Investigation of pulsed actuators for active flow control using phase locked stereoscopic Particle Image Velocimetry

by

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ABSTRACT

The dynamic behaviour of two pulsed pneumatic actuators were examined to understand first the effect of the system parameter (frequency, duty-cycle, waveform, pressure, actuator volume and feed line length) on the output signal, and second, the interaction of the actuator jet with a turbulent boundary layer. The investigation indicates that the skewed jet becomes most efficient for boundary layer control when the output-velocity has a span-wise component. In this case a strong large scale secondary flow is generated, due to the asymmetric injection of the fluid, which transfers high momentum fluid from the outer part of the boundary layer in the near wall region. Blowing with a strong component in stream-wise direction, on the other hand, seems to be less efficient, relative to the oblique one, because of the small effect in span-wise direction and the momentum loss of the jet due to turbulent mixing and viscosity. In case of the rectangular actuator it could be demonstrated that the efficiency decreases when the orientation of the actuator becomes perpendicular to the main flow direction. In this case no asymmetric large scale vortex structure is generated which transfers high momentum fluid from the outer region of the boundary layer towards the wall. Finally, it could be shown that the momentum pattern of the dynamic jets becomes very similar to the static ones shortly after opening the valve. However, during the opening and closing of the valve, a strong span-wise modulation of the base flow can be observed that stimulates the mixing.

1. INTRODUCTION

The control of boundary layer flow separation by means of synthetic jets is a well established method that has been frequently applied in many fields of fundamental and applied fluid mechanics. The actuation can be done directly, by transferring momentum into the desired region by means of tangential blowing (Chang, 1976), or indirectly. In this case, the blockage of the actuator jet is exploited to enhance the mixing of the base flow, similar to mechanical vortex generators (Johnston and Nishi 1990). In the past many attempts have been made to replace the stationary blowing actuators in favour of dynamic ones (Gad-el-Hak, 2001, McManus et. al. 1996). The motivation for the use of these actuators is the higher efficiency, due to the reduced mass flux, and the excitation of new turbulent structures which promote the mixing, such as starting vortices for instance. Johari and Rixon (2003) observed that with the dynamic actuation an increase of approximately 30 % of peak vorticity and a penetration of 50 % farther into the boundary layer can be achieved. However, due to the large amount of control parameter required for the operation of these pulsed actuators, many investigations have been performed to optimize the parameter for different applications. Compton and Johnston (1992) have varied the skew angle of a single round jet with fixed pitch angle at 45 deg and pointed out that a skew angle of 90 deg is an optimal configuration to produce a strong stream-wise vortex. McManus et.al. (1996) showed that the ratio between the jet diameter and the boundary layer thickness should be around four for an efficient control. Nagib et.al. (2001) concluded from the analysis of several experiments that the reduced frequency must be approximately one. In addition they describe that the most effective location for unsteady forcing is near the point of separation. The influence of the duty-cycle Δ, defined as the opening time of the valve relative to the time of one period, is another operational parameter discussed in the literature, because it leads to a variation of the durability of the starting vortex ring. In the present investigation, the dynamic behaviour of different pneumatic actuators where examined systematically to examine the physics of the mixing process and the potential of the actuators for flow control ap-
applications in the future. Of particular interest was the response of the actuators as a function of the frequency $f$, duty cycle $\Delta$, waveform, pressure $p_V$, actuator volume $V$, and feed line length $l_S$. For this investigation a commercial high speed magnetic valve of low cost, small size and sufficient robustness was applied because by using this device it becomes possible to vary the frequency and amplitude independently. The response of the pulsed actuator to the input signal of the frequency generator was investigated with a hot-wire probe and a phased-locked stereoscopic and time resolved PIV system. After the determination of the optimized operation parameter, a flat plate boundary layer experiment was performed to examine the effect of the actuators on the properties of the flow. Although such investigations are quite challenging due to the strong velocity variations, the small area of the actuator outlets and the difficulties associated with the injection of particles inside the dynamic actuator, the dynamical behaviour of the actuators can be determined as will be seen in the following.

2. PRELIMINARY INVESTIGATION

It is obvious that the flow structure of the jet and its response to an input signal depends on the design of the actuator. Beside the geometry and the size of the exit area $S$, the volume of the settling chamber $V$ and the length of the feed line $l_S$ are of primary importance. The volume of the settling chamber for example should be large to avoid inhomogeneities due to the piston, but small to avoid a significant damping or modification of the output velocity signal. For the investigation a modular construction that supports inlets with different size, geometries and orientation and a continuous variation of the volume $V$ and tube length $l_S$ was designed, see figure 1. In the present investigation a round jet-inlet with a 1 and 2 mm diameter drill and a rectangular one with a variable aspect ratio in the range $b = 5 - 20$ mm (width) and $h = 0 - 2$ mm (height) was studied. A variation of the pitch $\alpha$ and the skew angle $\beta$ in the range of $\alpha = 30 - 90$ deg and $\beta = 0 - 180$ deg can be adjusted in addition. This becomes important for the investigation outlined in the next section. The poppet valve is a commercial MH2 fast-switching valve from FESTO with a maximum switching frequency of 150 Hz. It has an operating pressure range from -0.9 to +8 bar and a response time of 2 ms ± 10 %. The feed pressure is held constant at $p_V = 1.5$ bar at a line position of $l_p = 3.5$ m in front of the valve. The timing control takes place with a HAMEG 8131-2 function generator which allows to adjust the frequency $f$ and duty cycle $\Delta$. Because of the valve design – the switch at a defined threshold voltage value – only rectangular input signals can be processed. For waveform investigations the FESTO MPYE-5 has to be applied, but this device has a maximum frequency of 100 Hz and an increasing leakage at high frequencies.

The dynamic behavior of the pulsed pneumatic actuator was investigated with a constant temperature hot-wire anemometer (Dantec CTA 56C01/CTA Bridge 56C17 system with a single probe 55P12). To preclude a mirror effect of the probe temperature the distance between the hot-wire probe and the jet-orifice was set to $z = 1$ mm. The valve driving signal of the frequency generator and the probe signal were sampled using a LeCroy Digital Oscilloscope with a sample rate of $10^4$ samples/second. A phase locked mean value was calculated based on 100 sweeps.

![Fig. 1. Actuator concept with a variable adjustment of the volume $V$, the tube length $l_S$ and a flexible change of the jet exit area by using inlets.](image-url)
Figure 2 indicates for a rectangular input signal the effect of the frequency $f$, the volume $V$ below the actuator orifice and the length of the tube $l_S$ on the velocity signal above the actuator drill. It can be seen that with an increasing frequency the normalized time delay of the output signal increases, according to figure 2a). This effect is reinforced by an increasing volume of the settling chamber, see figure 2b. In addition it can be seen that an oscillation occurs after closing of the valve. This effect, which has been already observed by McManus et. al. (1995) is associated with the resonance in the tube volume between the valve and the jet orifice. The oscillation frequency $f_N$ is given by the tube length according to the following equation with $a$ being the speed of sound in air.

$$f_N \approx \frac{a}{l_S} = f(l_S)$$

This equation is displayed in figure 3 (solid line) and the dots represent the frequency calculated from the results in figure 2a). Figure 2c) shows finally, that the maximum value of the jet velocity decreases with increasing tube length due to the increasing drag. The results indicate that the rectangular input signal is best reproduced by the actuator when $V = 2000 \text{ mm}^3$, $l_S = 1000 \text{ mm}$ and $p_V = 1.5 \text{ bar}$. Based on these results it was decided to use these settings for the following investigations. The frequency was set to $f = 100 \text{ Hz}$ in order to obtain a rectangular signal without the oscillation and leakage flow after closing the valve and the duty-cycle is 50%. Larger duty-cycles promote the leakage flow when the actuator is closed and decrease the efficiency of the actuator.

To validate the properties of the jet flow in air at rest, the Stereoscopic Particle Image Velocimetry (3C2D-PIV) dis-

![Fig. 2. Hot-wire measurements: Dynamic behaviour of a round actuator (d = 2 mm), $p_V = 1.5 \text{ bar, 1 mm above the exit.}$](image)

- a) Jet velocity at different actuator frequencies $f$, $V = 2000 \text{ mm}^3$, $l_S = 1000 \text{ mm}$
- b) Jet velocity at different settling chamber volumes $V$, $l_S = 1000 \text{ mm}$, $f = 100 \text{ Hz}$
- c) Jet velocity at different tube length $l_S$, $V = 2000 \text{ mm}^3$, $f = 100 \text{ Hz}$

![Fig. 3. Oscillation frequency as a function of the feed tube length $l_S$ according to the equation. The dots represent the result from the hot-wire measurements.](image)
played in figure 4 was installed. The illumination was performed with a frequency doubled Nd:YAG double-pulse laser system (Quantel Brilliant) with the following properties: Pulse energy 50 mJ at $\lambda = 532$ nm; Beam-pointing stability $\pm 5\%$; Beam-divergence 0.43 mrad; Direction stability $<100\mu$rad; Pulse-width 4.2 ns. The laser beam was formed into a light-sheet, approximately 1 mm in thickness, to illuminate the tracer particles which were generated with a 12 hole-nozzle atomizer. The light scattered by the particles was recorded by means of two Peltier cooled CCD cameras (FlowMaster 3S) equipped with TAMRON 180/3.5 Macro lenses.

The observation distance was approximately 1030 mm with an opening angle of 86 deg between both cameras and the field of view was $46.1 \times 28.0$ mm². The evaluation of the recordings was achieved with a 2nd order accurate multi-grid method, developed by LaVision, with $32 \times 32$ pixel interrogation windows and 50 % overlap. For the investigation the excitation frequency was sampled at eight phase angles ($\Delta \phi = 45$ deg) whereby $\phi = 0$ deg corresponds to $w = 0.9 \ w_{\text{max}}$ in all cases. To avoid a velocity bias due to loss of seeding when approaching the jet area, a special overpressure seeding atomizer was designed, that was installed in the feed line of the actuator system. The design is based on a standard seeding atomizer. Additionally, the pressure from the supply system is present over the liquid surface by a bye-pass line and can be adjusted to generate a pressure difference relative over the seeding nozzle. The pressure drop over a typical four-hole nozzle is limited and thereby a seeded air supply for the actuator can be realized. The seeding material for the pressure tube was DEHS with a nominal particle size of 1 µm. A detraction of the valve operation could not be observed. Oil particles generated with a 12-hole nozzle atomizer were used to seed the wind tunnel flow. The rectangular master signal is provided from the frequency generator HAMEG 8131-2 with the appropriate actuator frequency $f$ and the duty-cycle $\Delta$. The signal is connected with the PIV-PC by an external trigger input of the programmable timer unit (PTU), which is a 16 channel sequencer-card with integrated phase-shifter (Hardsoft PTU 8). This allows an adjustment of a delay in the range of approximate 0 – 40 ms. So according to the results of the hot-wire measurements a phase shift between the input signal and the actuator response can be set. Unfortunately this is only possible for actuator frequencies above 25 Hz. For frequencies below 25 Hz, the input signal was phase shifted by half a period using an inverter. One of the main problems with the determination of the three dimensional flow field of the actuator lies in the dynamic of the out of plane component and the high velocity gradient between the jet and the steady air volume. In order to capture the illuminated particle structures and to prevent a high level in loss of pairs the time delay between the illumination has set to $\Delta t = 2 \mu$s because of the high jet velocity at the exit. This results in a dynamic range of $0.1 < \Delta x < 4$ pixel. Based on the assumption that the resolution of the evaluation method is around 0.05 pixel, the ratio between the largest displacement to the measurement error is about 40. For the experiments described in section 3 this restriction was not a problem.

Figure 5 shows the flow structure of a round (left) and rectangular (right) pulsed jet in a steady environment for $p_f = 1.5$ bar, $V = 2000$ mm³, $l_s = 1000$ mm, $S = \pi$ mm², $\phi = 0$ deg, $f = 100$ Hz and $\Delta = 50\%$. Clearly visible are the different jet orifices with identical area ($S = \pi$ mm²) at $\phi = 0$ deg, $f = 100$ Hz:

- a) round, $d = 2$ mm
- b) rect. $b = 10$ mm, $h = 0.314$ mm

![Fig. 4. Experimental setup Stereoscopic Particle Image Velocimetry](image)

1) Actuator experiment
2) Overpressure seeding atomizer
3) 3D traverse.

![Fig. 5. Comparison of two different jet orifices with identical area ($S = \pi$ mm²) at $\phi = 0$ deg, $f = 100$ Hz](image)
symmetric vortex structures, which are sections of the starting vortex, and the entrainment process in the wake of this vortex ring. A temporal sequence indicate that after closing the valve this flow structure moves away from the wall and the amplitude decreases gradually. The general flow characteristics show the same behaviour for all frequencies investigated here \((f = 10, 50, 100 \text{ and } 150 \text{ Hz})\). Basically, the difference between the maximum jet velocity (compare figure 5a and b)) is a result of the losses due to the different length of the perimeter between both geometries by a factor of 3.28. The low axial velocity at the wall is a spatial averaging effect, because of the light sheet thickness of about 1 mm whereas the slot height has a dimension of \(h = 0.314 \text{ mm}\). An error may occur if the captured particle images represent a mean value of the fluid motion in the light sheet.

3. TURBULENT BOUNDARY LAYER CONTROL

To examine the effect of the orientation, the geometrical properties and the operation parameter of the actuators on the flow structure in a turbulent boundary layer, the actuator was installed 300 mm behind the elliptical leading edge of a flat plate, see figure 6. To generate a two-dimensional flow, the flat plate was mounted horizontally between a pair of side walls. In a previous experiment the flow quality along the flat plate was examined in detail to validate the boundary conditions (Kähler and Scholz, 2003). However, here the natural flow was disturbed by using a trip wire installed 40 mm behind the leading edge of the plate. The boundary layer thickness was about \(\delta \approx 14 \text{ mm}\) at the jet position at 14 m/s free stream velocity. The experiment was performed in the open test section of the small continuous atmospheric wind-tunnel of the Institute of Fluid Mechanics located at the Technical University of Braunschweig. The facility is designed in a sheet metal construction. The basic dimensions of the tunnel are \(4997 \text{ mm} \times 2450 \text{ mm}\), with a nozzle diameter of 505 mm and a 940 mm long test section. The settling chamber is equipped with a flow straightener and a steel screen. The maximum flow velocity is 65 m/s and the turbulence level at the center of the jet cross-section and 200 mm behind the nozzle exit was determined to 0.85 % at 40 m/s free stream velocity. For the PIV experiments, the free stream velocity was \(U = 14 \text{ m/s}\). The orientation of the light-sheet plane was perpendicular to the main flow \((yz\)-plane) and the stream-wise location was \(x = 10, 25, 40 \text{ and } 60 \text{ mm}\) according to figure 7 and 8. The observation distance was approximately 650 mm and the angle between the two cameras in stereoscopic recording configuration was set to 90 deg. The field of view measures \(50.1 \times 33.9 \text{ mm}^2\) with TAMRON 180/3.5 Macro lenses. The evaluation of the recordings was achieved with \(16 \times 16 \text{ pixel}\) interrogation windows and 50 % overlap and the resultant spatial resolution was 0.3 mm. In the following each displayed velocity field represents an average of 100 statistical independent measurements.

Fig. 6. Flat plate experiment: Acryl glass plate with the actuator installed flush with the surface.

Fig. 7. Results in the case of static blowing for comparison with figure 8.

\begin{itemize}
  \item \textit{a)} Round actuator, \(d = 1 \text{ mm}, \alpha = 45 \text{ deg}, \beta = 60 \text{ deg}\)
  \item \textit{b)} Rectangular actuator, \(b = 10 \text{ mm}, h = 0.314 \text{ mm}, \alpha = 90 \text{ deg}, \beta = 60 \text{ deg}\)
\end{itemize}
Figure 7 shows for comparison the static results for the round jet with $\alpha = 45\ \text{deg}$ and $\beta = 60\ \text{deg}$ and the rectangular jet $\beta = 60\ \text{deg}$. Blue indicates a loss of momentum relative to the undisturbed flow and red represents an increase of stream-wise velocity. The spatial dimension of the vortex structure in the steady case is large but farther away from the wall. In addition it can be seen that in the steady case a strong vertical flow is present in the near wall region but also a strong upward motion above the vortex structures. This may be a result of a blockage effect induced by the jet.

In the dynamic case, shown in figure 8 for the round (left) and rectangular (right) actuator, it can be seen that the vortex centres are much closer to each other and the structure is more compact. A comparison of the dynamic excitation indi-
cates that in any state of the dynamic process the upwash flow is as massive as in the steady case. The increasing and decreasing of the dominance of the induced vortex structures are conducted by a changing blockage effect.

The sequence of results displayed in figure 8 a-c) reveals for a fixed phase angle of $\varphi = 180$ deg the distribution of the mean momentum variation relative to the natural flow without operation of the actuator. The upper result was measured behind the actuator with the round orifice. The orientation of the jet axis was parallel to the $z$ direction which is normal to the wall. In case of the centre result the jet axis was in the $yz$ plane (stream-wise wall-normal) with $\alpha = 45$ deg and in the lower result the axis has a steam-wise velocity component against the main flow direction in addition with $\alpha = 45$ deg and $\beta = 60$ deg. It can be seen clearly that without a span-wise jet component no high momentum fluid is transferred in the near wall region. However, when the jet axis is rotated around the $z$ axis the flow around the jet becomes asymmetric and high momentum fluid from the outer region of the boundary layer is transferred indirectly towards the wall. This result indicates nicely the sensitivity of the actuator performance on the control parameter.

Figure 8 d-f) shows the results for the rectangular actuator, with $b = 10$ mm and $h = 0.314$ mm. In the upper image the long side of the orifice was parallel to the $y$ axis (skew angle $\beta = 90$ deg). The distribution of the mean momentum variation relative to the natural flow without operation of the actuator indicates that far away from the wall the stream-wise momentum is enhanced but in the near wall region, right behind the jet, the flow is delayed. This implies that this actuator concept is unable to prevent flow separation. However, when $\beta$ is altered to 60 and 30 deg, as shown in the other two images of the same figure, an efficient transfer of stream-wise momentum towards the wall takes place due to a spiral like secondary motion of the base flow. As this spiral motion is interacting with the starting vortex structures this interaction reinforces the mixing process. The vector field shown in figure 9 illustrates the vertical motion in more detail. It was measured 10 mm behind the actuator at the phase angle $\varphi = 180$ deg for the skew angle $\beta = 90$, 60 and 30 deg (top to bottom).

4. SUMMARY

The dynamic behaviour of different pneumatic actuators were examined to determine their potential for flow control applications in the future. Of particular interest was the response of the actuators as a function of the frequency, duty-cycle, waveform, pressure, actuator volume and the feed line length, but also

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**Fig. 9. Velocity distribution with the out of plane component at $\varphi = 180$ deg. Rect. actuator**

$b = 10$ mm, $h = 0.314$ mm, $f = 100$ Hz, $\Delta = 50\%$.

a) $\alpha = 90$ deg, $\beta = 90$ deg  
b) $\alpha = 90$ deg, $\beta = 60$ deg  
c) $\alpha = 90$ deg, $\beta = 30$ deg
effects of the geometrical properties of the different actuators were examined. However, due to the strong velocity variations and the small area of the actuator outlets only the far field structure of the jet could be investigated. The investigation indicates that the skewed jet becomes most efficient when the jet axis is not aligned with the main flow direction, because in this case a strong large scale secondary flow is generated that transfers high momentum fluid in the near wall region. Blowing with a strong tangential component, on the other hand, seems to be less efficient, relative to the oblique one, because of two reasons. First, no spiral motion of the base flow is induced due to the symmetry. Second, the decrease of the jet velocity is to strong for an efficient momentum transfer in the near wall region. In case of the rectangular actuator it could be demonstrated that the efficiency decreases when the orientation of the actuator becomes perpendicular to the main flow direction, because in this case no asymmetric large scale vortex structure is generated that transfers high momentum fluid from the outer region of the boundary layer towards the wall. Finally, it could be shown that the momentum pattern of the dynamic jet becomes very similar to the static one shortly after opening the valve. However, during the opening and closing of the valve, a strong span-wise modulation of the base flow can be observed that stimulates the mixing.

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