20th Australasian Fluid Mechanics Conference
Perth, Australia
5-8 December 2016

Control of the turbulent boundary layer by the application of a cavity array

A. Silvestri, F. Ghanadi, M. Arjomandi, B.S. Cazzolato and A.C. Zander

School of Mechanical Engineering
University of Adelaide, Adelaide, South Australia 5005, Australia

Abstract

The results presented in this paper provide an insight into the effect of a cavity array on the turbulence production within a turbulent boundary layer. In the present study, the turbulent energy production within a fully developed turbulent boundary layer has been reduced using a flushed-surface cavity array underneath a flat plate coupled with an acoustic actuator. The size of the holes in the cavity array were selected to be comparable with the dimensions of the expected coherent structures, based on the friction velocity. Experimental measurements were taken in a wind tunnel at a number of locations along the array in the streamwise direction and at a variety of acoustic frequencies generated by the acoustic actuator. A maximum turbulence intensity and sweep intensity reduction of 11% and 10% respectively occurred at $Re_\theta = 3.771 \times 10^3$ in the logarithmic region of the boundary layer when no drive frequency was provided. From this investigation it has been shown that the drive frequency of the acoustic actuator has no effect on the turbulence reduction by the cavity array. Instead the physical parameters of the array, including the number and diameter of the cavities in the array have a much more significant effect.

Introduction

By reducing the skin friction drag component of viscous drag, the efficiency of all aerospace applications, including aircraft can be improved. A reduction of 5-10% on the fuselage alone resulted in an annual fuel saving of approximately half a billion dollars in the United States during 1989 [1]. This equates to 1.5 billion dollars in today's economy with the increased number of aircrafts. A key focus by the fluid dynamics research community has been to reduce the skin friction drag by controlling the boundary layer, which comprises a significant 48% of the total drag for typical aircraft applications [2]. The most important part of the boundary layer are the coherent structures, which are responsible for the total shear stress in the near wall region. Coherent structures consist of the ejection of low speed fluid from the boundary layer and the inrush of high speed fluid which are known as sweep events [3, 4]. Corino and Brodkey [3] showed that ejection events generated approximately 70% of the total stresses in the near wall region, while the sweep events contributed to the remaining 30%. These two events were shown to be self-replicating and consequently were deemed to be very important during turbulence generation [5, 6]. It is believed a technique which targets this mechanism will cause a more significant reduction in turbulence generation and drag.

One method that will be discussed in this paper is the reduction of the streamwise vortices by producing a local jet at the orifice using an acoustic actuator below the cavity array. This method is very similar to the synthetic jet which has found great success by utilising a diaphragm set in a cavity and driven by a piezo electric element at its resonant frequency. With an open neck and orifice, fluid is drawn in and out of the cavity during the oscillation of the diaphragm. During the outflow cycle vortex rings are generated at the orifice and travel away from the opening [7]. During the inflow cycle fluid is drawn into the backing cavity below the orifice, which does not affect the vortex ring produced during the mext outflow cycle. The design is highly desirable in turbulent flow control due to its self-contained nature with no external fluid source. If timed correctly the ejection process from the acoustically excited cavity array targets fast moving fluid (sweep events), which is moved away from the wall. The inflow stage is used to bring the slow moving fluid (ejection events) closer to the wall. This results in the disruption of both events as research from Lockerby [8] has shown this to be successful.

The passive application of the cavity array to reduce the turbulence generation has also been considered by the authors. By using a cavity with a small orifice the shear layer shall be unaffected crossing the small opening, ensuring the resonance of the Helmholtz mode is not achieved [9, 10]. Consequently only the flow which acts normal to the wall will be affected by the cavity array. In the near wall region the sweep and ejection events act in this direction and consequently this would allow the cavity to be used as a drag reduction method for both higher and lower Reynold's numbers.

The purpose of the present work is to assess the ability of an array of micro-cavities in reducing the turbulent properties of a fully developed boundary layer using either of the two methods discussed above, namely the active and passive applications discussed. In the subsequent sections the characteristics of the cavity array will be discussed and details of the experimental setup will be given. A discussion on the results will be provided and an insight into the capabilities of the cavities' success in reducing the turbulent structures will be provided.

Experimental Procedure

All experiments were performed in a closed-return type wind tunnel located at the University of Adelaide. The tunnel can be operated up to a maximum velocity of 30 m/s with a low level turbulence intensity, fluctuating between 0.4% to 1%. The test section is rectangular with a cross section of $500\text{mm} \times 500\text{mm}$ and 2000mm in length. As shown in Figure 1, a horizontal 2000mm long flat plate was positioned inside the tunnel such that it spanned the whole width of the test section. The finite thickness of the flat plate can lead to bluff body separation effects, therefore to minimize any possible flow separation a super-elliptical leading edge of a nominal major radius of 114mm was attached to the flat plate. A 125mm long circulation flap was also mounted downstream of the plate to minimize any circulation developed over the plate and to ensure that the stagnation point is on the measurement side of the plate. The flap could also be adjusted as appropriate to balance the pressure gradient along the working section. The boundary layer investigated in the study was tripped by a 3mm rod located 140mm downstream of the leading edge as advised by Silvestri et al. [11]. This was done to ensure a fully turbulent boundary layer was achieved for the experimental procedure.

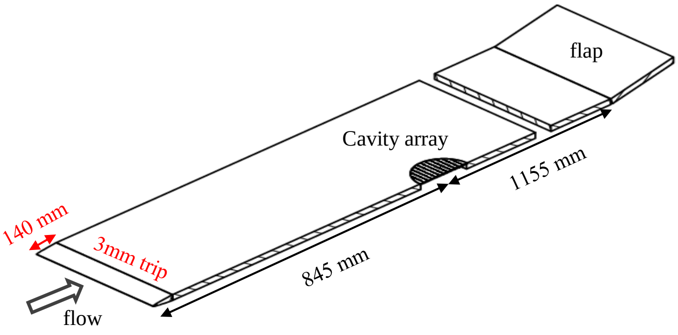


Figure 1: Schematic of the experimental arrangement

This research focuses on the near wall regions, as approximately half of the total turbulence production occurs within this small region [12]. A hot-wire anemometer was used downstream of the boundary layer trip and cavity array to characterize the changes within the boundary layer regions arising from the cavity array located 845mm ($x^+ = 5.13 \times 10^4$) downstream of the leading edge. This length was selected to ensure a fully turbulent boundary layer was developed for the experimental measurements. This was done at four locations ($x^+ = 5.5 \times 10^3$, $x^+ = 8.2 \times 10^3$, $x^+ = 10.9 \times 10^3$, $x^+ = 13.9 \times 10^3$) downstream from the cavity array's leading edge at a single Reynolds numbers and cavity dimension. The streamwise velocity measurements were made with an IFA 300 CTA system, using a single platinum-plated tungsten wire of $5\mu m$ in diameter and 1.25mm in length, which was operated in constant current mode at 0.2mA with an over-heat ratio of 1.8 and an operating temperature around 230°C, which provided sufficient sensitivity to measure the velocity fluctuations with minimum thermal effects. The repeatability of each measurement was also verified 3 times and the data were sampled at 10 kHz for 10 seconds to ensure suitable temporal resolution.

The cavity array (Figure 2) was designed based on the friction velocity value equal to, $u_\tau = 0.5\, m/s$, a value obtained previously by Silvestri et al. [11] for a Reynolds number approximately equal to, $Re_\theta = 1927$. Using this friction velocity value the spanwise and streamwise spacing and the approximate orifice diameter were calculated based on the method specified by Lockerby [8], which states the orifice diameter to be 40 times the size of the spanwise spacing of the coherent structures. This resulted in a cavity array being designed, utilising 1.2mm diameter holes, with a spanwise spacing of 3mm and a streamwise spacing of 15mm.

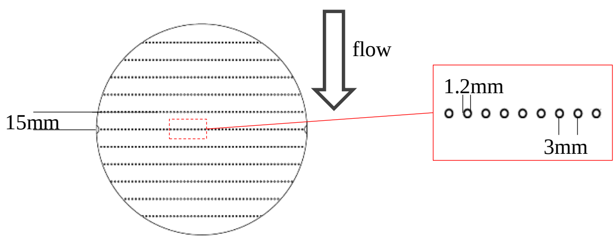


Figure 2: Schematic of the cavity array

This cavity array was tested under multiple conditions, including cases in which the array had an acoustic actuator oscillating at a variety of selected frequencies and as a completely passive control technique. This was done to quantify the turbulence reduction by the active and passive control methods.

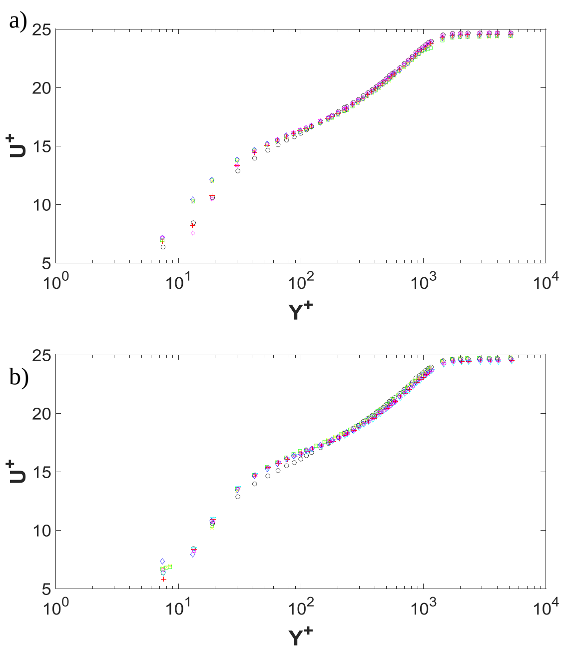
Effects of the cavity array on the streamwise and turbulence intensity profiles

When investigating the effect of the cavity array on the turbulent boundary layer a Reynolds number of $Re_\theta = 3771$ was selected. While the cavity array was designed for a Reynold's number of $Re_\theta = 1927$ the results sensitivity to Re_θ has already been discussed by Silvestri et al. [13] Figure 4 shows the streamwise profile of the boundary layer immediately downstream of the cavity array's leading edge at four locations. The cavity array investigated appears to reduce the thickness of the viscous and logarithmic subregion ($y^+ < 200$), while not changing the overall boundary layer thickness. This can be seen to cause a drag reduction, as with less of the boundary layer consisting of the viscous and logarithmic subregion a reduction in shear stress and skin friction drag will occur.

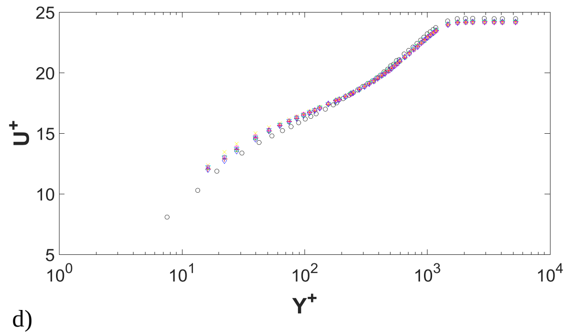
The array was shown to replicate this for all tested conditons, including the passive array with no excitation and all the experiments conducted with an acoustic actuator coupled at different frequencies. The results indicate that the same amount of reduction was achieved independent on which driving frequency the resonator was set to, including when the array was completely passive and the resonator was not excited.

The reduction of the viscous and logarithmic subregion was also shown to increase downstream of the leading edge. The initial measurement, which was taken at $x^+ = 5.5 * 10^3$ (the midpoint of the cavity array) demonstrated a 4.6% reduction in the viscous and logarithmic subregion in Figure 3(a). This value was shown to increase to 5.3% at $x^+ = 10.9 \times 10^3$ (the end of the cavity array), as shown in Figure 3(b&c). Thus demonstrating the cavity array was responsible for providing the effect on the boundary layer, as the effect was shown to increase once exposed to a larger proportion of the cavity array.

The decrease in the viscous and logarithmic subregion was also shown to continue significantly downstream after the cavity array ended. At a location of $x^+ = 13.9 \times 10^3$ the cavity array was shown to provide a decrease in the subregion by 4.1% (as shown in Figure 3(d)). Thus demonstrating a significant proportion of the boundary layer was changed downstream of the cavity array, showing the effect not to be localised. To illustrate this proposal further the turbulence intensity of the boundary layer was also considered.



c)



d)

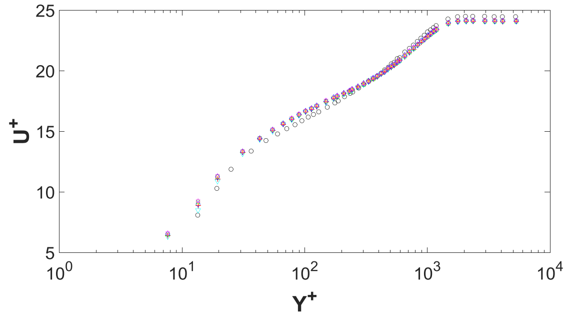
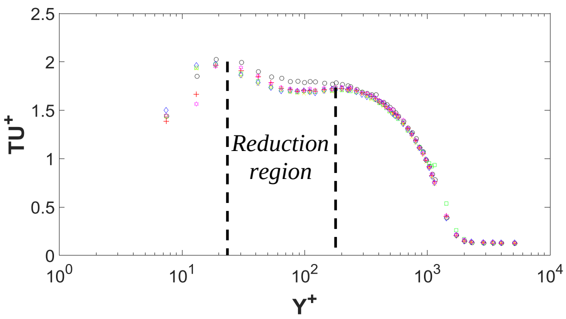


Figure 3: Mean velocity profile at $Re_\theta = 3771$. a) $x^+ = 5.5 \times 10^3$, b) $x^+ = 8.2 \times 10^3$, c) $x^+ = 10.9 \times 10^3$, d) $x^+ = 13.9 \times 10^3$. (o) No control, (△) cavity array – No excitation, (+) 500Hz excitation, (□) 1000Hz excitation, (◊) 2000Hz excitation, (x) 4000Hz excitation, (*) 8000Hz excitation

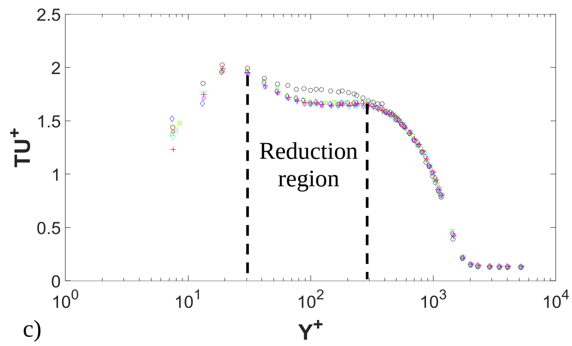
The reduction in turbulence intensity is clearly evident in Figure 4 and demonstrates a similar pattern to the results obtained in Figure 3. A turbulence intensity reduction was recorded for all the conditions tested, including the passive array with no excitation and all the experiments conducted with the acoustic actuator driven at different frequencies. The results indicate that the same amount of decrease was achieved independent of the driving frequency, including when the array was completely. This was also observed previously when investigating the mean streamwise profile.

The reduction of the turbulence intensity was also shown to increase the further downstream the measurements were taken. Turbulence intensity is a scale used to characterise the turbulence fluctuations in the boundary layer. The initial measurement, which was taken at $x^+ = 5.5 \times 10^3$ (the midpoint of the cavity array) demonstrated a 6.6% decrease in the turbulence intensity), as shown in Figure 4(a). This value was shown to increase to 11% at $x^+ = 10.9 \times 10^3$ (the end of the cavity array), as shown in Figure 4(b&c).

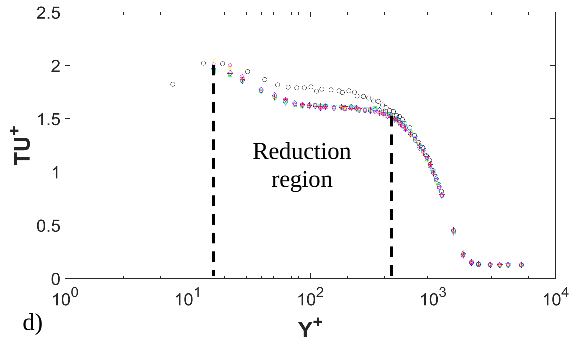
a)



b)



c)



d)

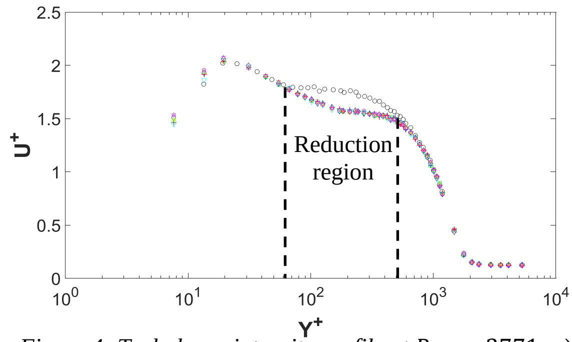


Figure 4: Turbulence intensity profile at $Re_\theta = 3771$. a) $x^+ = 5.5 \times 10^3$, b) $x^+ = 8.2 \times 10^3$, c) $x^+ = 10.9 \times 10^3$, d) $x^+ = 13.9 \times 10^3$. (o) No control, (△) cavity array – No excitation, (+) 500Hz excitation, (□) 1000Hz excitation, (◊) 2000Hz excitation, (x) 4000Hz excitation, (*) 8000Hz excitation

The decrease in the turbulence intensity was also shown to continue significantly downstream after the cavity array ended. At a location of $x^+ = 13.9 \times 10^3$ the cavity array was shown to provide a decrease in the turbulence intensity in the viscous and logarithmic subregion by 10%, as shown in Figure 4(d). Thus demonstrating a significant proportion of the boundary layer was changed downstream of the cavity array, showing the effect is not localised.

Discussion

The boundary layer was shown to be modified by the cavity array and consequent several important findings were discovered. The most noticeable finding was the acoustic actuator had no impact on the boundary layer and consequently the driving frequency had no effect on the boundary layer. Therefore the conclusions drawn from this research indicate the reduction achieved from these experiments was due to the passive cavity array. As discussed earlier, one of the methods proposed the cavity array would only impact the coherent structures which act normal to the wall. If this is the case a variable interval time averaging (VITA) technique can be used to detect the changes in the turbulent boundary layer associated with coherent structures. This technique, first applied by Blackwelder and Kaplan [14] for studying the near wall region, detects the sweep and ejection events where by the velocity rapidly changes. T^+ is time nondimensionalized by the inner wall variables, where the ensemble window length was selected to be between -30 to 30. The results at $Re_\theta = 3771$ show a reduction in the intensity and duration of the sweep events. Figure 5 demonstrates a reduction in intensity and duration by 7.6% and 10% respectively at $x^+ = 10.9 \times 10^3$.

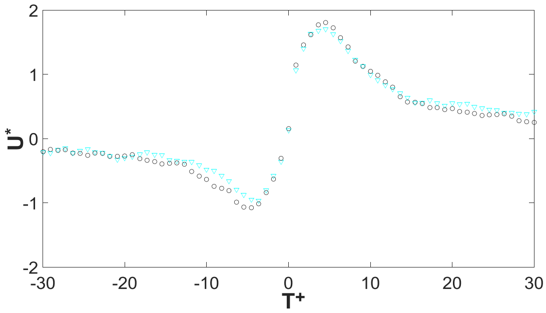


Figure 5: Average VITA sweep events at $Re_\theta = 3771$, $x^+ = 10.9 * 10^3$. (o) No control, (Δ) cavity array – No excitation

This reduction is also observed in Figure 6, at a downstream location of $x^+ = 13.9 \times 10^3$, where a sweep intensity reduction of 2.6% was achieved, however the change in duration was insignificant.

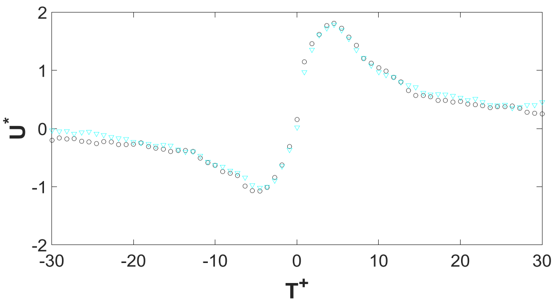


Figure 6: Average VITA sweep events at $Re_\theta = 3771$, $x^+ = 13.9 * 10^3$. (o) No control, (Δ) cavity array – No excitation

It was initially hypothesised that the cavities would operate by capturing the sweep events and disrupt the overall bursting process in the boundary layer. This is supported by the VITA results in Figure 5 and Figure 6. These changes in the sweep intensity and duration are strong indicators that the coherent structures have been modified by the use of the cavity arrays as a passive solution. It is believed that the individual cavity offices are too small to allow the shear layer to break apart during the traverse across the orifice. As such resonance of the Helmholtz mode is not observed, which was previously experienced by Ghanandi et al. [9, 10].

Conclusions

The basis of this paper, is the study of micro cavities or perforated plates as a potential control technique in reducing skin friction drag. In this study two mechanisms were considered, with one technique focusing on an active approach and the other as a passive solution. The characteristics of the boundary layer were analysed using hotwire anemometry at four locations; three along the implemented cavity array and one behind, and the results were used to calculate the streamwise boundary layer profile, turbulence intensity and the properties of the coherent structures.

The results from this study indicated the reduction achieved was due to the passive mechanisms suggested. The cavity array was shown to provide substantial reduction to the turbulence intensity, sweep intensity and sweep duration. A maximum reduction in intensity and duration of the sweep events of 7.6% and 10% respectively was achieved at $x^+ = 10.9 * 10^3$. It is believed this occurred due to the cavity array being small enough to be intrusive to the streamwise boundary layer. Consequently, the flow which acts normal to the wall, commonly associated with coherent structures to be impacted upon by the array. The conclusions drawn here are based on the results along a single cavity array.

References

[1] Zheng, XF, Yan, YY, 2010, *'A Biomimetic Smart Control of Viscous Drag Reduction'*, *Advances in Natural Science*, vol. 3, no. 2, pp. 139-151.

[2] Marec, J, 2000, *'Drag reduction: A major task for research', European Drag Reduction Conference 2000*, Springer Verlag.

[3] Corino, ER, Brodkey, RS, 1969, *'A visual investigation of the wall region in turbulent flow', Journal of Fluid Mechanics*, vol. 37, part. 1, pp. 1-30.

[4] Grass, AJ, 1971, *'Structural features of turbulent flow over smooth and rough boundaries', Journal of Fluid Mechanics*, vol. 50, part. 2, pp. 233-255.

[5] Offen, GR, Kline, SJ, 1975, *'A proposed model of the bursting process in turbulent boundary layers', Journal of Fluid Mechanics*, vol. 70, part. 2, pp. 209-228.

[6] Kim, HT, Kline, SJ, Reynolds, WC, 1971, *'The production of turbulence near a smooth wall in a turbulent boundary layer', Journal of Fluid Mechanics*, vol. 50, part. 1, pp. 133-160.

[7] Smith, BL, Glezer, A, 1998, *'The formation and evolution of synthetic jets', Physics of Fluids,* vol. 10, pp. 2281–2297.

[8] Lockerby, D, 2001, *'Numerical simulation of boundary-layer control using MEMS actuation', Ph.D. Thesis*, The University of Warwick, England, UK.

[9] Ghanadi, F, Arjomandi, M, Cazzolato, BS, Zander, AC, 2014a, *'Understanding of the flow behaviour on a Helmholtz resonator excited by grazing flow', International Journal of Computational Fluid Dynamics*, vol. 28, no. 5, 219–231.

[10] Ghanadi, F, Arjomandi, M, Cazzolato, BS, Zander, AC, 2015, *'Analysis of the turbulent boundary layer in the vicinity of a self-excited cylindrical Helmholtz resonator', Journal of Turbulence*, vol. 16, 705-728.

[11] Silvestri, A, Ghanadi, F, Arjomandi, M, Cazzolato, BS, Zander, AC, 2016, '*The characteristics of the turbulent boundary layer generated by induced transition using different tripping techniques'*, submitted to *Experimental Thermal and Fluid Science.*

[12] Robinson, SK, 1991, *'Coherent motions in the turbulent boundary layer', Annual Review of Fluid Mechanics*, vol. 23, pp. 601-639.

[13] Silvestri, A, Ghanadi, F, Arjomandi, M, Cazzolato, BS, Zander, AC, 2016, '*Attenuation of sweep events in a turbulent boundary layer using micro-cavities'*, submitted to *Experiments in Fluids.*

[14] Blackwelder, RF, Kaplan, RE, 1976, '*On the wall structure of the turbulent boundary layer', Journal of Fluid Mechanics*, vol. 76, part 1, pp. 89-112.