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Test stand for pulsed jet actuator command and characterization

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Abstract. The paper presents a test stand for characterization of a new design of a Pulsed Jet Actuator. The aim of the work was to characterize the performance of the PJA in terms of air parameters in the air supply line and velocity at the PJA outlet. To perform a detailed characterization of the system performance, the test bench comprised: a pressure reductor, a mass flow rate controller, a mass flow rate meter, a pressure sensor, a fast pressure sensor, a flow temperature sensor and a Constant Temperature Anemometer. The PJA was commanded by a real time controller with Field Programmed Gate Array architecture. The experimental results show good agreement with the results of Computational Fluid Dynamics simulations performed at the design stage of the PJA. It has been found that the flow parameters at the PJA nozzle outlet match the design goals. The developed bench testing procedures will be used for silent conditions tests of the PJA system integrated into a leading edge of a wind tunnel model.

1. Introduction

Development of greener aviation solutions requires improving aerodynamic performance beyond the actual state of art. Solutions like laminar wings and integration of larger-fanned engines are currently being intensely developed [1] with challenges in installation [2] and structural strength of airframes. Flow control has been envisioned as one of the key technologies to address these challenges [3,4]. Among solutions presented in the literature, fluidic devices has proven to be one of most effective [5-7].

Pulsed Jet Actuators (PJA) are currently being extensively tested for Active Separation Control in slat-less area at the Pylon-Wing Junction of Ultra High Bypass Engines [8,9]. Although new designs of actuators are emerging, the research and development procedure remains the same: it always includes a wind tunnel testing of devices integrated into the wind tunnel model [10-12]. To effectively control the flow around a wing, the flow control device must meet design flow parameters with respect to wind tunnel test conditions. Commonly, the PJA device must be compact to be integrated into the wind tunnel model and simultaneously provide high momentum flux form blowing slots [13].

Prior to implementing into a wind tunnel model, a new flow control device requires extensive testing in silent conditions [4,14]. Designing a test stand for PJA characterisation is a key importance to precisely determine the performance of the fluidic system. The paper describes a design of the test stand and a characterisation of the pulsed jet actuator concept developed for separation flow control at large aerodynamic surfaces. In the course of the presented research, the performance of the PJA components, i.e. 3D printed nozzle geometry, electromagnetic valves and an air supply line was tested.

The experimental results confirm that the developed system meets the wind tunnel testing requirements. The developed measurement system and the test procedures will be used for silent-condition tests of the PJA system integrated into a leading edge of a wind tunnel model.

2. Materials and Methods

The wind tunnel experimental testing of new actuation concepts requires a precisely characterized performance of the PJA design. The main goals of the presented tests and procedures were to:

a) determine the Mach number at the nozzle exit as a function of the supply pressure

b) determine the relation between Mass Flow Rate (MFR) and supply pressure for a given Mach number at the nozzle exit (rectangular slot)

The schematic of the developed test stand is presented in figure 1. The velocity and temperature of the jet at the nozzle exit was measured with use of Constant Temperature Anemometry and thermocouple, respectively. The actual test stand is presented in figures 2 and 3. To position velocity and temperature probes in the maximum of the jet velocity, the CTA probe and thermocouple were mounted on a motorized stage.

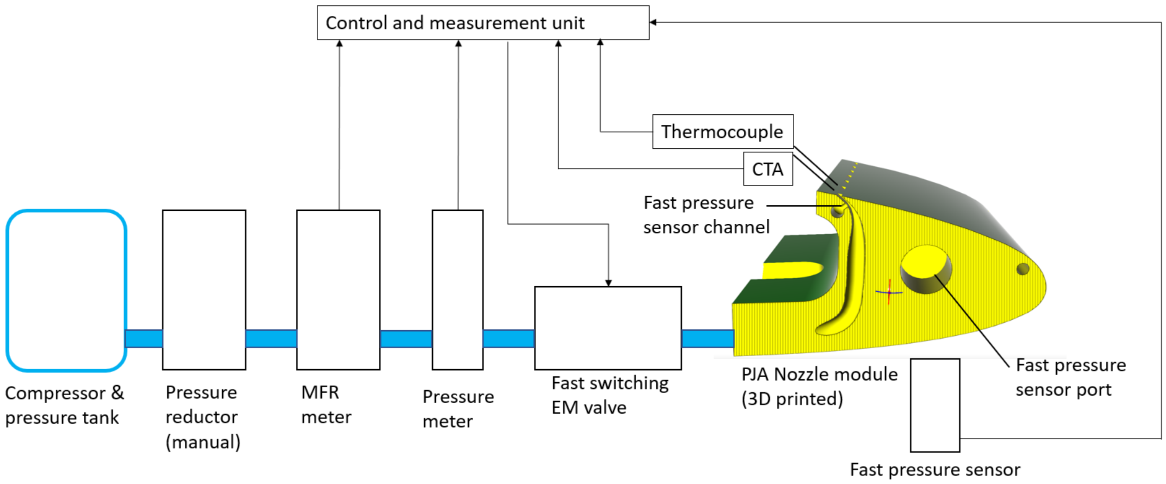

Figure 1. Schematic of the PJA test stand.

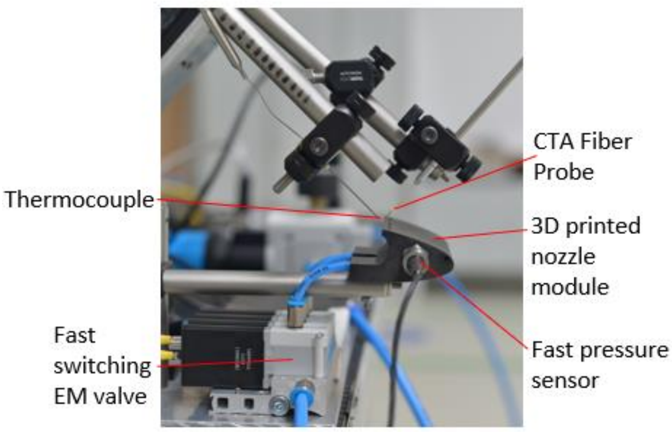

Figure 2. Placement of the PJA nozzle and probes.

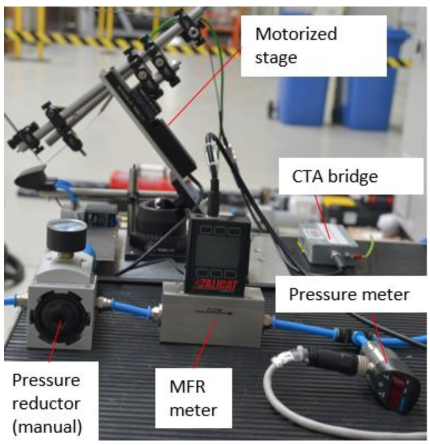

Figure 3. View of the test stand sensors.

2.1. Measurement and control system

The data acquisition (DAQ) and control system are based on a National Instruments cRIO Field Programmed Gate Array architecture controller (NI cRIO-9045, 1.3 GHz Dual-Core, 70T FPGA, 8-Slot, RT). The FPGA structure has been programmed in NI LabVIEW that enables real time control of valves and simultaneous acquisition of measurement signals. The sensors and actuator parameters are presented in table 1.

Table 1. Measurement and control system.

Sensor	Measured physical parameter	Meas. range	Meas. uncertainty	Sampling frequency
Dantec Dynamics MiniCTA, Fiber film probe	Velocity of the jet at the nozzle outlet	7.5-316[a] $m \cdot s^{-1}$	± 3%[b]	10 kHz
Kulite ETL-500-312M	Pressure at the PJA nozzle exit	0-2 BarA	± 0.1% FSO BSFL[c]	4 kHz
K-type thermocouple tau09 < 10 s	Temperature of the jet at the nozzle outlet	0-100 ºC	1,5 ºC	4 kHz
Alicat M-250 NLM	Mass flow rate delivered to EM valve	0-3.16 g/s	± 0.8 % + 0.2% FSO	4 kHz
Festo SPAW-P6R-G14F-2PV-M12	Pressure in EM valve air supply line	0-6 Bar	±1% FSO	10 Hz
Actuator	Role	Controlled parameter	Range	Resolution
Festo MHP2-MS1H-3/2G-M5 fast switching valve	Control of the jet pulsating frequency and Duty Cycle	Valve open and close time	Max valve switching frequency 330 Hz	0.3 ms
Thorlabs MTS50-Z8 50 mm Motorized Stage	Control over the position of CTA and thermocouple in the jet	Position of probes	Position Backlash <6 μm[d]	0.05 μm

[a] Calibration range
[b] Relative standard uncertainty for a single velocity sample acquired with a CTA under typical experimental conditions including calibrator uncertainty [15]
[c] Best Fit Straight Line (BFSL) calculation.
[d] Backlash - motion is lost due to the lead screw mechanism

2.2. CTA data reduction

Constant temperature anemometry is based on the cooling effect of flow on a heated body. Typically, electrically heated tungsten wire is placed in the investigated flow. The measurement principle uses the relation between heat flux Q, wire over-temperature and physical properties of flow [16]:

$$Q = hA_w(T_w - T) \tag{1}$$

where h – heat transfer coefficient between wire and flow (i.e. velocity and temperature depended), A_w – wire surface area, T_w – wire temperature, T – fluid temperature. The electrical current is controlled by a Wheatstone bridge and a servo amplifier. The aim of the control is to keep constant resistance of the wire and with this constant temperature, independently on the cooling of the flow.

One component CTA measurements provide time series of the bridge voltage. The bridge voltage E_{acq} was acquired by a fast A/D board. In the presented work, the data reduction consisted of the following steps:

1. Temperature correction: The bridge voltage is a function of both velocity and temperature. The discrepancy between the calibration temperature and the flow is a source of velocity measurement error. The CTA system producer declares that 1 K change gives approximately 2% change in measured velocity [15]. Therefore, temperature correction with use of the ratio between the over-temperatures during calibration and measurement needs to be performed. The corrected voltage, E_{corr}, was calculated from the following equation [15]:

$$E_{corr} = E_{acq}\left(\frac{T_w - T_{ref}}{T_w - T_{acq}}\right)^{0.5} \quad (2)$$

where E_{acq} – bridge voltage acquired during calibration or measurement, T_{acq} – temperature of the investigated fluid, T_{ref} – reference temperature, T_w – wire temperature

2. Conversion of the probe voltages into velocities with the polynomial function

$$U = P_0 + P_1 E_{corr} + P_2 {E_{corr}}^2 + P_3 {E_{corr}}^3 + P_4 {E_{corr}}^4 + P_5 {E_{corr}}^5 \quad (3)$$

Where P_i – coefficient of the polynomial determined by fitting CTA system calibration data. The calibration data set consists of bridge voltages measured in a steady flow passing the sensor of known velocity.

The CTA probes were calibrated with the Dantec Dynamic StreamLine® Pro Automatic Calibrator. The CTA probe during the calibration procedure is presented in figure 4. The calibration dataset, temperature corrected voltages and a fifth-order calibration polynomial are plotted in figure 5. In order to obtain good calibration sensitivity, an odd degree of the calibration polynomial is recommended [15].

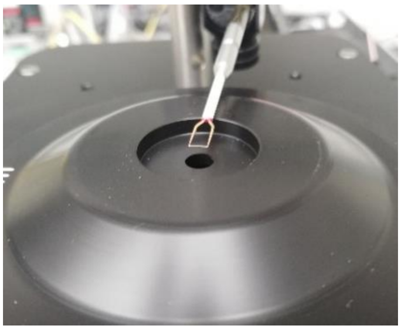

Figure 4. CTA Fiber-film probe positioned at the nozzle of the dedicated calibrator.

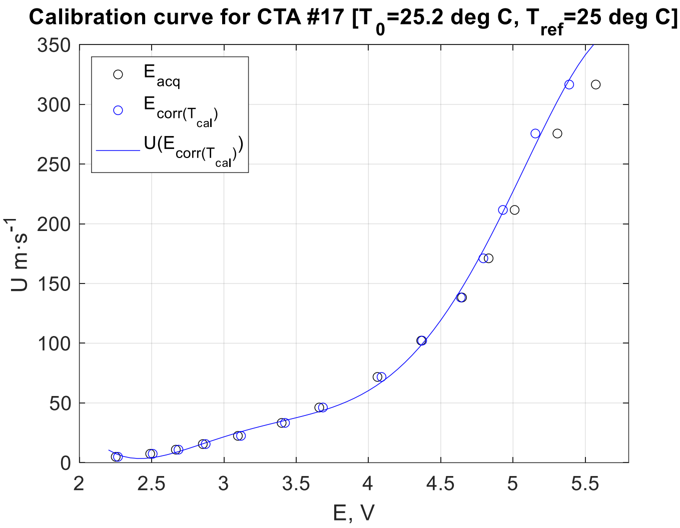

Figure 5. CTA probe calibration chart.

3. Results

The temperature and CTA voltage profile in proximity of the PJA slot in the plane perpendicular to the main jet velocity component is presented in figure 6. Based on these results, the CTA probe and the thermocouple were placed in the maximum of the jet velocity for further measurements. The characteristic of overpressure and Mass Flow Rate in the nozzle versus the Mach number at the PJA outlet are presented in figure 7.

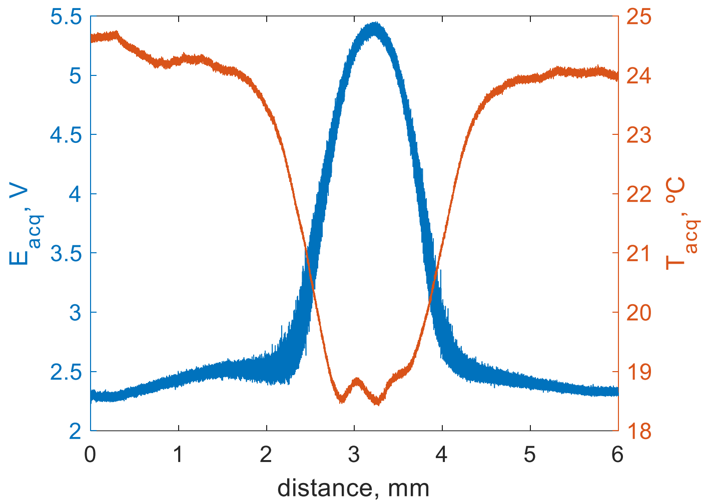

Figure 6. Temperature and CTA voltage profile acquired by a continuously traversing of the thermocouple and CTA probe in the plane perpendicular to the main jet velocity component with use of a motorized stage.

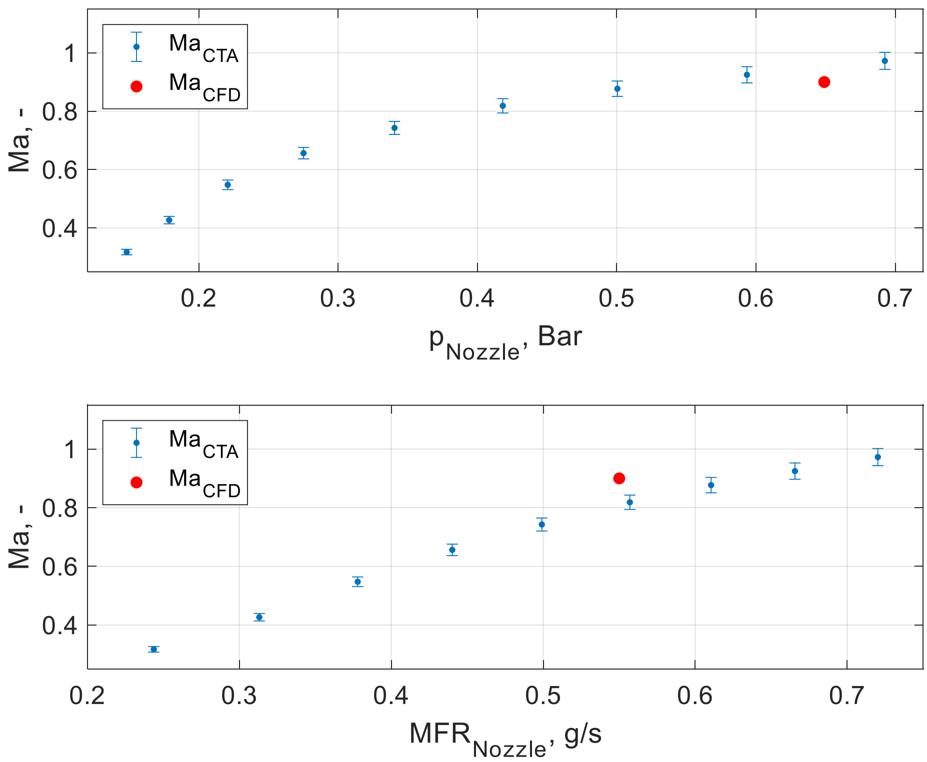

Figure 7. (Top) Pressure in the PJA nozzle versus the Mach number at the nozzle exit (Bottom) Mass flow rate in the PJA nozzle versus the Mach number at the nozzle exit.

The Computational Fluid Dynamics simulations were performed at the design stage of the PJA in ANSYS Fluent (a steady state Reynolds Averaged Navier-Stokes solver with a second-order discretization of flow equations has been used; a Boundary-Layer Mesh was set at the wall with Y+ between 0.11 - 1.3; the calculations were made with use of a viscous, turbulent turbulence model: k-ω SST). These results are plotted for comparison in figure 7. The performance of the PJA in terms of pressure in the air supply line and pressure in the PJA nozzle are presented in figure 8. The results give a characteristic of the pressure losses in the EM valve and the performance of the PJA system.

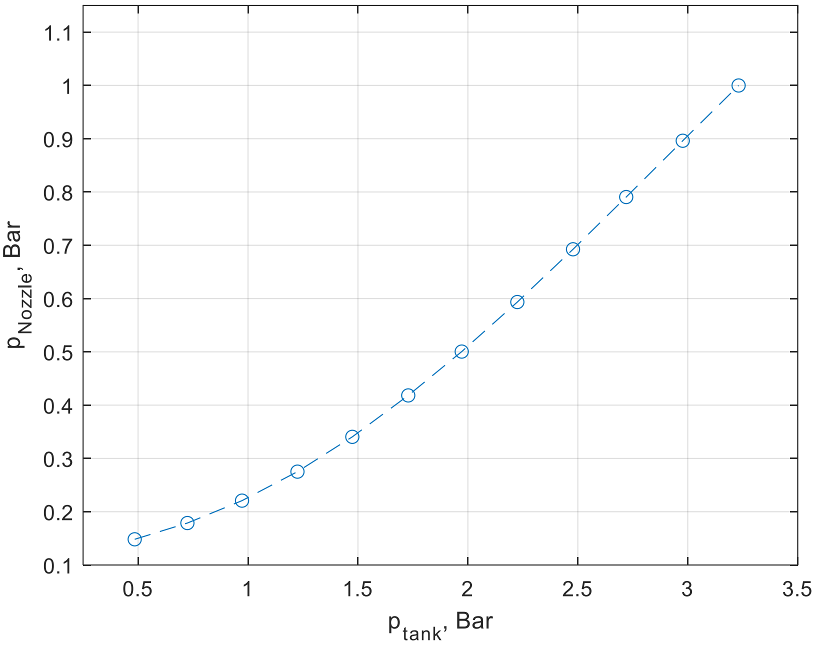

Figure 8. Pressure in the air supply line versus pressure in the PJA nozzle.

4. Conclusion

The presented results confirm that the developed test stand is capable of:

1. testing PJA device components like valves, pneumatic connections, 3D manufactured nozzles,
2. characterising the performance of a new design of the PJA system
3. developing procedures for testing PJA systems integrated into a wind tunnel model

The parameters of the PJA nozzle and the achieved Mach number are in good agreement with the results of Computational Fluid Dynamics, which allows us to conclude that the PJA device components were well selected and manducated. Especially, the selected 3D printing technique allowed for the precise manufacturing of small PJA nozzles.

The main research problem to solve was to measure the flow velocity at the PJA nozzle exit due to a small size of the slot (0.34 mm wide). The compared results in figure 7 show that the procedure for measuring flow parameters in small size jets (1.5 mm) with use of a standard aperture was successfully developed.

For the future implementation of the developed procedures, the Mach number at a slot exit can be measured in a large-scale wind tunnel only if a probe in the flow is used. This relates to invasive anemometry techniques such as CTA [17] or *n*-hole pressure probes [18]. Conversely, velocity measurement with use of non-invasive optical techniques such as Particle Image Velocimetry [19], [20] or Laser Doppler Velocimetry [21,22] in small size jets would be very hard to perform. Therefore, the correlation between pressure in the nozzle and pressure in the air supply line is discussed here. A measurement system based on a fast pressure sensor at the PJA nozzle can be implemented in a wind tunnel model to characterize PJA system performance during tests.

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