ABSTRACT

Warren Anthony Jones, Control of Diffusing Duct Flow Using Active Vortex Generators With Hot-Film Sensor Measurements. (Under the direction of Dr. Ndaona Chokani.)

Experiments have been conducted using vane-type vortex generators to control flow separation and exit flow distortion in a diffusing duct. The primary purpose is to examine the feasibility of using surface-mounted hot-film sensors to determine the extent of exit flow distortion. The experimental set-up consists of a two-dimensional blow down type wind tunnel with a variable diffuser exit. One diffuser wall is curved to produce a Stratford-like pressure gradient. The wall’s placement is adjustable such that the adverse pressure gradient can be adjusted to promote separation. An active vortex generator array that can be placed at three streamwise locations is used to reduce the extent of flow separation and exit distortion.

Diffuser surface pressure and exit total pressure measurements are obtained and compared to the hot-film data. The time-averaged mean and rms voltages from the hot-film data are used as indicators of flow separation and exit flow distortion.

Results show that, with the use of the vortex generators, high mean voltages and low levels of rms voltage correlate well with improved pressure recovery. Conversely, poorer pressure recovery is associated with lower mean voltages and higher rms values compared to the baseline cases. Increased total pressures at the diffuser exit are accompanied by increases in hot-film mean voltages. These indicate higher shear stresses, which also correspond to increased flow uniformity. Lower variations in the rms voltages compared to the baseline cases also correlated well with improved total pressures at the diffuser exit.
CONTROL OF DIFFUSING DUCT FLOW USING ACTIVE VORTEX GENERATORS WITH HOT-FILM SENSOR MEASUREMENTS

by

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BIOGRAPHY

Warren Anthony Jones was born in Kinston, North Carolina on February 3, 1976, to Stephen and Carolyn Jones. He was raised in Kinston with his older brother Christopher. He graduated from North Lenoir High School in the spring of 1994. In the fall of 1994, he enrolled in Lenoir Community College where he completed his Associate of Science degree in Engineering in May 1996. In the fall of 1996, he entered North Carolina State University in the College of Engineering to pursue a major in Aerospace Engineering. He graduated in the spring of 1999 with the degree of Bachelor of Science in Aerospace Engineering.

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Finally, I want to thank my parents Steve and Carolyn Jones for their encouragement and support. Their love and prayers were essential in my work. I would also like to thank my brother, Chris, for his interest and support.
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<tr>
<td>$C_p$</td>
<td>Pressure coefficient</td>
</tr>
<tr>
<td>$I_w$</td>
<td>Current through sensor</td>
</tr>
<tr>
<td>$\bar{I}_w$</td>
<td>Mean current through sensor</td>
</tr>
<tr>
<td>$i_w$</td>
<td>Fluctuation current through sensor</td>
</tr>
<tr>
<td>$\ell$</td>
<td>Vortex generator length</td>
</tr>
<tr>
<td>$m$</td>
<td>Time averaged mean voltage</td>
</tr>
<tr>
<td>$N$</td>
<td>Total number of data samples used in time averaged quantities</td>
</tr>
<tr>
<td>$n$</td>
<td>Discretized quantity index</td>
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<tr>
<td>$P_e$</td>
<td>Total pressure at the diffuser exit</td>
</tr>
<tr>
<td>$P_o$</td>
<td>Total pressure upstream of the diffuser inlet</td>
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<tr>
<td>$p_{ref}$</td>
<td>Static pressure at the inlet of the diffuser</td>
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<tr>
<td>$p_s$</td>
<td>Static pressure</td>
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<tr>
<td>$Q_f$</td>
<td>Heat transfer rate to fluid</td>
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<td>$Q_J$</td>
<td>Joulean heating</td>
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<tr>
<td>$Q_s$</td>
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<td>$R_F$</td>
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<tr>
<td>$R_T$</td>
<td>Total resistance of nickel sensor and copper lead</td>
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<td>$R_w$</td>
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Fluctuation resistance of the sensor

Spacing distance between counter-rotating vortex generator pairs

Reference temperature of the sensor

Fluid flow temperature

Fluid flow temperature and reference temperature difference

Flow velocity at the inlet of the diffuser, ft/s

Time averaged mean voltage signal

Root mean square voltage

Output voltage of CVA

Mean output voltage of CVA

Fluctuation output voltage of CVA

Voltage through sensor

Curved plate or flat plate cord location

Discretized data sample

Greek Symbols

Sensor thermal coefficient of resistance

Angle of vortex generator relative to flow direction, deg.

Boundary layer thickness, in.

Spacing distance between vortex generators for co-rotating pairs

and distance between sets for counter-rotating pairs

Deflection angle of curved plated diffuser wall
$\rho$  Air density, slug/ft$^3$

$\sigma$  Standard deviation (rms)

$\tau_w$  Local wall shear stress
Chapter 1
INTRODUCTION

1.1 Applications and Research Objectives

Most modern tactical aircraft have complex integrated airframe-inlet systems that allow the aircraft to operate at subsonic, transonic and supersonic speeds without compromising cruise performance. With the increasing demand for the use of uninhabited combat air vehicles (UCAV) in the role of tactical reconnaissance, these systems are becoming increasingly complicated and compact, Figure 1.1, as the UCAV design must have low observability and low drag. The advanced design requirements result in a highly integrated propulsion system on the UCAV that is characterized by top-mounted inlets followed by a compact serpentine (or S-shaped) duct that leads to the engine, Figure 1.2. The primary purpose of a diffusing serpentine shaped duct (S-duct) is to provide a uniform, high total pressure recovery flow to the engine compressor while providing line-of-sight blockage of the engine face. Size and weight restrictions often encourage the use of the shorter S-ducts. However, flow distortions can develop in the diffuser because of inlet and exit centerline offset and changes in cross-sectional shape. The curvature in the centerline can promote streamline curvature that leads to cross-stream pressure gradients. These cross-stream gradients can cause separation from the duct wall and induce the low momentum boundary layer to move towards the center of the duct. Changes in cross-sectional shape and increasing duct area can also lead to flow separation as a result of high adverse pressure gradients. The resulting non-uniform total pressures and velocity distortions at the engine
compressor face can lead to lower engine performance and reduced engine life cycles. Performance losses can occur from catastrophic compressor surges due to rotor blade stall. The flow distortions result in high frequency loading and unloading of the compressor rotor blades that can lead to premature failure of the compressor rotor blades due to structural fatigue.\textsuperscript{8,9} There is currently an undertaking using experiment and computation to develop new flow control methods to improve the performance of the systems.

The primary objectives of this research were i) to design and construct a small wind tunnel to simulate inlet duct flows, ii) to design and implement flow control using vane-type vortex generators and iii) to use multi-element hot-film sensors to monitor the characteristics of the duct flow.

### 1.2 Experiments Involving S-Ducts

A number of experiments have been performed to understand the performance losses and flow characteristics within S-duct diffusers as well as to demonstrate flow control techniques that alleviate the inherent S-duct diffuser separation and secondary problems. Reichert and Wendt\textsuperscript{10} performed a study to reduce inlet flow distortion and improving the total pressure recovery. They used tapered-fin type vortex generators for flow control in their setup of a diffusing S-duct with a circular cross-section. Instead of the standard application of vortex generators where higher momentum core flow is mixed with the lower momentum flow in the boundary layer to promote attached flow, Reichert and Wendt used the vortex generators more as boundary layer turning vanes. This method reduced the flow distortion by more than 50%. The performance and flow characteristics of an S-duct diffuser ingesting a thick boundary layer was examined in an experiment by Anabtawi \textit{et al.}\textsuperscript{11} The
setup consisted of an S-duct with a semi-circular inlet that transitioned to a wholly circular exit. Vane-type vortex generators, on the order of 0.25-1.0 times the boundary layer height, were used to eliminate boundary layer separation and improve the duct performance. Measurement techniques for this experiment involved surface flow visualization and total pressure surveys. With the use of the vortex generators, the exit flow distortion was decreased by 11% for some configurations and flow separation was prevented. A different approach was used by Brown et al.\textsuperscript{12} who integrally designed a subsonic diffuser incorporating vortex generators. The design arranged the vortex generators such that the resultant vortices were driven against the sidewalls of the diffuser eliminating separation. The diffuser design resulted in reductions of pressure recovery losses and distortion by about 40%. It was also shown in this experiment that vortex generators that are not ideally matched result in larger penalties with the integral design than with the conventional diffusers. Raghunathan et al.\textsuperscript{13} conducted flow control experiments using a short wide angle diffuser with pulse jets. The two-dimensional test section employed two diffuser walls on cylindrical mounts that were deflected to vary the pressure gradient in the diffuser, Figure 1.3. Without the use of flow control, the transitory stall, that is boundary layer separation, on the diffuser walls occurred at 15° resulting in poor pressure recovery. However, applying the pulse jets resulted in an improved pressure recovery as well as larger diffuser angles before the onset of separation or stall.

\subsection*{1.3 Computations Involving S-Ducts}

Numerical studies have also been conducted to aid in the design of S-duct diffusers. The more significant studies include the use of three-dimensional fully viscous analysis
codes that can simulate the vortex lift-off that is observed to be significant in diffuser designs. Anderson et al.\textsuperscript{1} used a three-dimensional implicit full Navier-Stokes code to analyze S-duct geometries with naturally occurring vortex lift-off characteristics. Several comparisons with experimental data were made. It was observed that although separation locations were consistently shown further downstream in the computations, the vortex lift-off topology was captured. A model of the grid geometry can be seen in Figure 1.4 and results of the computation showing total pressure contours and streamlines are shown in Figure 1.5.\textsuperscript{1,4,14} A three-dimensional, fully viscous design and analysis of a compact subsonic diffuser was demonstrated by Mayer et al.\textsuperscript{3} Initial calculations were made using Euler equations and subsequent analysis conducted using full Navier-Stokes calculations to incorporate the viscous effects. In the design process, parametric quantities defining the S-duct geometry were varied to produce a diffuser design with optimal flow qualities at the diffuser exit. Explicit grid models of vortex generators for S-duct flow control in Navier-Stokes codes were made at the expense of computer run-time and grid generation time to produce accurate CFD models. Bender et al.\textsuperscript{14} studied a method to simulate the effects of vortex generators in a finite volume Navier-Stokes Code that eliminated the need to define their geometry in the grid. This was accomplished by introducing the local vortex generator flow field effects (i.e. a force normal to the flow) as a source term in the momentum and energy equations. This modeling scheme produced a grid one-third smaller than the conventional model with gridded vortex generators. The computed results for both simulated and gridded vortex generators are shown in Figure 1.6 compared to the experimental setup results.
1.4 Active Flow Control

Active flow control is currently one of the leading areas of research in the field of fluid mechanics. The intent of flow control is to delay or advance boundary layer transition, suppress or enhance turbulence, or prevent or promote boundary layer separation. Some of the realized benefits are drag reductions, lift enhancement, and mixing augmentation, thus yielding improved performance, maneuverability and efficiency in aircraft applications. A classification of flow control methods is shown in Figure 1.7. Passive flow control techniques are tailored for only specific design conditions that may promote greater penalties with increased drag, decreased lift, or premature boundary layer separation in off-design conditions. Active control methods however, are applied only when desired. Active control methods fall into two categories, predetermined and interactive. The predetermined, or open-loop, control employs steady or unsteady inputs without feedback, but can be very effective in modifying the flow field. The work presented in this research examines an open-loop flow control approach, Figure 1.8, to develop the framework for subsequent closed-loop or interactive control methods. Vortex generators that have historically been used as actuators for flow control in inlet ducts are employed. Hot-film sensors that have been used in aerodynamic applications other than inlet ducts are evaluated to assess their suitability for this application.

1.5 Vortex Generators

Vortex generators (VGs) are small-aspect-ratio airfoils or vanes that are oriented at some incidence angle to the mean flow and perpendicular to the surface from which they are mounted so that streamwise trailing vortices are induced. VGs provide a means of
introducing momentum to a flow through a large-scale overturning of the mean flow. Fluid with high streamwise momentum near the boundary layer edge is swept along a helical path toward the surface to mix with lower momentum fluid flow and thus increasing the near-wall momentum.\textsuperscript{16} By increasing the near-wall momentum, flow at the surface remains attached, and separated flows can be minimized or eliminated. The governing parameters that characterize VGs, Figure 1.9, include planform shape, section profile and camber, angle of incidence, spacing and height with respect to the boundary layer thickness, $\delta$. An array of VGs each with the same angle of incidence produces co-rotating trailing vortices. Orienting a vortex generator pair at equally opposite angles produces counter-rotating vortices. Sub-scale or micro vortex generators were investigated as a means of flow control with lower device drag compared to boundary layer scale VGs by Lin.\textsuperscript{17} Micro vortex generators have heights on the order of one-fifth the boundary layer thickness, whereas boundary layer scale vortex generators have heights approximately equal to the boundary layer thickness. In the presence of a turbulent boundary layer, where the velocity profile is relatively full, the velocity at a distance one-fifth of the boundary layer thickness from the wall can be about 70\% of the boundary layer edge velocity. Therefore the micro vortex generators can still provide substantial momentum transfer over a region several times their own height. Additionally, for multi-element airfoils micro VGs can be stowed in flap wells while in retracted cruise configuration and only exposed to the flow when the flap is deployed in the high lift configuration.
1.6 Hot-Film Sensors

The hot-film sensor consists of a thin metallic film deposited onto a substrate. The operating principle of the sensor derives from the fact that the heat transfer from a sufficiently small heated surface depends only on the flow characteristics in the viscous region of the boundary layer. An electric current is passed through the sensor in order to maintain it at a constant temperature or voltage as heat is continuously transferred from the film to the boundary layer and to the film’s substrate, Figure 1.10. The Joulean heating in the hot-film sensor can then be expressed as:

\[ Q_I = Q_f + Q_s \quad (1.1). \]

If the flow is steady and laminar, and if the streamwise pressure gradient can be neglected, the resulting heat transfer rate to the fluid is related to the wall shear stress as:

\[ \tau_w \propto Q_f^3 \quad (1.2). \]

This classical relation was derived from dimensional analysis by Liepmann and Skinner and from the laminar boundary layer equations by Bellhouse and Schultz. Menendez and Ramaprian followed the approach of Bellhouse and Schultz and derived an extended version for unsteady boundary layer flows that are exposed to a periodic freestream of the form,

\[ U(t) = U_o (1 + \varepsilon \sin \omega t) \quad (1.3). \]

In this context equation (1.2) then can be regarded as the relationship between the instantaneous values of the wall shear stress and heat flux. By taking ensemble averages of
equation (1.2) over a large number of cycles, we can also relate the wall shear stress and heat flux in a turbulent environment provided that the turbulent fluctuations are relatively small.\textsuperscript{21}

In a recent flight experiment, Moes \textit{et al.}\textsuperscript{22}, hot-film sensor were used to detect the location of shock-induced boundary layer separation on a wing at transonic speeds. The agreement between the hot-film data and pressure data were very good; this application also demonstrated the robustness of the hot-film sensors. Furthermore, the non-intrusive nature of the hot-film sensors makes these devices attractive for practical active flow control applications.

1.7 Outline of Thesis

The experimental setup and experimental procedure are presented in Chapter 2. The blow-down type wind tunnel that consists of a settling chamber, boundary layer transition section, and a diffuser test section are first described. Then, the experimental procedure including surface pressure, exit pressure surveys and hot-film data measurements is discussed. Finally, the data processing for the hot-film measurements is introduced. The results are presented in Chapter 3 and the relationship between the hot-film sensor measurements on the diffuser performance and exit flow distortion are examined. Lastly, Chapter 4 presents the conclusions of this research as well as suggestions for future work and applications.
Chapter 2
EXPERIMENTAL APPROACH

2.1 Experimental Apparatus

This experiment was conducted in a two-dimensional flow, boundary layer wind tunnel that was designed and built specifically for this research. The tunnel was of an open loop, blow-down type and consisted of a blower, settling chamber, transition section and a diffuser test section.

2.1.1 Blower

A 1200 CFM reverse impeller, radial blower was used to provide air to the wind tunnel, Figure 2.1. This centrifugal type blower was used in preference to an axial flow fan, as it is capable of providing a steady airflow, with low pulsation due to blade passage, Mehta.  

2.1.2 Settling Chamber

The settling chamber was designed to minimize fluctuations in the incoming airflow. The upstream portion of the settling chamber diverged from the \(5^{9/16}\)-in wide by \(7^{3/16}\)-in blower exit to a 15-in by 10-in. section. At this larger section, a \(1\frac{1}{4}\)-in thick aluminum honeycomb screen was placed. The 0.1-in hexagonal cells thus had a length-to-diameter ratio of 12.5, which is considered effective to reduce large-scale structures and swirl from the incoming flow. No wire screen was employed. Downstream of the honeycomb, the settling
chamber converged to a rectangular section of $2\frac{1}{2}$-in by 10-in. The settling chamber is shown in Figure 2.2.

### 2.1.3 Transition Section

The transition section, constructed from $\frac{3}{8}$-in Plexiglas®, Figure 2.3, was designed to develop a 0.5-in turbulent boundary layer at its exit. The overall tunnel length was determined by modeling the development of a laminar/turbulent boundary layer in a zero pressure gradient. The laminar boundary layer originated at the entrance to the transition section, and an assumed Blasius velocity profile is used to determine its thickness. A flat plate turbulent boundary layer with an assumed one-seventh-power law velocity profile was used to describe the flow downstream of the boundary layer transition location. The exit of the section was then determined when the desired boundary layer thickness was achieved. The transition section had an overall length of 82-in. At the entrance, the dimensions were $2\frac{1}{2}$-in wide by 10-in high. One sidewall diverged outward at $0.11^\circ$ so that there was no streamwise pressure gradient. A #36 transition grit was placed 71-in downstream of the entrance on all four sides of the transition section.

### 2.1.4 Test Section

The test section was located at the exit of the transition section. The two interchangeable sidewalls of the test section were mounted on pivot cylinders that were located at the exit of the transition section. These walls could be rotated independently about the cylinders to angles in the range $0$-$25^\circ$, thus the cross-sectional area, and hence pressure gradient, could be changed. This design is modeled after the work of Raghunathan et al.\textsuperscript{13}
One is a Plexiglas® flat plate that is instrumented with surface pressure ports. The other sidewall is a curved fiberglass plate; this plate was designed with the geometry of the aft portion of a NLF-0414 airfoil. The purpose of this curved plate was to provide a Stratford-like pressure gradient. This plate was instrumented with multi-element hot-film sensors.

2.1.5 Surface Pressure Instrumentation

The flat plate was instrumented with an array of static pressure ports to obtain the surface pressure distribution on the sidewall opposite to the curved plate. Twenty-seven ports evenly spaced 0.236-in (6 mm) apart were located along the centerline; the first port was 1.075-in (27.3 mm) downstream of the exit of the transition section. Two offset rows of pressure ports were located 1/3-in (42.3 mm) on either side of the centerline. Each row had seven ports evenly spaced 0.945-in (24 mm) apart. A schematic diagram of the array of pressure ports is shown in Figure 2.4 and the instrumented plate is shown in Figure 2.5.

2.1.6 Surface Hot-Films

The curved plate was instrumented with an array, Figure 2.6, of 64 hot-film sensors spaced 0.1-in apart along the centerline. The first sensor was located 1\(\frac{1}{16}\)-in downstream of the exit of the transition section. The nickel sensors are electron beam deposited onto a Kapton® substrate; the sensor dimensions are a thickness of \(<8\times10^{-7}\)-in (<20 µm) and 0.004-in wide by 0.057-in long. The non-conductive Kapton® substrate, a Upilex S polyimide film with a thickness of 0.002-in, was glued to the surface of the curved plate. Copper leads, having a thickness 0.0005-in and width of 0.030-in with resistance of \(<0.05\ \Omega/\text{in}\), supply power to the sensor. Only every other sensor was used in the present experiment. The cold
resistances of the sensors are listed in Table 2.1. The instrumented NLF plate is shown in Figure 2.7.

2.1.7 Pressure Measurement System

A Pressure Systems Inc. (PSI) ESP32HD miniature pressure scanner, Figure 2.8 was used to acquire the surface and exit pressures. The PSI module consisted of 32 silicone transducers, one for each port. 0.040-in nylon tubing was used to connect the PSI module to the pressure taps. A hex inverter with open-collector outputs was developed to interface the PSI module with the data acquisition computer. The open collector circuit is shown in Figure 2.9 and a schematic diagram of its interface to the PSI module is shown in Figure 2.10.

2.1.8 Traversing Pitot Rake

A single axis traverse system was used to move a pitot rake across the exit plane of the diffuser. The pitot rake consisted of 32, $\frac{1}{16}$-in diameter, copper tubes equally spaced at intervals of 0.23-in. The traversing apparatus, shown in Figure 2.11, consisted of a stepper motor, reduction gears, lead screws and pitot rake. The pitot rake was attached to the brass mounts that traversed the exit of the diffuser when the motor was driven. The traverse system was computer controlled through a Labview program.

2.1.9 Vortex Generators

For the present experiments, a single array of counter-rotating vane-type vortex generators was used to control the flow distortion and separation. Interchangeable sidewall plates provided three streamwise locations, 1.925-in, 2.925-in and 4.05-in upstream of the
exit of the transition section. The vortex generators were designed have an optimum configuration with a height of 0.1-in at the intermediate station. Thus, fourteen vortex generators spanned the sidewall. The angle of incidence was ±23°, the vane spacing was 0.25-in, pair spacing 1.25-in and length of 0.7-in, Figure 2.12. The vortex generators were made from brass sheet and affixed to a Plexiglas base plate. The vortex generator height could be adjusted in the range 0-0.5-in either by manually moving the base plate or by moving the base using the traverse system, Figure 2.13.

2.1.10 Constant Voltage Anemometer

A Tao Systems 16-channel constant voltage anemometer (CVA) system is used to operate the hot-film sensor array on the curved plate, Figure 2.14. The CVA consists of three basic elements: 1) a stable, low noise, DC power supply; 2) an operational amplifier; and 3) a T-resistor network, Sarma.\textsuperscript{24} The basic circuit for the CVA is shown in Figure 2.15. When current is passed through the sensor, its temperature is raised above the ambient temperature. The sensor resistance is governed by the equation:

\[
R_w = R_o \left[1 + \alpha_v \left(T_w - T_o\right)\right]. \tag{2.1}
\]

Fluctuations in the airflow change the convective heat transfer rate of the sensor and thus gives rise to resistance changes of the hot-film. In the CVA, the voltage, \(V_w\), through the center node of the T-resistor is constant and independent of the sensor resistance. Applying Kirchhoff’s current law to the center node yields:

\[
\frac{V_w}{R_F} + \frac{V_w}{R_w} + \frac{V_w - V_s}{R_2} = 0. \tag{2.2}
\]

The output voltage of the anemometer, \(V_s\), is given by rearranging the equation (2.2) to:
The feedback resistor is thus a proportional constant that is applied to the sensor voltage and sensor current. If the feedback resistance is large, small changes in the sensor current render large variations in output voltage of the CVA. If small fluctuations in the flow are considered, the output voltage is then given as:

\[ V_s = I_w R_2 + \left( \frac{R_F + R_2}{R_F} \right) V_w. \]  

(2.3)

Noting that the mean valued quantities satisfy equation (2.3), equation (2.4) then reduces to:

\[ v_s = i_w R_2. \]  

(2.5)

In the CVA, as the sensor voltage is constant, the changes in sensor resistance and current are related by,

\[ i_w R_w = -r_w I_w. \]  

(2.6)

Thus, the change in output voltage and change in resistance relative to a reference condition are related by:

\[ v_s = -I_w R_2 \frac{r_w}{R_w}. \]  

(2.7)

Or, in terms of the temperature change relative to a reference condition using equation (2.1) we obtain:

\[ v_s = -I_w R_2 \frac{\alpha \Delta T}{1 + \alpha \Delta T}. \]  

(2.8)

The auto-zero unit, shown in Figure 2.14, was used to discern the change in output voltage, \( v_s \), from the mean output voltage, \( V_s \), that is measure at the reference condition.
2.1.11 Data Acquisition

Two data acquisition systems were used in the present work. The first was an IOtech Wavebook/512™ that is used to sample the CVA output voltages, Figure 2.14. This consists of a pair of expandable units, each having eight differential input channels. The Wavebook/512™ acquisition system is a PC-based 1-MHz digitizer with 12-bit resolution. It has an analog bandwidth of 500-kHz and a sampling rate with 8 channels of up to 125-kHz per channel.

The second data acquisition system used to operate the traverse system and acquire pressures is a National Instruments PCI 6033E data acquisition (DAQ) computer board. This board has 64 single-ended analog inputs that can be sampled at 100 kS/s with 16-bit resolution; in addition, the board has eight digital I/O, and two 24-bit counter timers. A 700-MHz PC computer interfaced both data acquisition systems. Waveview software and LabVIEW were used to operate the Wavebook and NI data acquisition systems respectively.

2.2 Experimental Procedure

The experiments were conducted to examine the effects of deflection angle of the curved plate, height of the vortex generators and streamwise location of the vortex generators. Table 2.2 summarizes the test matrix for the surface pressure and exit total pressure measurements. Hot-film measurements were obtained for all diffuser angles, VG locations and heights in Table 2.2. The corresponding measurements of surface and exit pressures were also made.
2.2.1 Pressure Sensor Calibration

The PSI module was calibrated prior to the pressure measurements. In the calibration, a calibration pump was used to vary the pressure over the limits of the transducers, -10-in H₂O to +10-in H₂O. A water manometer was used to directly read the applied pressures. Typical calibration curves are shown in Figure 2.17, and are seen to be quite linear. In the actual experiments, after the PSI module was turned on and had warmed up to a steady state temperature, the first measurements were used as the calibration offset value for that set of runs. This was necessary to compensate for any possible thermal effects on the piezoresistive silicon sensors.

2.2.2 Surface Pressure Measurements

The surface pressure distribution on the undeflected flat plate was used to characterize the streamwise pressure gradients. Every other port along the centerline was measured. All the ports on the two offset rows were measured to verify the two-dimensionality of the flow.

2.2.3 Hot-Film Sensor Measurements

Hot-film sensor measurements were made for all the test cases show in Table 2.2. The initial current through the sensors in the no flow condition was 90mA. The reference condition for all hot-film measurements was flow on, no vortex generator deflection, and specified curved plate deflection; in other words, the CVA output was auto-zeroed at this condition. 8192 samples per channel were acquired at a sampling frequency of 1-kHz.
Additional tests at sampling frequencies of 500-Hz and 2-kHz showed that 1-kHz was a satisfactory sampling rate.

### 2.2.4 Exit Pressure Surveys

Exit total pressure surveys were made using the pitot rake. The vertical spacing of the measurements was $1/8$-in. The total pressure just upstream of the diffuser plates was also measured with a pitot probe to provide a reference condition for the exit total pressures.

### 2.3 Experimental Data Processing

The time mean sensor voltages were calculated as

$$m = \frac{1}{N} \sum_{n=1}^{N} x_n.$$  \hspace{1cm} (2.9)

As the sensor voltage is directly related to the convective heat transfer from the sensor, the mean voltage is a measure of the flow distortion and flow separation. The relatively high mean voltages indicate reduced flow distortion and/or reduced flow separation.\(^{20}\)

The standard deviation or root mean square (σ) sensor voltages are given by

$$s = \left( \frac{1}{N} \sum_{n=1}^{N} (x_n - m)^2 \right)^{1/2}.$$ \hspace{1cm} (2.10)

The root mean square (rms) attains relatively large values in the vicinity of a separation and reattachment point. This may also have large values in regions where the vortices impinge on a hot-film sensor.\(^{26,27}\)
Chapter 3

RESULTS & DISCUSSION

3.1 Surface Pressures

The effect of vortex generator height on the surface pressure distribution is examined in Figures 3.1 to 3.20. The pressure recovery is determined from the surface pressure measurements on the flat plate by comparisons of the pressure coefficients given by,

\[ C_p = \frac{P_s - P_{ref}}{\frac{1}{2} \rho U^2} \]  \hspace{1cm} (3.1)

The following sections will discuss the effectiveness of vortex generator height at each of the three array locations upstream of the diffuser inlet. The discussion includes: a) the characterization of the baseline flow and its two-dimensionality; b) the effect of VG heights at a given location and diffuser angle; and c) an assessment of the effectiveness of the vortex generators.

3.1.1 Baseline Flow

Figure 3.1 shows the effect of the curved plate deflection on the pressure distribution. For all the diffuser deflections, the pressure distributions are in close agreement until about x/c \approx 0.34. Downstream of x/c \approx 0.34, the smaller diffuser deflection, \( \theta = 6^\circ \), shows the largest increases in the pressure recovery. The subsequent pressure recovery decreases with increasing diffuser angles. The flow has likely started to separate on the curved plate that is on the side opposite the flat plate thus reducing the effectiveness of the diffuser. Once
separated from the curved plate, there remains a region of separated flow. The case for $\theta = 14^\circ$ has the largest extent of separated flow and accordingly the smallest pressure recovery. For an ideal flow without separation, the largest diffuser angle would be expected to produce the best pressure recovery. However, the results shown in the baseline flows indicate that there is significant separation at the larger diffuser angles.

Figures 3.2 to 3.4 show the extent of two-dimensional flow across the span of the diffuser. For the two smaller diffuser angles, $\theta = 6^\circ$ and $\theta = 10^\circ$, the pressure distribution along the upper row of pressure ports is offset from the centerline pressure distribution. The cause of this difference can be attributed to the no. 28 gage wires connected to the flush copper leads along the upper half of the curved plate, Figure 2.7. The presence of these wires is thought to distort the flow along the upper half of the curved plate, but has no effect in the lower half of the plate. For both diffuser angles, the pressures measured along the lower offset ports agree very well with the centerline values. This indicates that the centerline pressure ports are representative of the flow through the diffuser. In Figure 3.4, $\theta = 14^\circ$, the flow is separated along the entire span of the diffuser and the pressure distribution is the same for all three spanwise rows.

Overall, the results show that the flow through the diffuser is reasonably two-dimensional. As the diffuser angle is increased, the pressure recovery of the diffuser is decreased, and at the largest diffuser angle, the flow appears to be largely separated.

### 3.1.2 Effect of VG Height at the Downstream Location

The first set of vortex generators tested is located 1.925-in upstream of the diffuser inlet. This is referred to as the downstream location. For the small diffuser angle, $\theta = 6^\circ$,
Figure 3.5, the pressure recovery is not significantly improved for any of the three VG heights that are tested. There is only a small improvement in pressure recovery towards the exit with the 0.3125-in VGs. However, upstream of $x/c \approx 0.7$ the VGs have an adverse effect on the pressure recovery. Similarly, the 0.0625-in and 0.4375-in vortex generators have an adverse effect on the performance of the diffuser. These results show that for this small diffuser angle and the range of vortex generator heights examined, none of the VGs are successful in improving the pressure recovery through the diffuser.

The effects of the vortex generators for the moderate diffuser angle, $\theta = 10^\circ$, are examined in Figure 3.6. At this diffuser angle, there are significant improvements in the pressure recovery with the use of the vortex generators. The 0.0625-in and 0.3125-in VGs provide similar pressure recoveries through the diffuser. The most effective VGs are the 0.4375-in high vortex generators. These VGs show the best rate of pressure recovery up to about $x/c \approx 0.7$; downstream of this location, the rate of recovery is comparable to the two smaller VGs. However, the smaller two heights tested, while improving the overall pressure recovery, show rather irregular pressure distributions. The exit pressure recovery with the 0.4375-in vortex generators is also greater than the $\theta = 6^\circ$ baseline and flow control cases.

Figure 3.7 shows the pressure distributions for the largest diffuser angle, $\theta = 14^\circ$. As with the moderate deflection, this case shows considerable improvements in pressure recovery with the use of vortex generators. All three VG heights eliminate or minimize the apparent flow separation in the diffuser. The overall pressure recovery increases monotonically with increasing VG height and, the largest VGs provide the best improvements. At the exit, the pressure however is below the pressure of the $\theta = 10^\circ$ case.
3.1.3 Effect of VG Height at the Intermediate Location

The vortex generators tested for this case were located at their intermediate location that is 2.925-in upstream of the diffuser inlet. Figure 3.8 shows the results of vortex generators with the small deflection, $\theta = 6^\circ$. The results are very similar to the cases where the VGs were located 1.925-in from the inlet. Since there is little or no separation in the baseline flow, none of the VG heights improve the pressure recovery over the baseline. For the larger deflection angle, $\theta = 10^\circ$, Figure 3.9, the improvements that are observed with the more downstream VG location, Figure 3.6, are not seen here. Only the larger VGs, of heights 0.3125-in and 0.4375-in show improvements over the baseline flow; these improvements however are not very marked. The largest deflection angle, $\theta = 14^\circ$, Figure 3.10, shows a significant improvement in pressure recovery with the vortex generators. At the exit, the pressure increases monotonically with VG height. The streamwise pressure distributions, however, do not follow a smooth trend for the 0.0625-in and 0.3125-in VGs. The variations in the pressure for these two cases may be caused by vortices lifting off and then impinging on the curved plate periodically; this may also result in a less steady flow. The largest VGs, 0.4375-in, however produce a smooth pressure distribution along the length of the diffuser.

3.1.4 Effect of VG Height at the Upstream Location

The results next discussed are for the vortex generators located 4.05-in upstream of the diffuser inlet; this is also termed the upstream location. In Figure 3.11, it is seen that the vortex generators do not improve the pressure recovery and in fact the 0.3125-in VGs significantly degrade the diffuser’s performance. For the moderate deflection, Figure 3.12,
the intermediate VG height produces the best results. The 0.4375-in vortex generators show similar improvements at the exit, but overall, do not perform as well as the 0.3125-in VGs. This observation suggests that there is no additional benefit, in terms of pressure recovery, of the large VGs compared to the intermediate VGs. This trend is again observed in the results of the diffuser deflection of $\theta = 14^\circ$, Figure 3.13. The 0.3125-in vortex generators are overall more effective than either the 0.0625-in or 0.4375-in VGs. However, it is also apparent that the intermediate VGs perform as well as the largest VGs in terms of the exit pressure recovery; thus there is no additional benefit in using the largest VGs compared to the intermediate VGs.

3.1.5 Effect of Vortex Generator Location

The effect of the streamwise placement of the vortex generators on the diffuser pressure recovery is next examined, Figures 3.14 - 3.20. In Figure 3.14, the VG height is 0.3125-in and diffuser deflection is $\theta = 6^\circ$. The VGs improve the pressure recovery when the array is at the downstream location that is closest to the diffuser inlet, 1.925-in. As the array is moved further upstream of the diffuser inlet, the effect of the VGs is more adverse, and the most upstream position 4.05-in is the most deleterious. At the moderate deflection, $\theta = 10^\circ$, Figure 3.15, the effect of the 0.0625-in VGs is examined. The best pressure recovery again results from the array placed at the most downstream locations whereas the array furthest upstream from the inlet has little effect. In contrast to these cases, the intermediate location adversely affects the pressure recovery. However, with an increase in VG height to 0.3125-in, the VGs at all three locations, Figure 3.16, improve the pressure recovery at the exit. It is unclear why the 1.925-in and 4.05-in array placements produce almost identical results while
the VGs at the intermediate location produces dissimilar results. However, these results clearly point to the need for VGs of adjustable height. A similar trend is seen again for the VG height of 0.4375-in at a $\theta = 10^\circ$ deflection, Figure 3.17. The array nearest diffuser inlet produces the best pressure recovery at the exit. The second most effective array is again the most upstream array. The array that produces the best recovery in this case also shows a smoother pressure distribution.

Figures 3.18 to 3.20 examine the effect of the streamwise location on the pressure recovery at the largest diffuser angle, $\theta = 14^\circ$, for the VG heights of 0.0625-in, 0.3125-in, and 0.4375-in respectively. For the 0.0625-in vortex generators, the array nearest the diffuser inlet again is the most effective. However, this same array when placed upstream at 4.05-in results in a poorer pressure recovery but has a smoother pressure distribution than the array placed at 1.925-in. While improving the overall recovery of the baseline case, the intermediate location does not perform as well as the other two arrays. The vortex generator height at 0.3125-in, Figure 3.19 results in almost identical performance. The only significant difference between these two heights is that the pressure recovery for the 0.3125-in VGs at all three locations are improved compared to the smaller VGs. The best overall increase in pressure recovery based on the surface pressure data is shown in Figure 3.20 for the largest VGs. The 2.925-in and 4.05-in positions show almost identical increases in the pressure recovery. For the array located 4.05-in from the diffuser inlet, there is a decrease in pressure at entry into the diffuser. The decreased pressure coefficient suggests flow acceleration in this region. However, downstream of $x/c \approx 0.30$ the pressure is recovered. The vortex generators located most downstream at 1.925-in from the diffuser inlet yield the largest increase in pressure recovery.
3.1.6. Summary of Surface Pressures

Overall, we observed that at small plate deflections, when there is little or no flow distortion, deployment of the VGs can have a deleterious effect on the pressure recovery. On the other hand, at large plate deflections, and potentially large flow distortion, all VG deflections have beneficial effects on the pressure recovery. In these cases, it appears that there is an optimum VG height beyond which additional deployment may not be beneficial. For the large flow distortions, it is apparent that the VGs be located as close as possible to the onset of the adverse pressure gradient.

3.2 Hot-Film Measurements

The effect of the VGs as determined from hot-film sensor measurements is next examined in Figures 3.21 to 3.29. The time-averaged mean and rms values of the anemometer output voltages are presented here. Mean voltages are shown in the upper half of the graphs while the rms voltages are presented in the lower half of the graph. Low values of mean voltage and high values of rms voltage are considered as indicators of flow separation, flow reattachment, or other flow phenomena, such as vortex lift-off that may result in low levels of shear stress.

3.2.1 Effect of VG Height at the Downstream Location

Figure 3.21 examines the effects of the vortex generators for the small diffuser angle, $\theta = 6^\circ$. The vortex generators are located 1.925-in upstream of the diffuser inlet. As the anemometer output was auto-zeroed for the baseline, the mean values for the baseline are
close to zero. The standard deviation for the baseline shows relatively large values near \( x/c \approx 0.30 \) and at \( x/c \approx 0.75 \). When the vortex generators are deployed to a height of 0.0625-in, increased mean voltages indicate elevated levels of skin friction. The minimum in the mean at \( x/c \approx 0.45 \) is accompanied by a sharp rise in the rms values just ahead of this location. The sensors located downstream of \( x/c \approx 0.45 \) have relatively low rms values. In the absence of VGs, this is a good indication of separated flow. However, for the small plate deflection, flow separation is not expected. Rather these low rms values are likely associated with the vortex signature from the low profile VGs. It is significant to note that in the corresponding pressure distribution, Figure 3.5, there is a plateau in the pressure at \( x/c \approx 0.45 \) that also suggests the effect of the shed vortices. The vortex generators with height 0.3125-in produce much larger mean voltages across the length of the diffuser. The trends indicate an increase in skin friction up to \( x/c \approx 0.5 \) that is then followed by a decrease. If flow separation were present, it was expected that the mean voltages would have had values near zero. It is also interesting to note that the variations in the mean and the rms voltages for this VG height are considerably lower than the baseline or the 0.0625-in VG case. This VG height also exhibits the best overall pressure recovery, Figure 3.5. For the largest VGs, 0.4375-in, the mean values are lower than the intermediate VG height. These vortex generators while showing an improvement over the baseline and 0.0625-in VG case, suggest lower mean skin friction downstream of \( x/c \approx 0.60 \) but higher mean skin friction upstream compared to the 0.3125-in vortex generators. The results presented here show that the 0.3125-in VGs exhibits higher mean voltages and smaller variations in the rms voltages compared to the baseline case; these suggest that skin friction across the curved diffuser plate is increased. Also, since the rms
values along the extent of the plate were lowest of the four cases, the flow through the diffuser may be possibly the least distorted.

Figure 3.22 shows the results for the $\theta = 10^\circ$ case. The baseline rms values show two regions where the mean skin friction levels are relatively low. The first region is $x/c \approx 0.30$ and is followed by a sharp decrease in the rms values. The second region occurs from $x/c = 0.60$ to $x/c = 0.74$. The 0.0625-in VGs show a small increase of the mean values over the baseline case. The rms values show a corresponding decrease. There is still however a small peak near $x/c = 0.30$ followed by smaller peaks at $x/c = 0.5$ and $x/c = 0.75$. The 0.3125-in and 0.4375-in VGs both show larger values of mean voltages along the plate. The largest VG results in higher mean skin friction levels downstream of $x/c \approx 0.54$; these VGs also have the overall best pressure recovery, Figure 3.6. The rms values for the 0.4375-in VGs are however generally higher than the other cases, and show large variations in the streamwise direction. The 0.3125-in VGs on the other hand result in a diffuser flow with little variations of the low rms values over the length of the plate. For this diffuser angle and vortex generator location, the 0.3125-in VGs result in increased skin friction across the plate as well as small variations in the rms.

The effectiveness of the vortex generator for the large diffuser deflection, $\theta = 14^\circ$ is examined in Figure 3.23. The baseline case has mean voltages that are very close to zero because of the auto-zeroing. The rms voltages are very low downstream of $x/c \approx 0.40$ confirming as in the pressure distribution, Figure 3.7, that the flow is separated downstream of this location. The mean voltages of the 0.0625-in VGs show that the skin friction levels are increased. There are also large variations in the rms values whose overall values are also
large. The large rms values suggest that for this VG height the overall distortion in the flow is not substantially reduced. The mean voltages for the 0.3125-in and 0.4375-in VGs are significantly increased and the attendant rms voltages and their variations are reduced. For this diffuser angle, based on the mean voltages, the 0.4375-in VGs show the largest effect on the flow. The 0.3125-in vortex generators however result in the smallest variations and in smaller levels of rms. For the diffuser angle $\theta = 14^\circ$, both the 0.3125-in and 0.4375-in vortex generators are beneficial as is also seen in the pressure recovery, Figure 3.7.

### 3.2.2 Effect of VG Height at the Intermediate Location

Figures 3.24 to 3.26 show the effectiveness of the vortex generators located 2.295-in upstream of the diffuser inlet. The results for the small diffuser angle, $\theta = 6^\circ$, are shown in Figure 3.24. When the vortex generators are deployed to a height of 0.0625-in at this location, they do not noticeably increase the mean voltages as compared to the baseline case. The variations in the rms for the two cases also follow similar trends, though the baseline has lower rms values over most of the curved plate length. It is also seen from the pressure distribution that the pressure recovery is not improved for the small VGs. The 0.3125-in and 0.4374-in VGs produce much higher mean skin friction values compared to the baseline. In general, the 0.4375-in array has higher values downstream of $x/c \approx 0.52$. However, increased rms levels, most notably at $x/c \approx 0.45$ are also observed. The 0.3125-in VG for this diffuser angle, similar to the more downstream array location, has the lowest rms variation over the length of the curved plate. This VG height is considered the most effective in improving the diffuser’s pressure recovery.
Figure 3.25 shows the results for the moderate diffuser angle, $\theta = 10^\circ$. The mean voltages for the 0.0625-in VGs are lower than the mean values of the baseline case. It is seen from the pressure distribution that these vortex generators result in a poorer pressure recovery in the diffuser. The rms distribution also shows the same basic characteristics as the distribution for the baseline case. The 0.3125-in and 0.4375-in VGs have similar higher mean voltage values than the baseline case. Similar to the results of the $\theta = 10^\circ$ plate deflection that are presented in Figure 3.22, the upstream region of elevated mean voltages is followed downstream by a region of relatively low values. These data suggest that the region of low skin friction possibly arising from flow separation is limited to downstream of $x/c \approx 0.54$. The rms values for the 0.3125-in VGs are low across the length of the plate, whereas for the 0.4375-in VGs there are large values at $x/c = 0.40$.

The results for the large diffuser angle, $\theta = 14^\circ$, are shown in Figure 3.26. Similar to the $\theta = 10^\circ$ case, the 0.0625-in vortex generators result in lower mean voltages compared to the baseline. The basic characteristics seen in the distribution follow closely to the baseline case. The trends in the mean voltages for both the 0.3125-in and 0.4375-in vortex generators show that the mean skin friction decreases in the downstream direction. The two VG heights exhibit identical mean voltages downstream of $x/c \approx 0.72$. The rms values of the two cases are also very similar. However, the 0.4375-in vortex generators produce smaller rms downstream of $x/c = 0.60$. A comparison of the pressure distributions, Figure 3.10, suggests that the mixing arising from the 0.3125-in VGs is becoming less effective, whereas for the 0.4375-in VGs the mixing remains effective up to the exit.
3.2.3 Effect of VG Height at the Upstream Location

This section discusses the effects of the vortex generators placed 4.05-in upstream of the diffuser inlet. Figure 3.27 shows the results for the small diffuser angle, $\theta = 6^\circ$. The rms values for the baseline case show two distinct peaks, one at $x/c \approx 0.40$ and a second at $x/c \approx 0.72$. The VGs with height 0.0625-in increase the mean voltages compared to the baseline case. The rms shows two peaks at the same locations as those seen in the baseline case. The mean voltages for the 0.3125-in VGs reach a maximum at $x/c \approx 0.46$. The voltages however decrease progressively downstream. The rms values for this VG array shows two peaks at the same locations as the baseline and small VGs. The VGs with height 0.4375-in have lower mean voltages over the upstream portion of the diffuser plate compared to the 0.3125-in VGs, but higher values over the aft portion of the plate. The rms curve has a peak that is located further upstream, but the rms values quickly drop off downstream of $x/c \approx 0.42$. Low rms values over the aft section of the plate for the 0.4375-in array suggest that this case results in good diffuser performance as is confirmed by the pressure recovery, Figure 3.11.

Figure 3.28 shows the results for the moderate diffuser angle, $\theta = 10^\circ$. For the 0.0625-in VGs, the mean voltages are increased along the diffuser plate. The large peak in the rms at $x/c = 0.30$ is indicative of a region of low mean shear stress, as is also seen from the mean voltages. The mean voltages for the 0.3125-in and 0.4375-in VGs show that the intermediate VGs are more effective upstream of $x/c = 0.50$, while the larger VGs were more effective downstream of this location. However, for the largest vortex generators, there is a large region where the variation in the rms is great. For the 0.3125-in VGs, the variations in rms values are small. Thus, this diffuser angle and array location, the 0.3125-in VGs are most effective as is also seen from the pressure recovery, Figure 3.12.
Figure 3.29 shows the results for the large diffuser angle, $\theta = 14^\circ$. The mean voltages for the baseline case are close to zero as expected. Over the downstream portion of the plate, $x/c > 0.45$, the rms values are large, as would be expected in a region of low shear stress. It is seen that the 0.0625-in VGs increase the mean voltages by only a small amount, but their effectiveness as observed from the rms is quite pronounced. It is evident from the pressure distribution, Figure 3.24, that the pressure recovery is significantly improved over the baseline flow. The mean voltages for both of the larger vortex generator arrays are quite similar. With the vortex generators positioned 4.05-in upstream of the diffuser inlet, the effectiveness of the VG arrays is also seen from the substantially reduced rms values downstream of $x/c > 0.45$. For this diffuser angle, it is not clear which of the larger vortex generators is most effective, as they have comparable pressure recoveries, mean voltages and rms voltages.

### 3.2.4. Summary of Hot-Film Measurements

The following general observations can be made in relating the hot-film and surface pressure measurements. High mean voltages and low levels of rms voltage appear to correlate well with improved pressure recovery. At small and moderate plate deflections, a decrease in the mean voltages compared to the baseline suggests a poorer pressure recovery. Additionally, it is observed that large variations in the rms voltages also suggest poor pressure recovery.
3.3 Exit Flow Measurements

The effects of vortex generator height and location on the diffuser exit flow are examined in the contour plots shown in Figures 3.30 to 3.39. The contour levels indicate the ratio of the total pressure at the diffuser exit to the total pressure upstream of the diffuser inlet. An effective vortex generator array is one that maximizes the extent of the relative high total pressure at the diffuser exit. The red contour levels denote the core flow with the highest total pressure, while the blue regions have low total pressures.

3.3.1 Baseline Flow

For the baseline cases where no vortex generators are deployed, Figure 3.30, several salient features are observed. First, the extent of the separation at the diffuser exit is increased as the plate deflection is increased. The small plate deflection, \( \theta = 6^\circ \), shows that the flow adjacent to the curved plate, on the right side, has lower total pressures. For the plate deflection, \( \theta = 10^\circ \), the extent of the region of low pressure is increased. At the deflection angle of \( \theta = 14^\circ \), an extensive low-pressure region is observed along the curved plate. For the diffuser angles \( \theta = 6^\circ \) and \( \theta = 10^\circ \) there is more pronounced low pressure in the upper right region at the exit. In section 3.1.1 the surface pressure measurements suggest that this arises from the wires connected to the copper leads of the hot-films and results in a spanwise pressure variation. For the large plate deflection \( \theta = 14^\circ \), the region of low pressure spans more uniformly across the height of the plate.
3.3.2 Effect of VG Height on the Small Diffuser Angle

Figures 3.31 to 3.33 examine the effects of the three vortex generator heights at the three array positions for the curved plate deflection of $\theta = 6^\circ$. Figure 3.31 shows the exit flow contours with the VG height 0.0625-in. Except for the separation region in the top right corner of the diffuser, the baseline case does not show any large distortions in the exit flow. The hot-film measurements with the vortex generators (Figures 3.21, 3.24, 3.27) indicate increased mean skin friction along the curved plate wall. Overall, the intermediate VG location of 2.925-in shows the smallest change in mean voltages compared to the baseline, whereas the most upstream and downstream locations show larger changes. The exit surveys also indicate that the extent of relative high total pressures is larger for these two cases compared to the intermediate VG location. The relative change of mean voltages thus appears to correlate well with the improvement in flow uniformity.

The effects of the VG arrays with height 0.3125-in are shown in Figure 3.32. Although regions of relatively low total pressure remain in the upper and lower corners of the diffuser, the increase in total pressure along the centerline of the curved plate is marked. The increase in total pressure is accomplished by increases in the skin friction, as seen from the higher mean voltages in the hot-film measurements Figures 3.21, 3.24 and 3.27. The rms voltages for the arrays at 1.925-in and 2.925-in from the curved plate, Figures 3.21 and 3.27, respectively, demonstrate much lower values compared to the baseline case. The rms voltages for the array 4.05-in from the curved plate exhibits values somewhat higher and follow closer to the baseline rms values. Close examination of the exit survey for the array located at 4.05-in, Figure 3.32d, gives an indication for the higher rms values. There are
more small pockets of higher total pressure, yellow, within the moderate total pressure zone, green. The higher mean voltages for all cases correspond to the higher total pressures near the wall.

Figure 3.33 shows the exit total pressure of the 0.4375-in vortex generators. All three locations effectively increase the velocity of the flow along the surface of the curved plate. For this VG height, as the array is moved further upstream, the effectiveness increases. The array placed at 1.925-in and 2.925-in from the curved plate shows similar distributions. However, with the array at the 4.05-in upstream location, the region of higher total pressure is closer to the curved wall than for the other array locations.

### 3.3.3 Effect of VG Height on the Moderate Diffuser Angle

Figures 3.34 to 3.36 show the effects of the vortex generator on the exit flow for the curved plate deflection $\theta = 10^\circ$. The exit flow surveys with the 0.0625-in vortex generators are shown in Figure 3.34. The VG array located at 1.925-in from the curved plate slightly increases the total pressure over the curved plate compared to the baseline case. The corresponding hot-film measurements, Figure 3.22, show a moderate increase in the mean voltage over the baseline and the rms values for the VG case that are much lower than the baseline. The total pressure distributions for the arrays at 2.925-in and 4.05-in upstream from the diffuser inlet show only small improvements compared to the VGs furthest downstream. The corresponding surface pressure distributions, Figures 3.9 and 3.12, also show small differences compared to the baseline. The hot-film results presented in Figure 3.25 for the array 2.925-in and Figure 3.28 for the array 4.05-in upstream of the diffuser inlet also show that the mean and rms are quite similar.
Figure 3.35 shows the effects of the 0.3125-in VGs on the diffuser exit flow. Differences in the exit-flow contours, based on vortex generator array location, are not easily determined. The VGs have a more marked effect on the total pressure distribution for all cases. For all VGs, the region of higher total pressure is increased. The most upstream VGs also show that this high pressure region is closer to the curved plate. Thus, the corresponding hot-film data show that the mean voltages are overall highest for this case.

The effects of the 0.4375-in VGs on the exit flow are shown in Figure 3.36. There is enhanced mixing in the flow, and the region of higher pressures adjacent to the curved plate is enhanced. For all three cases with VGs, the height of the region of high total pressure is increased.

3.3.4 Effect of VG Height on the Large Diffuser Angle

The exit flow contours for the curved plate deflection of $\theta = 14^\circ$ are shown in Figures 3.37 to 3.39. The baseline case shows an extensive region of low total pressure along the curved wall. This region is associated with separated flow and results in poor pressure recovery. The extent of the low total pressure region is reduced for all cases with VGs. For the small height VG, Figure 3.37, the intermediate VG location shows the most uniform exit flow. Whereas the mean voltage for this case differs little from the baseline, the rms values are overall smaller. The intermediate height VGs show a more marked improvement in the exit flow. The region of relatively high pressure is more uniform, and the spanwise extent of the high total pressure adjacent to the wall is greater. The corresponding mean voltages are higher than the baseline flow. It is also noticeable that the variation in rms voltages is smaller. Similar observations are made for the largest VGs, Figure 3.39. However, whereas
the more uniform exit flow is seen for the intermediate VG location for the two smaller VG heights, the more downstream VG location appears to be more beneficial for the largest VG height.

Overall, it appears that high values of mean voltages compared to the baseline, and smaller variations in the rms voltages compared to the baseline are good indicators of improved total pressure at the exit of the diffuser.
Chapter 4

CONCLUDING REMARKS

4.1 Summary of Results

Experiments have been conducted in a diffusing duct using vane-type counter-rotating vortex generators to control the diffuser flow separation and exit flow distortion. A two-dimensional, blow-down wind tunnel was designed and constructed to simulate inlet duct flows. The test section at the exit of the tunnel is a diffuser that consists of two walls, a flat plate and a curved plate that produced a Stratford-like pressure gradient. The experiments were performed with the curved plate deflected at angles of $6^\circ$, $10^\circ$, and $14^\circ$ while keeping the flat plate undeflected. The vortex generators were positioned at three streamwise locations, 1.925-in, 2.925-in and 4.05-in upstream of the diffuser inlet on the same wall as the deflected plate. At each location, the effect of the vortex generators was examined for three vortex generator heights, 0.0625-in, 0.3125-in and 0.4375-in; baseline cases, that is with no vortex generators, were also examined.

The diffuser pressure recoveries were measured using surface pressure ports installed along the flat plate. A pitot rake was used to measure the diffuser exit total pressures, to assess the distortion in the exit flow. An array of surface-mounted hot-film sensors, installed along the curved plate, was used to monitor the characteristics of the diffuser performance. A constant voltage anemometer was used to operate the multi-element hot-film sensor array to document flow characteristics along the length of the diffuser. Mean and rms voltages
were calculated from the hot-film signals obtained to determine the changes in mean skin friction and flow unsteadiness along the diffuser wall.

The results from the surface pressures along the centerline and offset static pressure ports indicated that the flow through the diffuser was reasonably two-dimensional. It was observed that without flow control, increasing the diffuser angle produced decreases in the pressure recovery at the exit. It was also apparent that the largest diffuser angle produced results indicating that the flow seemed largely separated.

The vortex generators were deployed to improve the pressure recovery at the smaller angles and control flow separation at the largest angle. It was observed that the deployment of VGs for small deflection angles when little or no flow distortion was present in the diffuser could have deleterious effects on the pressure recovery. Conversely, for large plate deflections, and potentially large flow distortion, all VG deflections have beneficial effects on the pressure recovery and flow distortion. However, in these cases, there appeared to be an optimum VG height, beyond which additional deployment may not be beneficial.

Several conclusions were made from the comparisons of the hot-film measurements with the surface pressures. Typically, with increased VG height, the mean voltages increased above the baseline cases. However, a few cases demonstrated lower mean voltages with the deployment of VGs. The rms values for these cases were also either slightly higher than the baseline or relatively unchanged. In general, high mean voltages and low levels of rms voltage appear to correlate well with improved pressure recovery. Also, at small and moderate deflection angles, a decrease in the mean voltages compared to the baseline suggests a poorer pressure recovery. Finally, it was observed that large variations in the rms values suggest poor pressure recovery.
Comparisons between the hot-film measurements and the exit flow distortion also show promise. The baseline cases exhibited lower total pressures along the span of the curved plate. Typically, with the deployment of VGs, the total pressures along the curved plate were increased as compared to the baseline and thus the resulting exit flows were more uniform. Increased mean voltages in the hot-film data, indicate increased skin friction, as well as the increased total pressure at the exit adjacent to the curved plate. For one case, the most upstream and downstream VG arrays produced higher mean voltages than the intermediate array. The extent of relatively high total pressures for these two cases was also higher than for the intermediate case. This suggests that the relative change in mean voltages appears to correlate well with the improvement in flow uniformity. For all the cases examined, higher mean voltages correspond to higher total pressures near the wall. Furthermore, lower rms values in the hot-film data compared to the baseline cases, are indicative of improved total pressure at the exit of the diffuser.

4.2 Recommendations for Future Work

Possible future work should include flowfield surveys conducted inside the diffuser at multiple streamwise locations. In the work presented here, only flow surveys at the diffuser exit were conducted and therefore the evolution of the flow in the diffuser could not be documented. Possible improvements in the hot-film measurements could be accomplished by installing spanwise sensor arrays in the diffuser. As compact diffusing S-ducts are expected to be implemented on jet powered aircraft, pulse jet vortex generators could be used to replace the vane-type vortex generators used in the present work. On the aircraft, bleed-air
from the engine could be used to operate the pulse jet vortex generators. An advantage to using pulse jet vortex generators include quick actuation response times, and variable amplitude and frequency to adapt to changing operating conditions.
Chapter 5

REFERENCES


18. Chokani, N., Thermal Anemometry: Graduate Course MAE Department, NC State University, 2001.


Chapter 6

TABLES
Table 2.1. Resistance of Curved Plate Hot-Film Sensors

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Table 2.2. Experimental Test Matrix for Hot-Film, Surface Pressure and Exit Total Pressure Measurements

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Notes: S<sub>b</sub> indicates hot-film measurements with no VGs were obtained, S indicates hot-film measurements with VGs located 1.925-in, 2.925-in, and 4.05-in from diffuser inlet were obtained, X<sub>b</sub> indicates surface and exit pressure measurements with no VGs were obtained, X indicates surface and exit pressure measurements with VGs located 1.925-in, 2.925-in, and 4.05-in from diffuser inlet were obtained.
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\[ T = T_w + \Delta T \]

\[ Q_s \]

\[ \delta - \text{(velocity) boundary layer} \]

\[ \delta_T - \text{thermal boundary layer} \]

\[ \beta \]

\[ \lambda \]

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