THE EFFECT OF THE BACKING CAVITY ON THE CONTROL OF THE TURBULENT BOUNDARY LAYER BY THE APPLICATION OF A CAVITY ARRAY

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ABSTRACT

The streamwise velocity fluctuations within a fully developed turbulent boundary layer has been investigated downstream of a flushed-surface cavity array underneath a flat plate. 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. This study investigates the effect of the backing cavity volume on attenuation of turbulent energy production within the logarithmic region of the turbulent boundary layer. To this end the turbulence intensity profile and sweep attenuation for three different backing cavity volume have been investigated. All measurements were taken in a closed-loop low turbulence wind tunnel at two different free stream velocities. The results show that when the backing cavity's volume is equal to $V^+=3\times10^3$ the turbulence intensity and sweep intensity are reduced by up to 8% and 7.2% respectively. From this investigation it has been shown that the dampening of sweep events is not solely due to the walls of each individual cavity.

INTRODUCTION

The most important flow structure of a turbulent 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 (Corino and Brodkey 1969, Guo et al. 2010). These two events were shown to be self-replicating. It was shown that ejection events generated approximately 70% of the total stresses in the near wall region, while the sweep events contributed to the remaining 30 % (Offen and Kline 1975, Kim et al. 1971) and consequently were deemed to be very important during turbulence generation (Offen and Kline 1975, Guo et al. 2010). It is believed a technique which targets the sweep or ejection events specifically will cause a more significant reduction in turbulence generation and drag (Lockerby 2001, Choi et al. 2011, Ghanadi et al. 2014, Silvestri et al. 2016).

One such technique invesitgated is the passive application of the cavity array to reduce the turbulence generation has been considered by the authors (Silvestri et al. 2016, Silvestri et al. 2017a) due to the easy implementation and absence of a power source, which is favourable for aerospace applications. It was observed that by using a cavity with a small orifice diameter $(d^+ < 10)$ the shear layer is unaffected crossing the opening, ensuring the resonance of the Helmholtz mode is not achieved (Ghanadi et al. 2015). Consequently only the flow which acts normal to the wall will be affected by the cavity array, as the streamwise profile will be unaffected. In the near-wall region the sweep and ejection events act in this direction and consequently, this will have the potential to use the cavity array as a drag reduction method for both high and low Reynold's numbers. This has been shown previously by Silvestri et al. (2016 & 2017a) to be highly successful in reducing the turbulence intensity and sweep intensity after control was applied where a maximum reduction of 13% and 14% was achieved respectively at a Reynolds number $1.69 \times 10^5 <$ $Re_{\theta} < 1.18 \times 10^{6}$.

The events which do enter the cavity array are expected to be dampened by the walls of the cavity and/ or by the large mass of fluid beneath the orifice in the backing cavity. 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 and the effect of the backing cavity's volume on its ability. In the subsequent sections the characteristics of the cavity array will be discussed and details of the experimental setup will be given.

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, approximately 0.53%. The test section is rectangular with a cross section of 500mm × 500mm an 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 walls could also be adjusted as appropriate to balance the pressure gradient along the working section, which was selected to be a zero pressure gradient in this investigation. 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. (2017b). This was done to ensure a fully turbulent boundary layer was achieved for the experimental procedure.



Figure 1: Schematic of the experimental arrangement

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 $(x^+ = 5.07 \times 10^4)$ downstream of the leading edge. This was done three times with a backing cavity of varying dimensions to monitor the effect the backing cavity had on the boundayr layer. The streamwise velocity measurements were made with a TSI IFA 300 CTA system, using a single TSI platinum-plated tungsten wire of $5\mu m$ in diameter and 1.25mm in length, which was operated 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 20 kHz for 15 seconds.

As shown in Figure 2, the cavity array has a varing backing cavity. This was achieved by using backing faces with different geometries to restrict the total volume of the bakeing cavity. The friction velocity value equal to,

 $u_{\tau} = 0.5 m/s$, previously calculated by Silvestri et al. (2017b) was used to design the cavity arrays dimensions. Using this friction velocity value the spanwise and streamwise spacing and the approximate orifice diameter were calculated based on the method specified by Lockerby (2001), which states that the orifice diameter to be 40 times the viscous length scale and the spanwise spacing to be 100 times the viscous length scale. These approximations were based on the expected size of the coherent strutures in the boundary layer. This resulted in a cavity array comprising 1.2mm diameter holes and a spanwise spacing of 3mm. The cavity array plate was manufactured using a 3D printer with a constant streamwise spacing of 15mm and constant thickness of 4mm as shown in Figure 3. Literature states that the length of coherent structures can be up to 10 times the spanwise spacing (Blackwelder and Eckelmann 1979) Consequently 15mm falls well below this value. In order to investigate the effect of momentum thickness on the turbulence generation within the boundary layer, all measurements have been conducted at two different Reynolds numbers of $Re_{\theta} = 1927$ and 3771





EXPERIMENTAL RESULTS

Figure 4 shows the streamwise profile of the boundary layer immediately downstream of the cavity arrays and the corresponding unaltered turbulent boundary layer for comparison. The three backing cavity arrays investigated appear to shift the viscous and logarithmic subregion $(y^+ < 200)$ upwards, while not changing the overall boundary layer thickness. This effect is expected to result in a drag reduction as shown by (Savins and Seyer 1977, Patterson et al. 1977, Hooshmand et al. 1983) where an upward shift of the logarithmic region results in a decreased friction velocity and skin friction coefficient.



Figure 4: Mean velocity profile at $Re_{\theta} = 3771$. (o) No control, (Δ) $V^+ = 300$, (+) $V^+ = 1500$, (x) $V^+ = 3000$

This reduction is also clearly evident in Figure 5, which shows the turbulence intensity of the same boundary layers investigated. The cavity array is shown to provide a substantial turbulence intensity reduction within the logarithmic region $15 < y^+ < 200$ for all the backing cavities investigated. The largest backing cavity ($V^+ = 3000$) was shown to cause the largest turbulence intensity reduction by 8%. This value was shown to decrease when investigating the other backing cavities, where the values decreased to 3.3% ($V^+ = 300$) and 4.5% ($V^+ = 1500$).



Figure 5: Turbulence intensity profile at $Re_{\theta} = 3771$. (o) No control, (Δ) $V^+ = 300$, (+) $V^+ = 1500$, (x) $V^+ = 3000$

This efffect is also shown to continue at a lower Reynolds number. Figure 6 shows the effect of the backing cavity on the turbulence intensity at a Reynolds number of $Re_{\theta} = 1927$. Similar to the previous figure the largest backing cavity ($V^+ = 3000$) was shown to cause the largest turbulence intensity reduction of 5.6%. As also shown in Figure 6, when the backing cavity volume is reduced by half the turbulence intensity decreases by approximately 3.5% ($V^+ = 1500$). Significant reduction in the backing volume, $V^+ = 300$, results in a turbulence intensity reduction of 2.0%.



Figure 6: Turbulence intensity profile at $Re_{\theta} =$ 1927. (o) No control, (Δ) $V^+ = 300$, (+) $V^+ =$ 1500, (x) $V^+ = 3000$

A variable interval time averaging (VITA) technique has also been used to detect the changes in the turbulent boundary layer associated with coherent structures. The technique was initially applied by Blackwelder and Kaplan (1976) for studying the near wall region and detecting the sweep and ejection events. The VITA analysis for the current boundary layer analysis will focus on the sweep events, since these are the major contributor to turbulent skin friction (Orlandi and Jimenez, 1993). The sweep events are monitored by calculating the VITA of the streamwise velocity fluctuations according to the definition

$$\hat{u}(t, T_W) = \frac{1}{T_W} \int_{t-T_W/2}^{t+T_W/2} u(s) \, ds, \tag{1}$$

The intensity of the events is calculated based on the peak-to-peak value of the streamwise velocity of the events. The duration on the other hand is calculated from the time separation of the peaks in each VITA analysis. Increased duration or intensity of the events reveals an increase in the turbulence energy production. Throughout the investigation a total of 950 ensembles were used in

each VITA analysis. This occurred at a $Y^+ = 100$ for all cases investigated.

At $Re_{\theta} = 3771$ the cavity array was shown to have an effect in reducing the duration and intensity of the sweep events also. Figure 7 shows a maximum reduction in sweep intensity of 7.2% when using a backing cavity of $V^+ = 3000$, whilst the reduction that occurs when using the other backing cavities were reduced by only 3.4% ($V^+ = 300$) and 4.4% ($V^+ = 1500$). Sweep duration however was shown to remain unaffected.



3771 at $Y^+ = 100$. (o) No control, (Δ) $V^+ = 300$, (+) $V^+ = 1500$, (x) $V^+ = 3000$

This efffect is also shown to continue at a lower Reynolds number similar to the turbulence intensity. Figure 8 shows the effect of the backing cavity on the sweep intensity at a Reynolds number of $Re_{\theta} = 1927$. A maximum reduction in sweep intensity of 6.2% was achieved when using a backing cavity of $V^+ = 3000$, whilst the reduction that occurs when using the other backing cavities investigated differ as the intensity was reduced by only 3% ($V^+ = 300$) and 3.1% ($V^+ = 1500$). Sweep duration however was once again shown to remain unaffected by the cavity array at all backing volumes



DISCUSSION

It has been hypothesised that the cavities operate by capturing the sweep events and consequently disrupt the overall bursting phenomenon in the boundary layer. It is however unclear what happens to the sweep events as it enters the cavity array. One hypothesis from the authors is that the sweep event's energy is dampened by the cavity array's walls and the backing cavity's volume. This would therefore result in the backing cavity having an effect on the reduction of the turbulent energy production.

However an alternative theory would result in the turbulence energy reduction being independent of the backing cavity's volume. While the cavity array would still form an integral part of passive mechanism, a conservation of energy would occur in the device resulting in no loss of the sweep energy. The corresponding reduction would be a result of a captured sweep event's energy being ejected back into the turbulent boundary layer across all of the cavity array's individual openings. Consequently each event would be redistributed across the large amount of holes resulting in a small, but unnoticeable change in the boundary layer while still retaining the turbulence energy reduction and conservation of momentum from removing a sweep event from the inner wall region of the boundary layer.

While both hypothesises described above appear plausible the results from this work suggest the former hypothesis to be valid. Throughout the work presented a clear trend can be identified where by reducing the backing cavity's volume a reduction in the control of the turbulent boundary layer is visible. This difference is quite significant when comparing the values. At the largest backing cavity volume ($V^+ = 3000$) a significant 7.2% and 6.2% reduction in sweep intensity is achieved at the largest and smallest Reynolds numbers investigated. However at the smallest backing cavity volume $(V^+ = 300)$ this value is a reduced to only 3.4% and 3% respectively. As mentioned above if the backing cavity only acted as a channel to link all the cavities together to allow the redistribution of the sweep event's energy then it would be expected that these values are much more similar in value.

CONCLUSION

The basis of this paper, is the study of a cavity array as a potential control technique in reducing skin friction drag. In this study the effect of the backing cavity's volume was specifically investigated and two mechanisms were considered. The characteristics of the boundary layer were analysed using hotwire anemometry at a single locations where the results were used to calculate the streamwise boundary layer profile, turbulence intensity and the properties of the coherent structures.

It has been shown that the dampening of sweep events is not solely due to the skin friction loses from the walls of each individual cavity, as the backing cavity volume also has a significant effect on the sweep attenuation values, where a maximum reduction of 7.2% was achieved when the backing cavity's volume was selected to be V = $5.1 \times 10^{-3} m^3 (V^+ = 3000)$.

The conclusions drawn here are based on the results along a single cavity array. Future work intends to focus more intently on the volume of the backing cavity and if the effect continues for other cavity arrays with different geometries. Furthermore future work will endeavour to analysis the effect of having a backing cavity with zero volume. The results presented here are only the beginning of the development of the knowledge required for this area of work.

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