AN EXPERIMENTAL STUDY OF A PULSED AIR JET AND AN ACOUSTIC SYNTHETIC JET ON A LOW SPEED TURBULENT BOUNDARY LAYER

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Abstract

This experimental study compares the effectiveness of steady and pulsed air jet vortex generators (AJVGs) with an acoustic synthetic jet. The results showed that: i) The flow physics associated with the formation of the boundary later embedded streamwise vortices by steady AJVG blowing is different to that occurring with corresponding pulsed air jet blowing, where a well defined vortex does not appear to be forming. This supports the view that the physical mechanism involved with pulsed air jets involves the formation of a "train" of discrete vortical structures which locally promotes significant levels of mixing and boundary layer re-energization. ii) Acoustic synthetic jets, at least using the technology employed in this study, cannot cause the large scale distortions of turbulent boundary layers in moderate to high speed flows which are seen with AJVG blowing and are known to be effective in promoting the high levels of mixing necessary for the re-energization of turbulent boundary layers.

1 Introduction

This paper presents experimental results comparing the effectiveness of steady and pulsed air jet vortex generators (AJVGs) and corresponding acoustic synthetic jets, for the formation of streamwise boundary layer embedded vortical structures, known to be effective in the re-energization of turbulent boundary layers.

1.1 Steady Blowing Air Jet Flow Control

Various flow control techniques, to reenergise boundary layers and thereby suppress flow separation, have been identified and successfully tested, such as slot blowing, tangential blowing and synthetic jets. The method of increasing fluid mixing rates by the artificial generation of near surface longitudinal vortices has been found to be a particularly powerful technique. The vortices act to entrain high-energy flow from the undisturbed outer air stream and transport it into the low momentum near-wall region deep inside the boundary layer. Mechanical, passive, vane vortex generators, first devised by Taylor and Hoadley[1] (1948), are the most common and widely used streamwise fluid vortex generators, and commonly consist of thin solid strips fixed to the surface, usually located ahead of a separated flow region, at an angle to the on-coming flow. However, it has been shown that these impose an increase in drag, caused by both the flow blockage by the device itself, and by an increase in surface skin friction downstream of the device.

An alternative to passive solid vane type vortex generators is an active fluid vortex-generating device, which was proposed by Wallace[2] (1952). The idea was to use fluid injection via inclined and skewed (relative to the freestream flow vector) vortex generating jets, to induce longitudinal vortices for flow control, instead of solid vane type vortex generators. Air jet vortex generators usually consist of an array of small orifices, embedded on a surface and supplied by a pressurized fluid source, wherein longitudinal vortices are induced by the interaction between the jets issuing from each orifice and a moving fluid along the surface, as shown in Figure 1.

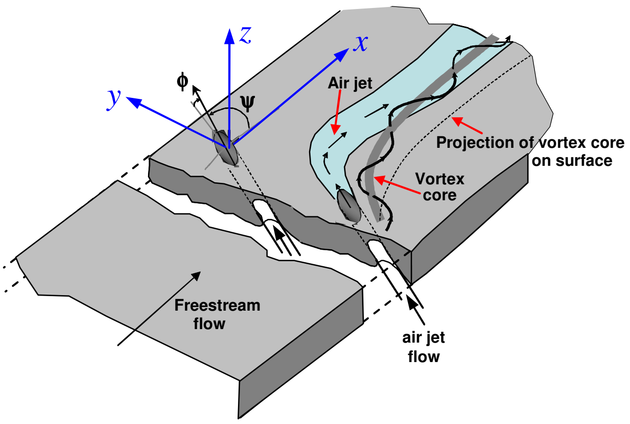


Fig 1: Schematic of.steady air jet flow / streamwise vortex generation.

The orifices can be pitched with respect to the surface tangent and skewed with respect to the moving fluid over the surface. Air jet vortex generators, unlike passive, mechanical vane type vortex generators, do not induce a large increase in drag and they can be actively operated and controlled, depending on the flow characteristics over a surface.

Pearcey[3] (1961) undertook a series of experimental studies showing that AJVGs could effectively by employed to bifurcate transonic shock wave / boundary layer interactions and control shock induced separation, in a similar way to vane vortex generators. Freestone[4] (1985) performed a study of both vane vortex generators and AJVGs (with both circular and rectangular jet orifices) at low speeds and identified that the optimum jet orientation for maximum vorticity generation was a pitch angle, ϕ, (relative to the local surface tangent) of 30^o and a skew angle, ψ, (relative to the freestream flow vector) of 60^o. With this orientation Freestone showed that the resulting vortex strength could match and, in some cases, exceed that generated by an equivalent vane vortex generator.

Compton & Johnston[5] (1992) undertook another extensive study, this time performing a parametric investigation of air jet skew angle and jet velocity ratio, where the co-rotating AJVG array, consisting of circular jet orifices pitched at a constant 45^o, was used to suppress low speed turbulent boundary layer separation due to a strong adverse pressure gradient. The authors compared their own results for AJVGs with those of Pauley & Eaton[6] (1988) and concluded that:

- The thinning of the boundary layer in the downwash region of the longitudinal vortex appears to coincide with the local increase in the skin friction.
- Maximum streamwise vorticity is strongly dependent on the jet to freestream velocity ratio, *VR*, and the skew angle of the AJVG, and the location of maximum vorticity appears to be underneath the centre of the longitudinal vortex.
- The optimal skew angle for this experimental arrangement was 45 - 90^o.
- The rate of streamwise vorticity decay in a longitudinal vortex, induced by an AJVG, is more rapid immediately following the initial formation, compared to a solid vane vortex generator, but significantly lower further downstream.
- Longitudinal vortices induced by solid vane vortex generators have extremely low velocity cores, in the centre of the vortical region, these very low velocity regions were not detected in longitudinal vortices induced by air jet vortex generators, even with the low velocity ratios investigated (0.7 - 1.3).

The results of subsequent studies[7-11], both experimental and computations, verified these findings.

1.2 Pulsed Air Jet Blowing Flow Control

The first exploratory study of unsteady blowing flow control on a wing section was by Oyler & Palmer[12] (1972) who developed an unsteady tangential blowing system on a trailing edge flap. Their experiments demonstrated a significant improvement of stall suppression, and corresponding maximum lift capability, compared to steady blowing of equivalent total mass flow.

During the following years, many researchers[13-24] have conducted extensive fundamental studies of free turbulent mixing layers using artificial unsteady flow excitation, by means of mechanical oscillators. They highlighted the complex flow physics and fluid dynamic benefits of introducing periodic disturbances to control the mixing of a fluid flow.

1.3 Acoustic Synthetic Jet Flow Control

Synthetic jet actuators for active unsteady separation control have been in the focus of unsteady flow control research during the last decade. This type of active flow control usually involves small-scale high-frequency cyclic actuation of enclosed air cavities, with small exit holes for oscillatory suction/blowing, with the aim of manipulating the external flow field. The actuator usually consists of an oscillating elastic surface or diaphragm within a cavity, as shown in Figure 2, which generates a suction/blowing cycle without mass injection, since the net air mass ingested is expelled out of the orifice.

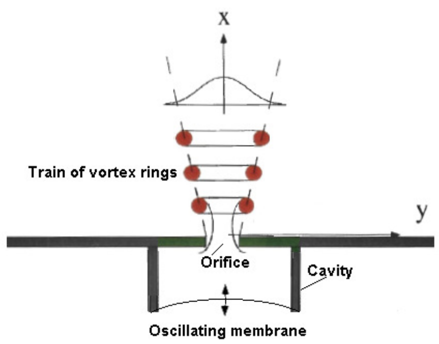


Fig 2: Schematic of acoustic synthetic jet flow.

The synthetic jet is composed entirely of entrained fluid synthesized by the formation of a time-harmonic train of ring vortices that are created at the sharp edges of the orifice and shed at high frequencies. The fluid is drawn into the cavity by the low pressure created within, and then expelled out of the cavity by the time periodic motion of an oscillating diaphragm or by an oscillatory pressure-inducing static or dynamic source. Actuators of these types have been shown to exercise significant control authority in many applications including; separation control, heat transfer, thrust vectoring and turbulence control.

The manipulation of a boundary layer by unsteady aero-acoustic excitation is not a new idea. The earliest documented attempt was by Schubauer & Skramstad[25] (1948), who introduced periodic acoustic perturbations to trigger Tollmien-Schlichting waves, initiating a premature transition from a laminar to turbulent boundary layer. They observed that sound at a particular frequency and amplitude could enhance the momentum exchange within a boundary layer. It was Ingard & Labate[26] (1950) and Ingard[27] (1953) who later discovered the original concept of the acoustic actuator, which induced a cyclic zero-net mass-flux jet like flow from an orifice. Ingard et al. used standing waves in an acoustically driven circular tube, to induce an oscillating velocity field in the vicinity of an orifice plate, placed near a pressure node and observed the formation of a jet formed from trains of vortex rings shed at high frequencies on both sides of the orifice, with zero net mass flux. Applying this knowledge Lebedeva[28] (1980) created a jet with velocities of up to 10 m/s, by transmitting high amplitude sound waves (150 dB) from an enclosed chamber.

Acoustically driven synthetic jet actuators commonly use loudspeakers, as an oscillatory pressure source, by inducing periodic waves inside the cavity. This concept has been explored for flow control purposes by a number of researchers including, Huang et al.[29] (1987), Erk[30] (1997), McCormick[31] (2000) and Nagib et al.[32] (2001). Acoustic based designs are compact, light, simple and reasonably reliable actuator systems. The main drawbacks of acoustic based SJA designs, however, are low jet exit velocities depending on the size and power of the speaker. The effect of the small compact speaker-based actuator is limited to a few aerodynamics applications such as boundary layer transition and turbulence manipulation, but larger high power speakers, could be capable of producing jet exit velocities that can be used to control flow separation at higher speeds.

2 Experimental Details

2.1 The Wind Tunnel and Instrumentation

The experiments were performed in the City University T4 (0 – 40m/s) open return wind tunnel, where the air jets were applied to the upper working section wall boundary layer. The working section has a rectangular cross-sectional shape being 1830mm in length and 560 x 400mm in cross-section. Tunnel flow speed was measured, to an accuracy of ±0.1m/s, using a pitot-static probe mounted from the bottom wall of the working section.

The dynamic pressure profile through the tunnel wall boundary layer / vortex was acquired using a 46 probe pitot rake shown in figure 3, which also incorporated two static pressure tubes. The pressures were measured using a high-sampling rate, 64 channel, electronic pressure scanner. The position of the rake could be changed by sliding it along a longitudinal track hung from two transverse supports, attached to the lower wall of the tunnel, and could be moved across the tunnel to any measurement positions. The accuracy to which these boundary layer / vortex measurements were acquired was about ±0.1m/s, except in the locality of a strong vortex core, where accuracy (degraded by strong lateral velocities) is estimated at around ±1m/s.

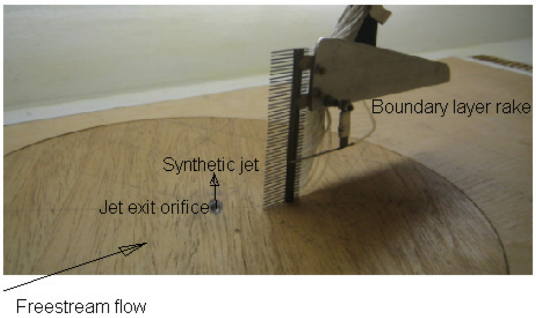


Fig 3: Experimental arrangement of boundary layer rake.

2.2 Steady/Pulsed Air Jet Design

Pulsed air actuation was achieved using the Synerject air injector detailed in ref 24. The air jet was delivered through a 4.8mm ID circular pipe which was pitched at 30° to the upper tunnel wall (*x-y* plane) and skewed at 60° to the freestream direction (*x-z* plane). The literature shows that this orientation is within the optimum range for maximum vorticity generation in the boundary layer.

The air injector was driven with a square wave signal input at a duty cycle of 50% and at frequencies up to 300Hz, as well as in steady blowing mode. The air jet exit velocity was calibrated by traversing a dynamic pressure probe through the air jet, measuring the jet-axis velocity profile at tunnel freestream velocities, U, of 25, 30 and 35m/s and blowing pressures, p_b, of 20, 30 and 40psi. The resulting values of jet to freestream velocity ratios are given in table 1, while figure 4 presents a typical dynamic pressure output trace for a 5Hz pulsing frequency.

	U (m/s)		
p_b *(psi)*	25	30	35
20	1.6	1.3	1.1
30	2.4	2.0	1.7
40	3.2	2.7	2.3

Table 1: Variation of jet to freestream velocity ratio (VR) with freestream velocity and blowing pressure.

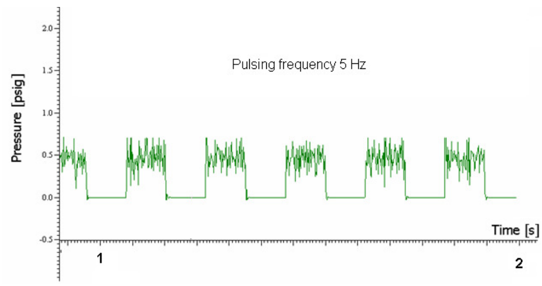


Fig 4: Typical measured jet output dynamic pressure trace.

2.3 Synthetic Jet Design

An acoustic synthetic jet actuator (SJA), illustrated in figure 5, was developed using a simple cone shaped cavity of diameter of 75 mm and a depth of 18 mm with an inclined tube of diameter 4.8mm ID connecting the cavity with the upper wind tunnel wall. The dimension for cavity volume and port length was determined using the Helmholtz cavity resonance formula, with the aim of inducing a cavity resonance frequency of about (100Hz) close to the speaker resonance frequency, in order to amplify the jet exit pressure. The jet orifice was oriented with 30° pitch and 60° skew so as to be equivalent to that of the pulsed air jet experiment.

The speaker used in the experiment as the diaphragm for the SJA was the VISATON SC8N8 8 ohm, magnetically shielded 8 cm speaker with full-range driver and a cellulose cone with an inverse rubber shielding.

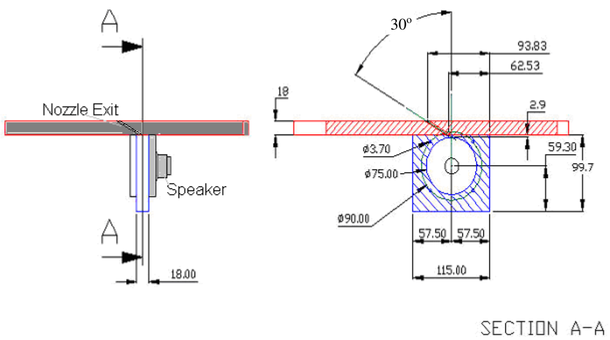


Fig 5: The acoustic synthetic jet actuator design.

The characteristics of the air jet generated by the SJA were measured using a dynamic pressure probe using the same method outlined for the pulsed air jet case. Figure 6 presents a typical output dynamic pressure trace as well as the variation of average output velocity with driving frequency.

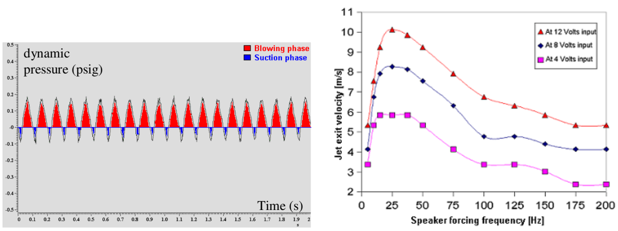


Fig 6: Output characteristics of the SJA

2.4 The Experimental Test Matrix

The experiments were designed to acquire the contour map of the time averaged streamwise component of the flow velocity, through the downstream boundary layer / vortex flow at streamwise stations (constant *y*-*z* planes) of *x* = 50, 100, 200, 300 and 400mm. The rake was traversed 100mm across the span, from *y*=-20mm to *y*=80mm, with measurements taken at intervals of 5mm.

An initial experiment, designed to capture the evolution of the streamwise vortex generated by a steady blowing jet, with a jet to freestream velocity ratio (*VR*) of 2.0, was first undertaken to identify the spanwise extent of the disturbed boundary layer.

For the subsequent steady / pulsed air jet experiments, measurements were taken for each of the nine cases (freestream velocity and blowing pressure combinations) given in table 1, with readings taken for pulsing frequencies of 0 (steady), 1, 5, 10, 50 and 100Hz pulsing frequencies. For the synthetic jet cases, measurements were taken for pulsing frequencies of 5, 10, 25, 50 and 100Hz , all with a driving voltage of 12V.

3 Results and Discussion

3.1 Assessment of AJVGs

3.1.1 Streamwise Vortex Formation by Steady Blowing, VR=2.0.

Figure 7 presents the measured contours of the average streamwise component of velocity, $\bar{u}_x$, at the five measurement stations downstream of the air jet for the freestream speed of U = 30m/s with steady blowing at VR = 2.0, together with the measured, undisturbed, boundary layer at x=50mm with the air jet smoothly sealed with a full span strip of selotape.

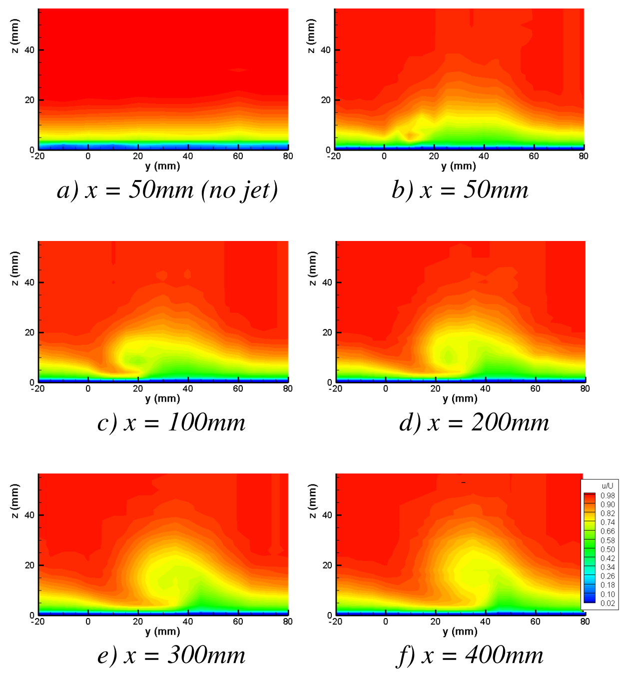
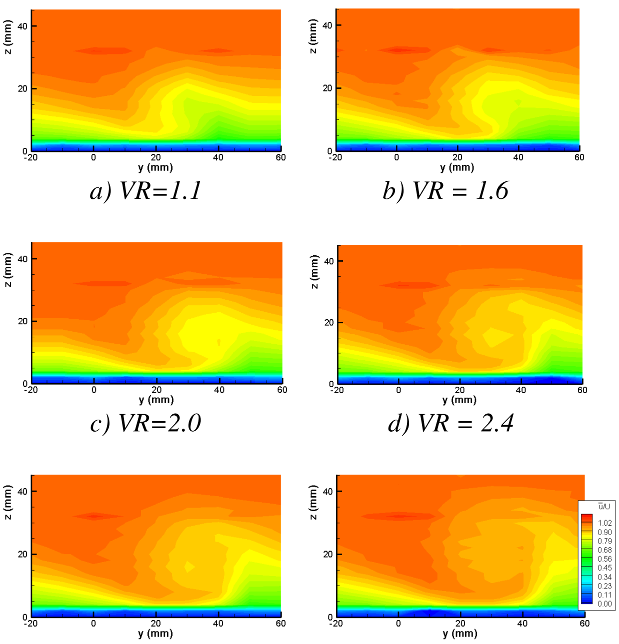


Fig 7: Contours of Streamwise Component of Velocity. Steady Blowing. U=30m/s, VR=2.0.

Steady air jet blowing at *VR*=2.0, with orientation 30^o pitch and 60^o skew angles, can clearly be seen to effectively induce the roll-up of a strong streamwise vortex. The vortex core, which is seen to be formed by 100mm downstream of the jet itself, is seen to have a significant velocity deficit. The vortex persists with a clearly identifiable core, and a feeding shear layer swept up from the thinned out boundary layer below. This result confirms that the strong boundary layer embedded streamwise vortices generated by AJVGs at modest values of *VR* can penetrate well downstream of the air jet orifices before breakdown.

3.1.2 The Effect of the Jet to Freestream Velocity Ratio.

The questions addressed in the analysis of this section are i) what is the effect of *VR* on the strength and structure of the boundary layer embedded streamwise vortices generated by AJVGs, and ii) does pulsed air jet blowing through pitched and skewed air jets act to generate coherent vortex structures in the same way as steady blowing air jets?



a) VR=1.1 *b) VR = 1.6*

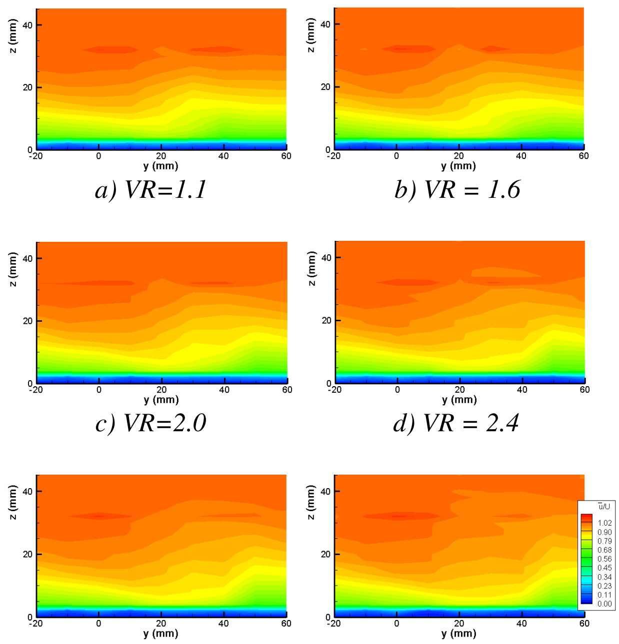
c) VR=2.0 *d) VR = 2.4*

e) VR=2.7 *f) VR = 3.2*

Fig 8: Contours of Streamwise Component of Velocity. Steady Blowing, x = 400mm.

Figure 8 presents the contours of $\overline{u}_x$ at the crossflow plane at *x*=400mm, for a range of jet to freestream velocity ratios. Interestingly, a *VR* as low as 1.1 is seen to be capable of generating strong streamwise vortices far downstream of the air jet orifice. With a *VR* of 3.2, the vortex is significantly larger and more fully developed, causing a greater distortion of the boundary layer and external flow, with a much reduced velocity deficit in its core.

The corresponding result for pulsed blowing at 1Hz pulsing frequency is plotted in figure 9. While there is evidence of significant boundary layer distortion with 1Hz pulsed blowing with *VR*=1.1, it appears that the boundary layer is affected in a similar way as steady blowing (a thinning in the region immediately down span of the air jet axis, followed by an abrupt thickening. However the spanwise flow is not, in this case, strong enough to cause a significant crossflow separation and associated streamwise vortex.



a) VR=1.1 *b) VR = 1.6*

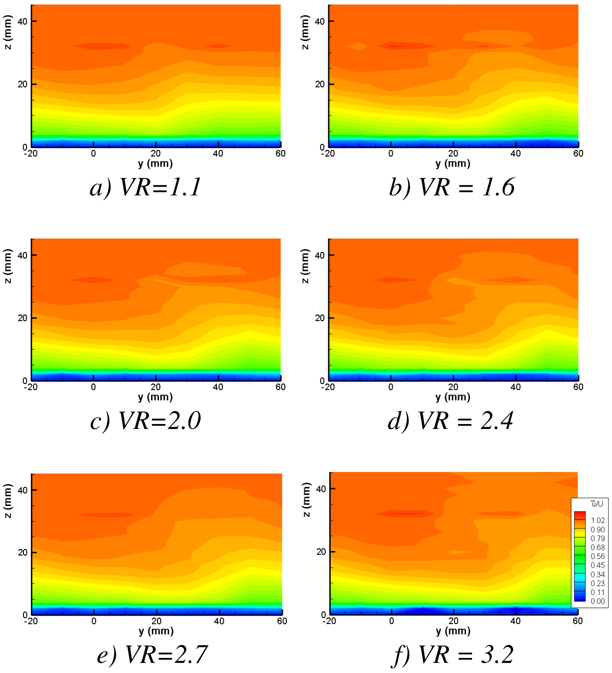
c) VR=2.0 *d) VR = 2.4*

e) VR=2.7 *f) VR = 3.2*

Fig 9: Contours of Streamwise Component of Velocity. Pulsed Blowing at 1Hz,, x = 400mm.

Even with blowing at *VR*=3.2, there does not seem to be evidence of a well structured streamwise vortex. This suggests that at this low pulsing frequency the effect of pulsed injection of air into the boundary layer is not the formation of a single coherent streamwise vortex, but perhaps a procession of vortical eddies convecting downstream through the boundary layer. The effect of increasing the jet *VR* is to force the occurrence of boundary layer thickening further down span.

A similar result is found when analyzing the measurements obtained at the same station for a pulsing frequency of 100Hz, shown in figure 10. No significant difference in the structure of the contours of time averaged streamwise velocity component can be distinguished when comparing the 1Hz and 100Hz blowing results.



a) VR=1.1 *b) VR = 1.6*

c) VR=2.0 *d) VR = 2.4*

e) VR=2.7 *f) VR = 3.2*

Fig 10: Contours of Streamwise Component of Velocity. Pulsed Blowing at 100Hz, x = 400mm.

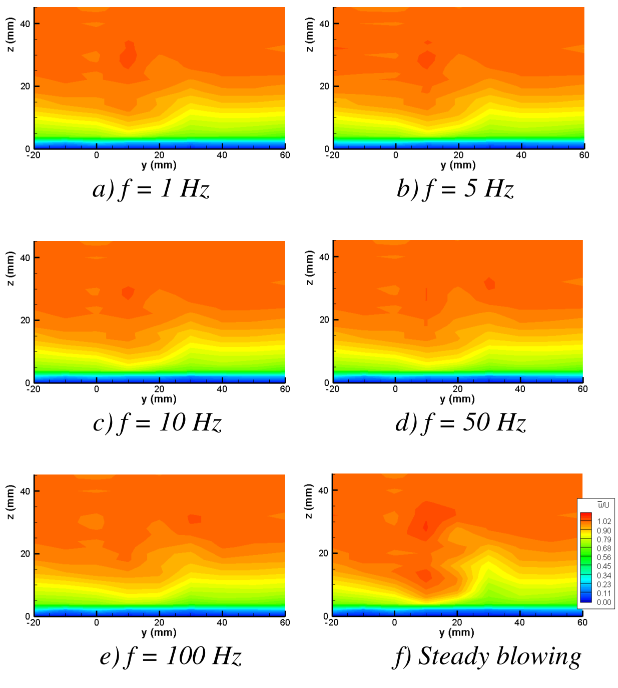
The results for all of the other blowing frequencies and streamwise plane locations all exhibit the same trends as those presented for 1Hz and 100Hz blowing frequencies.

Many studies[17-24] have shown, however, that pulsed air jet blowing, with jet to freestream velocity ratios greater than 1.0, is generally more effective at suppressing downstream boundary layer separation, than that of a corresponding steady blowing air jet (ie: same jet to freestream velocity ratio, but with higher total mass flow rate). This suggests that despite the lack of a strong coherent vortex being formed with pulsed air jet blowing, the resulting periodic forcing of the boundary layer, almost certainly involving a train of vortical eddies passing downstream through the boundary layer, is still able to promote high levels of mixing of the near wall fluid layers.

3.1.2 The Effect of Jet Pulsing Frequency.

The effect of air jet pulsing frequency, for a constant freestream velocity (25m/s) and jet to freestream velocity ratio (3.2), is assessed in this section. Figure 11 presents the time averaged streamwise component of velocity in the crossflow plane at *x* = 100mm for the steady blowing case as well as for pulsed blowing at frequencies from 1Hz to 100Hz.

While there appears to be a significant difference between the result for steady air jet blowing and those for pulsed blowing, the effect of pulsing frequency, in the frequency range investigated, appears to be minimal in the vicinity immediately downstream of the airjet. The structure of the distorted boundary layer, and the location of its minimum thickness is shown to be unchanged by a variation in pulsing frequency of the air jet.



a) f = 1 Hz *b) f = 5 Hz*

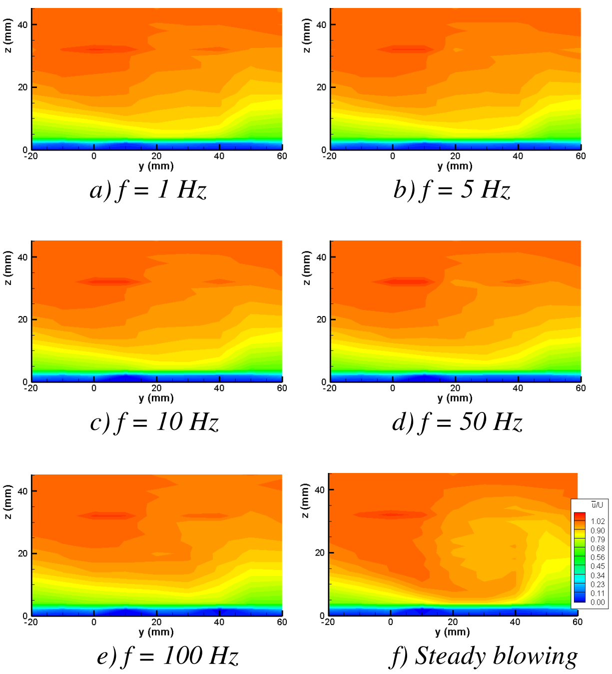
c) f = 10 Hz *d) f = 50 Hz*

e) f = 100 Hz *f) Steady blowing*

Fig 11: Contours of Streamwise Component of Velocity. VR=3.2, x = 100mm.

The same trends were found much further downstream at x = 400mm, the results for which are presented in figure 12. Here the steady air jet blowing results in a circular, well defined, vortex structure with a clearly defined separated shear layer. Pulsed air jet blowing is seen to cause a boundary layer thinning effect analogous, and in broadly the same spanwise location, to that seen with steady blowing, but without the formation of a clearly defined streamwise vortex. The flow structure also appears to remain unaffected by pulsing frequency in the range 1Hz to 100Hz.

The results for the blowing at the other jet to freestream velocity ratios, which are not presented here, follow exactly the same trends. The pulsing frequency of the air jet does not appear to have any effect on the time averaged flow structure downstream of the air jet orifice. Of course, there must be a significant effect of pulsing frequency on the instantaneous structure of the flow, with many more, smaller vortical features being generated with increasing pulsing frequency.



a) f = 1 Hz *b) f = 5 Hz*

c) f = 10 Hz *d) f = 50 Hz*

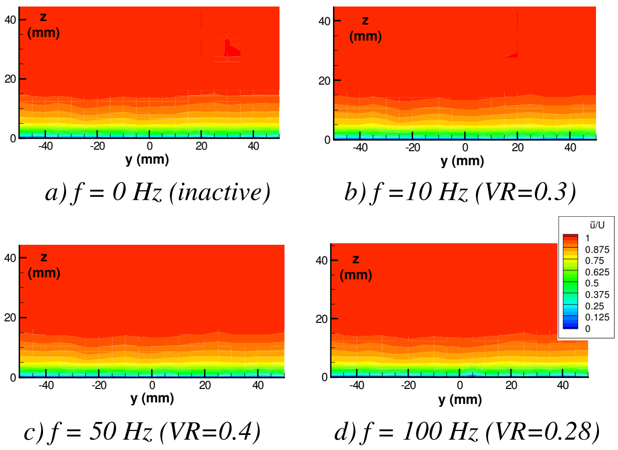
e) f = 100 Hz *f) Steady blowing*

Fig 12: Contours of Streamwise Component of Velocity. VR=3.2, x = 400mm.

3.2 Assessment of the Acoustic SJA.

A series of experiments were performed to assess the acoustic synthetic jet, under exactly the same geometric and freestream conditions as those seen in the AJVG experiments. The SJA was driven at a voltage of 12V to provide a peak jet velocity of 10m/s. In these cases the jet to freestream velocity ratio varies with pulsing frequency.

The results presented in figures 13 and 14 are for the case of the lowest freestream speed of U = 25m/s. Figure 7 presents the measured contours of the average streamwise component of velocity, $\bar{u}_x$, at a crossflow station of x = 50mm downstream of the air jet orifice.

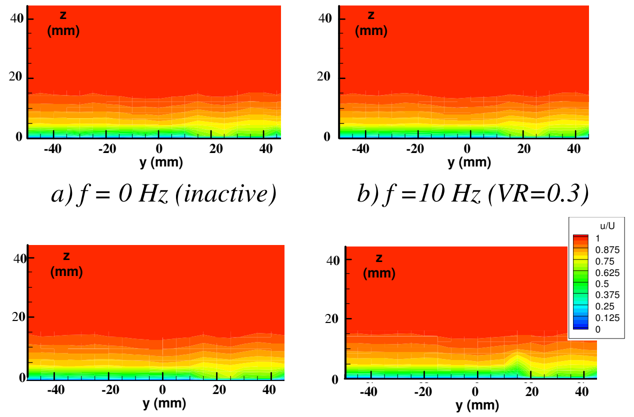


a) f = 0 Hz (inactive) *b) f =10 Hz (VR=0.3)*

c) f = 50 Hz (VR=0.4) *d) f = 100 Hz (VR=0.28)*

Fig 13: Contours of Streamwise Component of Velocity. Synthetic Jet, U = 25m/s, x = 50mm.

The results show that the acoustic synthetic jet, providing such low jet velocities, was unable to distort the time averaged boundary layer flow structure, although the instantaneous flow field will have been significantly affected. Figure 14 presents the corresponding results for a crossflow station at x = 100mm. Here there is some evidence of some localized boundary layer thinning in the vicinity of y = 20 - 22mm indicating some level of distortion of the time averaged velocity field in the boundary layer. This, however, is tiny in relation to the distortions seen with pulsed and steady blowing AJVGs.



a) f = 0 Hz (inactive) *b) f =10 Hz (VR=0.3)*

c) f = 50 Hz (VR=0.4) *d) f = 100 Hz (VR=0.28)*

Fig 14: Contours of Streamwise Component of Velocity. Synthetic Jet, U = 25m/s, x = 100mm.

3.3 General Discussion.

Though the results of this study have been informative, a detailed study of the instantaneous flowfields of this class of flow is required to properly identify the physics of the effectiveness of both pulsed air jets and acoustic synthetic jets to promote the desirable mixing and associated re-energization of "tired" turbulent boundary layers.

4 Conclusions

This study has revealed that:

i) The flow physics associated with the formation of the boundary later embedded streamwise vortices by steady AJVG blowing is different to that occurring with corresponding pulsed air jet blowing, where a well defined vortex does not appear to be forming. This supports the view that the physical mechanism associated with pulsed air jets involves the formation of a "train" of discrete vortical structures which locally promotes significant levels of mixing and boundary layer re-energization.

ii) Acoustic synthetic jets, at least using the technology employed in this study, cannot cause large scale distortions of turbulent boundary layers in moderate to high speed flows. Unless the physics of the way that such low velocity air jets interact with the boundary layer is different to that of pulsed AJVGs, it would seem unlikely that they will be found suitable for the re-energization of high Reynolds number turbulent boundary layers.

The prospect of new synthetic jet actuators, capable of delivering similar levels of jet velocities and mass flow rates as conventional AJVGs would, however, appear to be promising, as these would represent a much better practical proposition for aeronautical flow control.

References

[1] Taylor, H. D., Hoardley H. H., "*Application of Vortex Generator Mixing Principle to Diffusers*" United Aircraft Corporation, Report. R-15064-5, East Hartford, Connecticut, 1948.

[2] Wallis, R. A., "*A Preliminary Note on a Modified Type of Air Jet for Boundary Layer Control*" Aeronautical Research Council, Ministry of Aviation, A.R.C. Technical Report, C.P. No. 513, 1960.

[3] Pearcey, H.H. "*Shock Induced Separation and its Prevention by Design and Boundary Layer Flow Control*" Boundary and Flow Control - Its Principals and Applications, Pergamon Press, Oxford, 1961, pp. 1312-1315.

[4] Freestone, M.M., "*Preliminary Tests at Low Speeds on the Vorticity Produced by Air-Jet Vortex Generators*" Research Memo Aero 85/1, City University London, February 1985.

[5] Compton, D. A., Johnston, J. P., "*Streamwise Vortex Production by Pitched and Skewed Jets in a Turbulent Boundary Layer*" AAIA Journal, Vol. 30, No. 3, March, 1992 pp. 640-647.

[6] Pauley, W. R., Eaton, J. K., "*The Fluid Dynamics and Heat Transfer Effects of Streamwise Vorticies Embedded in a Turbulent Boundary Layer*" Rept. MD-51, Thermosciences Division, Dept. Mechanical Engineering, Stanford, CA, USA, August, 1988.

[7] Lin, J. C., Robinson, S. K., McGhee, R. J., "*Separation Control on High-Lift Airfoils via Micro-Vortex Generators*" Journal of Aircraft, Vol. 31, No. 6, November-December, 1994, pp. 1317-1323.

[8] Henry F. S., Pearcey H. H. "*Numerical Model of Boundary-Layer Control Using Air-Jet Generated Vortices*" Aeronautical Journal, Vol. 32, No. 12, December 1994, pp. 2414-2425.

[9] Innes, F., Pearcey, H. H, Sykes D. M., "*Improvements in the Performance of a Three Element High Lift System by the application of Air-jet Vortex Generators*" Aeronautical Journal, August-September, 1995, pp. 265-274.

[10] Zhang, X., "*Counter-Rotating Vortices Embedded in a Turbulent Boundary Layer with Inclined Jets*" AAIA Journal, Vol. 37, No. 10, October, 1999, pp. 1277-1284.

[11] Bray, T. P., Garry, K. P., "*Optimisation of air-jet vortex generators with respect to system design parameters*" The Aeronautical Journal, October, 1999, pp. 475-479.

[12] Oyler T E, Palmer W E, "*Exploratory investigation of pulsed blowing for boundary layer control*" Report NR 72H-12, North American Rockwell corp. 1972.

[13] Oster D, Wygnanski I, Dziomba B, Fiedler, "*The effect of initial conditions on the two-dimensional turbulent mixing layer*", Lecture noted in physics, vol.75, Berlin: Springer, 1978.pp.48-64.

[14] Oster D, Wygnanski I, "*The forced mixing layer between parallel streams*", J. Fluid Mechanics, Vol.123. pp.91-130, 1982.

[15] Ho CM Huerre P, "*Perturbed free shear layers*", Annual review of fluid Mech, vol: 16.pp.365-424, 1984.

[16] Wygnanski I, Pedersen R.A., "*Coherent motion in excited free shear flows*", AIAA Journal, Vol. 25, No. 2 , pp.201-213, 1987.

[17] Weaver D., McAliser K.W., Tso, J., "*Suppression of Dynamic Stall by Steady and Pulsed Upper-Surface Blowing*" NASA Technical Paper 3600, ATCOM Technical Report 95-A-005, NASA Ames Research Center, 1996.

[18] Wygnanski, I., Seifert, A., Darabi, A., "*A Delay of Airfoil Stall by Periodic Excitation*" Journal of Aircraft, Vol. 33, No. 4, July-August, 1996, pp. 691-698.

[19] Johari, H., Pacheco-Tougas, M., Hermanon, J.C., "*Penetration and Mixing of Fully Modulated Turbulent Jets in Crossflow*" AAIA Journal, Vol. 37, No. 7, July, 1999, pp. 842-850.

[20] Magill, J. C., McManus, K. R., "*Exploring the Feasibility of Pulsed Jet Separation Control for Aircraft Configurations*" Journal of Aircraft, Vol. 38, No. 1, January-February, 2001, pp. 48-56.

[21] Hasegawa H., Matsuuchi K., Tanaka J., "*Generating Mechanism of Longitudinal Vortices using Pulsed Vortex Generator Jets*" JSME International Journal, Series B, Vol. 44, No. 3, 2001, pp. 361-368.

[22] Moore K., Wolff M., Polanka M., Sondergaard R., "*A Large-Scale Investigation of a Flat-Plate Pulsed Vortex Generator Jet in Crossflow Using PIV*" 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Tucson, Arizona, 10-13 July 2005, AIAA-2005-4221.

[23] Scholz P., Casper M., Ortmanns J., Kähler C., Radespiel R. "*Leading-Edge Separation Control by means of Pulsed Vortex Generator Jets*" AIAA Journal, Vol. 46, No. 4, April, 2008, pp. 837-846.

[24] Prince S. A., Khodagolian V., "*Low-Speed Static Stall Supression Using Steady and Pulsed Air-Jet Vortex Generators*" AIAA Journal, Vol. 49, No. 3, March, 2011, pp. 643-654.

[25] Schubauer G. B., Skramstad H. K., "*Laminar boundary layer oscillations and transition on a flat plate*", NACA Rep. 909-1948, 1948.

[26] Ingard, U., and Labate, S., "*Acoustic Circulation Effects and the Nonlinear Impedance of Orifices*" Journal of the Acoustical Society of America, Vol. 22, No. 2, pp. 211–218, 1950.

[27] Ingard, U. "*On the theory and design of acoustic resonators*". J.Acoustical Soc. Of America, Vol. 25., No. 6, 1037–1060, 1953.

[28] Lebedeva I. V., ''*Experimental study of acoustic streaming in the vicinity of orifices*'' Sov. Phys. Acoust. Vol. 26, No. 331, 1980.

[29] Huang, L. S., Maestrello, L and Bryant. D., "*Separation control over an aerofoil at high angles of attack*", AIAA Paper: 87-1261, 1987.

[30] Erk, P. P. "*Separation control on post-stall aerofoil using acoustically generated perturbations*", PhD Thesis, Technical University of Berlin, 1997.

[31] McCormick D. C., "*Boundary layer separation control with directed synthetic jets*" AIAA paper 2000-0519, 2000.

[32] Nagib H, Kiedaisch J, Greenblatt D and Hassan A., "*Effective Flow Control for Rotorcraft Applications at Flight Mach Numbers*", 31st AIAA Fluid Dynamics Conference & Exhibit 11-14 June 2001 / Anaheim, CA, AIAA paper: 2001-2974, 2001.

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