Pulsed Air High Performances Valves Improve Aerodynamic Flow Over Airplane Wings

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Abstract:
The objective of the European Cleansky project is to develop new technologies for future aircraft enabling a 20-30% fuel burn reduction and related CO2 emissions and a similar reduction in noise levels compared to current aircraft. One of the ways to reach this goal is to improve the aerodynamic performances of current high lift devices. Active flow control is unanimously seen as the best mean to reach this objective. By suppressing flow separation and/or delaying stall, active flow control will increase wing aerodynamic performances. The partnership between CTEC and ONERA in the framework of the VIPER project has led to the design, manufacturing and test of an innovative pulsed jet actuator based on a CTEC amplified piezo-actuator (APA). Its aim is to provide a pulsed sonic jet up to 500Hz with a mass flow around 34 g/s through a slot 1mm wide and 80mm long. Coupled with CTEC SA75D switching power amplifier this actuator produces the expected sonic jet with an electrical consumption around 40W thanks to energy recovery. The results of the actuator characterisation (mechanical, fluidic) are presented in this paper.

Keywords: Pulsed Blowing Actuator, Piezoelectric Actuator, Fast Piezo Valve, Active Flow Control, Switching Power Amplifier.

Introduction

The main objective of European research in aeronautics is to reduce the fuel burn and environmental impact of current aircrafts by improving their aerodynamic performances. One of the means to fulfil this target is to control the airflow around the wings, rudders, etc. At high angle of attack, the apparition of flow separation decreases the aerodynamic performances on two aspects: the lift is reduced and the drag is increased. Therefore, the main objective of active flow control is to keep the flow attached on the largest part of the wing.
Several techniques are investigated to control the flow. In the framework of the VIPER project, a pulsed blowing jet is studied (see Fig. 1). This kind of actuator uses the engine bleed air and blows it along the span which allows a delay or a suppression of flow separation. The air which is blown through the actuators adds energy to the boundary layer and prevents it from separating from the wing.

Fig. 1: *Concept of blowing to suppress flow separation.*

VIPER actuator features

Many pulsed jets actuators have been designed and tested in the past. VIPER actuator is innovative because:

- The mass flow rate reached is the highest one obtained on an actuator within this volume (more than 420g/s per meter span at 500Hz);
- The improved efficiency when the actuator is coupled with CTEC switching amplifier SA75D;
- The high power density of the actuator;
- The enduring lifetime.

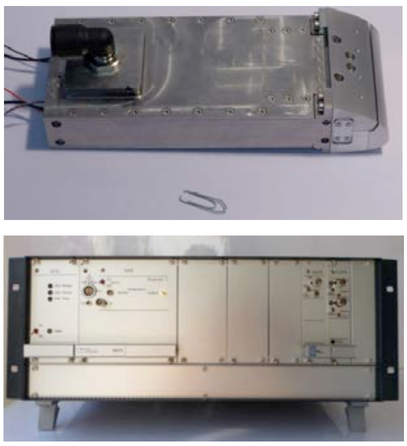

Fig. 2: *VIPER pulsed jet fluidic actuator and its driving electronic SA75D (lab version).*

The fact that the motion is created with piezo ceramics makes it very interesting in terms of bandwidth, compacity and weight.

In parallel to the actuator development, CTEC has designed a specific switching power amplifier called SA75D. This power amplifier is very efficient. Its electrical consumption is around 40W while producing 3.4kVA on the actuator side.

Determination of APA specifications

The fluidic actuator was designed by ONERA so that its characteristics are compatible with the bandwidth and flow rate specified. It led to determine the stroke and the blocked force needed for the APA to be used to drive the valves.

The jet exit area depends on the length of the slot that can be driven by the fluidic actuator. Basically this value is directly linked to the dimension of the APA.

In order to produce a sonic jet through the slot the area for flow circulation through the valves driven by the APA must be larger than the slot area itself. It leads to a minimum value for the stroke of the actuator.

Furthermore the fluidic actuator is designed in the ways that without electric power supply the valve is closed. The piezoelectric actuator must be designed so that the opening of the valve is possible in this configuration. The difference of pressure between the inside of the actuator and the volume downstream the valve which depends on the pressure loss in the fluidic actuator allows one to estimate the requested blocked force of the APA.

This study was based on fluidic actuators using the same principle that were designed and manufactured by ONERA within previous studies for wind tunnel models.

Numerical simulation of the flow inside the actuator

The numerical simulation has been performed with ONERA's unstructured solver CEDRE. The Navier-Stokes solver of the CEDRE code is a fully unstructured solver developed at ONERA with main applications in the energetics and propulsion fields where it can be coupled with other solvers to perform multiphysics simulations [1]. Figures 3 and 4 show different views of the unstructured grid

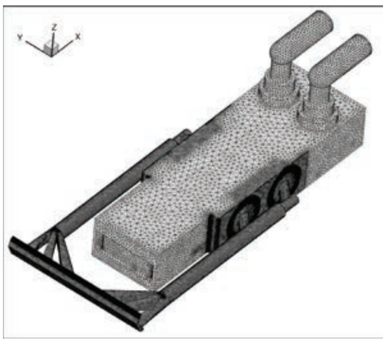

Fig. 3: *3D view of the mesh.*

The work has been carried out as follows. A first geometry has been designed by the ONERA model shop. Then, a first numerical simulation of the flow inside this actuator has been performed. Shape modifications have been proposed to suppress the recirculation zones in order to decrease the pressure loss and improve the velocity homogeneity at the slot exit. These modifications took place mainly in the diffuser and the slot. Finally, a second computation has been done to check the effect of these shape modifications.

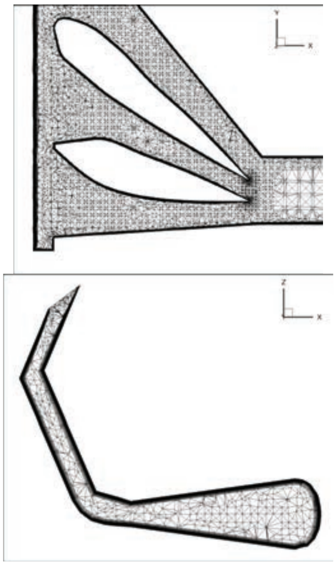

Fig. 4: *Details of the mesh in the diffuser region (top) and in the slot region (bottom).*

The slot geometry has also been modified as shown in Fig. **5** to suppress the recirculation zones and so decrease the pressure losses and improve the flow homogeneity at the slot exit.

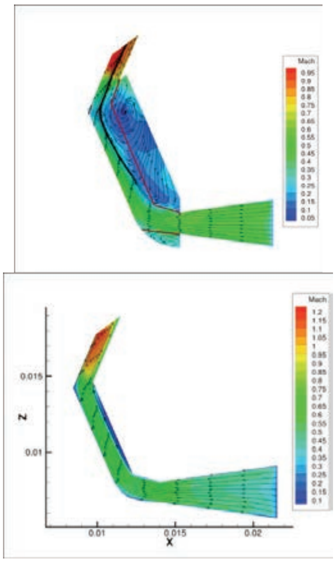

Fig. 5: *Mach number field in the slot (spanwise plane at a quarter of the slot width) before (top) and after shape modification (bottom).*

The actuator bandwidth is limited by the flow volume between the valve and the exit slot. A simple model has been developed to estimate this bandwidth. It consists in an isentropic model of the flow inside the actuator cavity that treats the volume filling as a series of isentropic and adiabatic compressions and expansions and flow through the orifice as inviscid has been used. This model enables to compute the velocity signal at the orifice exit and in particular to find the actuator bandwidth in terms of time response of cavity. It also enables to quickly optimize the volume cavity and the slot width in order to fulfil the actuator bandwidth requirements. Fig. **6** shows the estimated response of the actuator for two frequencies: 375Hz and 500Hz.

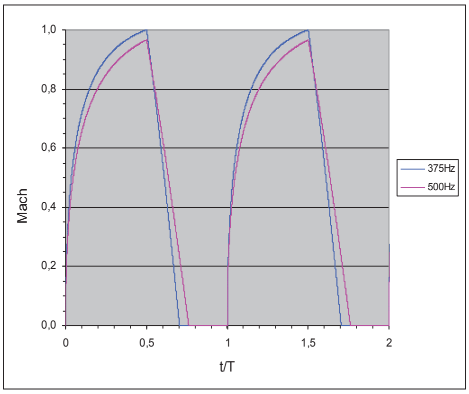

Fig. 6: *Mach number at the slot exit as function of time.*

Up to 375Hz, the expected peak exit velocity is constant equal to Mach = 1. Beyond this frequency, the peak velocity starts to decrease. At 500Hz the exit peak velocity is close to Mach = 0.97. Nevertheless the closing of the actuator is still observable.

The resonance frequency of the APA 1000L being highly greater than 500Hz (1320Hz), one can assume that the actuator bandwidth will be about 375Hz and that a functioning at 500Hz with a slightly lower peak velocity is possible.

Actuator mechanical characterisation

The VIPER prototype was tested at CTEC to measure the piezo actuator capabilities with and without the airflow. The comparison is made between the two types of embedded sensors which are eddy current (ECS) and strain gages (SG) technologies.

First the APA static behaviour is characterized. On the following figures, the stroke measurement is given with and without air flow. On each graph the measurement of each sensor type is given.

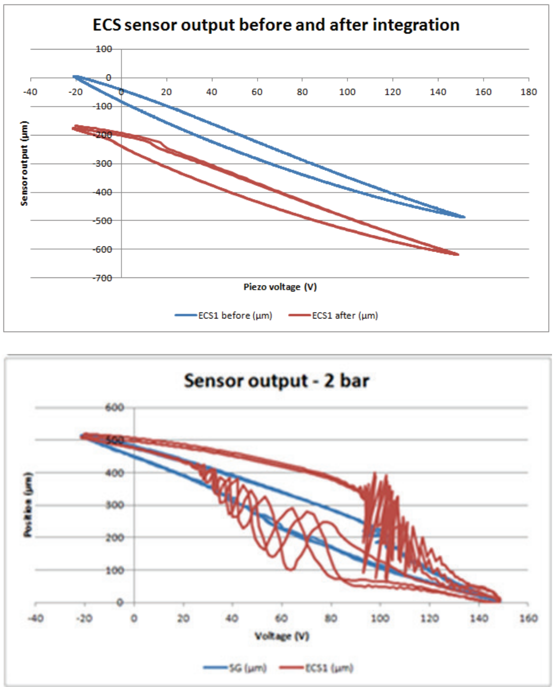

Fig. 7: *Stroke without (top) and with (bottom) airflow seen for each sensor type.*

The sensors are not placed at the same location on the actuator. ECS sensor measures a direct output displacement while SG sensor measures the strain on the ceramic stack. It can be noticed on the ECS curve that the airflow adds some oscillation that is modifying the controllability properties

VIPER control and inputs signals

The input signal is optimized to reduce the oscillations. These oscillations have two sources which are, on one hand, the mechanical ones due to the step response and on the other hand, the ones due to the airflow.

VIPER valve is working with square signals. However, open loop square signal is worst case in terms of ringing excitation. Therefore, 2 techniques have been tested. First, a notched filtered input signal is proposed, in order to cancel contribution of resonance frequency within the input signal. This leads to reduction in ringing but is not compatible with short repeating periods, due to duration of the filter input signal. The second solution is using pseudo period. In that case, square signal is replaced by a controlled ramp corresponding to the exact natural period of the system. This leads to strong ringing reduction, with no need of closed-loop technique.

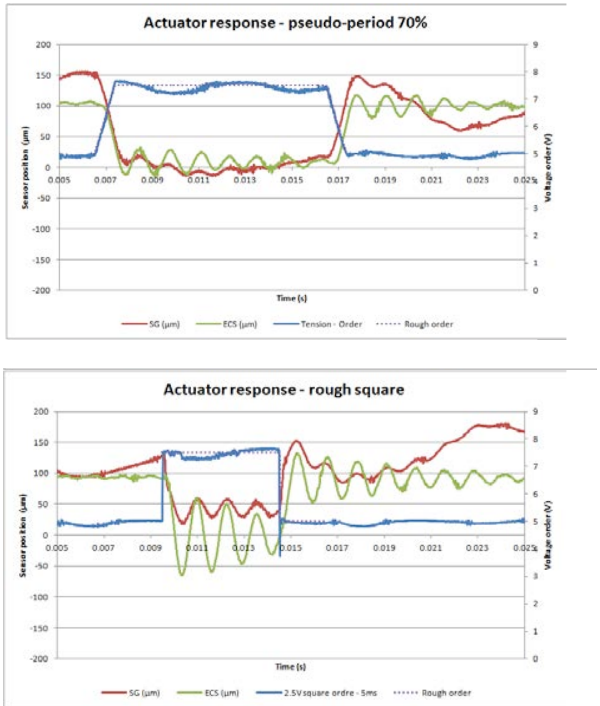

Fig. 8: Actuator position as function of time.

The test and optimization campaign at CTEC has allowed defining the VIPER actuator capabilities: min/max duty cycle, stroke, operating inlet pressures etc. Following sections summarizes the actuator performances.

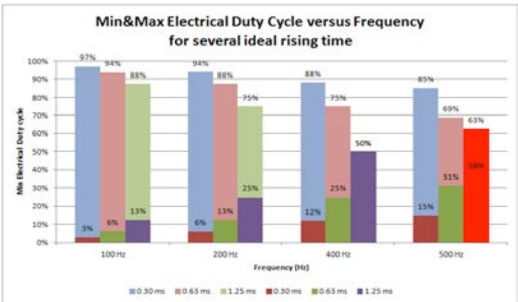

Fig. 9: Actuator capabilities in terms of duty cycle.

Actuator fluidic characterisation

The tests performed by ONERA aimed at characterizing the air flow response of the VIPER actuator. The characterisation is first performed in static mode (continuously blowing jet) in order to observe the velocity distribution along the slot length, then in pulsed blowing mode in order to qualify the frequency response in the range [10-500 Hz]. The input pressure is set between 1 and 4 bars (relative pressure) and a square-type input electric command has been used, with duty cycles 25%, 50% and 75%.

First, a Pitot probe is used to assess the spanwise velocity distribution along the slot span. An unsteady pressure sensor installed inside the slot is then calibrated versus the input mass flow, so that the dynamic characterisation of the actuator is performed in terms of instantaneous mass flow rate.

The actuator is attached to a console on the ONERA actuator characterisation bench [2], using a clamping system.

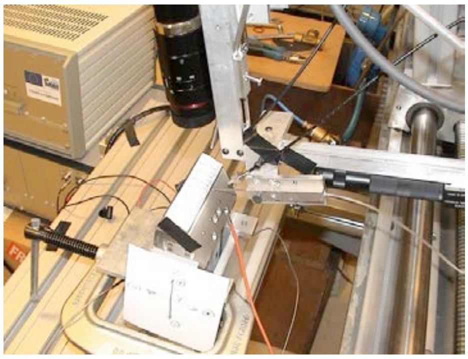

Fig. 10: View of the VIPER actuator on the ONERA test bench.

From the CTEC amplifier, various cables allow the actuator to be electrically powered as well as the actuator sensors feedback signals.

During the characterisation tests, an additional unsteady pressure sensor has been installed on the actuator cover in order to measure the absolute stagnation pressure inside the air supply chamber of the valves.

The acquisition equipment employed on the actuator characterisation bench is comprised of a PC dedicated to the measurements and National Instruments cards allowing the simultaneous generation of a command signal for the actuator and measurement of the various sensors.

A software developed under the LABVIEW environment is used to manage the tests. Once the air supply pressure is reached in the feeding tank, the required settings for the actuator are entered through the user interface and an acquisition sequence of 2 seconds is launched. Note that at the beginning of the tests, only one air inlet channel was installed on the actuator; this has been modified and for the final tests, the actuator has been fitted with three air inlet channels to reduce the pressure loss inside the actuator chamber.

The actuation settings are:

- the feeding tank pressure,
- the actuation frequency,
- the duty cycle for the actuation frequency.

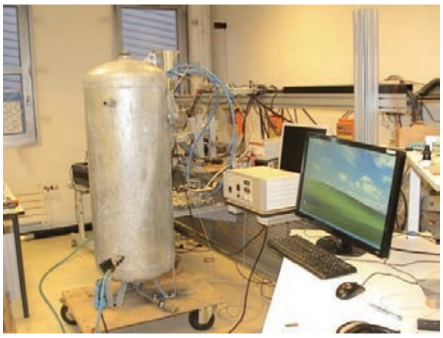

Fig. 11: *General view of the bench with the feeding tank.*

Static characterisation results

The total pressure probe is positioned in front of the slot, where the blockage effect is not significant. Measurements are carried out each 2 mm along the slot. The maximum velocity is first identified (through small probe displacement in the transverse direction), then the probe pressure is recorded and finally the velocity and Mach number are derived from St-Venant equations.

The velocity profile obtained allows the identification of possible sonic blockage for an input relative pressure of 3 bars upstream of the actuator. However, this pressure level includes an important pressure loss at the unique actuator air inlet; this pressure loss will be drastically reduced by the addition of two air inlet on the actuator and the inlet relative pressure level will be brought to 2 bars (instead of 3 initially).

The flow homogeneity is very good (purple curve in Fig. 12). A very small velocity deficit is observed close to the partitions (blue curve in Fig. 12) or flow rectifiers existing in the diffuser upstream of the slot.

The absolute pressure recorded on the sensor located in the slot is around 1.4 bar (0.4 bar relative pressure); it can be concluded that for equivalent atmospheric and air supply pressures, such a pressure level will signify sonic conditions (Mach=1) at the slot exit.

Then, a specific device is used to obtain the transfer function between the mass flow rate and the pressure recorded in the slot. It can be noticed that for data of Fig. 12, where the absolute pressure in the slot is 1.4 bar, the mass flow rate is around 37 gr/s. In the following dynamic measurements, it will therefore be considered that, if the instantaneous mass flow rate of 37gr/s is reached, conditions at the slot exit are sonic.

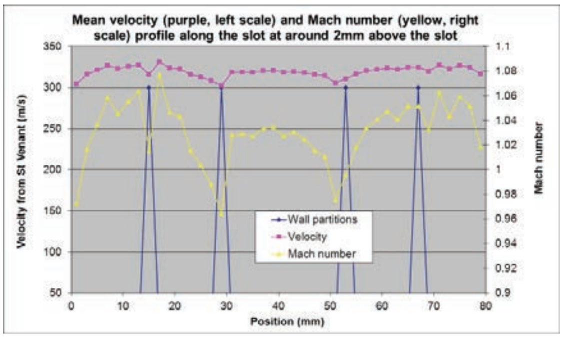

Fig. 12: *Velocity and Mach number response along the slot. The probe is located 2 mm above the slot.*

Dynamic characterisation results

The main goal of the dynamic characterisation is to set an upstream pressure value so that the pulsed flow at the orifice slot is sonic (in amplitude) for the maximum instantaneous flow rate, and at all frequencies between 10 Hz and 500 Hz with a 50% duty cycle, and if possible with 25% and 75% duty cycles as well.

Starting from a relative pressure of 1 bar at the feeding pressure tank outlet to a value of 4 bars by 0.5 bar steps, the frequency range is explored for the 3 duty cycles specified.

For each set of input pressure, the frequency response of the maximum instantaneous flow rate is plotted and the results are stored when the mass flow rate equal to 37 g/s is obtained, whatever the frequency is.

Two campaigns of measurements have been performed: the first one for the acquisition of the first four measurement channels (input command signal and pressure measurements); the second one with the addition of the remaining channel out of the 8 available (strain gage and displacements). These two campaigns serve to test the measurements repeatability.

As shown in Fig. 13, the level of 37 g/s (bold dashed red line) is reached for an input relative pressure of 2 bars, especially during the 2^{nd} test campaign (continuous lines) compared to the 1^{st} campaign (dash lines). However, one can observe a significant drop on the curves beyond 250Hz in the 25% duty cycle case. On the opposite, for the 50% and 75% duty cycles, the curves are rather flat, which is close to the ideal case that was targeted during the design phase of the actuator. For the two campaigns, one can notice that these two curves at 50% and 75% duty cycles are always above the theoretical threshold value of 34 g/s (bold continuous red line).

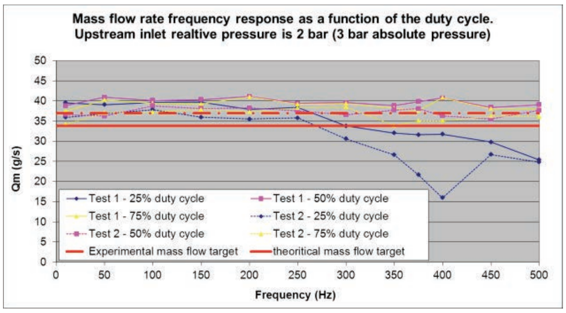

Fig. 13: Mass flow rate as function of frequency for different duty cycles. Inlet pressure is 3 bar (absolute pressure).

With a lower input relative pressure of 1.5 bar (Fig. 14), the curves are within 30 and 35 g/s, which is acceptable with respect to the theoretical mass flow of 34 g/s that was aimed during the actuator design process.

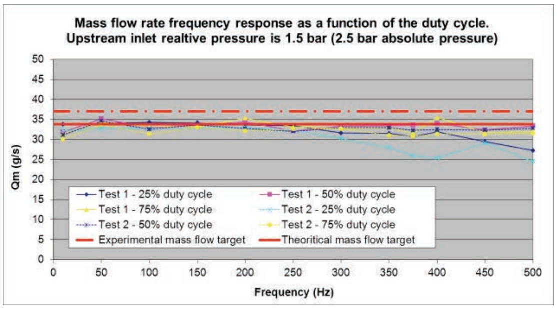

Fig. 14: Mass flow rate frequency response for different duty cycles. Inlet pressure is 2.5 bar (absolute pressure).

Finally, for a greater inlet relative pressure of 2.5 bar, the curves are more scattered and non-reproducible between the two campaigns (Fig. 15). This phenomenon may be due to the incoming pressure that is perturbing the valve openings, which therefore are not functioning properly anymore.

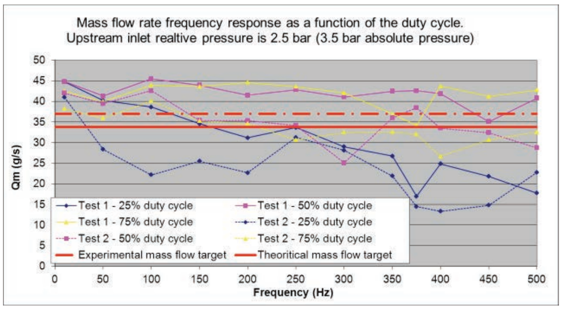

Fig. 15: Mass flow rate frequency response for different duty cycles. Inlet pressure is 3.5 bar (absolute pressure).

About the time response, an example is given for a 2 bar relative input pressure. Fig. 16 shows the filtered temporal pressure signal coming from the slot exit sensor. The maximum mass flow is directly deduced from the pic amplitudes of such signal for the different frequencies tested. Similarly, the time response of the strain gage is provided in Fig. 17, and the time response of the APA displacement from ECS 1 sensor in Fig. 18.

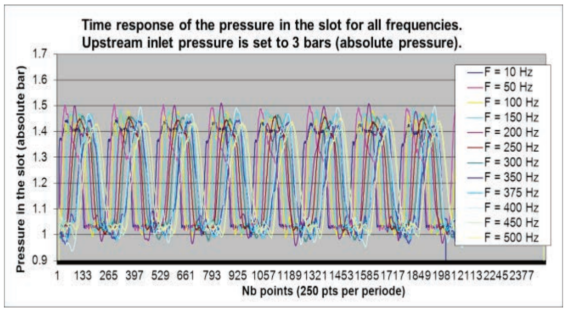

Fig. 16: Time response of the slot pressure for all frequencies. Inlet pressure is 3 bar (absolute pressure).

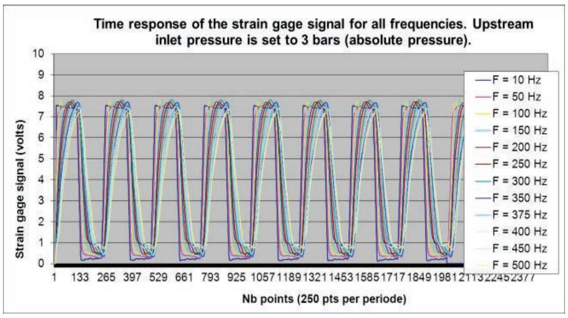

Fig. 17: Time response of the strain gage signal for all frequencies. Inlet pressure is 3 bar (absolute pressure).

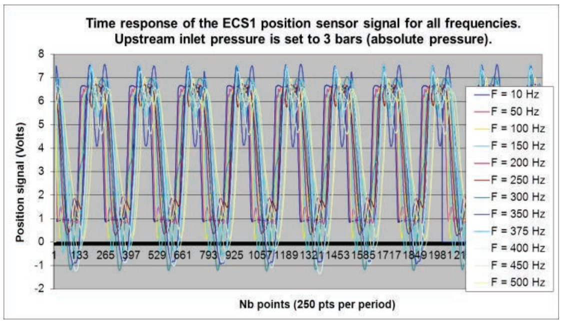

Fig. 18: Time response of the ECS1 position sensor signal for all frequencies. Inlet pressure is 3 bar (absolute pressure).

Conclusion

In the continuously blowing case first, the homogeneity of the flow at the slot exit has been assessed and showed to be very good. Moreover, it was shown that for a mass flow rate around 37g/s, it is possible to reach a sonic regime almost all along the slot. Then in the pulsed blowing case, an inlet relative pressure equal to 2 bars upstream of the valve openings enables to get the same mass flow rate (in amplitude), therefore insuring a sonic exit flow for this pressure setting value. It was also shown that in these conditions, the frequency response is quite flat over the all bandwidth tested. After testing, the experimental performances of VIPER can be summarized in the following table.

Specification	Value	Unit
Slot dimensions	1*80	mm²
Pitch angle of the slot exit	< 30°	°
Exit peak velocities	1	Mach
Exit peak mass flow	462	g/s/m
Actuation Max Frequency	500	Hz
Duty Cycle	50-75	%
Volume	45.4*79.6*208.9	mm3
Efficiency *(Flow + Actuator)*	37.5	%

Table 1: *VIPER experimental performances synthesis.*

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