EFFECTIVENESS OF SYNTHETIC JETS ENHANCED BY INSTABILITY OF TOLLMIEN-SCHLICHTING WAVES

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Abstract

The control effectiveness of synthetic jets on flow separation in an adverse pressure gradient boundary layer was investigated experimentally in a low speed wind tunnel. Of particular interest was the enhancement of the control effect by the Tollmien-Schlichting (T-S) instability of the boundary layer flow to be controlled, at lower forcing frequencies. In our experiments, the forcing amplitude and forcing frequency of the synthetic jet actuator were varied over a set range. This paper reports the results of the synthetic jets generated with a forcing frequency of 100 Hz, one of the most effective frequencies, and low forcing voltage of ±7.5V. The displacement thickness Reynolds number in the measurement region was between 800 and 1300. The mean velocity and turbulence profiles with the synthetic jet on and off are used to demonstrate that flow separation is effectively resisted by synthetic jets driven by low power at T-S frequency. The spectra of velocity are used to analyze the interaction between the synthetic jets and the T-S waves in the boundary layer flow.

Introduction

MEMS-based active flow control has forged new avenues and visions for fluid management. Possible and feasible MEMS flow control systems have been demonstrated in recent research. Pioneering work includes the ‘flexible skin’ developed at UCLA and Caltech for controlling the leading-edge vortices of a delta wing UAV [8,11,19]. In this system, shear stress sensor arrays were used to map out the leading edge separation line. Two types of actuators, magnetic micro flap and micro balloon, were tested, and a normalized rolling moment was used to assess the performance of the actuators. Different devices for active and passive control of gas flows were investigated in NASA Langley Research Center, including passive vortex generators, micro bumps and piezoelectric synthetic jet actuators [9]. The effectiveness of these devices with secondary flows present was evaluated. They concluded that the micro vortex generator was very effective and that synthetic jet actuators must have sufficient velocity output to provide comparable control.

The synthetic jet actuator has been developed in recent years. It fits within the MEMS discipline and has the advantages of simple structure, low cost and easy operation. With this type of actuator, a jet is synthesized by oscillatory flow in and out of a cavity with a small orifice in one side. The flow is induced by a vibrating membrane located on one wall of the cavity. In much of the previous work, the properties of synthetic jets were investigated experimentally or numerically in a condition without cross flow [4,7,9,10,12]. For synthetic jets in cross flow, Amitay et al. and Smith et al. demonstrated significant lift generated on a two-dimensional cylinder using synthetic jets [1,18]. Seifert et al. investigated experimentally 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 [15,16]. In the more recent work, a two-dimensional numerical model was developed by Mittal et al. to investigate the structure of a synthetic jet in the cross-flux.
flow of a boundary layer under zero pressure gradient [13].

Sinha et al. developed an elastomeric MEMS as a flexible wall actuator for controlling separating flows [17]. As this actuator consists of elastrostatically active strips under flexible surface, the actuator can also be used as a sensor. This EMEMS device was tested and shown to be capable of delaying separation in flows over a cylinder and controlling marginal separation on a NACA 0012 airfoil at high Reynolds numbers. However, they emphasized that extrapolation of this technique needs proper understanding of the actuator’s action on the flow. The results reported in this paper contribute to the understanding of the synthetic jet actuator’s operation in a boundary layer under an adverse pressure gradient.

Our work on synthetic jet actuators has been focussed on how and at what forcing voltages and frequencies the jets can provide resistance to separation in a boundary layer at an adverse pressure gradient. This control is based on the knowledge in classical fluid mechanics that turbulent boundary layer is more resistant to flow separation than a corresponding laminar boundary layer. Recently we have investigated experimentally the control effectiveness of synthetic jets on flow separation in a boundary layer under an adverse pressure gradient. This paper reports our experimental investigation of how the synthetic jet and the boundary layer flow interact, coupled with the instability of the boundary layer flow. Of particular interest was effectiveness at lower frequencies enhanced by T-S waves.

**Experimental Setup**

The actuator's input to the boundary layer to be controlled is the electrical signal driving the synthetic jet actuator. The output is the boundary layer parameters required to meet the control objectives. The experiments were set up, aiming to acquire the information on the correlation of the actuator's input and the boundary layer to be controlled. The input signal was characterized by the forcing voltage and forcing frequency. The output was the velocity profile, downstream of the actuator, in the region involving flow separation when the synthetic jet was on or off.

The experiments were performed in the low speed wind tunnel in the Aerodynamics Laboratory at the University of Technology, Sydney. The wind tunnel is an open section tunnel with a 608mm x 608mm octagonal working section. Air enters the wind tunnel through a bell mouth to the settling chamber, which contains a honeycomb for reduction of swirl and a set of screens for turbulence reduction. The maximum free stream velocity achievable is 40 m/s and the minimum turbulence is 0.3%. Figure 1 shows the arrangement of the working section in the wind tunnel. $x$ is the streamwise direction, and $y$ is normal to the flat plate. Measurements were made on the upper surface of the polished aluminum flat plate which is horizontally located in the working section. The leading edge of the upper surface is of elliptical arc form and is located 1200 mm from the working section entrance. The plate has 0.25° negative incidence to avoid leading edge separation. A fairing was set above the flat plate with its angle adjustable for establishing the desired pressure gradient, similar to that of a diffusion compressor blade. Static pressure taps are located every 25 mm along the flat plate and the pressure distribution was measured using a multi-tube manometer. Figure 2 shows the pressure distribution, represented by pressure coefficient along the center streamline.

The synthetic jet actuator was installed underneath the flat plate. The orifice open to the boundary layer flow has a diameter of 0.5 mm. The center of the orifice is on the streamwise centerline and 305 mm downstream of the leading edge of the flat plate. The synthetic jet actuator was driven by a sine wave signal generated by a standard electrical signal generator. Detailed configuration and structure of the synthetic jet actuator are given in [7].

Instantaneous velocity was measured using a Dantec hot wire anemometry. The sample rate was 6 kHz, and the sample size of each realization was 4096. The axial center of the orifice of the synthetic jet actuator is defined as $x = 0$ mm. Measurements were made at $x = 40 - 160$ mm downstream of the actuator orifice at 20 mm intervals. At each of the $x$ stations, the hot wire probe was positioned at $y = 0.2$ mm to beyond 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 was ±7.5V, and forcing frequency 100 Hz. The freestream velocity measured was 8 m/s at $x = -50$ mm, just upstream of where the pressure started to increase.

**Results and Discussion**

Velocity and turbulence profiles at sequential streamwise positions are used to demonstrate the flow separation, which occurs in the boundary layer under an adverse pressure gradient and is prevented by synthetic jets. The integral boundary layer property, displacement
thickness, is used to identify the boundary layer conditions modified by the synthetic jets. Spectra of the time series of velocity at selected positions are used to analyze the interaction between the properties of the synthetic jets and the T-S instability of the boundary layer flow.

**Effect of synthetic jets with and without cross flow**

Figure 3 shows how the mean velocity responds to the forcing frequency in the operating condition with or without crossflow. In the case without crossflow, the velocity was measured at a position \( y/d = 1.5 \) (0.75 mm from the orifice) along the centerline of the jet. Here \( d \) is the diameter of the orifice. The forcing voltage without crossflow was \( \pm 7.5V \). The peak mean velocity occurs at frequency of 1.5 kHz, which is related to the resonant frequency of the membrane material of the synthetic jet actuator. In the low frequency bandwidth, a secondary peak velocity appears in the range of 100–300 Hz.

In the case with crossflow, the velocity was measured at 0.4 mm from the wall and 120 mm downstream to the synthetic jet actuator. As shown in the figure, the peak velocity occurs at three frequency points, two are in the higher frequency range, 1.3 kHz and 1.5 kHz. The third one is in the lower frequency range between 100–400 Hz, which is the frequency range of T-S waves in the current study. Comparing the mean velocity profiles with the jet on and off, this shows that the effectiveness of the synthetic jets at lower forcing frequencies is much enhanced, and this is mostly likely due to the T-S waves in the boundary layer.

**Resistance to flow separation**

Figure 4 shows the mean velocity and turbulence profiles at each measurement station along the streamwise direction. In each diagram the velocity/turbulence profiles with the synthetic jet on and off are compared. As shown in Figure 4, in the condition with the jet off, the separation point happens between \( x = 40\text{mm} \) and \( x = 60 \text{ mm} \). At \( x = 60, 80, 100, \) and \( 120 \text{ mm} \), the mean velocity profile at the \( y \) positions close to the wall is quite vertical to the wall, and the velocity profile has an inflection point. This separation continues to a position between \( x = 120 \text{ mm} \) and \( x = 140 \text{ mm} \). When the synthetic jet actuator is switched on, as shown by the velocity profiles with the legend of “100 Hz, \( \pm 7.5V \)”, the jets amplifies the turbulence which leads to resistance of separation.

The turbulence profiles in Figure 4 are useful to help understand how the synthetic jet works to prevent flow separation. At \( x = 40 \text{ mm} \), although the mean velocity profile is not modified yet, significant turbulence has been generated by the jet at \( y = 0.5 \sim 2.4 \text{ mm} \). Then the turbulence level increases in both \( x \) and \( y \) dimensions until \( x = 100 \text{ mm} \). After that, the turbulence level decreases downstream. It is interesting to notice that at \( x = 160 \text{ mm} \), the mean velocity profile with the jet on is ‘fuller’ than that with the 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 accelerating and decelerating turbulence in different applications.

Hatman and Wang developed a prediction model for distinguishing three separated-flow transition modes, transitional separation, laminar separation-short bubble and laminar separation-long bubble [6]. The first mode involves transition starting upstream of the separation point, and the latter two have the onset of the transition downstream of the separation point by inflexible instability. In laminar separation, the maximum displacement of the shear layer happens at the onset of the transition, and the maximum turbulence level occurs at the first reattachment point. The boundary layer condition in the current study belongs to laminar separation. As shown in Figure 5, the maximum displacement is at about \( x = 115\text{mm} \) downstream of the synthetic jet actuator when the jet is off. According to the identification method in [6], this position with maximum displacement thickness should be the onset of the transition in laminar separation. This maximum displacement point is not obvious when the synthetic jet actuator is in operation, as the transition mode may have been changed from laminar separation (non-frictional separation) to frictional transition. It is more difficult to define maximum turbulence at a \( x \) position than maximum displacement. However, the turbulence level at \( x = 140 \text{ mm} \) in Figure 4 may be recognized as higher than that at other \( x \) positions. Therefore, the first reattachment point should be between \( x = 120 \text{ mm} \) and \( x = 140 \text{ mm} \). The corresponding mean velocity profiles in Figure 4 also support this identification.

Early studies by Wehmann showed that a flexible wall might be used as an actuator to control the flow transition by enhancing or attenuating T-S waves [20]. However, due to the inherent physical constraints, the minimum T-S wavelength generated by vibrating ribbons upstream was 4.2 cm. The free stream velocity was 7.7 m/s, and therefore the corresponding T-S frequency should be about 183 Hz. The vibrated wall was effective only in a range of \( y/8 \) of 0 to 0.15, due to
the limited motion of the flexible wall, and the control effect was stronger closer to the wall and weaker further from the wall. As shown in Figure 4, the synthetic jets are effective up to \( y/\delta \) of 0.6–0.8, and most effective at \( y/\delta <0.4 \). Compared with the flexible wall, it would therefore appear that the control effect of the synthetic jet actuator is more dramatically enhanced by the T-S instability.

**T-S instability**

The neutral instability for laminar boundary layer profiles with pressure decrease or increase can be described by \( \alpha \delta_1 \), here \( \delta_1 \) is the displacement boundary layer thickness, and \( \alpha = 2\pi / \lambda \). \( \lambda \) is wavelength. The Pohlhausen parameter, \( \Lambda = (\nabla^2/\nu)(dU/d\lambda) \), determines the velocity profile with decreasing pressure (\( \Lambda > 0 \)) and adverse pressure gradient (\( \Lambda < 0 \)). Here \( \delta \) is the boundary layer thickness, \( \nu \) is the kinematic viscosity, and \( U \) freestream velocity. The T-S wavelengths depend on \( Re_\delta \) and the pressure gradient [14]. The \( Re_\delta \) along the streamwise direction is between 800 and 1,300 in the condition without the jets and between 750 and 850 with the jets. For a T-S frequency of 100 Hz, the wavelength is 80 mm when the free stream velocity is 8 m/s. The Pohlhausen parameter, as calculated, is less than –5. By referring to \( \Lambda, \alpha \delta_1 \) and \( Re_\delta \), the wavelength of 80 mm is confirmed to be in the unstable region.

As shown in Figure 4, the turbulence level increase due to the synthetic jets is higher for \( y = 1.5 \sim 2.5 \) mm. Time series of the velocity at different \( y \) positions in this range were selected and the spectra were derived to examine the interaction between the effect of synthetic jets and the T-S waves. Figure 6 shows the spectra at \( y = 2.5 \) mm along the streamwise direction. As interpreted from the spectra in the condition with the synthetic jet off, the adverse pressure gradient is strong and the turbulence production process is not sufficient to bring in more momentum to overcome the adverse pressure gradient and to avoid the non-frictional separation. When the jet is on, instability waves of T-S type, coupled with synthetic jets upstream of the separation point still present within the detached shear layer, so that the separation flow is avoided. The peak amplitude at the forcing frequency of 100 Hz increases along the streamwise direction and reaches its maximum between 60 to 100 mm, and then decreases and becomes indistinguishable at \( x = 140 \) mm. It is noted that at \( x = 160 \) mm, the turbulence level of the flow modified by the synthetic jet is lower than that of the flow without the jet. These observations are very consistent with data obtained at other \( y \) positions (1.8 and 2.1 mm), examined in the course of our studies. The maximum values of this peak component are not significantly different at different \( y \) positions, but further from the wall, the peak at 100 Hz remains distinct for a greater downstream extent..

**Conclusions**

The effectiveness of synthetic jets for boundary layer flow control under an adverse pressure gradient condition was investigated experimentally. The enhancement of this effectiveness by the T-S instability waves was noticed and analyzed. The conclusions are summarized as follows.

1. The effectiveness of synthetic jets on boundary layer flow control can be enhanced by the natural instability of the boundary layer flow.
2. The synthetic jets are effective when the forcing frequency is low, in the range of T-S frequencies.
3. The effectiveness of synthetic jets may depend more on the forcing frequency rather than on the forcing voltage.
4. Synthetic jets can play dual roles in resisting separation by accelerating turbulence and reducing turbulence in a naturally turbulent boundary layer.
5. The effectiveness of the synthetic jet actuator in boundary layer control may not be predictable with only the output of the synthetic jet actuator operating in a condition without cross flow.
6. Synthetic jet actuators operating at lower forcing frequency may be more preferable than those at higher forcing frequency, because the audible noise generated at higher frequencies is avoided.

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**References**


Figure 1 Experimental setting in the wind tunnel

Figure 2 Pressure distribution along the wall of the flat plate ($X_0 = 0$ at the leading edge of the flat plate)

Figure 3 Changes of outputs of the synthetic jets to forcing frequencies in the conditions with and without cross flow
Figure 4 Mean velocity profiles and turbulence profiles in the separation regions with the synthetic jets on and off.
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Figure 4 Mean velocity profiles and turbulence profiles in the separation regions with the synthetic jets on and off.

Figure 5 Variation of displacement thickness in streamwise direction

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Figure 6 Spectra of velocity at $y = 2.5$ mm