} \tag{2}$$

with A, B empirical coefficients and a the speed of sound. Unlike the Rossiter modes, this phenomenon is characterized

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by frequencies harmonic of each other. Both Rossiter and East mechanisms can interact with each other, yielding a local maximum in the global modes growth rate. As detailed in [10], the East phenomenon can strengthen the Rossiter phenomenon for low Mach numbers flow, as the one considered in the present study. As a result, both mechanisms are responsible for noise radiation and structural vibrations, which could damage structures. Therefore damping these flow oscillations through control strategies is of interest.

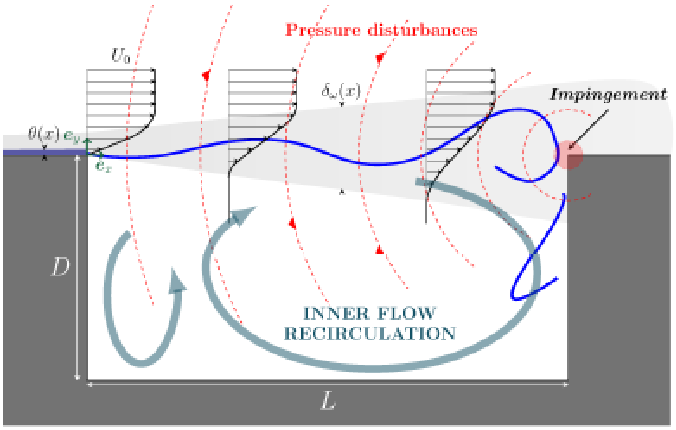

Figure 1: Scheme of the flow developing over an open-cavity [20].

Flow control techniques can be defined as methods modifying a flow behavior in order to obtain positive changes in the flow, such as avoiding separation, delaying transition or reducing aerodynamic induced noise [11]. It can be divided in two categories, respectively passive and active methods. Passive devices such as vortex generators do not need an external energy input to act on the flow, in contrast with active flow control technologies [12]. However, passive devices permanently act on the considered flow, even at off-points design, for which their effects is undesirable. Active flow control techniques do not have this drawback, as their actuation on the flow can be triggered and tuned either manually considering open-loop control strategies or can be automatically triggered and adapted regarding closed-loop control strategies [11]. Depending on the adopted control strategy and on the flow configuration studied, different actuation technologies can be employed. Regarding the open-loop control case of an open-cavity, as detailed in [2], effects of steady injection of mass flow have been studied in [13] and [14] respectively through injection at the cavity base and through porous plates placed upstream the cavity edge. Both studies proved the efficiency of the actuation technique to damp the cavity flow oscillations. Mechanical oscillating flaps have also been employed for such a study case as described in [15,16]. Despite the actuators limited bandwith, reduction in the cavity tones could be observed. The use of pulsed mass flow injection was also examined such as in [15,17,18]. These open-loop studies highlight that the unstable flow developing over an open-cavity is sensitive to flow fluctuations induced by the actuators. Therefore, the forcing ability to follow arbitrary command signals and the forcing linearity are critical when designing actuators dedicated to the control of such flow cases.

We propose in the present study a design of Micro-Magneto-Mechanical Systems (MMMS) microvalves, generating both quasi-steady and pulsed jets with a linear behavior, to perform open-loop flow control experiments on an open-cavity flow. The actuators, based on the technology presented in [19], have the advantage to be able to follow arbitrary command signal. A linear array of these microvalves has been integrated onto an open-cavity upstream edge and placed inside a low speed wind tunnel. This paper second part is dedicated to the microvalves working principle and characterization while the third part discusses the open-loop flow control results.

2. Micro-Magneto-Mechanical microvalves

2.1 Microvalves description

The MMMS microvalve is composed of a general packaging, several micromachined silicon layers and Polydimethylsiloxane (PDMS) seals, ensuring the microvalve airtightness. As sketched in Figure 2, a microvalve consists in an air inlet, a micro-channel with inner walls ensuring the airtightness when the microvalve is closed and an outlet. A silicon pad is placed over the microchannel and a couple of permanent magnets is glued on it. A coil, contained in the global microvalve packaging, encompasses these magnets. Fed with pressurized air, the microvalve generates either a quasi-steady jet or a pulsed jet. In the case of a quasi-steady jet, a controlled pressure difference is

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applied through the microvalve. The silicon pad is therefore raised to an equilibrium position, defined by the pressure inside the microchannel and air flows through the microvalve. In the case of a pulsed jet, a variable current runs in the coil surrounding the magnets. The variable magnetic force induced by the current moves the silicon pad up and down around its equilibrium position, generating a pulsed jet at the microvalve outlet.

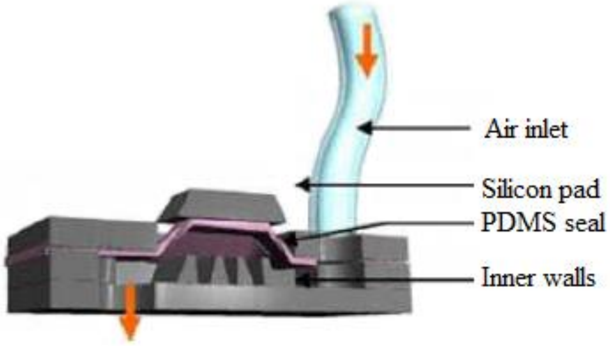

Figure 2: Scheme of a MMMS microvalve. Orange arrows indicate the air direction.

Given that an array of microvalves has to be integrated to an open-cavity upstream edge, the actuators outlet had to be enhanced such that the outlet flow spreads over a slot. That slot was fabricated in resin via stereolithography and is composed of two parts. A microvalve with this jet adapter is presented in Figure 3. The adapter induces a 45° deflection angle to the outlet jet.

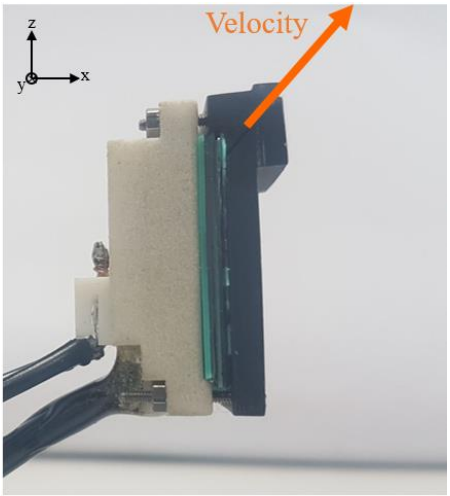

Figure 3: Microvalve with the jet adapter with the outlet jet direction (orange arrow).

2.2 Microvalves characterization

A linear array of 15 microvalves has been assembled and integrated to the open-cavity upstream edge to characterize each microvalve used in the flow control experiments. Considering the quasi-steady jet, the mass flow rate versus applied pressure characteristic was derived for pressures ranging between 0 mbar and 200 mbar. For pressures below 25 mbar microvalves remain closed and no mass flow rate can be measured. For pressures above 25 mbar, the mass flow rate versus applied pressure mean characteristic is described by equation (3) :

$$D = -0.15 + 0.01\ \Delta P \tag{3}$$

where D stands for the mass flow rate expressed in L/min and ΔP denotes the pressure applied through the microvalve expressed in mbar. The assembled microvalves proved to have a similar mass flow rate versus applied pressure with a maximum data discrepancy of 14%, between the highest and lowest mass flow rate measured for a given applied pressure. Hot wire measurements completed the quasi-steady jet characterization. For an applied pressure of 150 mbar the maximum velocity measured at the actuators outlet is about 25 m/s. Measurements for these conditions were

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performed in the (YZ) plane of an actuator, for an horizontal spacing between the microvalve outlet and the hot wire of 0.5 mm. Results are presented in Figure 4. The velocity spatial distribution derived from these measurements show a Gaussian distribution spanning along the actuators slot.

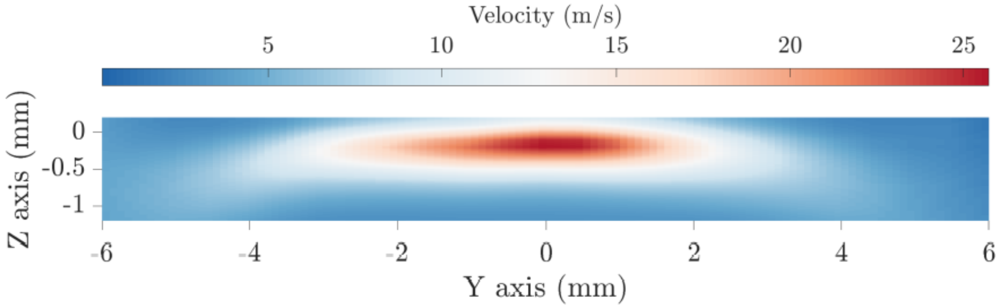

Figure 4: Hot wire velocity measurements performed in the (YZ) plane of an actuator for ΔP = 150 mbar.

Pulsed jet characterization induced by the microvalves were also performed with hot wire measurements. For this dynamics characterization of the microvalves, the entire set of actuators is fed with pressurized air for an applied pressure of 250 mbar. The microvalves linearity was examined using sine waves excitation signals with different amplitudes A and for frequencies f between 20 Hz and 380 Hz. Figure 5 illustrates an outlet velocity measurement for an input signal of frequency 20 Hz and amplitude 2 V. It can be observed that the studied microvalves do not behave as common valves as the minimum pulsed jet outlet velocity is non-zero. Instead, the pulsed jet consists in a modulation of the outlet velocity around a mean value, whose depth modulation depends on the excitation signal amplitude. In this case, the mean velocity is about 21 m/s and the velocity oscillates between 9 m/s and 32 m/s. Microvalves proved to behave linearly on the entire tested bandwith.

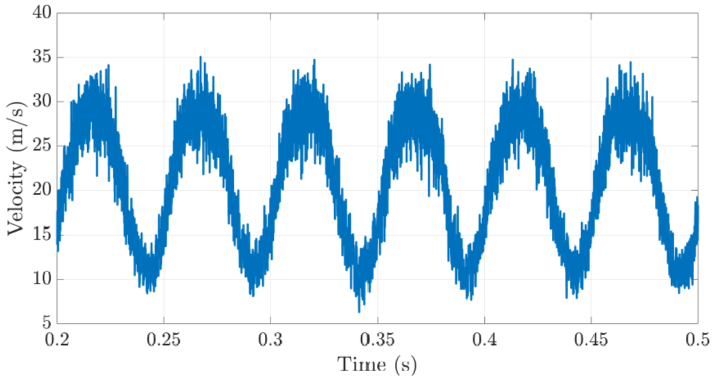

Figure 5: Hot wire velocity measurement for an input signal frequency of 20 Hz and an amplitude of 2 V.

3. Open-loop flow control experiments on the open-cavity

3.1 Wind tunnel configuration

Once characterized, the linear array of microvalves was integrated to the S19 wind tunnel of the ONERA. A sketch of this wind tunnel is presented in Figure 6. The wind tunnel is composed of a plenum chamber, in which total pressure and total temperature measurements are performed. A static pressure tap placed upstream the cavity is used to compute the freestream velocity. The test section has a rectangular shape of height 150 mm and span 300 mm, for a total length of 1910 mm. The open-cavity, inserted in the lower wall of the wind tunnel has a total length of 134 mm and is composed of two parts with different depths. The first part has a depth of 300 mm and spans over 300 mm. The second part has a depth of 600 mm and spans over 216 mm. Actuators are integrated on the cavity upstream wall and Kulite pressure sensors are placed on the cavity downstream wall. Unsteady pressure measurements are therefore performed at this location to characterize the flow dynamics without and with control.

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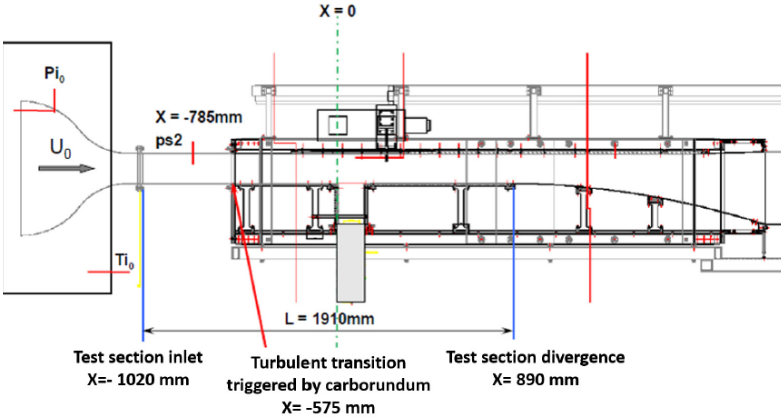

Figure 6: Sketch of the S19 wind tunnel with the open-cavity.

3.2 Uncontrolled flow

The uncontrolled flow developing over the open-cavity was firstly characterized for freestream velocities varied between 10 m/s and 46 m/s, with the objective of identifying low frequency periodic flow regimes. Such flow regimes constitute a convenient test bed for the open-loop flow control experiments to be carried out with the microvalves. Based on the unsteady pressure measurements, the Power Spectral Density (PSD) is derived and the Sound Pressure Level (SPL) expressed in dB is computed according to equation (4) :

$$\mathrm{SPL} = 20\log_{10}\left(\frac{\sqrt{\mathrm{PSD}}}{\mathrm{P_{ref}}}\right) \tag{4}$$

where P_{ref} stands for the threshold of human hearing and is used as a pressure reference value of 20 µPa. The evolution of SPL against frequency for a freestream velocity of 20 m/s is presented in Figure 7. The cavity spectrum for this velocity is characterized by a fundamental oscillation frequency of 128.6 Hz and by the presence of two harmonics, respectively at 257.2 Hz and 385.9 Hz. A parasite peak at 50 Hz can also be observed in the spectrum but can be ignored as this frequency is due to electrical noise. Effects of the array of microvalves quasi-steady and pulsed jets have been examined on this flow configuration.

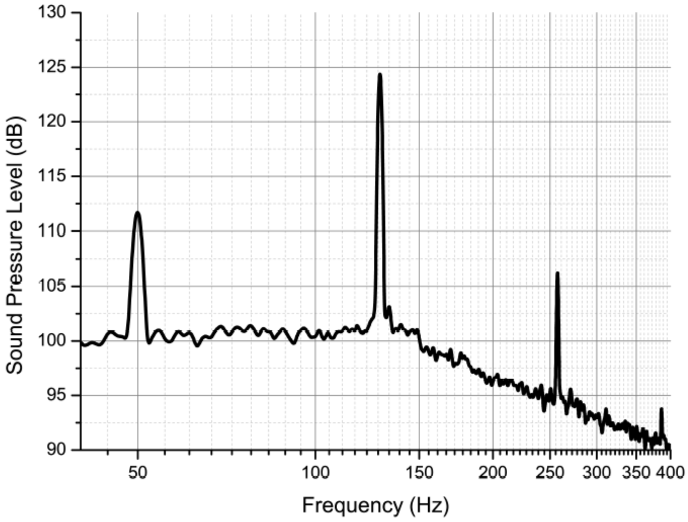

Figure 7: Evolution of the SPL (dB) against the frequency (Hz) for a freestream velocity of 20 m/s.

3.3 Open-loop flow control

Effects of the quasi-steady jets were firstly investigated for different applied pressures between 150 mbar and 290 mbar for the entire array of microvalves. The higher the applied pressure is, the lower the fundamental cavity oscillation amplitude is. This observation is presented in Figure 8 for the freestream velocity of 20 m/s and for applied pressures of 200 mbar and 290 mbar. The fundamental oscillation amplitude is reduced by the effect of the quasi-steady jets. The harmonics are also damped by those quasi-steady jets. It was observed that both harmonics disappear for ΔP above 200 mbar. The encapsulated figure outlines the SPL reduction in the cavity fundamental frequency against the different tested supplied pressures. A maximum reduction in the cavity fundamental frequency SPL of 20 dB is obtained for the highest pressure of 290 mbar.

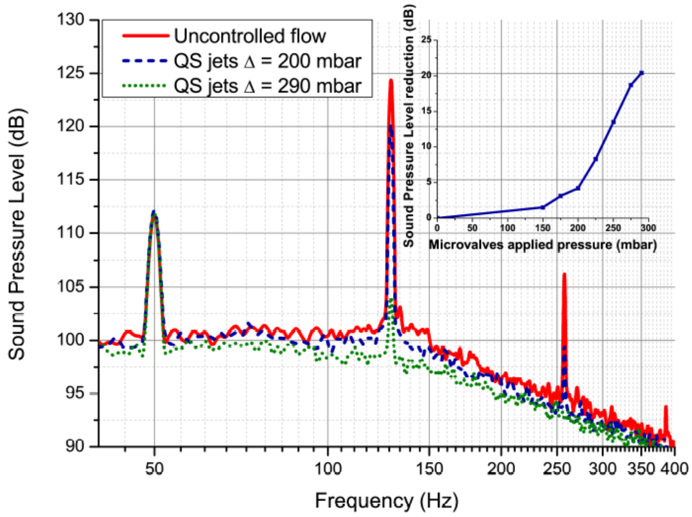

Figure 8: Comparison of the cavity spectra for $U_\infty = 20$ m/s in the uncontrolled case and with quasi-steady (QS) jets. The inner figure shows the evolution of the SPL reduction (dB) against the supplied pressure (mbar).

Pulsed jets effects on the flow have then been examined for different command signal amplitudes and frequencies. As the pulsed jets generated by the microvalves consist in a modulation of the velocity around a mean value, similar effects to those observed with the quasi-steady jets were noted. More important, are the effects of the velocity fluctuations on the flow. The actuator dynamics superimposed in the cavity spectra with the flow dynamics. The peak amplitude at the actuation frequency depends on the forcing frequency and amplitude considered. Figure 9 illustrates this point for a forcing frequency of 160 Hz with electrical forcing amplitudes A of 2 V and 1 V. The pulsed jets induce a further decrease in the cavity fundamental oscillation amplitude of few dB. Cavity response to pulsed jets can be seen as non-linear, as the forcing at a given frequency influences the cavity fundamental frequency amplitude. However, considering the cavity response at the forcing frequency, the cavity response is quasi-linear. This constitutes a key step towards the closed-loop control of this flow.

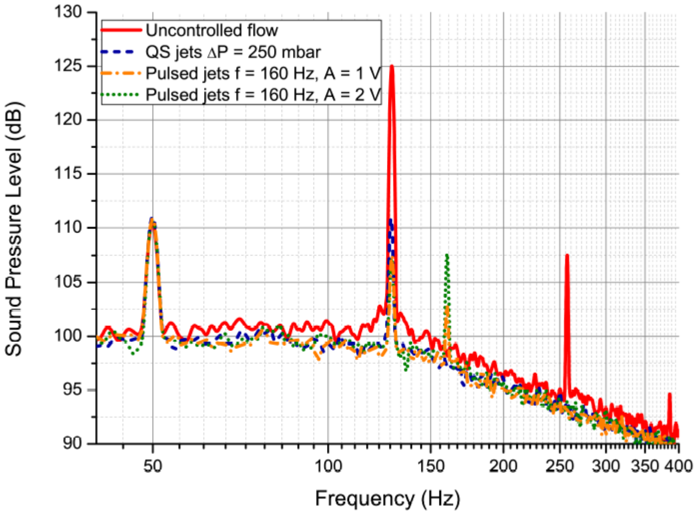

Figure 9: Comparison of the cavity spectra for $U_\infty = 20$ m/s in the uncontrolled case, with quasi-steady (QS) jets with $\Delta P = 250$ mbar and for pulsed jets f = 160 Hz and A = 2 V and 1 V.

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4. Conclusion

In this paper, MMMS microvalves employed in open-loop flow control experiments on an open-cavity are presented. Their design enables to generate both quasi-steady and pulsed jets, consisting of a modulation of the outlet velocity around a mean value. Characterized with hot wire measurements, microvalves proved to behave linearly on a large bandwith. Integrated as a linear array in a wind tunnel on an open-cavity, both quasi-steady and pulsed jets proved to have an effect on the flow dynamics. Quasi-steady jets reduced the cavity fundamental frequency amplitude down by 20 dB at best. The pulsed jets could further decrease this amplitude depending on the forcing frequency and amplitude. The actuators pulsed jets dynamics superimpose with the cavity dynamics. This important result constitutes a basis for future work on the closed-loop control of this open-cavity flow with the MMMS microvalves.

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