PHASE-LOCKED PIV INVESTIGATION
OF THE EFFECTS OF THE BLOWING RATIO
OF A PULSED VORTEX GENERATOR JET
IN A LOW-PRESSURE TURBINE

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ABSTRACT


At very high altitudes the Reynolds number flow through the low pressure turbine section of the gas turbine engine can drop below 25,000. At these low Reynolds numbers the flow is laminar and extremely susceptible to separation which can lead to increased losses and reduced lift. Small jets of air injected through the suction surface of the airfoil, called Vortex Generator Jets (VGJs), have been shown successful in suppressing separation and maintaining attached flow. Pulsing of these jets has been shown to be as effective as steady jets while reducing the amount of mass flow needed. An experiment using Particle Image Velocimetry (PIV) was set up to study the interaction of the VGJ flow with the main flow. A cascade of Pratt and Whitney Pack-B turbine blades were mounted in the test section of a low speed wind tunnel at Wright Patterson Air Force Base. On the middle six blades were rows of 1mm VGJ holes. The VGJ holes were oriented with a 30° pitch angle and 90° skew angle. The pitch angle is the angle the jet makes with the surface of the turbine blade while the skew angle is the angle the jet makes with the cross-flow. Blowing ratios, a ratio of the jet velocity to the cross-flow velocity, of 0.5, 1, and 2 were examined. These three blowing ratios were selected because they represent when the cross-flow momentum dominates the fluid interaction (B=0.5); when the momentums of the jet flow and cross-flow are equal (B=1); and when the momentum of the jet flow dominates the interaction. Blowing ratios of 0.5 and 1 were studied for pulsing frequencies of 10Hz and 0.4Hz while the blow ratio of 2 was studied only with 10Hz pulsing. A duty cycle of 50% was used for both pulsing frequencies. The two pulsing frequencies allowed data to be taken to show how the pulsed VGJ maintains attached flow (10Hz) and how the pulsed VGJ suppresses the separation bubble (0.4Hz). Results show that jets interacting with separated flow are able to suppress the separation bubble almost immediately for a blowing ratio of 1 and 0.5. The results for suppression and separation growth show the response of the crossflow is very similar in magnitude and timing between the two blowing ratios. The results for the 10Hz pulsing frequency show blowing ratios of 0.5, 1, and 2 are effective. A blowing ratio of 2 is undesirable because it carries more momentum than is needed and would therefore use more massflow than the B=1 or 0.5 case. Results from the B=0.5 case suggest that a blowing ratio of 0.5 is near the minimum effective blowing ratio.
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Nomenclature

\( C_x \)  Axial Chord

\( FSTI \)  Free stream turbulence intensity

\( \delta^* \)  Displacement thickness, \( \int (1 - \frac{u}{U}) \)

\( \theta \)  Momentum Thickness, \( \int \frac{u}{U} (1 - \frac{u}{U}) \)

\( H \)  Shape Factor, \( \frac{\delta^*}{\theta} \)

\( \rho \)  Air Density

\( V \)  Inlet Velocity

\( \mu \)  Viscosity

\( Re \)  Inlet Axial Reynolds Number, \( \frac{\rho V C_x}{\mu} \)

\( u \)  Local boundary layer velocity

\( U \)  Maximum boundary layer velocity

\( C_p \)  Pressure coefficient, \( \frac{p-p_{\infty}}{\frac{1}{2} \rho V_{\infty}^2} \)

\( D \)  Vortex generator jet diameter

\( F^+ \)  Reduced Pulsing Frequency, \( \frac{F C_x}{V} \)
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1

Introduction

1.1 Motivation

During high altitude cruise conditions the Reynolds number, a ratio of the inertial forces of a fluid to the viscous forces, can drop below 25,000. At these low Reynolds numbers the airfoil boundary layer is largely laminar and therefore prone to separation under the influence of the adverse pressure gradient at the rear of the blade. Sondergaard [15], showed a dramatic increase in the loss coefficient as the Reynolds number was decreased. The rise in the loss coefficient happens at the same Reynolds number in which a separation bubble starts to develop. The flow in a separation bubble is very low speed relative to the freestream creating a momentum deficient region. Losses are highest if the flow is unable to reattach before the trailing edge of the blade, although in some cases separated flow is able to reattach. This reattachment is caused by a transition of the flow from laminar to turbulent before the flow reaches the trailing edge of the airfoil. Many researchers have studied boundary layer separation and methods to suppress the separation.

1.2 Literature Review

Dorney [5] compared numerical results of an uncontrolled Pack-B turbine blade to experimental results. Dorney employed two overlapping grids; an O-grid was used near the blade surface while and H-grid was used for the remainder of the freestream flow. The full Navier-Stokes equations were solved on both grids. A fully implicit finite difference method was used to advance solution while convective and viscous terms were evaluated using a third-order accurate upwind-biased Roe scheme and central difference scheme which is second-order accurate in time and space. Linearization and factorization errors at each step were reduced using a Newton-Raphson sub-iteration scheme. Two different turbulence models were used during this study. The first was based on the work of Baldwin
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and Lomax. The second was a two-equation $\kappa$-$\omega$ model based on work by Towne [17]. The numerical simulations were compared to results found by the co-author J. Lake. Lake used the low speed wind tunnel at Wright Patterson Air Force Base with a cascade of Pack-B blades. The test section of the induction type wind tunnel was set to a 95°, turning angle. Single element hot wires were used to read boundary layer profiles, which were used for comparing data, while static pressure taps were used to measure the $C_p$ distribution. Reynolds numbers of 43,000, 86,000, and 172,000 based on inlet velocity and axial chord were studied. The data showed that at low Reynolds numbers the flow transitioned from laminar to turbulent over the separation bubble, but at the highest Reynolds number, 172k, the flow transitioned naturally, before the separation region. Boundary trips, employed in the test, were shown to be beneficial and effective at suppressing separation at low Reynolds numbers. These same trips however were shown to have a parasitic effect at higher, design (non-separating) Reynolds numbers.

Sondergaard [15] looked at the effects of steady blown VGJs applied to the suction surface of the Pack-B low pressure turbine blade profile. Rows of vortex generator jets oriented at 30° pitch (angle from the surface) and 90° skew (angle from the mean flow direction) were independently studied at 45%, 53%, 63%, 73%, and 83% axial chord (Cx). Blowing ratios, the ratio of the jet velocity to the local freestream velocity, of 0 (no blowing), 1, 2, and 4 were studied. Boundary layer velocity and total pressure loss profiles were used to show the effectiveness of the VGJs. Without flow control measures being employed a significant increase in pressure losses occurred as the Reynolds number decreases below 50,000, this is also when flow separation starts to appear. Also noted by Sondergaard was that, after a separation bubble has appeared, further decreasing the Reynolds number increases the area of separation and therefore increases the pressure losses. Sondergaard et al., studied VGJs placed at 63%Cx and showed that increased blowing ratios, the ratio of the jet to the freestream per-area momentum, resulted in substantial reduction in the total pressure loss. They showed that the boundary layer velocity profiles at 68%, 73%, 75%, 77%, 84%, and 92%Cx all indicated attached flow when the VGJs are implemented with a blowing ratio above a critical minimum value, in this case roughly 1.5. Sondergaard et al. also took boundary layer velocity profiles at three spanwise locations between the jets at both 68%Cx and 83%Cx. They found that the boundary layer profiles had noticeable spanwise variations at the upstream location just behind the jets (68%C$_x$) but at the downstream location no noticeable spanwise differences were observed. Sondergaard et al. concluded this indicates that no coherent spanwise differences persist and that the jet vortices tend to mix out. For the VGJs at 63%C$_x$ on the Pack-B airfoil, the minimum effective blowing ratio was found to be between 0.8 and 1 while the blowing ratio which resulted in the greatest decrease in pressure loss coefficient was between 1.5 and 2.0. The pressure loss coefficients actually increased with blowing
rations greater than 3.0 and Sondergaard surmised that this loss increase was most likely due to the VGJs having so much momentum that they blew off the boundary layer, causing premature separation. Sondergaard et al. also studied the influence of injection location. The blowing ratios with the maximum effect at each injection location were measured and compared. The minimum blowing ratio with the maximum effect is about 2 could be located anywhere from 53% $C_x$ to 63% $C_x$, both upstream of the nominal separation location of roughly 71% $C_x$. Also noted in this study was that increasing the freestream turbulence intensity (FSTI) or the Reynolds number reduced the amount of separation and also accelerated boundary layer transition and reattachment. Zhang, 

Zhang [18] used hot-film measurements coupled with surface mounted static pressure taps on the suction surface of a Pack-B in a cascade. 3-hole pressure probe traverses were also used to acquire data. The FSTI levels were varied from 0.4% to 4.5%. Reynolds numbers of 25k, 50k, 100k, and 150k, were examined. The hot-film, quasi-wall-shear stress was analyzed in the time domain and in the frequency domain. Static pressure taps were used to obtain a $C_p$ plot for all run conditions. The point of separation onset was determined from these plots. For the two low Reynolds numbers (25,000 and 50,000) at low FSTI the data show laminar separation and no reattachment. This indicates low entrainment of freestream fluid by the free shear layer. The hot-film data from the same two Reynolds numbers at high FSTI levels indicated laminar separation with turbulent reattachment. This points out that the higher FSTI levels induced earlier transition. Lastly, for the cases with the elevated Reynolds numbers the flow was shown to be turbulent even before the onset of separation. This separation was due to the strong adverse pressure gradient experienced by the flow. This early transition increases entrainment of the freestream into the separated boundary layer causing reattachment. The flow was shown to be in the last stages of transition upon reattachment. Zhang also showed that hot-film, a surface measurement technique, can be used to detect flow separation and reattachment.

Suzen [16] developed a numerical transport model for intermittency which used a multi-block Navier-Stokes code called GHOST and pressure based code called SIMPLE which is 2nd order in time and space. This numerical simulation was compared to three different sets of experimental data obtained by J. Lake [Lake et al. 1999] and [Lake et al. 2000], Corke [Suzen et al. 2003] and R. Volino [Volino 2002]. J. Lake studied Pack-B low pressure turbines in an 8 blade cascade. Each blade had an axial chord length of seven inches. Surface mounted static pressure taps were used to obtain $C_p$ profiles for all cases. Suzen looked at Reynolds numbers of 43k, 86k, 172k with FSTI levels of 1% and 4%. The grid Suzen employed to simulate these results consisted of five zones. Four grids were 125x225 H-grids. The other grid was a 401x101 O-grid. Corke looked at the same profile but examined more Reynolds numbers. The Reynolds numbers he studies included
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10k, 24k, 50k, 75k, and 100k. Three different FSTI levels were studied, 0.08%, 1.6%, and 2.85%, although an FSTI of 0.08% was only employed at 24k. Like Lake, Corke used surface mounted pressure taps to determine $C_p$ plots. Suzen used the same type of grid as used when simulating Lakes study but the code was modified to allow for upstream turbulence generation. Volino looked at $C_p$ plots and boundary layer velocity profiles over the suction surface of the Pack- B. Volino looked at four Reynolds numbers ranging from 10,291 to 82,324. The FSTI was set to 0.5%. To simulate this Suzen used a 31 multi-grid block. In all three cases the numerical results matched the experimental results for the high Reynolds numbers reasonably well. However at lower Reynolds numbers and/or FSTI levels the code under predicted the size of separation bubbles. In the case of Volinos results for Re=20,581 the experimental results showed no reattachment of the separated flow while numerical results suggested reattachment. Also noted was that numerical results tended to show earlier separation and reattachment. Lastly, Suzen showed that the size of the separation bubble decreased with an increase in either FSTI or Reynolds number.

Eldrege [6] studied the effects of steady blown vortex generator jets using two experimental set-ups. They looked at 2.6mm diameter vortex generator jets spaced ten diameters apart oriented with a 30° pitch and 90° skew angle on the suction surface of a Pack-B blade. They also studied 4mm diameters VGJs with the same orientation and relative spacing on a flat plate with a sharp leading edge. Two run conditions were imposed, first, the flow over the flat plate experienced no adverse pressure gradient while the second run condition included an adverse pressure gradient which was created by using a contoured surface opposite the flat plate. Split film anemometers were used in all three experimental set-ups to extract angles and velocities, which indicated the presence of spanwise vortices. The extracted velocities were then used to calculate the shape factors of the boundary layer velocity profiles at different axial positions. These calculated shape factors were then used to determine effectiveness of the applied vortex generator jets. Eldrege and Bons showed that in all cases the application of the vortex generator jets reduced the shape factor to a range of 1.5 - 1.8, indicative of turbulent flow. The effect was observed for separated flow as well as non-separated flow. Non-separated flow had a constant shape factor of 2.5 while shape factors of 3.55 or larger indicated flow separation had occurred. They concluded from this study that wall curvature along with the adverse pressure gradient has a significant effect on jet migration into the freestream. Moore [9] looked at a super-scale 30° pitch vortex generator jet with a diameter of one inch injected into quiescent air. The jet was pulsed at 0.5 Hz with duty cycles of 10%, 25%, 50%, and 100% (steady blowing). Particle image velocimetry as well as a standard X hotwire probe were used to acquire full field velocity contours. They pointed out that each case had distinct beginning and ending events, which they stated were results of the opening and closing of the valve. They also noted that the
starting vortex generated before significant mass flow had exited the jet, and was likely due to a pressure wave caused by the opening of the valve. They showed the starting vortex had the most effect at a duty cycle of 10%. They also proposed the starting vortex is the key to understanding how pulsed vortex generator jets are able to suppress separation despite significantly reduced mass flow compared to the steady jets.

Moore [8] later used the same super-scale vortex generator jet setup to study and characterize the jet flow and its interactions with the boundary layer. They again used the standard X wire probe to obtain time resolved velocity data. They varied only the duty cycle. They showed the development of the starting vortex was the same for all three duty cycles and in all cases the starting vortex had enough time to develop and move away from the jet. They did note that the jet pulse with 50% duty cycle carried more momentum which caused it to penetrate further into the quiescent air. The jet pulse with a 10% duty cycle did not carry enough momentum to penetrate very far but the residual effects were seen for the entire pulsing cycle of the jet. Finally, they noted that the starting vortex was significant a mere 3ms after the valve opens, which they pointed out, could indicate duty cycles as low as 1% could still suppress separation.

Bons [1] studied a Pack-B blade profile in the Low Speed Wind Tunnel at Wright Patterson Air Force Base. He looked at Reynolds numbers ranging from 25,000 to 100,000 and used surface mounted static pressure taps to measure the $C_p$ distribution over the suction surface. These readings showed a plateau where the separation bubble was located. The data showed that although the plot started to plateau at the same axial location, the plateau became smaller as the Reynolds number was increased. Boundary layer profiles taken at 67%, 73%, and 79% $C_x$, by means of a single element hotwire located on a 3-axis traverse, confirm the decrease in size of the separation bubble with an increase in Reynolds number. Boundary layer velocity profiles taken at the same axial locations for the Re=100,000 showed velocity profiles which are consistent with attached flows. Bons then employed steady blown vortex generator jets at 73% $C_x$, which is after the mean separation line, with blowing ratios ranging from 0 to 4. His data showed the injected air flow decreased the wake momentum deficit, but blowing at the higher blowing ratios showed no improvement. He also showed that high Reynolds numbers have the same effect as increasing the free stream turbulence intensity. He said this is due to a reduction of the separation bubble due to boundary layer transition.
Rivir [13] numerically and experimentally studied dimples and VGJs. Dimples located at 50%, 55%, 65%, and 76% $C_x$ as well as VGJs oriented with a 30° pitch and 90° skew located at 45% and 63%$C_x$ were used to control the separating flow over a Pack-B blade. Static pressure measurements were taken using surface mounted pressure taps and velocity measurements were taken using hotwire anemometers on suction and pressure side. The dimple rows were studied independently. The dimples were 177mm in diameter, 1.59mm deep, and spaced 22.2mm. A single row of dimples (65% $C_x$) and two dimple rows (65% and 76% $C_x$) were also studied. Results showed the single row was a better configuration. Rivir then increased the dimples spacing to 44.4mm and compared the results to the dimple spacing of 22.2mm. He showed that the results were the same within experimental uncertainty. Rivir employed steady and pulsed VGJs. He stated the steady jets mix the flows and cause early transition, however, pulsed VGJs never show classic transition instabilities indicating the mechanism for separation is quite different. He went on to show the pulsing frequency and multiples of the pulsing frequency influence the flow within and beyond the original boundary layer.

Vane-Blade Interaction (VBI), a 2-D direct Navier-Stokes was used to predict the separation point location on an uncontrolled blade. The results were confirmed experimentally. Also used for numeric analysis was a 2-D Reynolds-averaged Navier-Stokes called MISES. This code was also used to predict the separation point. Results showed that both codes predicted the point of separation to be near the point of uncovered turning. This was also true for the case of increased pitch. The numerical results we compared to experimental results.

Hansen ,[Hansen and Bons 2004], looked at 21 planes in the spanwise direction over a total of 1 pitch. He used particle image velocimetry to obtain full field velocity contours. 40 image pairs were taken for every z-plane. The tests were performed over a flat plate in a straight wind tunnel with and without an adverse pressure gradient. The adverse pressure gradient was created by means of a contoured upper surface. VGJs oriented with a 30° pitch and a 90° skew were studied as well as normal injected jets. A case of flow with no control was run and taken as a baseline case. In both cases the jet diameter was 0.4cm and the jets, spaced 10D apart, were pulsed at 5Hz, which results in $F+=0.34$. Hansen showed that both jet orientations create double vortices. The vortex created by both jets grew in size but the strength diminished as it propagated downstream. As it propagated downstream it was seen migrating away from the wall but remained in the same spanwise position. Hansen also showed the pitched and skewed jet created one dominant vortex that migrated in the pitch direction and also in the spanwise direction. The vortices created by the pitched and skewed jet remained coherent longer than those created by the normal jet. Also the pitched and skewed jet was able to mix and entrain more freestream fluid with wall bounded flow. He also pointed out that jet cycle-average losses were about the same for both cases. Lastly Hansen showed the effects of the
normal jet propagated more quickly but the effects of the pitched and skewed jets were greater in magnitude.

Amitay [3] tested the effectiveness of pulsed synthetic jets on the cylinder 60° relative to the incoming flow with a Reynolds number of 310,000 on an airfoil comprised of a 62mm diameter cylindrical leading edge fitted to a NACA four digits series symmetric airfoil. The angle of attack was varied from 0° to +25° while reduced pulsing frequencies (F+) was varied from 0.95 to 20. The results showed the flow separated at an angle of attack of 5° with no control, however, with forcing the flow stayed attached at an angle of attack of 20°. The variation in pulsing showed that the higher reduced pulsing frequencies resulted in a higher maximum lift coefficient, however, the mean lift coefficient was lower than the low pulsing frequency cases studied. The results also showed a nominal 35% increase in the lift to drag ratios for reduced pulsing frequencies around a value of 1.

Rizzeta [14] numerically simulated the effects of pulsed VGJs to study the effects they have on a highly loaded Pack-B low pressure turbine. Rizzeta used a direct Navier-Stokes solver with a time-accurate implicit approximately factored finite difference algorithm of Beam and Warming using Newton-like sub-iterations. Three meshes were used, a coarse grid, a baseline grid, and a grid for flow control. The simulated pulsing resulted in an F+ = 3.1 with a duty cycle of 50%. The blowing ratio studied was 2. Rizzeta loosely followed work done by Bons even though the parameters did not match up perfectly. Rizzeta stated that his results showed that turbulent kinetic energy spatial wave-number spectra indicated the transitional nature of flows. He went on to show the flow-field was dominated by the pulsed VGJs. These effects lessened as the flow propagated downstream. In the uncontrolled cases Rizzeta showed the flow-field was dominated by the natural shedding frequency of the vortices. The simulated pulsed VGJs mitigated the effects of extensive separation that typically occur at low Reynolds numbers. Rizzeta said that increasing the jet momentum coefficient may increase the performance. He then suggested increasing the number of jets, increasing the jet diameter, or increasing the blowing ratio as methods to increase the jet momentum coefficient.

Olsen [10] used Bons [1] wind tunnel with the VGJs oriented in the same manner as during Bons study. The VGJs were located at 59%C_x and spaced every 10D. Blowing ratios of 0, 2, and 4 were studied. A turbulence generating grid was used to augment the FSTI level. The levels of FSTI studied were 0.4%, 3%, 6%, and 10% while the freestream Reynolds numbers is 25,000. Using a hotwire anemometer time-averaged, spanwise-averaged data points along a line normal to the local tangent were taken at the following axial locations 68%, 75%, 81%, and 87%. Boundary layer velocity profiles showed that as the FSTI levels are increased the separation bubble becomes smaller. The boundary layer momentum flux losses were calculated and used as a means of comparison.

Olsen
showed that at increased FSTI levels the effectiveness of the VGJs were reduced because of the separation bubble is already smaller due to the earlier transition of the flow. Also, the increased turbulence increases the dissipation of the induced vortex which decreases the ability to entrain high momentum flow.

1.3 Literature Review - Summary

It can be understood from the literature review that flow separation is a big problem and substantial time, money, and effort has gone into trying to find a way to reduce the losses associated with separation. Previous work in this research area has shown that as the freestream turbulence intensity increases the flow transitions from laminar to turbulent earlier. This was also found true for higher Reynolds numbers. So, it is a known fact that increasing FSTI or Reynolds numbers reduces losses due to separation. However in the study done by Rivir [13] he stated that although steady blown vortex generator jets suppress separation and decrease losses by increasing the turbulence and causing earlier transition pulsed vortex generator jets showed no classic signs of transition instabilities and predicted the mechanism suppressing separation is much different. The studies by Moore [9] and [8] and Bons ,[Bons et al. 1999], shed light on to how pulsed vortex generators actually work. They agreed that the initial vortex caused by the opening of the jet is the key to understanding the mechanism by which pulsed vortex generator jets suppress separation. Research by Hansen [7] and Rizzeta [14] studied pulsed vortex generator jets numerically and experimentally. Rizzetas work showed that the forcing of the jet influenced the flow not only in the boundary layer but outside the boundary layer as well. This means the pulsing frequency is a critical factor. Hansens experimental work showed how the vortices created by a pitched and skewed jet and a normal jet propagate downstream. He showed how using a pitched and skewed jet is more beneficial than a normal jet. The pitched and skewed jet creates one large, strong, slowly decaying, and slowly propagating vortex. Since it is slow to decay means it influences the flow for a longer period of time and since the vortex is slow to propagate it will not wash off the surface as quickly.

1.4 Current Study

The focus of the current study was to look in depth at the flow physics of a pulsed vortex generator jet on a Pack-B blade. The pulsing frequency first studied was 10Hz with a duty cycle of 50% to match work previously done by Bons [1] and Dr. Sondergaard [15]. At this pulsing blowing ratios of 0.5, 1, and 2 were studied. The pulsing frequency was then reduced from 10Hz to 0.4Hz, with a duty cycle of 50%, so the flow had ample time to relax and separate between pulses of the jet.
Blowing ratios of 0.5 and 1 were studied. A particle image velocimetry system was phase locked to 32 points during the jet cycle. Vorticity and velocity contours with streamlines were studied; in addition, boundary layer profile data was extracted and the shape factor of the boundary layer calculated. This data allowed for better understanding of the interaction of vortex generator jets with the cross flow on the suction side of a low pressure turbine.
2

Experimental Facility

2.1 Wind Tunnel and Cascade

The induction type wind tunnel used in this study was the same tunnel used by Sondergaard [15], Bons [1], and Rivir [13]. The wind tunnel housed the 0.85m tall by 1.22m wide test section and within the test section was the linear turbine cascade used. A 125-hp electric motor drove the axial flow fan which drew air through the test section at up to 80m/s, roughly a Reynolds number of 1,000,000 based on the axial length of the Pack-B profile used. Reynolds numbers for all testing was calculated based on inlet velocity and axial length. To convert to Reynolds number based on true chord multiply by 1.1. To convert to Reynolds number based on suction side length multiply by 1.46. To convert to Reynolds number based on design exit velocity, multiply by 1.64. Honeycomb flow straighteners are located in the 3.0m by 2.7 meter inlet of the wind tunnel. The bell mouth inlet reduces the cross-sectional area of the flow from 3.0m by 2.7m to 0.85m by 1.22 m. This 8-1 reduction in area results in flow uniformity less than 1% although an optional turbulence generation grid can be used to increase the freestream turbulence to 12%. The turbulence generating grid is a square mesh array of 1 inch diameter metal tubes spaced three inches apart. Eight blades which measure 0.88m spanwise and 0.18m axially plus two partial end-blades comprise the linear cascade. (See Figure 2.1) The 2-D blades were designed with the Pack-B profile and manufactured using polyurethane and mounted to the top and bottom of the test section using four $\frac{1}{4}$ - #20 bolts per blades. The Pack-B profile was selected because it is a Mach scaled model of a modern highly aft loaded turbine blade. The cascade has an axial chord to blade spacing, or solidity, of 1.13. The design inlet flow angle is 55 degrees with a design exit angle of 30 degrees. Both of these previous angles were measured from the plane of the cascade. The innermost and outermost two blades, numbers 1,2,7, and 8 respectively, are very near the exit tailboards and therefore not desirable to test on. In the current study blades 2-7 were equipped with vortex generator jets rows located at
The active separation control blades were designed and manufactured with a large internal cavity which ran from 40% - 90%Cx. Fittings were installed in the bottom of the blades to allow static pressure measurements of the cavity to be taken. Pressurized air was fed into copper tube which was 1.2 cm in diameter which ran the entire length of the cavity via a needle-valve located upstream of the feed port which enabled the mass flow to be controlled with high precision. The copper tube was inserted into the blade cavity through a hole drilled through the bottom of the blade. A silicon based RTV sealant/adhesive was used to seal the tops and bottoms of the blades so air flow could only exit through the jets. The air flow exhausted from the copper tube into the hollow cavity through 25 1.5mm diameter holes spaced 25.4mm apart bored into the copper tube.

The 1mm diameter vortex generator jets were drilled from the surface of the blade. They had an orientation of 30° pitch and 90° skew. See figure 2.3. The pitch angle is defined as the angle between the jet and the local blade surface while the skew angle is defined as the angle between the jet and the cross flow. The aspect ratios of the jets, defined as length divided by diameter, and were approximately 8. The jets spaced 10 diameters apart. Each row of jets holes consisted of 47 holes located in spanwise center of the blade. All active separation control blades were equipped with jets located at 45%Cx and 63% Cx. In addition, blade 5 had rows of jet located at 53%Cx, 73%Cx, and 83%Cx. Jet holes at locations not studied were covered with 0.05mm translucent tape.
Figure 2.2: Top View of the Low Speed Wind Tunnel Test Section.

Figure 2.3: The Active Separation Control Blade: The hollow cavity is shown in red.
2.2. PARTICLE IMAGE VELOCIMETRY

The tape was sufficiently thin as to not trip the boundary layer. The discharge coefficient of the jets was measured to be 0.6 +/-0.03. The flow variation between all the jets was measured and found to be less than 5%. The blowing ratio, a ratio of momentum of jet flow to momentum of freestream could be reduced to a ratio of the jet velocity to freestream velocity because the flow is essentially incompressible.

A single element hotwire and pitot probe mounted upstream of the cascade were used to monitor the Reynolds number of the flow. The velocity response of the jet to the valve control was measured for pulsing frequencies ranging from 0.5Hz to 100Hz, back pressures ranging from 15psi 60psi, and duty cycles ranging from 10% and 50%. The velocity of the air flow exiting the jet was measured with a single filament high speed mini-hotwire. Velocity measurements were taken for 100 cycles and then averaged. The response of the jet for the cases run for this thesis can be found in Appendix A.

2.2 Particle Image Velocimetry

Particle Image Velocimetry (PIV) is a non-intrusive measurement technique which yields full field instantaneous velocity measurements. The technique can only be considered non-intrusive if the seeding is appropriately chosen. PIV works by utilizing two instantaneous images of a seeded flow taken a known time interval. The PIV system uses the Solo 120-XT to illuminate the seeded flow with a high power, short duration pulse of light. The PCO1600 camera captures an image of the
2.2. PARTICLE IMAGE VELOCIMETRY

Figure 2.5: Diagram of how a simple PIV works. The laser (upper left) produces a beam of light which is converted to a light sheet via high power optics. The laser sheet illuminates a seeded flow (right) and the images are captured by a digital camera (bottom left).

illuminated, seeded flow. A short time later the second head of the laser emits another high power short duration pulse and again the camera records the image. This process is repeated approximately 700 times for each of 32 phase locked points 2.5.

The images were divided into areas of interrogation and these areas were there correlated. An easy way to think of how the correlation works is to imagine the two interrogation areas, one from each image at the same location, superimposed on each other. Dozens of particles would be seen, some from the first image and some from the second image. With the first interrogation image fixed in a location the second interrogation area is slowly moved around. As the second interrogation is moved some of the particles from the first and second images start to overlap, while the second interrogation area continues to move sometimes more particles overlap and sometime less overlap. The more particles overlap the stronger the correlation signal produced. The point at which the signal is the strongest is how far the particles have displaced on average in the 'x' and 'y' direction. This process is repeated for all interrogation areas on the images. See figure 2.6
2.3. PARTICLE IMAGE VELOCIMETRY SYSTEM

The particle image velocimetry system [11] was composed of 5 components, the laser, the camera, the valve drivers, the pulse generator, and the fog machine. All components are discussed in detail in the following sections.

The PIV system setup can be seen in Figure 2.7. The camera was located beneath the wind tunnel test section. A laser arm was used to direct the laser beam from the laser head mounted below the test section to the externally mounted optics.

The field of view of the camera (Figure 2.8) extends from approximately $62\%C_x$ to approximately $99\%C_x$ in the axial direction. In the pitch direction the field of view extends far enough to capture activity in the boundary layer but cuts out a lot of freestream flow, which was not of interest for this thesis.

2.3.1 Laser

The laser used was a NewWave Solo120-XT [12]. The Solo120-XT employed a thermally compensated resonator and used a dual headed flash lamp-pumped Neodymium-doped Yttrium Aluminum Garnet (Nd:Y3Al5O12), or Nd:YAG, rod head to generate radiation at 1064nm. The frequency of the radiation is doubled by passing the radiation beam through an angle tuned Potassium Titanyl Phosphate (KTP) crystal. Dichroic mirrors were then used to separate the second harmonic, which is vertically polarized, from the fundamental light. Third and Fourth Harmonic Generators could also be used to obtain radiation with wavelengths of 355nm and 266nm respectively although they
2.3. PARTICLE IMAGE VELOCIMETRY SYSTEM

Figure 2.7: PIV setup.

Figure 2.8: Field of View.
were not employed during this thesis. The Solo120-XT is capable of emitting 120mJ +/- 4mJ pulses of 532nm light at a rate of 15Hz. The beam diameter emitted was 4mm with a divergence of less than 3 millirads. The pulse width of the laser was 3-5 nanoseconds. After being generated the laser output beam is then directed through an adjustable light arm to two externally mounted optical lenses located between the outer exit board and the wind tunnel wall. The first optical lens the beam encountered was a 1000mm spherical lens, mounted approximately 1000mm away from the blade of interest. The purpose of this lens was to focus the beam down to a point. Directly after the spherical lens was placed a -75mm cylindrical lens, this lens was used to spread the beam in one dimension, as to illuminate particles in the plane of interest. The thickness of the laser sheet was $\lambda$1mm within the field of view of the camera.

The Solo120-XT has capability of being fired externally or internally. The frequency of the firing when controlled by the laser can be adjusted by use of an adjusting attenuator located on the control panel of the laser. Externally triggering the laser gives the user more control over the timing of the laser than when internally triggered. The laser was triggered externally for the current study.

The Solo120-XT allows the user to control just the flash lamp or both the flash lamp and the quality switch, commonly referred to as the Q-switch. The flash lamp is the means by which the lasing medium is energized. The Q-switch prevents feedback of light into the lasing medium from the optical resonator. This causes the lasing medium to experience a population inversion, a state when more atoms exist in an excited state than in a ground state. The amount of energy released in a pulse is dependent on the amount of energy stored in the lasing material. While the flash lamp increases the amount of energy stored in the lasing material processes such as spontaneous emission reduced the energy stored. At a point the lasing material is saturated with energy, meaning further pumping will not increase the energy. At this time the Q-switch is "opened" allowing the lasing material to experience feedback from the resonator. This is what allows lasing.

The Solo120-XT has an adjustable internal Q-switch time. However, preliminary tests on the Solo120-XT being used showed the Q-switch timing had a tendency to drift and differed between the two laser heads. This could cause the energy per pulse to fluctuate which could cause problems when correlating the images. To reduce complications when correlating the images it was necessary to externally control both the flash lamp and the Q-switch.

2.3.2 Camera and Software

The camera used was a PCO1600 SensiCAM [2]. The resolution of the camera was 1600 pixels wide by 1200 pixels high. It was mounted on a 2 foot by 8 foot optical bread board located directly beneath the test section of the wind tunnel, a small portion of the optical table protruded from
under the test section. On this portion of the optical table was mounted the Dantec Dynamics 
adjustable light-arm. The laser head, camera, and camera power supply were also mounted on the 
optical table under the test section. The camera was mounted on Newport Model 470 rotating stage 
which was mounted on a Newport Model 400 XY translation stage. This was all finally mounted on 
an adjustable height stage and placed under blade 4. A 64mm Nikkor lens was used with the camera 
to zoom in on the area of interest. For course focusing an F-number of 2.8 was used with a low level 
of ambient light. For fine focusing and when acquiring data an F-number of 8 was used with a high 
intensity of light, from the Solo 120XT, to illuminate the particles. The F-number is a ratio of the 
focal distance to the diameter of the aperture, the larger the F-number the smaller the aperture. 
Small F-numbers have a plane of focus that is much thinner than large F-numbers. It important 
that the plane of focus is thicker that the laser sheet and the laser sheet be fully contained in the 
plane of focus lest particles which are out of focus will be recorded and processed.

A 2 inch by 2 inch grid etched on a 2.5 inch by 2.5 inch thin piece of glass was secured on a 
fixture specifically designed to hold the focusing target. The fixture was bolted to the base of a post 
holder which was inverted and placed on a post. The opposite end of the post was inserted into 
another post holder, this post holder was mounted to a magnetic base for stability. This arrangement 
was then placed inside the wind tunnel and the height adjusted so the glass target lay in plane of 
interest. The camera was then adjusted by use of the focus ring on the lens while real time images 
of the target were displayed. After focusing the camera the height and width of the field of view 
were determined.

To determine the dimensions of the image two points on the image grid were chosen. Using 
CAMWARE the pixel locations of both points on the image of the target were noted. The pixel 
locations were recorded as x-pixel, y-pixel for both points. Knowing the number of pixels between 
the two points in the x and y directions, the actual distance between the two points in the x and y 
directions, and the total number of pixels in the x and y direction in the image it was possible to 
calculate the actual size of the field of view by a simple linear correlation. To determine to location 
of the of the field of view with respect to the blade a shroud was made from a 1/8 inch thick piece 
of a rigid fiber reinforced polymer. The shape of the suction surface was cut into the shroud so that 
the shroud could easily be fitted around the suction side of blade #4. Images of the shroud wrapped 
around the blade could be captured. Tick marks on the shroud indicating axial location could then 
be correlated to pixel locations on the image.

The software used to control the camera was CAMWARE v2.14. Using CAMWARE the exposure 
mode of the camera was set to exposure trigger start. This allowed the camera to record an image, or 
two images in double frame mode, only after an external trigger was sent to the camera. The shutter
was controlled by the CAMWARE software because the Quantum Composers Delay Generator did not have enough channels for it to be controlled externally as well. While in double frame mode only the exposure time for the first frame could be adjusted. By default the shutter time for the second frame was 33ms, to avoid correlation complications the first frame shutter time was adjusted to be 33ms. To transfer the image from the photo-sensitive CCD to the internal camera memory 2 ADC converters were used each processed at a rate of 40,000,000 pixels per second. At these settings image pairs could be captured at a rate of 10Hz. The software was set to record in double frame mode. This setting allowed the computer to pair corresponding images to be processed together. The internal memory of the camera could hold 347 8-bit image pairs. After the run was complete all images in the internal camera memory were then transferred from the camera to a 1 TB RAID stack.

### 2.3.3 Delay Generator

A Quantum Composers 9300 Series Pulse Generator [4] was used to drive the valves supplying the vortex generator jets, the flash lamps and Q-switches for both laser heads, and the opening of the camera shutter. The pulse generator has 8 output channels and one input channel. The pulse generator utilized an internally produced signal to synchronize the entire system. The Iota-One and PCO 1600 SensiCAM were the only components which were not dependent on the timing of another component. The timing of the lasers and the Q-switches are based off the firing of the camera, not the signal from the pulse generator. The timing of the system is discussed in detail later in the paper.

### 2.3.4 Seeding

A Rosco 4500 Fog Machine was used for seeding the flow. Propylene Glycol is heated to produce fog. The fog particles were on the order of 1 micrometer in diameter. The fog then exits the machine through a nozzle. The nozzle is coarsely aimed at the bell mouth inlet. The alignment of the fog machine nozzle to the wind tunnel inlet is adjusted as necessary. A 6 inch diameter electric fan was used to mix the hot fog with cooler room-temperature air before it entered the wind tunnel to reduce thermal buoyancy of the seeding. Initial tests without the cooling fan showed that the position of the hot fog in the test section was very unstable and was unpredictable. Cooling the fog allowed the position of the fog to be more predictable so positioning the fog generator was easier.
2.3. PARTICLE IMAGE VELOCIMETRY SYSTEM

2.3.5 Setting Up the PIV System

Once all the components were physically moved to the wind tunnel and the laser containment curtains were in place the PIV system could be set up.

The first step was to verify the laser was still focused and the two laser heads were still aligned. This was a very important step because if the laser heads were not lined up each laser head would illuminate a different plane in the flow and results from the correlation process would be meaningless. To verify the laser heads were aligned the laser was powered on but the laser power kept at the lowest possible setting. The laser head was aimed at a beam stop via a monochromatic mirror which was used to increase the beam length. A piece of burn paper was placed in the path of the beam about six inches from the laser head. After fixing the paper to a post holder laser one was activated and the beam location was marked on the paper, than the same for laser two. This procedure was repeated for a location about twenty feet away from the laser head. Also, when the burn paper was located at twenty feet the focus of the beam was checked. At twenty feet the beam should be 2-3 cm in diameter. Had the beams not aligned at both positions or the laser heads been out of focus the laser manual [?] would have been consulted for directions on aligning or focusing the beams.

After the individual beams were aligned the beams were aligned within the light arm. This was a multi-step process. First the light arm base was mounted on an adjustable height stage with a rubber alignment tool mounted in the top. With the laser lasing the height of the base was adjusted and the base adjusted to the left or right so the beam exiting through the top of the base hit the center of the rubber top. Once this step was completed the laser was put in standby mode and the rubber alignment tool removed and the metal alignment tube mounted. The alignment tube has two circle inserts within the interior of the tube with are visible to operator. Using the mirror deflection thumb screws and adjusting the position and height of the base the beam passing through the center of both inserts in the alignment tube. This step ensured that as the beams passed through the light arm they would not reflect off the inside. This kind of reflection would have caused problems taking and correlating the data.

The appropriate lenses then needed to be chosen which was accomplished by measuring the distance from the location where the lenses would be mounted to the blade that was to be imaged. Since it is desirable to have the laser sheet as thin as possible a spherical lens with a focal length equal to the distance the lens was mounted away from the blade. In this case the lenses were mounted 1 meter away so a spherical lens with a focal length of 1000mm was chosen. Placed directly behind the spherical lens was a cylindrical lens with a focal length of -75mm. The focal length of the cylindrical lens was chosen so that laser sheet illuminated the entire field of view of the camera. The wider the fan angle of the laser sheet the larger the area that could be imaged but also that would increase
2.3. PARTICLE IMAGE VELOCIMETRY SYSTEM

the amount of power required by the laser.

Once the laser sheet was in place the vertical location (distance from the floor) of the laser arm
exit was measured and the same measurement taken for the height of the laser sheet on the opposite
side of the test section. In fact the inner laser containment curtains were temporarily removed so
the laser sheet could pass through the test section and hit the second layer of laser containment
curtains. The purpose of this measurement was to verify that the laser sheet was level. Had the
laser sheet not been level most of the flow though the test section would have been out-of-plane of
the laser sheet making any results from the correlation invalid.

After the previous step was completed the laser set up was considered complete and extreme
cautions was exercised not to disturb (e.g. bump) the laser, the laser arm, or the optical table on
which the laser was sitting.

The next step was to set up the camera. The PCO1600 was mounted on a 2-axis stage, which
was mounted on a rotating stage, which was mounted on an adjustable height stage giving the
camera four degrees of freedom in movement. The camera was roughly put in position and a glass
target inserted at the same height location of the laser beam. The camera was then turned on so
that it imaged in real time to the computer monitor. The stages were then adjusted to obtain the
desired field of view and camera focused on the target which had been etched with a grid of known
dimensions. Images of the target were then capture so the dimensions of the field of view could be
calculated. The glass target was removed and a shroud made of a ridged polymer which wrapped
around the suction surface of the blade was inserted in the same plane. The shroud had tick marks
on it indicating axial location. Images of the shroud were captured to verify what part of the blade
was being imaged. Then, after all laser containment curtains were replaced the laser was powered
up and the laser power set to a high level while the F-stop of the camera with had been set high
was know lowered to allow in less light. The flow was seeded and the camera imaged the illuminated
flow while the operator focused the camera on the seeded flow. When the seeding appeared grainy
as opposed to cloudy a good focus had been achieved.

The final set was to create a timing system to ensure that images would be taken at the times
they were intended to be taken. To create a timing diagram please refer to the laser manual [?], the
camera manual [2], and the delay generator manual [?].

2.3.6 Procedure for Taking Data

The fog machine, laser, camera, and wind tunnel were turned on and allowed to warm up for
10 minutes. During this time the atmospheric pressure and dew point temperature were taken
using a barometer with a dial gauge and a Traceable Hygrometer/Thermometer/Dew Point Sensor,
respectively. These values were input into a LabVIEW program written by Dr. Rolf Sondergaard for operation of the wind tunnel. Signals from the upstream hotwire and the pitot probe were used in conjunction with the environmental conditions (pressure and dew point temperature) and blade dimensions to determine flow velocity and Reynolds number at the inlet to the test section. The flow velocity and Reynolds number were shown in real time and were adjusted using an adjustable attenuator located on the wind tunnel control panel inside the wind tunnel control room. Once the Reynolds number was set LabVIEW was closed and the upstream hotwire was lowered into its protective sheath. The hot wire was retracted into a protective sheath to protect the filament from fog fluid condensing on it which could affect voltage readings across the filament and lead to increased error.

The next step was to set the vortex generator jet feed pressure. The velocity history of the jets had been measured using a mini-hotwire. The jets pulsed into quiescent air while the frequency, duty cycle, and feed pressure were all varied. The jet velocity was taken and averaged over 100 cycles for each case. An average jet velocity for the "valve open" portion of the cycle was calculated. Due to curvature effects the freestream velocity over the suction surface varied, therefore the definition of blowing ratio was slightly modified to the ratio of the jet velocity to the local freestream velocity. The local freestream was calculated by multiplying the inlet velocity by the square root of the $C_p$ at the axial jet location which had already be measured by Sondergaard [15]. To set the back pressure for a run the matrix of calibrated data was referenced and a back pressure for the exact duty cycle, pulsing frequency, and required jet velocity was determined. To see calibration data refer to Appendix A.

Once this was completed the equipment was sufficiently warmed-up and ready to be used. The Iota-One was then turned on and the power source for the fog machine mixing fan was also powered on. The Quantum Composers delay generator was then adjusted to capture the phase desired. Lastly the Solo-120XT was set to the high setting and the attenuator was adjusted so the output screen on the Solo-120XT control panel showed 920. This setting was determined by trial and error. Then, after verifying both the flash lamp and the Q-switch were being triggered externally the shutters were activated.

The fog machine, located at the bell mouth inlet, was remotely operated from inside the laser containment area. With the wind tunnel running a constant stream of low density fog was generated. When the fog reached the test section the delay generator was manually activated, sending signals to the laser, camera, and Iota-One. Once the internal memory of the camera was filled the delay generator was stopped and the images transferred to the 1TB raid stack. Images captured in double frame mode could be exported as two files each with one image or one file with the two images
combined. Initially, exporting the images pairs as one file seemed to be the better option. However, later it was discovered, FlowManager could not process two images in one file. A MATLAB code was written to split the two images into two different files which could be processed by FlowManager.

2.3.7 Timing of the PIV System

Two jet pulsing frequencies were studied, which necessitated two separate timing diagrams. The maximum double-frame imaging rate obtainable with the PCO1600 was 10Hz. For the 10Hz pulsing case the PIV system was set to capture 1 image pair during each pulsing cycle. The internal memory of the PCO1600 camera could hold 347 image pairs. To collect the nearly 700 image pairs used, two runs per phase locked point were collected. However, collecting data from the 0.4Hz case posed a challenge. Using the same method of taking one image pair per pulsing cycle would required a 2 runs each almost 15 minutes long to collect the data needed for one phase locked point. Instead, multiple phase locked points were captured for each pulsing of the jet. This was done by generating a 6.4Hz signal. A 6.4Hz signal has frequency 16 times greater than a 0.4Hz signal. The camera and lasers received signals at 6.4Hz but only every sixteenth pulse from the generator pulse was allowed to go to the Iota-ONE. This was done by utilizing a pulse count feature on the Iota-ONE. Effectively, the VGJs were being pulsed at 0.4 while the PIV system was imaging at 6.4Hz. 16 phase locked images were captured for every pulse of the jet. Data was taken for 30 runs, 21 image pairs at each phase were collected per run. The delay going to the camera was then changed from 0.000000s to 0.078125s to collect the remaining 16 phase locked points. To understand the timing diagram of the PIV system it is first necessary to understand the timing diagram of the individual components.

2.3.8 Timing Diagram - PCO1600

Table 2.1 and Figure 2.9 show the internal timing of the PCO1600 camera with all internal delays. The trigger acknowledge delay ($t_{td}$), intrinsic delay ($t_{id}$), and the inter-framing time ($t_{itf}$) are non-adjustable delays. The readout time ($t_{read}$) and exposure time of frame two ($t_{exp2}$) are dependant on the readout settings. In this thesis two AD converters operating at 40MHz were used resulting in a readout time of 33ms. The exposure time of frame one ($t_{exp}$ the only adjustable delay) was set to 33ms in order to avoid complications that might have arisen while trying to correlate images taken with different exposure times.
2.3. PARTICLE IMAGE VELOCIMETRY SYSTEM

Figure 2.9: Timing diagram of PCO1600 camera

<table>
<thead>
<tr>
<th>$t_{td}$</th>
<th>Trigger Acknowledge Delay</th>
<th>200±13ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{id}$</td>
<td>Intrinsic Delay</td>
<td>5.3µs</td>
</tr>
<tr>
<td>$t_{exp1}$</td>
<td>Frame 1 Exposure Time</td>
<td>Adjustable</td>
</tr>
<tr>
<td>$t_{itf}$</td>
<td>Inter-framing Time</td>
<td>180ns</td>
</tr>
<tr>
<td>$t_{read}$</td>
<td>Readout Time</td>
<td>33ms</td>
</tr>
<tr>
<td>$t_{exp2}$</td>
<td>Frame 2 Exposure Time</td>
<td>$t_{read}$</td>
</tr>
</tbody>
</table>

Table 2.1: PCO1600 camera: delays
2.3.9 Timing Diagram - Solo120-XT

The internal timing diagram of the New Wave Solo-120XT is shown in Figure 2.12. This diagram is the same for both laser heads, which operate independently due to the flashlamps and Q-switches for each laser head being externally controlled. The External Lamp and External Q-Switch Trigger were 200µs long while the Adjustable Q-Switch Delay was varied to capture different phase locations.

2.3.10 Timing Diagram - Entire System

After all phases were taken the images were then imported into FlowManager, the commercial correlation software used. A single iteration was used with a correlation window size of 32 pixels by 32 pixels. A 75% overlap of the correlation window was used to increase vector resolution of the images.

Approximately 700 image pairs were taken for each phase. These raw image files were processed and a resulting vector field was produced. These vectors were sent through a validation process in which the correlation signal was analyzed and either accepted or rejected based on characteristics.
2.3. PARTICLE IMAGE VELOCIMETRY SYSTEM

Figure 2.11: Illustration of the timing dependence of some pIV system components to other PIV components. The red lines indicate timing dependence.

of the signal. This process was repeated for all image pairs in a phase. The vector fields were then averaged and the resultant file was exported to TecPlot.

In TecPlot vorticity and velocity contour plots were produced, streamlines were also added to the velocity contour files. Boundary layer profile data was extracted at a number of axial locations. This data was exported and a Matlab script written to calculate the boundary layer shape factor. The shape factors were then plotted as a function of phase and as a function of axial chord.

2.3.11 Error Reduction

Large interrogation areas have the benefit of drawing from large numbers of particles with the interrogation area. However, using large interrogation areas results in fewer calculated vectors as well as the averaging over smaller flow structures; however, smaller interrogation areas are better able to resolve small scale flow structures. The draw back to using very small interrogation areas is that there are fewer particles available to obtain a reading from. To increase the number of calculated vectors a method known as overlapping was used. The overlapping method increases the number of calculated vectors by shifting the interrogation area only a fraction of the height or width.
2.3. PARTICLE IMAGE VELOCIMETRY SYSTEM

<table>
<thead>
<tr>
<th>Phase</th>
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<th>Phase Delay: 0.4Hz</th>
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</tbody>
</table>

Table 2.2: Phase delays: 10Hz and 0.4Hz
This method is demonstrated in Figures 2.13 and 2.14.

Choosing a correct time interval over which to image the flow also had an effect on the error. A short time interval can lead to increased errors due to inherent particle location uncertainties within the imaging process. However, a long time interval will lead to an increase in particle fallout. Particle fall out happens when a particle imaged in the first frame travels out of the field of view of the camera. This can be due to out of plane movement of the particle or a particle moving past the field of view.

The optimal distance for a particle to travel between images in one-third of the length of the smallest zone of interrogation. For this thesis the smallest zone of interrogation was set to 32 pixels square. Therefore, the timing was designed so particles would travel approximately 8 pixels between images. To accomplish this a time interval of 0.0001816 seconds was chosen. To further reduce error the background light being seen by the PCO1600, was reduced as much as possible. This was done by draping heavy black welding curtains over and around every portion of the test section that was constructed from a transparent or translucent material. Also, PIV data was captured at the mid-span, away from the top and bottom walls, to reduce out of plane movement of the particles.
2.3. PARTICLE IMAGE VELOCIMETRY SYSTEM

Figure 2.13: Representation of vector output with no overlap

Figure 2.14: Representation of vector output with 50% overlap
3

Introduction

3.1 No Blowing

To first understand how a vortex generator jet suppresses separation it is necessary to study the problem of separation with no flow control implemented. Figure 3.1 shows velocity and vorticity contours with streamlines added to the velocity contours for an uncontrolled flow with a Re=25,000 based on inlet velocity and axial chord. The flow over the blade is traveling from left to right. The same plots for Re=40,000, Re=50,000, and Re=100,000 can be found in Appendix B. If Figure 3.1(a) the large separation region can easily be seen as the blue area on the right side of the image. The same separation region appears in Figure 3.1(b) where the shear layer deviates from the surface of the turbine blade. The shear layer shown in the vorticity plot shows indicates the thickness of the shear layer increases downstream of the separation point. This is likely due to the location of the shear layer being unsteady. It is important to note these images are the mean flow field and do not show instantaneous flow structures. The streamtraces do show a large recirculation zone which starts at approximately 69%\(C_x\) and does not reattach within the field of view.

![Velocity and Vorticity Contours](image)

(a) Velocity  
(b) Vorticity

Length:  0  2.25  4.5  
5  5

Figure 3.1: Time averaged PIV results of Re=25,000
3.2. BASELINE CASE: 10Hz; B=1

For a complete set of vorticity and velocity plots for the 10Hz pulsing case with a duty cycle of 50% refer to Appendix C.

The two pulsing frequencies, 10Hz and 0.4Hz, can also be quantified in terms of the reduced frequency. The reduced frequency of the 0.4Hz case is $F^+ = 0.03$ while for the 10Hz case $F^+ = 0.8$ which is roughly 1 and has been shown by Amitay [3] to be a very efficient reduced pulsing frequency. The equation for calculating the reduced frequency can be found in Equation 3.1, however, the pulsing frequencies of the jet will be discussed in terms of the absolute pulsing frequency (10Hz or 0.4Hz)

$$F^+ = \frac{f_C x}{V} \quad (3.1)$$

Figure 3.2 shows the response of the jet flow to the 10Hz TTL control signal that drove the solenoid valves. The TTL pulse was normalized to a maximum value of 1, while the jet velocity was normalized to the mean flow-on velocity. This plot is for the B=1 case, but the shape and response of the jets were largely independent of the blowing ratio. There was a noticeable lag in the response of the jet due to the air volume between the valve and the jet exit. After the valve opened (Phase 00) air flow did not begin to exit the jet until roughly 0.005 seconds later (between Phases 01 and 02). Likewise, after the valve closed (Phase 16) the flow did not stop until roughly 0.005 seconds later (between Phases 19 and 20, although some residual flow remained for several more phases).
For a complete set of vorticity and velocity plots for the 10Hz pulsing case with a blowing ratio of 1 and a duty cycle of 50% refer to Appendix C. This shows the flow interaction when the jet momentum is approximately equal to the freestream momentum (on a per area basis). The time between phases is 0.003125 seconds. During that time the freestream moves approximately $4\% C_x$ (2 tick marks) along the abscissa, while the shear layer is assumed to move roughly half that distance ($2\% C_x$ or 1 tick mark). The black triangles indicate the VGJ injection location. The red bars at the bottom of the plots represent the approximate domain of influence of teh jets, assuming the jet influence propagates near the shear layer velocity.

Both the velocity and vorticity plots show attached flow over the aft portion of the blade for the entire VGJ pulsing period. There is little change of the state of the boundary layer during the pulsing cycle. This indicates that a blowing ratio of 1.0 the VGJs exert sufficient control over the boundary layer that there is no opportunity for separation to begin to reestablish while the jets are off.

Vorticity plots show in Phase 02 (Figure 3.3(b)) that a small buldge in the appears near $64\% C_x$. It can be seen in Phase 05 (Figure 3.3(b)) through Phase 19(not shown). This bulge is due to the mass flow ejecting from the VGJ which sits astride the measurement plane and causes a disturbance near the wall much as if there were a small bump at that location. Mass exiting the neighboring VGJ can also be seen interacting with the shear layer in the data plane. The flow from the neighboring (spanwise injected) VGJ penetrates the data plane and shows up as low momentum “tails” above the boundary layer as far upstream as $74\% C_x$ and continuing downstream (Figure 3.3(f)). These are most evident by the perturbations they create in the vorticity field. As the valves close and the VGJs stop flowing the low momentum tails begin to dissipate and eventually disappear. The same time the low momentum tails disappear and the domain of jet influence passes a small growth in the shear layer is seen (Figure 3.3(h)). This growth, which is due to the shear layer becoming unsteady, propagates downstream until the jets are turned back on and disrupt the instabilities before the flow is able to separate.

### 3.3 10Hz; B=0.5

For a complete set of vorticity and velocity plots for the 10Hz pulsing case with a duty cycle of 50% refer to Appendix D.

Velocity and vorticity contour plots for select phases are shown in Figures 3.4 through 3.6. At this lower blowing ratio, where the jet momentum is dominated by the freestream momentum, the VGJ control is not as strong, and the boundary layer is much more active that for the blowing ratio
3.3. 10Hz; B=0.5

(a) 10Hz; B=1; Velocity Phase 02

(b) 10Hz; B=1; Vorticity Phase 02

(c) 10Hz; B=1; Velocity Phase 05

(d) 10Hz; B=1; Vorticity Phase 05

(e) 10Hz; B=1; Velocity Phase 06

(f) 10Hz; B=1; Vorticity Phase 06

(g) 10Hz; B=1; Velocity Phase 27

(h) 10Hz; B=1; Vorticity Phase 27

Figure 3.3: Time averaged PIV results of Re=25,000
of 1 case, where the momentum of the jet and freestream roughly match.

From Phase 00 (Figures 3.4(a) and 3.4(b)) through Phase 06 (Figures 3.4(c) and 3.4(d)) the boundary layer is attached and relatively quiescent. Shortly before Phase 07 (Figures 3.4(e) and 3.4(f)) the boundary layer begins to become unstable as evidenced by the spreading of the vorticity field between 80% and 90% \( C_x \). In the velocity plots, though, the boundary layer is still attached. Most likely this indicates that there is a small, unsteady, non-phase locked separation bubble beginning to form, and the shear layer above it is showing up in the vorticity field.

The instability grows through Phase 09 (Figures 3.5(a) and 3.5(b)) and by Phase 11 (Figures 3.5(c) and 3.5(d)) there is a separation bubble clearly visible between 88% and 96% \( C_x \). As the influence of the VGJ pulse propagates towards the trailing edge of the blade (approximated by the red bars) the separation bubble is driven aft (Figures 3.5(c) and 3.5(d)) through (Figures 3.5(e) and 3.5(f)) until by Phase 14 (Figures 3.6(a) and 3.6(b)) the bubble is eliminated. For the rest of the cycle, the velocity field shows attached flow. The vorticity field, however, shows continued instability until the effect of the VGJ has finally propagated past, around Phase 29 (Figures 3.6(c) and 3.6(d)), at which point the shear layer begins to lift off the surface of the blade indicating the flow begins to separate immediately after the jet effects have passed.

The level of activity in the boundary layer indicates that for this blowing ratio the influence of the VGJs is much weaker than for the blowing ratio of 1.0 case (where the boundary layer stayed attached and stable for the entire pulsing cycle). It is likely that a blowing ratio of 0.5 is therefore very close the minimum effective blowing ratio for pulsed blowing for a duty cycle of 50%.

3.4 10Hz; B=2

For a complete set of vorticity and velocity plots for the 10Hz pulsing case with a duty cycle of 50% refer to Appendix E.

Velocity and vorticity contour plots for select phases for the case of 10Hz pulsing, 50% duty cycle, and a blowing ratio of 2. For this blowing ratio the jet momentum dominates the freestream momentum. For this case, just as for the blowing ratio of 1.0 case, the boundary layer remains attached for the entire pulsing cycle. The striking features in this data are the large low momentum zones in the velocity between Phases 04 and 07 (Figures 3.7(a) through 3.7(g)). These structures also show up in the vorticity plots as arcs (Figures 3.7(b) through 3.7(h)). These are caused by the fluid from the neighboring jets penetrating the measurements plane. Since the VGJs have high spanwise momentum, but no streamwise momentum, they show up as low momentum wakes. They appear only for the part of the jet cycle during which their spanwise momentum is within a narrow
3.4. 10Hz; B=2

(a) 10Hz; B=1; Velocity Phase 00

(b) 10Hz; B=1; Vorticity Phase 00

(c) 10Hz; B=1; Velocity Phase 06

(d) 10Hz; B=1; Vorticity Phase 06

(e) 10Hz; B=1; Velocity Phase 07

(f) 10Hz; B=1; Vorticity Phase 07

Figure 3.4: Velocity and Vorticity Plots: 10Hz, B=0.5 Phases 00, 06, and 07
3.4. 10Hz; B=2

(a) 10Hz; B=1; Velocity Phase 09

(b) 10Hz; B=1; Vorticity Phase 09

(c) 10Hz; B=1; Velocity Phase 11

(d) 10Hz; B=1; Vorticity Phase 11

(e) 10Hz; B=1; Velocity Phase 13

(f) 10Hz; B=1; Vorticity Phase 13

Figure 3.5: Velocity and Vorticity Plots: 10Hz, B=0.5 Phases 09, 11, and 13
3.4. 10Hz; B=2

(a) 10Hz; B=1; Velocity Phase 14
(b) 10Hz; B=1; Vorticity Phase 14

(c) 10Hz; B=1; Velocity Phase 29
(d) 10Hz; B=1; Vorticity Phase 29

(e) 10Hz; B=1; Velocity Phase 30
(f) 10Hz; B=1; Vorticity Phase 30

Figure 3.6: Velocity and Vorticity Plots: 10Hz, B=0.5 Phases 14, 29, and 30
range of values which causes them to intersect the measurement plane.

Clearly a blowing ratio of 2.0 causes a significant penetration of the boundary layer by the VGJ. This overshoot of the VGJ into the freestream causes localized areas of low momentum flow which apparently do not significantly increase overall losses.

3.5 Boundary Layer Profiles, $\delta^*$, and The Shape Factor

The shape factor (H) of a velocity profile is a ratio of the displaced flow the momentum of the displaced flow and can be calculated using Equation 3.2. Values of H larger than 3.5 indicate separated flow (flow flat plate flows). Values around 2.5 indicate a laminar flow while values of H less than 1.7 indicate turbulent flow (for flow over a flat plate). These numbers, while they cannot be directly applied to flow over a curved surface and encountering an adverse pressure gradient, can be used to gauge the flow.

$$H = \frac{\int (1 - \frac{u}{\bar{U}}) \, du}{\int \frac{u}{\bar{U}} \, (1 - \frac{u}{\bar{U}}) \, du} \quad (3.2)$$

Figure 3.9 shows the evolution of the shape factor (H) for all three blowing ratios over the cycle of the jet pulsing. At 70% $C_x$ (Figure 3.9(a)) large fluctuations are visible in the shape factor for all three cases. The B=1 and B=2 cases have a mean value of the shape factor much lower that for the B=0.5 case. The unsteadiness for a blowing ratio of 2.0 case seems the be limited to Phases 04 through 21 (roughly the period of jet flowing). The exact reason for this is not clear.

At 75% $C_x$ (Figure 3.9(b)) the profile for the B=1 case becomes less erratic, though it still shows significant variation. The shape factor profile for the B=2 case becomes nearly steady around a value of H=2.1 for most of the cycle. This value is higher than would be expected for a turbulent boundary layer, but lower than for a laminar boundary layer, suggesting the boundary layer at this station is somewhere between. The value of the shape factor deviates during the phases in which the wake from the neighboring jet impinges upon the data plane. The shape factor for the B=0.5 case was still unsteady, fluctuating between values of H=2 and H=8.

At 80% $C_x$ (Figure 3.9(c)) and downstream, the shape factor for both the B=1 and B=2 cases becomes steady around a value of H=2.1, again a value somewhere between what would be expected for a laminar and turbulent boundary layer. The profile for the B=0.5 case remains unsteady, but has become weakly phase locked to the pulsing, indicating a greater influence of the VGJs. This phase locking becomes stronger as the flow progresses downstream (Figures 3.9(e) and 3.9(f)).

The 90% and 95% $C_x$ profiles (Figures 3.9(e) and 3.9(f)) illustrate the propagation of the influence of the VGJs. The B=0.5 case at 90% $C_x$ shows the effects of the jet appear around Phase 15 (when
3.5. BOUNDARY LAYER PROFILES, $\delta^*$, AND THE SHAPE FACTOR

(a) 10Hz; B=2; Velocity Phase 04

(b) 10Hz; B=2; Vorticity Phase 04

(c) 10Hz; B=2; Velocity Phase 05

(d) 10Hz; B=2; Vorticity Phase 05

(e) 10Hz; B=2; Velocity Phase 06

(f) 10Hz; B=2; Vorticity Phase 06

(g) 10Hz; B=2; Velocity Phase 07

(h) 10Hz; B=2; Vorticity Phase 07

Figure 3.7: Velocity and Vorticity Plots: 10Hz, B=2 Phases 04 - 07
the shape factor drops rapidly and then remains steady around $H=2.2$). This same evolution is seen for $B=0.5$ at the $95\%C_x$ location. There is a slight shift to the right (from Phase 15 to 18) indicating roughly how long it takes the full effect of the VGJs to pass between the two stations.

The full set of boundary layer shape profiles can be found in Appendix ??.

Concern over the accuracy and validity of the values of the shape factors calculated resulted in further investigation of the boundary layer profiles to see if they could shed light onto how the jet effects the flow inside the boundary layer. Higher resolution plots of the shape factor plotted over the surface of the blade (not displayed) reported the value of the shape factor in some instances varied by a factor of 2 over over on a distance of $0.5C_x\%$. When the actual boundary layer profiles that the shape factors were calculated from were plotted it was seen that although the boundary layer profiles did not deviate much from one another the shape factor differed greatly. After observing results such as this it is not difficult to understand that additional analysis had to be performed on the shape factor calculation and boundary layer extractions.

To understand the fluctuation in the shape factor the boundary layer profiles and $\delta^*$ were both analyzed. Boundary layer profiles were extracted from $66\%-94\%C_x$ at increments of $2\%C_x$ for the case of 10Hz pulsing with a blowing ratio of $B=1$. The boundary layer profiles from $80\%-90\%C_x$ were then plotted for a phases 12 through 18 and 25-31. These phases were chosen because they show the flow at critical times through out the cycle of the jet pulsing. Phases 12-18 captured the flow when the jet turned off while phases 25-31 show the reaction of the flow to the jets being off. It was hoped these profiles would shed light on the reaction of the boundary layer to the jets presence. These boundary layer profiles can be found in Appendix H.

The boundary profiles did show the value of $U_{\text{max,local}}$ seemed to vary with phase. For this reason the value of $U_{\text{max,local}}$ was plotted over the blade surface from $66\%-94\%C_x$ for all even numbered phases. The $U_{\text{max}}$ distribution for Phase 16 and 26 are shown in Figure 3.8. The location of $U_{\text{max}}$ remains approximately in the same location however the magnitude of $U_{\text{max}}$ varies from 3.15 in Phase 16 to 3.7 in Phase 26, which is a variation of 15%. The exact reason for this is unclear at this time. A full set of these plots can be found in Appendix I.

The last analysis of the boundary layer profiles was calculate the value of $\delta^*$ using $U_{\text{max}}$ at each axial location from the time averaged plot and varying the the upper integration limit. The purpose of this analysis was to see if the value of $\delta^*$ was dependent on the limits of integration. A complete set of these plots can be found in Appendix J.
3.6 0.4Hz; B=1

Figure 3.10 shows the response of flow from the VGJs to the 0.4Hz TTL control signal that rove the solenoid valves. The TTL plot has been normalized to a maximum value of 1.0, and the velocity has been normalized to the mean flow-on velocity. This particular plot is for the B=1.0 case, but the shape and response of the jets are largely independent of the blowing ratio. There were small time lags experienced when the jet valve was opened and closed, however, the time lags were very small compared to the time between phases. In phases. In Phase 00 the valve opened and no flow was seen exiting, however, by Phase 01 the jet velocity had already reached the maximum. Likewise, in Phase 16 the valve closed and by Phase 17 the velocity of the flow exiting was very small.

After taking data for all three blowing ratios for the 10Hz case the pulsing frequency of the jet was reduced to 0.4Hz in order to study the transition of the crossflow from being separated to being attached as well as the natural development of separation. For a complete set of vorticity and velocity plots for the 0.4Hz pulsing case with a duty cycle of 50% and a blowing ratio of 1 refer to Appendix F.

Phase 00 through 02 show the response of the separated flow to the initiation of the jet flow. At Phase 00 (Figure 3.11(a)) the valves controlling the VGJs had just opened, but the jets had not begun to flow due to the response lag of the system. By Phase 01 (Figure 3.11(b)), 0.078 seconds after the jet opened, the VGJs were flowing and separation had been largely suppressed. There was a small reattaching bubble still evident near the aft portion of the blade. This small bubble continued to move downstream, and propagated off the trailing edge of the blade by Phase 02 (Figure 3.11(c)). The small hump in the vorticity field near 65%\(C_x\) was due to flow exiting the VGJ in the plane.
3.6. $0.4\text{Hz}; B=1$

Figure 3.9: Shape Factor Evolution: 10Hz
3.7 0.4HZ; B=0.5

The effects of the VGJs pulsed at 0.4Hz with a blowing ratio of B=0.5 was also studied. For a complete set of vorticity and velocity contour plots refer to Appendix ??.

Results show that, phase to phase, the reaction of the separated flow to the jet flow flow was very similar to that of the 0.4Hz pulsing with a blowing ratio of 1. The greatest evidence of this is seen in Figure 3.13, in this figure the evolution of the shape factor for the B=1 and B=0.5 cases are presented in the same plot. These plots show the reaction time of the cross flow is the same for both blowing ratios.

Figure 3.13 shows the time evolution of the shape factor (H) for boundary layer profiles taken at several axial locations. At 70%$C_x$ 3.13(a) location, there is no strong influence of teh VGJ pulsing. The H value remains at roughly 5 whether the VGJs are flowing (Phases 01 through 16) or not (Phases 17-31). Downstream, however, the influence of the jets on the shape factor is apparent.
3.7. 0.4HZ; B=0.5

(a) 0.4Hz; B=1; Vorticity Phase 00

(b) 0.4Hz; B=1; Vorticity Phase 01

(c) 0.4Hz; B=1; Vorticity Phase 02

(d) 0.4Hz; B=1; Vorticity Phase 17

(e) 0.4Hz; B=1; Vorticity Phase 18

(f) 0.4Hz; B=1; Vorticity Phase 22

(g) 0.4Hz; B=1; Vorticity Phase 27

(h) 0.4Hz; B=1; Vorticity Phase 28

(i) 0.4Hz; B=1; Vorticity Phase 29

(j) 0.4Hz; B=1; Vorticity Phase 31

Figure 3.11: Vorticity Plots: 0.4Hz, B=1 Select Phases
The separated flow (Phase 00) is driven to a near attached state almost immediately (by Phase 01 for 75%$C_x$ (Figure 3.13(b)) and Phase 03 for 95%$C_x$ (Figure 3.13(f))). The rate at which the separation reestablishes after the jets stop flowing (after Phase 16) depends on the axial location. The separation near the trailing edge redevelops almost immediately (Figure 3.13(f)) while the separation further upstream (Figure 3.13(e)) reestablishes itself only gradually. A complete set of shape factor evolution plots for the 0.4Hz pulsing case can be found in Appendix ??.

The shape factor plots were also plotted over the surface of the blade at every phase to give a shape factor profile. Select phases are presented in the body of this paper. For a complete set refer to Appendix G.

In Phase 00 (Figure 3.14(a)) the shape factor for both blowing ratio cases increased from 65%$C_x$ to 85%$C_x$. Downstream of 85%$C_x$ the shape factor in both cases decrease, which is not a physical result but, rather, due to the separation bubble extending out of the field of view making it impossible to extract the maximum local velocity ($U_{local,MAX}$) which is used in calculating the shape factor.

Figure 3.14(b) shows the shape factor profile at Phase 01, 0.078 seconds after the jet was turned on, and is similar to the shape factor profiles for Phases 02 through 16. For both blowing ratios the shape factor gradually decreased by at least a factor of 2 from 65% to 95%$C_x$. For both cases the value of the shape factor at 95%$C_x$ was approximately 2, which is between the values of $H$ expected for an attached laminar and attached turbulent flow, suggesting the flow is transitional at the aft portion of the suction surface.

Phase 17 (Figure 3.14(c)) showed the boundary layer shape factor 0.078 seconds after the jet was shut off. The shape factor for both blowing ratios ranges within a value of 3 to 5 from 65%$C_x$ to 90%$C_x$. The shape factor then drops to nearly 2 at 95%$C_x$ for both blowing ratios.

Phases 18 through 25 (Figures 3.14(d) through 3.14(f)) showed the boundary layer shape factor profile in transition from the profile of an attached flow (Figure 3.14(b)) to a fully separated flow (Figure 3.14(a)). During these phases the value of the shape factor is increased on the aft portion of the blade, indicating the separation bubble was growing. At 65% and 70%$C_x$ the value of $H$ was not seemingly affected by the jet being on or off. This suggests the activity in the boundary seen in the plane being studied was due to the adjacent jet. Only Phases 18, 21, and 25 are presented in the main section of the paper. For a complete set of boundary layer shape factor profiles refer to Appendix G.
Figure 3.12: Vorticity Plots: 0.4Hz, B=0.5 Select Phases
Figure 3.13: Shape Factor Evolution: 0.4Hz
3.7. 0.4HZ; B=0.5

(a) Phase 00

(b) Phase 01

(c) Phase 17

(d) Phase 18

(e) Phase 21

(f) Phase 25

Figure 3.14: Shape Factor Profile: 0.4Hz Select Phases
4

Conclusions

Results from the pulsing at 0.4 Hz show the pulsed vortex generator jets with a blowing ratio of 1 and 0.5 were able to suppress the separation almost immediately after the opening of the jet. For both blowing ratios the flow had fully reattached by Phase 01 meaning that the opening of the valve plays an important role in attaching the separated flow. Furthermore, the flow stayed attached in both cases for as long as the jet remained on and when they were shut off the flow gradually started to separate. This would indicate that the mass flow exiting the jet maintains attached flow. Also, comparing the B=0.5 case to the B=0.5 case shows that the oscillating shear layer is more damped by the higher blowing ratio. Once the jet was shut off the boundary layer was seen gradually lifting off the surface of the blade while quasi-phase-locked structures were seen developing in the unsteady shear layer. The developing structures seemed to be more strongly locked to the pulsing of the jet in the B=1 case when compared to the B=0.5.

Results from the 10Hz case show all three blowing ratios are able to maintain attached flow. A small phase locked separation bubble does develop on the aft portion of the blade for the B=0.5 case and is forced downstream with each pulse of the jet before the separation bubble develops much. Even while the jet flow with a blowing ratio is influencing the flow the boundary layer is still unsteady and once the VGJ influence passes the boundary layer immediately begins to separate., indicating the blowing ratio of 0.5 is near the lower limit for effective values. The B=1 case is free from activity, the flow stays attached with no separation forming. The shear layer tails also indicate that B=1 is a sufficient blowing ratio for VGJ influence to cover the entire blade in the spanwise direction. A blowing ratio of 2 causes the wake of a jet to penetrate well into the plane of the adjacent jet suggesting the momentum of the jet flow is excessively high and thus undesirable.

Results from the boundary layer profile, $\delta^*$, and shape factor plots indicate there is not enough resolution near the blade to extract meaningful data. Also, the boundary layer profiles were very unsteady suggesting that more data at each phase needed to be taken. To counter these issues the
next researcher should use a longer lens to focus in on the jet location as opposed to looking at
the overall blade surface. This will allow better resolution near the blade wall and make shape factor
calculations and boundary layer profile plots more meaningful. Also, the next researcher should use
smaller interrogation area sizes which will also aid in analyzing the boundary layer.

Smaller interrogation windows would allow higher spatial resolution along the surface of the
blade. Using the smaller interrogation window would make it possible to resolve smaller
fluidic structures that would have been passed over with the larger window size used in this thesis.
The interrogation window size used for this study was a 32 pixel by 32 pixel square. Based on a
magnification of 13.85 pixels/mm data within 2.3mm could be inaccurate due to the inability of the
correlation software to handle curved surfaces.

The method of seeding could be described best as "cross your fingers and hope for the best".
The fog generator was aimed at the wind tunnel inlet and its position adjusted using on the basis
of trial and error. A better, more reliable, method of seeding the flow needs to be implemented. The
possibility of seeding the jets should be investigated thoroughly, however, the seeding has to leave
no residue in the jet holes lest the deposited fog fluid effect the response of the jet.

Further work is required to look more deeply into how the vortex generator jet suppresses sepa-
ration. Suggestions for further work include increasing the phase resolution between Phase 00 and
Phase 01, perhaps putting 10 to 15 phase locked point in the first 0.078 seconds of the cycle. The
majority of the data, either with the jet on or off, could be effectively described as quasi-steady
state, and can be accurately measured with a low phase resolution.
A

VGJ Response
Figure A.1: Velocity and Vorticity Plots: 10Hz, B=2 Phases 04 - 07
B

No Blowing: Velocity and Vorticity
Contours
Figure B.1: Velocity: No Blowing

(a) Re=25,000 - Velocity  
(b) Re=40,000 - Velocity  
(c) Re=50,000 - Velocity  
(d) Re=100,000 - Velocity  

Figure B.2: Vorticity: No Blowing

(a) Re=25,000 - Vorticity 
(b) Re=40,000 - Vorticity 
(c) Re=50,000 - Vorticity 
(d) Re=100,000 - Vorticity
C

Contours: 10Hz; B=1

Figure C.1: 10Hz; B=1; Mean Contours
Figure C.2: 10Hz; B=1; Vorticity - Phases 00-11
Figure C.3: 10Hz; B=1; Vorticity - Phases 12-23
(a) 10Hz; B=1; Phase 24
(b) 10Hz; B=1; Phase 25
(c) 10Hz; B=1; Phase 26
(d) 10Hz; B=1; Phase 27
(e) 10Hz; B=1; Phase 28
(f) 10Hz; B=1; Phase 29
(g) 10Hz; B=1; Phase 30
(h) 10Hz; B=1; Phase 31

Figure C.4: 10Hz; B=1; Vorticity - Phases 24-31
Figure C.5: 10Hz; B=1; Velocity - Phases 00-11

(a) 10Hz; B=1; Phase 00
(b) 10Hz; B=1; Phase 01
(c) 10Hz; B=1; Phase 02
(d) 10Hz; B=1; Phase 03
(e) 10Hz; B=1; Phase 04
(f) 10Hz; B=1; Phase 05
(g) 10Hz; B=1; Phase 06
(h) 10Hz; B=1; Phase 07
(i) 10Hz; B=1; Phase 08
(j) 10Hz; B=1; Phase 09
(k) 10Hz; B=1; Phase 10
(l) 10Hz; B=1; Phase 11

Legend:

Length: 0 2.25 4.5
Figure C.6: 10Hz; B=1; Velocity- Phases 12-23
Figure C.7: 10Hz; B=1; Velocity - Phases 24-31
D

Contours: 10Hz; B=0.5

Figure D.1: 10Hz; B=1; Mean Contours
Figure D.2: 10Hz; B=0.5; Vorticity - Phases 00-11
Figure D.3: 10Hz; B=0.5; Vorticity - Phases 12-23
Figure D.4: 10Hz; B=0.5; Vorticity - Phases 24-31

(a) 10Hz; B=0.5; Phase 24
(b) 10Hz; B=0.5; Phase 25
(c) 10Hz; B=0.5; Phase 26
(d) 10Hz; B=0.5; Phase 27
(e) 10Hz; B=0.5; Phase 28
(f) 10Hz; B=0.5; Phase 29
(g) 10Hz; B=0.5; Phase 30
(h) 10Hz; B=0.5; Phase 31
Figure D.5: 10Hz; B=0.5; Velocity - Phases 00-11
Figure D.6: 10Hz; B=0.5; Velocity - Phases 12-23
Figure D.7: 10Hz; B=0.5; Velocity - Phases 24-31
Contours: 10Hz; B=2

Figure E.1: 10Hz; B=1; Mean Contours
Figure E.2: 10Hz; B=2; Vorticity - Phases 00-11
Figure E.3: 10Hz; B=2; Vorticity - Phases 12-23
Figure E.4: 10Hz; B=2; Vorticity - Phases 24-31
Figure E.5: 10Hz; B=2; Velocity - Phases 00-11
Figure E.6: 10Hz; B=2; Velocity- Phases 12-23
Figure E.7: 10Hz; B=2; Velocity - Phases 24-31
F

Contours: 0.4Hz; B=1
Figure F.1: 0.4Hz; B=1; Vorticity - Phases 00-11
Figure F.2: 0.4Hz; B=1; Vorticity- Phases 12-23
Figure F.3: 0.4Hz; B=1; Vorticity - Phases 24-31
Figure F.4: 0.4Hz; B=1; Velocity - Phases 00-11
Figure F.5: 0.4Hz; B=1; Velocity - Phases 12-23
Figure F.6: 0.4Hz; B=1; Velocity - Phases 24-31
G

0.4Hz: Shape Factor Plots
Figure G.1: Time evolution of the boundary layer shape factor: 0.4Hz
Figure G.2: Time evolution of the boundary layer shape factor: 0.4Hz
Figure G.3: Boundary layer shape factor profile: 0.4Hz
Figure G.4: Boundary layer shape factor profile: 0.4Hz
Figure G.5: Boundary layer shape factor profile: 0.4Hz
Figure G.6: Boundary layer shape factor profile: 0.4Hz
Figure G.7: Boundary layer shape factor profile: 0.4Hz
Figure G.8: Boundary layer shape factor profile: 0.4Hz

(a) Phase 30

(b) Phase 31
H

B=1; 10Hz: Boundary Layer Profiles
Figure H.1: Boundary Layer Profiles: 80%$C_x$; Select Phases
Figure H.2: Boundary Layer Profiles: 82% $C_x$; Select Phases
Figure H.3: Boundary Layer Profiles: 84% $C_x$; Select Phases
Figure H.4: Boundary Layer Profiles: 86% $C_\alpha$; Select Phases
Figure H.5: Boundary Layer Profiles: 88% $C_x$; Select Phases
Figure H.6: Boundary Layer Profiles: 90\%C_x; Select Phases
Figure H.7: Boundary Layer Profiles: 80% C - 90% C; Phases 12 - 18

(a) Phases 12
(b) Phases 13
(c) Phases 14
(d) Phases 15
(e) Phases 16
(f) Phases 17
Figure H.8: Boundary Layer Profiles: 80% $C_x$ - 90% $C_x$; Phases 25 - 31
I

$B = 1; 10\text{Hz}: U_{max} \text{ Profiles}$
Figure I.1: $U_{\text{max}}$ profile
Figure I.2: $U_{max}$ profile
Figure I.3: $U_{max}$ profile
Figure I.4: $U_{\text{max}}$ profile
$J$

$B = 1; 10\text{Hz}: \delta^* \text{ vs. Limits of Integration}$
Figure J.1: Boundary Layer Profiles: 80% $C_x$; Select Phases

(a) Phases 12-15

(b) Phases 15-18

(c) Phases 25-28

(d) Phases 28-31
Figure J.2: Boundary Layer Profiles: 82% $C_x$; Select Phases

(a) Phases12-15

(b) Phases15-18

(c) Phases25-28

(d) Phases28-31
Figure J.3: Boundary Layer Profiles: 84% $C_z$; Select Phases
Figure J.4: Boundary Layer Profiles: \( 86\% C_z \); Select Phases
Figure J.5: Boundary Layer Profiles: 88% $C_x$; Select Phases

(a) Phases 12-15

(b) Phases 15-18

(c) Phases 25-28

(d) 88% $C_x$
Figure J.6: Boundary Layer Profiles: 90% $C_x$; Select Phases

(a) Phases 12-15
(b) Phases 15-18
(c) Phases 25-28
(d) 90% $C_x$
Figure J.7: Boundary Layer Profiles: 80% $C_x$ - 90% $C_x$; Phases 12 - 18

(a) Phases 12
(b) Phases 13
(c) Phases 14
(d) Phases 15
(e) Phases 16
(f) Phases 17
Figure J.8: Boundary Layer Profiles: 80% - 90% C<sub>x</sub>; Phases 25 - 31
References


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