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Measurement of micro synthetic jet actuation using intensity of disturbance

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Abstract

Synthetic jet actuator (SJA), as a zero-net-mass but non-zero momentum device, has shown great potential in controlling laminar separation caused by adverse pressure gradient in a boundary layer flow. The effectiveness of a SJA has been evaluated in different ways. However, the strategy of using SJAs in controlling boundary layer flow separation is to disturb the boundary layer flow and consequently to accelerate the transition from laminar to turbulence which has greater momentum than laminar flow to resist flow separation. Therefore, the level of disturbance originated by a SJA may be used to evaluate the ability of the SJA to control laminar separation. Intensity of disturbance, originally defined for measuring the 'degree of disturbance' in the external flow in boundary layer theories, has been first time used to quantitatively evaluate the level of disturbance triggered by a SJA. This paper reports the intensity of disturbance triggered by three micro synthetic jet actuators which were installed at three streamwise locations and driven at two forcing frequencies. Quantitatively measured by the intensity of disturbance, the results will show the dependency of the SJA's actuation on the streamwise position, on the forcing frequency and on the forcing amplitude.

Introduction

Increasing the momentum in the boundary layer flow and turbulent mixing may be recognized as two different methods in control of boundary layer flow separation. Classified by the types of control, one may be passive control and the later active control. The work reported in [1,4,5] demonstrated the successful application of increased momentum, while the work of [6,7,8] showed the effects of turbulence generation on the laminar separation bubble using a SJA. These two methods work in different ways on separating flow. Momentum addition forces the separation point downstream by increasing the ability of the boundary layer flow to resist energy loss, while disturbance generation and the subsequent turbulence in the boundary layer enhances mixing between the internal and external flows and increases near wall momentum to overcome laminar separation. Momentum addition to the separated boundary layer is used to increase the energy in the near wall flow, thereby overcoming the energy lost through the increasing pressure. This may limit the extent at which a micro actuator can have any effect over separation, as it requires the actuator's size big enough in order to provide sufficient energy.

Flow instabilities have been identified as a mechanism that initiates the transition from laminar to turbulent flow [9]. Through the development of the Orr-Summerfeld equation it was demonstrated that the generation of small disturbances led to the linear instability associated with the transitional process from laminar to turbulent flow [9,11]. In the method of small oscillations, small harmonic waves of a specified range of wavelengths are generated after a critical Reynolds number is achieved. In this condition, the disturbances will develop to be Tollmien-Schlichting instabilities and result in the onset of the transition process, typically in a frictional boundary layer at a zero pressure gradient.
Disturbances to the flow can be generated in different ways. Typical methods include internal vibrations from mechanical devices or reaction of sound waves on a rivet. T-S waves were generated in this manner, or by curvature discontinuities on a surface [2]. The evolution of these disturbances leads to the early onset of transition from laminar to turbulence.

It was proposed based on preliminary demonstration that flow instabilities be used to enhance the effectiveness of SJAs on turbulent mixing of momentum into the near wall flow that was at risk of separating [7]. Turbulent mixing of flow transfers momentum to the near wall flow, and therefore is more capable resisting flow separation over a broader range of adverse pressure conditions. Tuning a jet to the instability frequencies of the baseline flow may suggest that using a SJA to trigger a disturbance in the near wall boundary layer and using the instability of the baseline flow to amplify this disturbance be a much more economic and effective method to achieve control of laminar separation. When this method works, the SJA becomes independent of the size and power of the actuator.

Experimentation

The experiments were performed in the low speed wind tunnel in the Aerodynamics Laboratory at the University of Technology, Sydney. The maximum free stream velocity of this is $40ms^{-1}$, with a minimum turbulence of 0.3%. Figure 1 shows the arrangement of the working section in the wind tunnel and the positions of three SJAs on the streamwise centerline. x is the streamwise direction, and y is normal to the flat plate. The flat plate, located 1200 mm from the working section entrance, has a high quality surface finish. The leading edge of the upper surface is of slender elliptical form and the plate has a 0.250 negative incidence to avoid leading edge separation. As shown in Figure 1, a fairing was set above a flat aluminium plate with its angle adjustable for establishing the desired pressure gradient, similar to that of a diffusion compressor blade. Further details for the experimental setting up are provided in [6,7,8].

The locations of the three SJAs were 207, 307, and 357mm respectively from the leading edge of the flat plate. The SJA used in present study consists of a membrane located at the bottom of a small cavity which has an orifice in the face opposite the membrane. The actuator membrane is a thin circular brass disc, 0.25mm 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. The SJA was installed underneath the flat plate. The orifice open to the boundary layer flow has a diameter of 0.5 mm. In operation, the SJA was driven by a sine wave signal generated by a standard electrical function generator. An air jet is synthesized by oscillatory flow in and out of the cavity through the orifice open to the boundary layer [7].

Results shown in the figures in this paper were derived from the streamwise velocity which was measured using a single-wire Dantec hot wire anemometry, in the boundary layer over the upper surface of the flat plate. The Reynolds number of the baseline flow was $1.78\times10^5 \sim 2.24\times10^5$. Measurements were made in the region of X = 345 – 465mm at 20mm intervals.

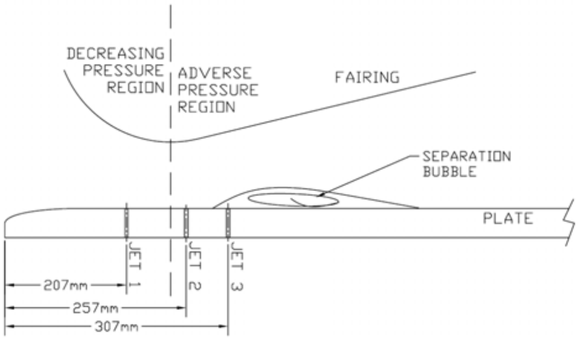


Figure 1. Working section setup in wind tunnel

Intensity of Disturbance

Different methods have been developed to demonstrate and evaluate the effectiveness of a SJA. The work reported in [6, 7, 8] used mean and fluctuating velocity profiles to show boundary layer laminar separation successfully resisted by a micro SJA. To directly measure the achievement reaching the ultimate aim of separation control, the lift coefficient was used to show the improved performance of the flow about an airfoil [1,4,5].

Some coefficients have been used to investigated the effectiveness of a SJA. For example, the reduced frequency, $F^+ = f\,(x_c/U_\infty)$. Here f is the forcing frequency, x_c is a characteristic length in the separation region and U_∞ is the local free stream velocity [1]. The other one is the momentum coefficient, $C_\mu = h(\rho\, u^2{}_{max})_{jet}/[c(\rho U)_\infty]$, which is defined with the dimensions of SJA and the maximum jet velocity in the condition without cross flow [10]. It was indicated that $C_\mu \geq 0.002$ was necessary before any substantially actuating effects on the flow could be noticed.

As reviewed previously, the SJA will become independent of its size and dimensions when a SJA is used to trigger a disturbance which is amplified by the instability of the baseline flow. In this case the effectiveness of SJA may be measured directly by the disturbance or turbulence in the baseline separation zone. Therefore, intensity of disturbance is selected. The intensity of disturbance is an integral of the fluctuating velocity over the boundary layer at a particular streamwise position. It is calculated with Eq. (1) [9]:

$$I_d = \int_0^\delta u'\,dy \tag{1}$$

Where I_d is the intensity of disturbance, u' is the fluctuating velocity, y is the distance to the wall, and δ is the boundary layer thickness. The fluctuating velocity is calculated with Eq. (2).

$$u' = \sqrt{\frac{\sum_{i=1}^{N}(u_i - \bar{u})^2}{N}} \tag{2}$$

Where u_i is the instantaneous streamwise velocity, $\bar{u}$ is the sample mean of instantaneous streamwise velocity and N is the sample size.

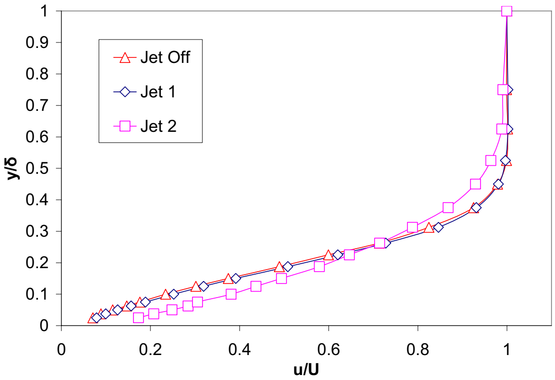
Results and Discussion

Combined with velocity profiles, intensity of disturbance was used to investigate the dependency of SJAs on forcing frequency and streamwise location.

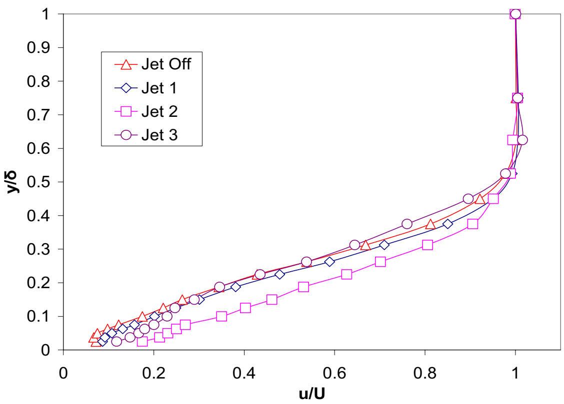
The mean velocity profiles in Figures 2(a-g) compare the effects of three SJAs on resisting laminar separation at seven measurement stations in the boundary layer from X=347mm to X=467mm. Note that the mean velocity profile of Jet 3 is not included in Figure 2(a), as Jet 3 was located between the first and second measurement stations, and the streamwise velocity was not recorded at the first measurement station which was upstream of Jet 3. At X=347mm, the mean velocity profile for 'jet off' shows no inflection. As intensity of disturbance is a measure of the turbulence level over the boundary layer, Figure 3 shows that the intensity of disturbance at X = 347 mm is very low. Therefore, the flow is still laminar at the first measurement station for 'jet off'. However, at the next station, X=357mm, there is a small but clear inflection point for 'jet off'. It can therefore be assumed that the onset of separation be between the first two measurement stations. At subsequent positions, from X=387mm to X=467mm, the mean velocity profiles for 'jet off' show that the separation bubble grows substantially in thickness. Through the same region the intensity of disturbance increases slowly until X = 447mm, indicating a laminar separation. The intensity of disturbance increases more quickly between X=447mm and X=467mm. this may show the boundary layer flow at 'jet off' is close to transition from laminar to turbulence but not reached yet.

When the three SJAs are switched on with forcing frequency of 100 Hz, the separation bubble is completely resisted by Jet 2 and Jet 3, as shown in Fig. 2(a)-(g). Jet 1 looks less effective as the mean velocity profiles are still reflectional, although reduced, at the first four measurement stations, as shown in Fig. 2(a)-(d). The intensity of disturbance shown in Fig. 3 explains the different performance of three SJAs shown in Fig. 2. At the first two measurement stations, X=347mm and X=367mm, the disturbance generated by Jet 2 is already significant in comparison with the intensity of disturbance for 'jet off'. It grows continuously to maintain a certain level of momentum for protecting the flow from separation. Its growth is due to the baseline flow's instability which effectively amplifies the small disturbance triggered by Jet 2. Jet 3's performance on resisting separation is similar to Jet2's as shown in Fig. 2. The disturbance generated by Jet 3 is smaller than that of Jet 2, as shown in Fig. 3, but it is big enough to stop the separation bubble. The disturbance generated by Jet 1 is nearly zero at the first measurement stations as shown in Fig. 3. This is the region which covers the separation point. Downstream of the second measurement station, X=367mm, the disturbance generated by Jet 1 starts to be amplified by the instability associated with the laminar separation. However, this occurrence may be too late and also the amplified disturbance is still not big enough to resist the separation completely.

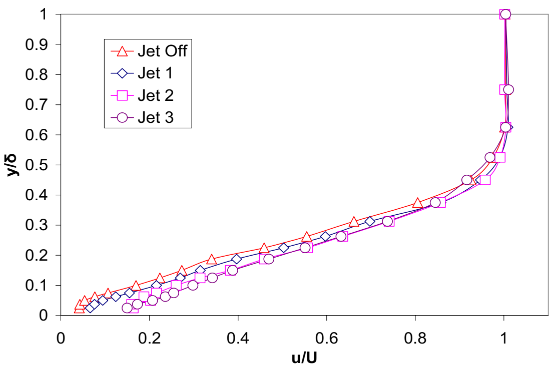
All the three SJAs had the same structure and materials. They were driven simultaneously at the same forcing amplitude and the same forcing frequency in the experiments. Therefore, the difference in their performance for controlling the separation bubble was caused by their different locations along the streamwise direction. The different streamwise locations of the three SJAs result in a phase difference between any two SJAs, and different pressure distribution in the region between the SJA and the separation point. The small jets triggered by three SJAs interacted with flows with different pressure gradient at different time, although they are all in the same baseline flow. Consequently, they may be damped or amplified by the baseline flow, and this damping or amplification can occur at different levels and vary temporarily and spatially. The physics of the evolution of the disturbance triggered by the SJA can be understood by applying the linear instability theories. However, more investigation is required to examine the optimal position of SJAs when they are used in boundary layer separation control.



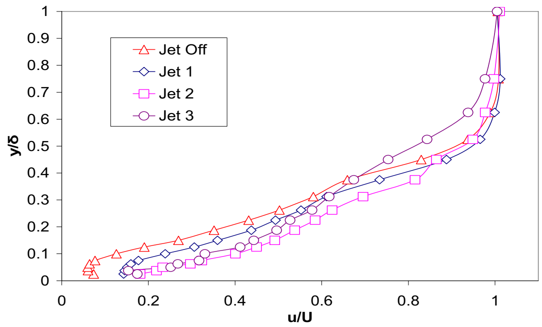
(a) x = 347mm



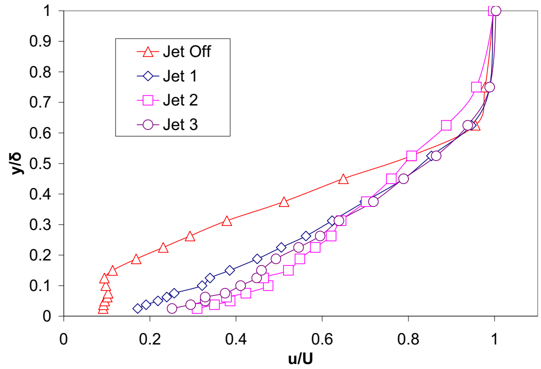
(b) x = 367mm



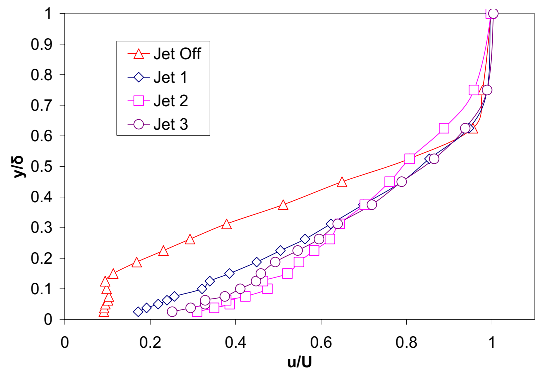
(c) x = 387mm



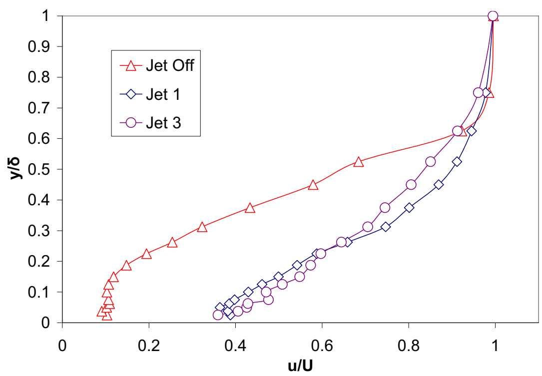
(d) x = 407mm



(e) x = 427mm



(f) x = 447mm



(g) x = 467mm

Figure 2. Mean velocity profiles at seven measurement stations when the SJAs at three positions are all off and all on. Forcing frequency: 100Hz. Forcing amplitude: ±7.5V.

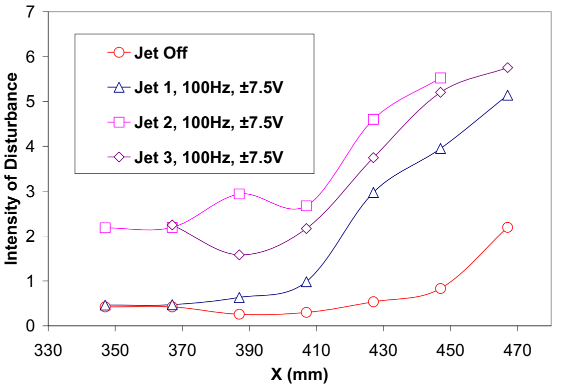


Figure 3. Intensity of Disturbance at seven measurement stations when the SJAs at three positions are all off and all on. Forcing frequency: 100Hz. Forcing amplitude: ±7.5V.

Dependency of SJA on forcing frequency

The intensity of disturbance has also been used to investigate the dependency of the SJA on different forcing frequency. Figure 4 shows the mean velocity profiles with the SJAs operated at 300Hz and Figure 5 shows the corresponding intensity of disturbance. As shown in Figure 4, all three SJAs present insignificant actuation on controlling the laminar separation. Results show that Jet 1 is ineffective through the whole collection region, and Jet 2 and Jet 3 are only slightly effective in the region between the first two measurement stations *X*=387mm and *X*=407mm. The difference in Figures 2 and 4 show a strong dependency of the SJAs on the forcing frequency.

The SJA's dependency on the forcing frequency is also demonstrated by comparing the intensity of disturbance in Figures 3 and 5. Figure 5 shows that the disturbance generated by the SJAs driven at a forcing frequency of 300Hz is almost negligible. The sudden increase of turbulence at the last two measurement stations, *X*=457mm and *X*=467mm, should be resulted from the burst of the laminar bubble, the natural transition to turbulence in a laminar separation. As also shown in Figure 5, Jet 1, located upstream of the adverse pressure gradient region, actually has enhanced this bubble bursting.

Dependency of SJA on streamwise position

Figure 6 shows the pressure distribution measured along the streamwise central line over the flat plate in Figure 1. It simulates the pressure gradient in the boundary layer over the blade of a diffusion compressor.

Jet 1 was in the favourable pressure region (*X* = 0.207m). As shown by the less effect of Jet 1 on resisting laminar separation in Figures 2, the disturbance triggered by Jet 1 might have been damped by the decreasing pressure in the baseline flow. As shown in Figure 3, the disturbance generated by Jet 1 does not grow until it enters the separation zone whose onset point was identified between *X*=347mm and *X*=357mm. Jet 2 and Jet 3 were installed in the adverse pressure region. As also shown in Figure 3, the small disturbance triggered by the Jet 2 and Jet 3 are significantly enhanced more by the baseline flow downstream than Jet 1 is, and become strong enough to protect the flow from separation.

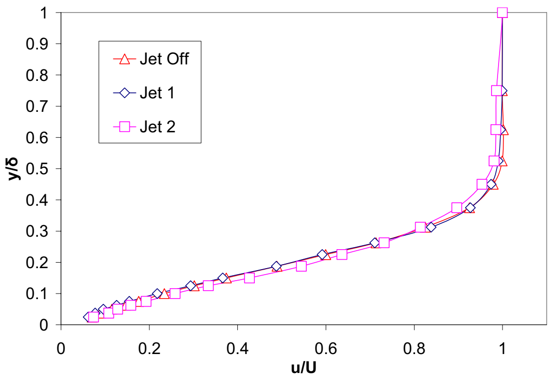
Jet 3 is located inside the separation zone of the baseline flow, X=357mm, between the first two measurement stations. The effect of Jet 2 and that of Jet 3 on resisting the separation bubble are similar, as shown in Figure 2 (b-g). However, the intensity of disturbance of Jet 2 is obviously greater than that of Jet 3.

The comparison of these three SJAs shows that there is an optimal position for the jet upstream of the separation point. It seems that the position of the jet should be as far from the separation point as possible, but within the adverse pressure region. This should maximise the amplification of the disturbance triggered by the SJA to generate the frictional T-S instability waves and to accelerate the transition to turbulence before the onset of separation. The accelerated turbulence enhances the flow mixing and then stops separation by adding momentum to the near wall flow.

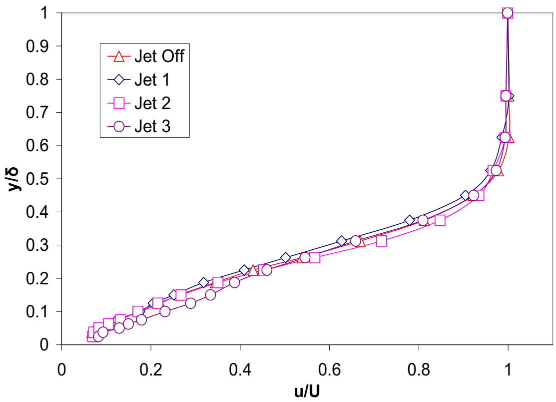
Dependency of SJA on Forcing Amplitude

Figures 7 and 8 show the influence of forcing amplitude on the SJA. Jet 1 and Jet 2 were operated individually at ±7.5 and ±10 Volts with forcing frequency of 100 Hz. As shown in Figures 7 and 8, the changes in the intensity of disturbance at two forcing amplitudes are small. Compared with the intensity of disturbance showing the dependency of SJAs on forcing frequency in Figures 3 and 5, the dependency of SJAs on forcing amplitude is much weaker than that on forcing frequency, regardless the streamwise position of the SJA.

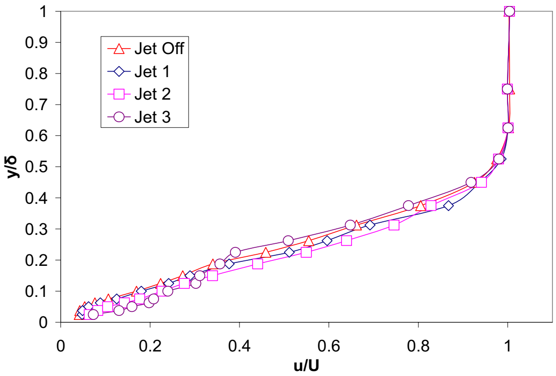
Previous work by [8] on the same test rig demonstrated that there was a minimum forcing amplitude ±5 V. about which the SJA should be driven to be effective. However, when the forcing amplitude is above this minimum level, the effect of a SJA, measured by the intensity of disturbance is not significantly enhanced when the forcing amplitude is increased from ±7.5 V. to ±10 V.



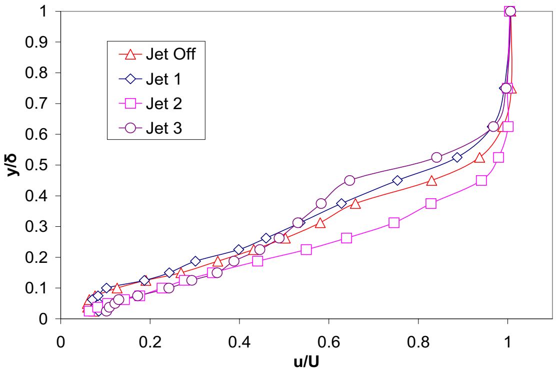
(a) *x* = 347mm



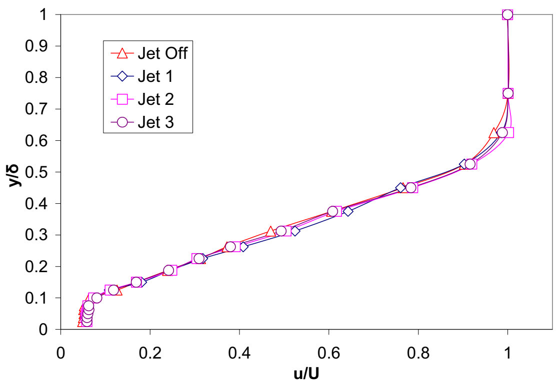
(b) *x* = 367mm



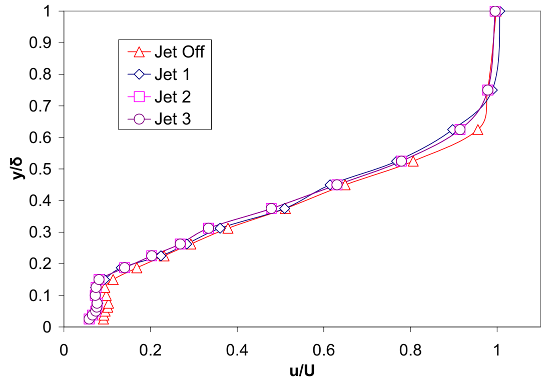
(c) x = 387mm



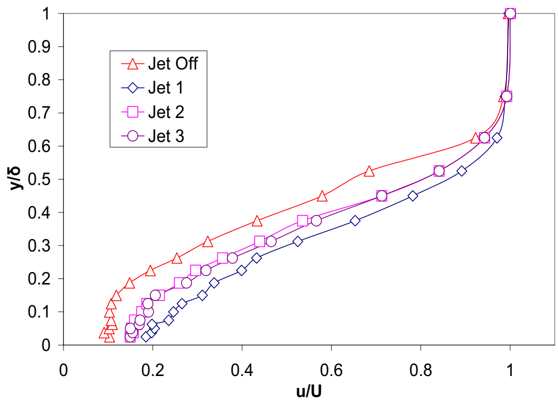
(d) x = 407mm



(e) x = 427mm



(f) x = 447mm



(g) x = 467mm

Figure 4 (a-g). Mean velocity profiles at seven measurement stations when the SJAs at three positions are all off and all on. Forcing frequency: 300Hz. Forcing amplitude: ±7.5V.

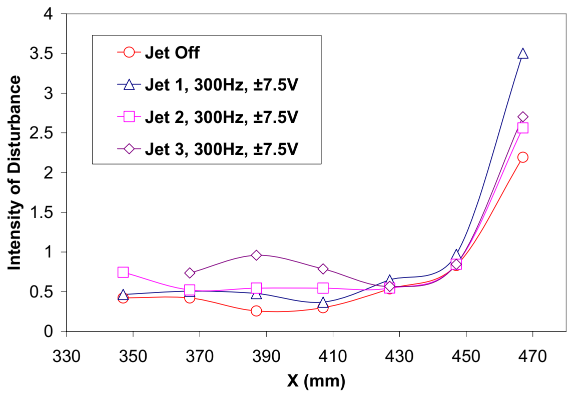


Figure 5. Intensity of Disturbance at seven measurement stations when the SJAs at three positions are all off and all on. Forcing frequency: 300Hz. Forcing amplitude: ±7.5V.

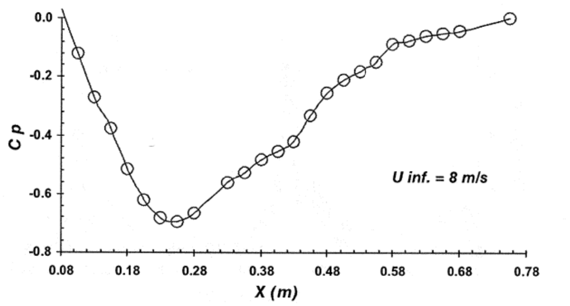


Figure 6 Pressure gradient created by the fairing over the flat plate [7]

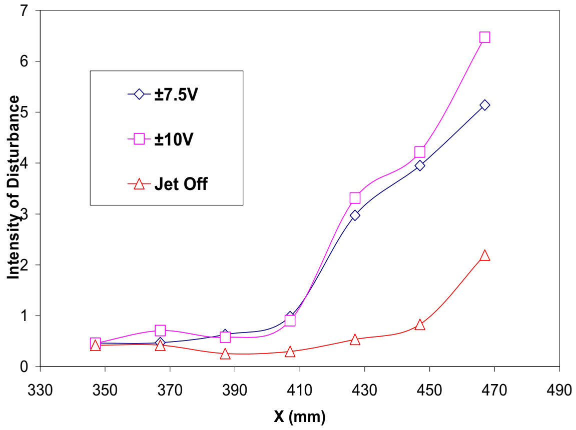


Figure 7. Intensity of Disturbance at seven measurement stations when Jet 1 was off and on. Forcing frequency: 100Hz. Forcing amplitude: ±7.5V.and ±10V

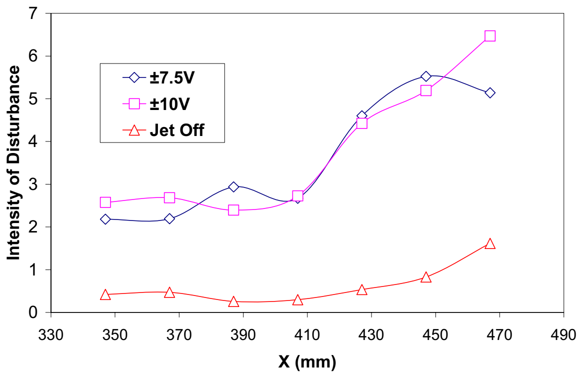


Figure 8. Intensity of Disturbance at seven measurement stations when Jet 2 was off and on. Forcing frequency: 100Hz. Forcing amplitude: ±7.5V.and ±10V.

Conclusion

Intensity of disturbance has been used with mean velocity profiles to evaluate the effective actuation of synthetic jet actuators to prevent the boundary layer flow from laminar separation by accelerating the transition to turbulence. Results of three SJAs installed at three streamwise positions and driven at two forcing frequencies and two forcing amplitudes are presented. The dependency of the SJA's actuation on streamwise position, forcing frequency and forcing amplitude is discussed.

The results show that the effective actuation of the SJA, measured by intensity of disturbance, may be maximised by positioning the jet at the upstream edge of the adverse pressure region at an effective forcing frequency. The control of laminar flow separation was previously demonstrated to be achieved through the use of flow instabilities. To maximise the ability of the SJA to achieve this goal, the SJA should be positioned within the adverse pressure region as far upstream of the separation point as possible so that the disturbance triggered by the SJA will have sufficient chance to be amplified by the baseline flow and hence to generate the frictional instability.

The actuation of three SJAs to generate sufficient disturbance is significantly different when the SJAs are driven at two forcing frequencies, 100 Hz and 300 Hz. At forcing frequency of 300 Hz, the SJAs show little effectiveness on resisting laminar separation, independent of the SJA's position. More work is required to investigate the range of forcing frequency associated with the flow instabilities. Driven individually at forcing amplitude increased from ±7.5 V to ±10.0 V, both Jet 1 and Jet 2 show insignificant improvement in intensity of disturbance.

Acknowledgments

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