A piezoelectrically actuated micro synthetic jet for active flow control
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Abstract

The synthetic jet actuator (SJA) is a low power, highly compact microfluidic device which has potential application in boundary layer flow control. In recent work we have shown how synthetic jets work without cross flow and how effectively they modify the flow structure in the boundary layer under an adverse pressure gradient. This paper describes the piezoelectric synthetic jet actuator used in our experiments. The experimental set-up for flow control using this type of actuator is detailed. The results obtained show a significant enhancement of the jet effectiveness by forcing the boundary layer flow at the natural instability frequency. The actuators must have sufficient velocity output to produce strong enough vortices if they are to be effective for flow control. The forcing effect can occur at a frequency lower than the driving frequency of the actuator when used without cross flow. The forcing frequency appears to be an important parameter in synthetic jet boundary layer flow control.

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1. Introduction

Flow control involves passive or active devices that cause a beneficial change in boundary layer or free shear flows, with useful end results including drag reduction, lift enhancement, mixing augmentation and flow-induced noise suppression. Active flow control is a multidisciplinary research area combining sensing, actuation, flow physics and control with the objective of modifying flow field characteristics to achieve a desired aerodynamic performance. Unlike passive techniques, such as geometric shaping to adjust the gradient pressure or placement of longitudinal grooves or riblets on a surface to reduce drag, active control manipulates a flow field by using a time dependent forcing system, typically to leverage a natural instability of the flow and thus to amplify the control effectiveness. Advantages of active flow control include the ability to attain a large effect using a small, localized energy input, and to control complex dynamical processes; for example, the reduction of skin friction and hence viscous drag [1,21] in turbulent boundary layers.

A synthetic jet actuator (SJA) is a jet generator that requires zero mass input yet produces non-zero momentum output. Developed in recent years, the synthetic jet actuator falls within the area of micro-electro-mechanical systems (MEMS) if the characteristic dimension or the diameter of the orifice, through which the jets are generated, is less than 1.0 mm [1]. Advantages of using SJA include simple compact structure, low cost and ease of operation. The basic components of a SJA are a cavity and an oscillating material. A jet is synthesized by oscillatory flow in and out of the cavity via an orifice in one side of the cavity. The flow is induced by a vibrating membrane located on one wall of the cavity. There are many types of actuator that can be used in active flow control, such as thermal, acoustic, piezoelectric, electromagnetic and shape memory alloys. Here, a piezoelectric material is chosen to drive the oscillating diaphragm because of such desirable characteristics as low power consumption, fast response, reliability, and low cost [9]. Flow enters and exits the cavity through the orifice by suction and blowing. On the intake stroke, fluid is drawn into the cavity from the area surrounding the orifice. During one cycle of oscillation, this fluid is expelled out of the cavity through the orifice as the membrane moves upwards. Due to flow separation, a shear layer is formed between the expelled fluid and the surrounding fluid. This layer of vorticity rolls up to form a vortex ring under its own momentum. By the time the diaphragm begins to move away from the orifice to pull fluid back into the cavity, the vortex ring is sufficiently distant from the orifice that it is virtually unaffected by the entrainment of fluid into the cavity. Thus, over a single period of oscillation of the diaphragm, whilst there is zero net mass flux into or out of the cavity, there is also a non-zero mean momentum flux. This momentum flux
is, effectively, a turbulent-like jet that has been synthesized from the coalescence of a train of vortex rings, or vortex pairs, of the ambient fluid [10,18,23]. Flow control can be achieved using traditional devices such as steady [19] and pulsed [20] jets. The obvious benefit of employing SJAs as a flow control device is that they require no air supply and so there is no need for piping, connections, and compressors associated with steady jets.

The emergence of micro-electro-mechanical systems technology, which employs the methods developed for the fabrication of silicon chips to construct very small-scale mechanical devices, provides a means of batch-fabricating mechanical parts integrated with electronics and control circuitry. The feasibility of MEMS-based active flow control has been demonstrated in recent research [2]. Among the many micro-active devices that have been a focal point of recent research into flow control, SJAs have demonstrated a potential in modification of aerodynamic lift and drag [3], forebody flow-asymmetry management [4], jet vectoring and enhanced entrainment [5], actone mixing control [6], flow separation control [7], and aircraft maneuverability [8].

The properties of synthetic jets in the absence of cross flow have been investigated experimentally and numerically [10,11,24]. For synthetic jets in external cross flow, it was demonstrated in [3] that significant lift could be generated on a two-dimensional cylinder using synthetic jets. The effect of oscillatory blowing on increasing post-stall lift for a symmetric airfoil and the dependency on the location and the operation of the jet were investigated experimentally, as given in [12]. A simulation study on the jet dynamics and its interaction with a flat plate boundary layer under zero pressure gradient has been systematically carried out using an incompressible Navier–Stokes solver [13]. Recent research in the field has emphasized on the need of understanding the SJAs’s effect on the flow and in particular its operation in a boundary layer under an adverse pressure gradient.

Based on the well-known fact that a turbulent boundary layer is more resistant to flow separation than a corresponding laminar boundary layer [7,9,22], we have focused on how and at what forcing voltages and frequencies the jets can delay separation in a boundary layer and particularly under an adverse pressure gradient. In our previous work, the mean velocity and the local momentum along the jet centerline were used to characterize the actuator performance [14]. We have experimentally demonstrated a significant enhancement of the jet effectiveness by forcing the boundary layer flow at its natural instability frequency [16]. It was found that the forcing effect, in the condition with cross flow, could occur at a frequency lower than resonant frequency of its membrane material, which is believed to be the effective driving frequency of the actuator in the condition without cross flow. It was also noticed that the forcing frequency appeared to be an important parameter in synthetic jet boundary layer flow control, of particular interest the effectiveness at lower frequencies enhanced by Tollmien–Schlichting waves. An experimental investigation on how the synthetic jet and the boundary layer flow interact, coupled with the instability of the boundary layer flow, is reported in [16]. This paper describes the piezoelectric synthetic jet actuator used in our experiments and examines the effect of forcing parameters on the interaction with an adverse pressure gradient boundary layer.

2. Piezoelectrically actuated synthetic jet actuator

Different geometries have been proposed for SJA design. As summarized in [17], the more popular synthetic geometries consist of an enclosed cavity with a small orifice on one face. The shapes of the cavity can be square, rectangular or round. The actuator used in our experiments consists of a membrane located at the bottom of a small cavity which has an orifice in the face opposite the membrane. Fig. 1 shows the schematic of the synthetic jet actuator for present study installed underneath a flat plate to be fixed in the working section of a wind tunnel. The actuator membrane is a thin circular brass disc, 0.25 mm in thickness, held firmly at its perimeter. A piezoceramic disc is bonded to the outside face of the membrane. The lowest resonant frequency of the membrane is 900 Hz and its lump sum capacitance is approximately 140 nF. In operation, the piezoceramic disc is driven by a sine wave from a standard electrical signal generator.

In the experiments without cross flow, the instantaneous velocity at the centerline of the jet was measured using a Dantec hot-wire anemometry system. The sample rates were set at 3–10 kHz and the sample size is 4096 (2^12) to 16384 (2^14) for each realization. The sample rates and sample size were adjusted in the above range in terms of the forcing frequency, which was chose between 0 and 3000 Hz. The wire diameter and length are 5.0 μm and 1.25 mm. Considering that the length of the hot wire is greater than the orifice diameter of the actuator, the instantaneous velocity sensed...
by the hot wire is actually a spatial average of the velocity over the length of the hot wire [10,14]. Measurements made at distances greater than approximately 20 orifice diameters from the orifice were noticeably susceptible to small amplitude motions caused by air fluctuations in the laboratory [10]. Each measurement was repeated at least five times and average values were obtained from these.

In our previous work, the flow generated by a synthetic jet actuator with a circular orifice in the condition without cross flow was investigated not only experimentally [10,14] but also computationally [10]. The experimental results and computational predictions are in fair to good agreement with each other and with the theory for a steady turbulent jet. It is found, however, that the synthetic jet establishes itself much more rapidly than the steady jet, primarily because of turbulent dissipation. The centerline distributions of the mean, \( U_c \), and fluctuating, \( u'c \), velocity are presented in Fig. 2 for the present actuator, which differs from previous designs by having a sub-cavity connecting the orifice and main cavities. The sub-cavity is present due to difficulties in obtaining access to the underside of the flat plate for machining. Both \( U_c \) and \( u'c \) are seen to fall rapidly with distance from the orifice, with the fluctuating component decreasing more rapidly for \( y/d_o > 5 \), where \( y \) is the distance from the orifice normal to the wall, \( d_o \) is the diameter of the orifice. The velocity appears to vary as approximately \( 1/y \) for \( y/d_o > 10 \), indicating self-similar flow. Thus, the present actuator seems to behave in a similar manner to our previous designs, suggesting that the sub-cavity has only a minor effect on the outflow properties.

Fig. 3 shows how the mean and rms velocities, on the centerline of the jet at \( y = 1.2 \text{ mm} \), vary with the forcing frequency while the forcing amplitude was kept constant at \( \pm 7.5 \text{ V} \). The maximum mean and rms velocity at the centerline of the jet are 6.4 and 7.4 m/s, respectively, at 1.5 kHz. In the low frequency range, a secondary peak velocity appears at around 100–300 Hz with a much smaller magnitude. From our ongoing project on the use of synthetic jets to modify boundary layer flows, we have noticed that the synthetic jets are more effective when the forcing frequency
is in the range of T-S frequencies [14]. Further, the sound generated by the synthetic jet actuators at higher frequencies (>1 kHz) is audible and it is desirable to avoid such noise.

3. Flow control experimental set-up

The experiments on synthetic jets operating with a cross flow were performed in the Aerodynamics Laboratory at UTS using an open circuit, suction type wind tunnel. Air enters the working section via a bell mouth inlet, a honeycomb section, and a short settling chamber fitted with screens for turbulence reduction. The maximum free stream velocity achievable is $40 \text{ m s}^{-1}$ and the minimum turbulence is 0.3%. All of the experiments reported in this paper employed a wind tunnel free stream velocity of $u_\infty = 8 \text{ m s}^{-1}$.

Fig. 4 shows the arrangement of the working section in the wind tunnel ($x$ is the streamwise distance downstream of the plate leading edge). An octagonal test section, $608 \text{ mm} \times 608 \text{ mm}$, was employed and a slot channel was made through the center of the top of the test section to allow hot-wire probes to be placed in the flow. A polished aluminum plate, $1500 \text{ mm} \times 608 \text{ mm} \times 25 \text{ mm}$, was mounted horizontally in the test section. The actuator, stepped orifice instead of straight orifice, shown in Fig. 1 was attached under the plate with the orifice centered at $x = 307 \text{ mm}$ on the plate center.

Measurements were made at $X_j = 40 - 160 \text{ mm}$ downstream of the actuator orifice at 20 mm intervals. At each of the $x$ stations, measurements were made at positions from $y = 0 \text{ mm}$ to the edge of the boundary layer. At each measurement position, the streamwise velocity was recorded in both conditions of jet on and off. The forcing voltage for the synthetic jets were $\pm 7.5 \text{ V}$ and $\pm 10 \text{ V}$, and forcing frequencies were 100, 140 and 180 Hz.

4. Results and discussions

The mean and rms velocity profiles, at $y = 0.4 \text{ mm}$, $X_j = 120 \text{ mm}$, with the jet off and on, are shown in Fig. 6 versus forcing frequency. The synthetic jet actuator is driven at frequencies between 0 and 1.6 kHz, with two different forcing amplitudes of $\pm 7.5 \text{ V}$ and $\pm 10 \text{ V}$. In Fig. 6a, it can be seen that the synthetic jet is most effective with a driving frequency of 50-200 Hz when the forcing amplitude is $\pm 7.5 \text{ V}$, and 40-350 Hz when the forcing amplitude is $\pm 10 \text{ V}$. The mean velocity was $1.9 \text{ m s}^{-1}$ with the jet off, and was amplified up
Fig. 6. Mean and rms of the flow velocity vs. frequency at \( y = 0.4 \text{ mm}, X_j = 120 \text{ mm} \) (a) mean velocity; (b) rms.

Fig. 7. Mean velocity profiles with jet on and off at \( X_j = 120 \text{ mm}, U_\infty = 8 \text{ m s}^{-1} \). (a) Effect of forcing amplitude; (b) effect of forcing frequency.

Fig. 8. Critical forcing amplitude for boundary layer flow control at \( X_j = 120 \text{ mm}, U_\infty = 8 \text{ m s}^{-1} \).

The flow separation suggested by the pressure distribution, as shown in Fig. 5, can be confirmed by examining the boundary layer velocity profiles. Fig. 7 demonstrates that the velocity profile stays almost constant for \( y < 0.8 \text{ mm} \) when the jet is off, which is characteristic of boundary layer flow in the separation region [15]. As a result of the backflow close to the wall, a strong thickening of the boundary layer takes place and with this, boundary layer mass is transported away into the outer flow. At the point of separation, the streamlines leave the wall at a certain angle. The position of separation is given by the condition that the velocity gradient perpendicular to the wall vanishes at the wall [22]. With the jet on, the profile is fuller, indicating that boundary layer separation was suppressed. The mean velocity profiles remain almost unchanged when the forcing amplitude changes, whilst varying the frequency appears to have a more significant effect. For example, in the region \( y < 0.3 \text{ mm}, \)
the mean velocity is amplified more than 20 times with the jet on. These results, together with those above, suggest that forcing frequency may be a more important parameter for actuation effectiveness than forcing amplitude.

The piezoelectric synthetic jet actuators must have sufficient velocity output to produce strong longitudinal vortices if they are to be effective for flow control \[11\]. Fig. 8 shows the effect of forcing amplitude at a forcing frequency of 180 Hz. There were three different forcing amplitudes, ±5, ±7.5 and ±10 V, and 180 Hz forcing frequency applied with jet on. The mean velocity profile was hardly changed when the forcing amplitude was ±5 V. When forcing amplitude is just over ±5 V, the effectiveness of the flow control seems to be stable. Thus, it would appear that a critical forcing amplitude exists, below which the control effect of the present actuator is negligible.

Fig. 9 shows the mean velocity and turbulence profiles at each measurement station along the streamwise direction. Examining the mean profiles, it can be seen that in the condition with the jet off, the separation happens between \( X_j = 40 \) and 60 mm. At \( X_j = 60, 80, 100 \) and 120 mm, the mean velocity profile at the \( y \) positions close to the wall is nearly constant, and the velocity profile has an inflection point. This separation continues to a position between \( X_j = 120 \) and 140 mm. When the synthetic jet actuator is switched on, the jet amplifies the turbulence which leads to resistance of separation \[16,22\]. The turbulence profiles in Fig. 9 are useful to help understand how the synthetic jet works to prevent flow separation.

At \( X_j = 40 \) mm, although the mean velocity profile is not yet modified, significant turbulence has been generated by the jet at \( y/\delta = 0.04-0.5 \) (equivalent \( y = 0.2-2.5 \) mm), where \( \delta \) is the thickness of the boundary layer. The peak turbulence level and vertical extent of disturbed flow increases up to \( X_j = 120 \) mm. As the flow proceeded further downstream, the turbulence decreases. It is interesting to notice that at \( X_j = 160 \) mm, the mean velocity profile with the jet on is “fuller” than that jet off, but the corresponding turbulence profiles show that the turbulence level with the jet on is less than jet off. This indicates that the synthetic jets may play dual roles in both accelerating and decelerating turbulence in different applications \[16\].

5. Conclusions

Previous experiments and simulations have been introduced and demonstrated the feasibility of active boundary layer control in turbulent flows using synthetic jets. The current work has focused on the effect of synthetic jets without cross flow and on boundary layer flows under adverse pressure gradients. Significant enhancement of the
jet effectiveness is observed by forcing the boundary layer flow at the natural instability frequency, which is lower than the frequency at which the actuator produces the maximum velocity without cross flow. The piezoelectric synthetic jet actuators must have sufficient velocity output to produce strong longitudinal vortices if they are to be effective for flow control. The effectiveness of synthetic jets seems to depend more strongly on the forcing frequency than on the forcing voltage. The variation of the control effectiveness of SJA with frequency does not correlate exactly with output of the synthetic jet actuator operating in a condition without cross flow and this is most probably due to an interaction with the natural instability frequency of the flow. The results obtained have shown that the synthetic jet generator is an effective and promising device for controlling separation and turbulence levels in an adverse pressure gradient boundary layer.

References


Biographies

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