Comparison of Large Scale Features in Zero and Adverse Pressure Gradient Turbulent Boundary Layers

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This paper presents a detailed description of a scanning 3D flow visualization technique which was used to compare and contrast the large scale features in a zero pressure gradient (ZPG) turbulent boundary layer with those in two adverse pressure gradient (APG) turbulent boundary layers. Ramps were installed in a wind tunnel to produce an adverse pressure gradient on the wind tunnel wall. The boundary layer flow was seeded with smoke from a reservoir that was drawn into the tunnel. A high-repetition-rate laser formed into a light sheet was scanned in the wall-normal direction through the boundary layer. The 2D images were captured using a high-speed camera and reconstructed into a nearly instantaneous 3D flow visualization volume of the intensity of the smoke in the turbulent boundary layer. Static pressure measurements and 2D particle image velocimetry (PIV) were taken to characterize the flow with and without the ramps. Observations about the boundary layer structures were made by investigating the flow visualization volumes, the power spectral density of the images, the features from binary image slice, and conditionally averaged volumes around a structure. In general, the ZPG structures were larger and spaced farther apart compared to the APG cases. The structures in the APG cases were more elongated in the streamwise direction and occurred at a steeper angle from horizontal compared to the ZPG case.

I. Introduction

Coherent motions in the turbulent boundary layer are the source of significant research in the field of fluid dynamics. Specifically, the understanding of the three-dimensional dynamics of these organized structures in an adverse pressure gradient is of utmost importance as researchers attempt to model and predict wall-bounded flows. More research into the large scale motions in a turbulent boundary layer on the verge of separation could provide insight to those seeking to manipulate the flow using active or passive flow control mechanisms. This paper presents an effort to compare the three dimensional size, spacing, and structure of zero pressure gradient large-scale motions with those in an adverse pressure gradient using a 3D scanning flow visualization technique.

Decades of research has led to the basic picture of the turbulent boundary layer which consists of a near wall region dominated by long streaks of high and low momentum fluid produced by streamwise vortices. The log layer is dominated by hairpin-type vortices which, while generally depicted as symmetric and inclined at 45 degrees, are usually one-legged and occur at a variety of orientations. These vortices can travel in packets, which connects their dynamics with the large scale motions observed in flow visualization experiments. Important works such at Robinson, Panton, Smits and Delo, Adrian, and Marusic et al. give great detail to the structures in the turbulent boundary layer.

The structures in turbulent boundary layers on the verge of separation is less well defined though many engineering applications experience this type of flow including helicopter blades, turbines, ships, and aircraft. Historically, turbulent boundary layers with an adverse pressure gradient have been considered one of the most difficult flows to predict with turbulent models. A few characteristics of the coherent motions that have been found

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in an APG turbulent boundary layer include the observation that the large scale motions are larger and erupt more violently than those in a ZPG turbulent boundary layer. The frequency of ejections is reduced and sweeps last longer in the APG flow. Krogstad and Skare (1995) showed that the inclination angles of eddies did not change in the APG flow, however, Lee and Sung (2009) found that the hairpin-type vortices aligned at about 18° relative to the streamwise axis compared to 13° for the zero pressure gradient turbulent boundary layer. Marusic and Perry (1995) applied the attached eddy hypothesis to adverse pressure gradient flows and made the assumption that each eddy is not dependent on the pressure gradient; however, they failed to reproduce the turbulence statistics and concluded that the impact of the adverse pressure gradient on the individual eddies must be taken into account.

Because of the need for more research into APG turbulent boundary layers, this paper looks into the large scale motions under three different pressure gradients using 3D flow visualization. In using a scanning, 3D flow visualization technique, this paper avoids the pitfalls of trying to characterize very three dimensional features with only 2D measurements. With 2D measurements, the size, spacing, and orientation of structures in the third dimension are obviously missing. Possibly more important, the size and spacing of structures in the dimensions being investigated may also be inaccurate. An image that does not incorporate the spanwise dimension can present a more complex picture of the flow than actually exists. Smits and Delo (2002) showed that sampling the image in 2D can distort one structure with a spanwise offset into several pieces which could appear not to be connected. This will overestimate the variety of structures present in the flow and can neglect important interactions in the spanwise direction.

There are, of course, many very good 3D velocity measurement techniques that have emerged in the last decade. Holographic and tomographic PIV, to name a few, have been valuable in giving insights into 3D structures in the turbulent boundary layer. A recent review of a few of these three-dimensional, three-component (3D-3C) techniques is given by works such as Elsinga and Ganapathisubramanii and Westerweel et al. In general, these techniques have been limited to thin volumes, but they are rapidly improving.

Using Taylor’s frozen flow hypothesis in conjunction with time-resolved, stereoscopic PIV is a beneficial technique that acquires velocity measurements in a quasi-instantaneous three dimensional spatial field. Taylor’s hypothesis assumes that structures are “frozen” - their shape is not appreciably changed across the projected distance. While this can technique be applied to some flows, it can fail for larger fields of view. Taylor’s hypothesis could be applied for distances up to a maximum of 6Δ in a zero pressure gradient turbulent boundary layer according to Dennis and Nickels (2008), whose paper details the capabilities of this technique for large structures.

The field of view for most PIV measurements is limited due to the need for imaging individual particles. Flow visualization, however, can be performed at a lower resolution and without the need for the double pulsing of a laser, providing for a greater flexibility in the experimental setup. Flow visualization techniques are less quantitative, but in general, can look at larger fields of view compared to many 3D PIV techniques. Thus, flow visualization is a valid technique when 3D PIV is not possible, particularly when investigating the large scale motions at the edge of the turbulent boundary layer as done in this experiment.

This paper uses a scanning flow visualization technique in a similar way as Delo and Smits and Smits and Delo to give more insight into the structures in a turbulent boundary layer. There has been little information about the global spanwise arrangement of large scale coherent structures. Delo and Smits, investigating a low Reynolds number (Re0=701), ZPG turbulent boundary layer, observed a relatively small number of structures, but they varied greatly in size and shape and were felt to be representative of turbulent boundary layers in general. They clearly saw large-scale structures in the x-z (streamwise-spanwise) plane aligned along diagonals +/- 50 degrees from streamwise. The spacing along the lines varied, but was approximately 16 in the outer portion of the BL. This spanwise orientation had not been documented extensively prior to their experiment. They found that ejections appeared to be spatially organized and linked to the passage of the large scale motions. Elsinga et. al found large scale hairpins 0.48 in spanwise dimension and spaced 1.5Δ in the streamwise direction in the ZPG turbulent boundary layer. Looking in the outer region of the boundary layer, (in their case, y = .156 to .898), the hairpins had a preferential alignment in the streamwise direction of 45 degrees from streamwise. They say that this is indication of the spanwise-streamwise orientation of coherent structures in the turbulent boundary layer. There is little to no information about the spanwise arrangement of large scale motions in an adverse pressure gradient, thus this paper investigates their size, shape, and spacing.
II. Experimental Arrangement

In this paper, we use the term flow visualization images to describe the intensity images that result when smoke is introduced into the boundary layer through a slit, as is done in a traditional fashion. Historically, flow visualization of a turbulent boundary layer using the intensity of light scattered from smoke seeded into the flow has served a very important role in examining the large-scale structures. Important flow visualization studies such as those of Praturi and Brodkey, Head and Bandyopadhyay, and Smits and Delo, just to name a few, have uncovered characteristics of the structures, which led to more quantitative, follow-up measurements.

A drawback associated with the use of traditional flow visualization techniques is the uncertainty surrounding the smoke seeding process. Researchers have argued that the smoke gives a “very fair” indication of vorticity, and that because the smoke is transported by turbulence, the smoke “should” mark the edge of the vortical/non-vortical boundary layer interface, but quantitative proof that the flow visualization accurately depicts active structures instead of the possibility of “history of turbulence” effects is limited. Recently, Melnick and Thurow (2014) simultaneously applied 2D flow visualization and 2D PIV to explore the relationship between qualitative flow visualization images and quantitative planar velocity data. They found that the direct spatial cross-correlation between the measured velocity deficit and flow visualization image intensity was as high as 0.7 to 0.8 with slightly higher correlation values possible using a complementary POD/LSE technique. They found that while flow visualization may obscure some of the small scale features of the flow, it is quite effective in identifying the large scale features in the flow, in particular, the boundary layer edge. The experiments performed in this paper build on those findings.

The three-dimensional flow visualization in this trial was accomplished by scanning a high-repetition rate laser light sheet through the desired flow field and acquiring 2D images of the flow throughout the scan. The resulting sequence of 2D images was used to reconstruct a 3D image of the flow field. The unique aspect of this 3D technique is its high speed capabilities which are made possible using a third generation pulse-burst laser system with a galvanometric scanning mirror and a high framing rate CCD camera.

A. Facility and Particle Seeding

All experiments were conducted in Auburn University’s 0.6 m x 0.6 m wind tunnel. It is an open circuit, blow-down wind tunnel, with a 2.4 m long test section and a maximum speed of 30 m/s. A square contraction of 2.5 to 1 with a length of 1.8 m is used to accelerate the flow to the test section. Preceding the test section are a stainless steel honeycomb and three screens of 80% porosity to condition the flow and to create a uniform velocity across the test section.

For this experiment the boundary layer formed on the top wall of the wind tunnel was investigated. The flow on the wall was tripped to a turbulent flow by a strip of k-type roughness elements approximately 2 to 3 mm extending approximately 4 to 6% into the local boundary layer thickness. The strip was 38 mm in the streamwise direction and covered 0.46 m or about 75% of the spanwise length of the test section. Smoke was introduced through a slit the top of the wind tunnel 0.3 m downstream of the slit, as shown in Figure 1. Smoke was produced using a ViCount Compact 1300 oil-based smoke generator that produces particles 0.2-0.3 micrometers in size. The slit was 3 mm in the streamwise dimension and spanned 75% of the spanwise length of the test section. The smoke traveled along the top of the tunnel 132 cm downstream to the measurement location. The average boundary layer thickness at this location was approximately 50 to 56 mm for the boundary layers investigated in this experiment. Figure 1 illustrates the experimental setup in which x is the streamwise direction, y is the wall-normal direction, and z is the spanwise direction.
The high-speed camera, detailed later, was mounted directly above the tunnel, and a mirror was used to view the streamwise-spanwise planes of the illuminated boundary layer. Figure 2 shows the downstream view of the experiment (with the flow normal to the page). The laser was directed from the side of the tunnel and scanned from bottom to top to capture the 2D planes which were reconstructed to a 3D visualization. The field of view used in this case was 1284 pixels by 1636 pixels in the streamwise and spanwise directions, respectively which correspond to 3.4$\delta$ by 4.3$\delta$. The scan in the wall-normal direction consisted of 15 slices which spanned approximately 0.5$\delta$ to 1.2$\delta$.

B. 3D Flow Visualization Technique

The main piece of instrumentation used in this technique is a home-built pulse burst laser system capable of producing laser pulses at repetition rates in excess of 1 MHz over a 1 msec long window. An in depth discussion of this flow visualization technique can be found in Thurow and Lynch (2009). Recently, additional amplifier stages have been added to the system such that, for this experiment, the laser energy is greater than 50 mJ for each pulse in the burst. See Thurow et al (2013) for a review of applications of these ultra-high repetition rate lasers. For 3D flow visualization, a burst of 16 laser pulses was produced at 1 MHz repetition rate and deflected off of a 6 mm aperture galvanometric scanning mirror. A long focal length spherical lens and a cylindrical lens located in front of the scanning mirror were used to form an approximately 1 mm thick laser sheet whose position is determined by the momentary angle of the scanning mirror. For this experiment, the laser was directed into the tunnel and scanned from top to bottom with the camera positioned (using mirrors) looking into the tunnel from overhead. The distance from the scanning mirror to the field of view was 1.93 meters. The laser sheet is scanned from a distance of 25 mm from the tunnel wall to 63 mm in the wall normal direction capturing approximately 0.5$\delta$ to 1.2$\delta$ of the boundary layer for the velocities in this experiment.

For these trials, images were acquired for each successive laser pulse using a Cordin gated intensified CCD framing camera. The camera is capable of acquiring 16 images with 2,048 x 2,048 pixel resolution at framing rates.
up 40MHz. In this experiment the framing rate was 1 MHz, thus, a sequence of 16 images was acquired in 16 microseconds, so that the movement of the flow field between the first and last image was negligible (on the order of 2-3 pixels).

C. Adverse pressure gradient ramps

Following the method outlined by Stratford,\textsuperscript{25} a ramp was built that created an adverse pressure gradient with a boundary layer close to separation. A Stratford ramp produces an adverse pressure gradient that causes minimum shear stress over the pressure recovery area region. The Stratford ramp allows for a maximum pressure recovery over a minimum length at which the flow is on the verge of separation at all points. The ramps which were built modified the Stratford profiles to create adverse pressure gradient turbulent flows on the top of the tunnel wall. The profiles of the adverse pressure gradient ramps are shown in Figure 3. A parabolic favorable pressure gradient ramp precedes the adverse pressure gradient ramps. A 127 mm flat section joins the two ramps. The ramps installed in the wind tunnel are shown in Figure 4.

![Figure 3. Profile of adverse pressure gradient ramps.](image-url)

![Figure 4. Ramp installed in wind tunnel.](image-url)

III. Flow visualization processing

The Cordin camera takes 16 images of the intensity of smoke in the seeded boundary layer. The rate of the camera and scanning mirror is fast enough that the displacement between the first and last image is negligible. The 16 images are then combined to form a volumetric visualization of the turbulent boundary layer for the cases in this paper. A dark image subtraction was performed to eliminate some hot pixels. The average frame-to-frame image
intensity fluctuation is corrected so as to smooth the differences in image intensity between the 16 images. The intensity is also normalized from the upstream to downstream edges of the images to correct for the decrease in image intensity at the edges of the field of view. The images were also smoothed with a 9 x 9 moving average smoothing filter.

The boundary layer edge in flow visualization images was found objectively by using the technique of calculating the inflection point of the average smoke intensity of pixels above a set threshold proposed by Prasad and Sreenivasan. This accurately marks the edge of the boundary layer which has been demonstrated in our previous work. The images were then converted to binary so that the intensity inside the boundary layer was one and outside the boundary layer was set to zero. The full intensity images and binary images were both used for most of the investigative techniques described in the paper. Figure 5 shows an example of the original images from the high speed camera at different wall-normal heights and the binary images after smoothing and boundary layer edge detection. Figure 6 shows a sample 3D flow visualization volume with dimensions and an overhead view of the same instance.

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Figure 5. Original intensity images and binary images after boundary layer edge detection for the $\beta = 0$ case. Flow is from left to right. Shown are 4 out of the 14 boundary layer heights.

Figure 6. Orthogonal and overhead view of an example 3D flow visualization for the $\beta = 0$ case.
IV. Boundary layer parameters

Two-dimensional particle image velocimetry was performed to calculate the boundary layer parameters for the three different cases presented in this paper. First, a trial was performed without any ramp in the wind tunnel for a zero pressure gradient case. Then, trials were run with two adverse pressure gradient ramps. The velocities for the three cases were adjusted to give comparable Reynolds numbers based on momentum thickness, \( \text{Re}_\theta \). From the velocity profiles, the boundary layer thickness, \( \delta \), displacement thickness, \( \delta^* \), momentum thickness, \( \theta \), and shape factor, \( H \), are calculated and displayed in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>( U ) (m/s)</th>
<th>( \delta ) (mm)</th>
<th>( \delta^* ) (mm)</th>
<th>( \theta ) (in)</th>
<th>( H )</th>
<th>( \text{Re}_\theta )</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZPG</td>
<td>18.6</td>
<td>55.9</td>
<td>7.92</td>
<td>6.02</td>
<td>1.32</td>
<td>8380</td>
<td>0</td>
</tr>
<tr>
<td>Mild APG</td>
<td>20.8</td>
<td>51.5</td>
<td>8.41</td>
<td>4.90</td>
<td>1.72</td>
<td>7610</td>
<td>8.1</td>
</tr>
<tr>
<td>Strong APG</td>
<td>21.0</td>
<td>52.1</td>
<td>8.61</td>
<td>4.72</td>
<td>1.82</td>
<td>7420</td>
<td>9.7</td>
</tr>
</tbody>
</table>

The friction velocity, \( v^* \), and wall shear stress, \( \tau_w \), are calculated using the technique described by Kendall and Koochesfahani (2008) of fitting the data points to the Spalding profile in the log region of the boundary layer.\textsuperscript{27} Pressure measurements were taken from static pressure ports at the top tunnel wall (at the measurement locations) spaced 101.6 mm in the streamwise direction. The pressure measurements were sampled for 0.5 seconds at a rate of 1kHz and averaged over 5 trials using a monometer calibration. The canonical pressure coefficients are defined as:

\[
C_p = 1 - \left( \frac{U}{U_{max}} \right)^2
\]

Thus, \( C_p=0 \) in the region of maximum velocity and \( C_p \) is 1 when the flow would be slowed to zero velocity. Using the wall shear stress and pressure measurements from static pressure ports on the top of the wind tunnel wall, the equilibrium pressure gradient parameter, \( \beta \), can be found. As described by Clauser,\textsuperscript{28}

\[
\beta = \left( \frac{\delta^*}{\tau_w} \right) \left( \frac{dP}{dx} \right)
\]

For the first APG trial, the average pressure gradient across the field of view was 103.9 Pa/m, which corresponds to a \( \beta \) of 8.2, generally considered to be a moderate to strong adverse pressure gradient. The steeper adverse pressure gradient ramp produced a flow with an average pressure gradient of 129.1 Pa/m or a value of \( \beta = 9.7 \) for the velocity measured in the third trial.
V. Results

For each of the three cases ($\beta = 0$, $\beta = 8.1$, $\beta = 9.7$), 488 instantaneous snapshots of the smoke intensity of the turbulent boundary layer were captured. Each 3D flow visualization reconstruction was processed for smoothing and filtering of the non-uniformity in the laser sheets and correction of frame-to-frame intensity differences. The boundary layer edge was calculated and the images were converted to binary so as to view the large scale motions at the boundary layer edge.

A. Flow Visualization Images

A few observations can be made simply by looking through the flow visualization images in 2D and in 3D with an isosurface at the boundary layer edge. Figure 8 shows examples from each of the three trials that give a general indication of the structures found in each of the cases. The color in the flow visualization volumes corresponds to the wall-normal height of the boundary layer edge. The first noticeable difference seen in the flow visualization is the larger structures features in the zero pressure gradient case compared to the two adverse pressure gradient cases.

![Sample instantaneous 3D flow visualizations at different pressure gradients (flow from left to right).](image)

Figure 8. Sample instantaneous 3D flow visualizations at different pressure gradients (flow from left to right).

Figure 8 shows the orthogonal views of one instance from each of the three cases. The flow is from left to right and the dimensions are $3.4\delta$ in the streamwise direction and $4.3\delta$ in the spanwise direction for all three cases. The wall normal height spans from $0.5\delta$ to $1.2\delta$ for all three cases. Figure 9 shows overhead views of the same three instances plus two more overhead views of an example from each of the pressure gradients. For the first instance of the zero pressure gradient case, there appears to be three large features. There are also two large valleys in the image- one at the center and one in the top left which show the boundary layer edge dipping under $0.5\delta$.

For the first case of $\beta = 8.1$ in Figure 9, the features vary in size and are spaced at different distances. There is a large feature (or conglomeration of features) in the upper half of the overhead view which extends over $1.5\delta$ in the streamwise and spanwise direction. There are some smaller structures in the lower half of the image. This depicts a common observation in the adverse pressure gradient images, that there are structures of more random sizes differing across the boundary layer. For the first overhead view of the $\beta = 9.7$ case, small structures of about a size of $0.5\delta$ are seen scattered throughout the image. From investigating the flow visualization images in 3D and slices in 2D, general observations can be made. Not exclusively, but in a lot of the instances, the zero pressure gradient boundary layer features larger structures than the adverse pressure gradient cases. These large scale structures are more uniform in size and are spaced farther apart in the zero pressure gradient.
Figure 9. Overhead views of flow visualization volumes for the $\beta = 0$, $\beta = 8.1$, $\beta = 9.7$ cases (flow from left to right).
B. Power Spectral Density

While some differences can be seen visually in the flow visualization images, a more objective tool to compare the three cases is the Fourier transform. By using this technique to transform the intensity images from the spatial domain to the frequency domain, one can compare the amplitude and phase of structures (sine waves) of certain wavelengths between different wall normal slices and different pressure gradients. Each wall normal slice of the flow visualization volumes was transformed using a two-dimensional fast Fourier transform. The magnitude of the transform for a certain wave number ($\kappa_x$ or $\kappa_z$) gives an objective indication of the relative importance of structures of that size in the image. The average of the magnitude of the Fourier transform for each wall normal slice can be calculated. In all of the wall-normal heights for all pressure gradients, the lowest frequencies contained more energy than the higher ones. There was not a peak at a certain frequency which could correspond to a maximum length scale observed in the images. This indicates that scales larger than the field of view (4.3$\delta$ by 3.4$\delta$) are present in the flow for all cases. To compare the size of structures in the flow visualization data at different slices and at different pressure gradients, the magnitude of the Fourier transforms for certain wave numbers ($\kappa_x$ or $\kappa_z$) are compared. Figure 10 shows the power spectral density of the intensity images integrated over all $\kappa_z$ values and normalized by unity for each of the three pressure gradients. The wave numbers ($\kappa_x$) are normalized by the boundary layer thickness $\delta$.

![Power spectral density of the Fourier transformed intensity images integrated over all $\kappa_z$ values and normalized by unity for each of the three pressure gradients at a wall normal height closest to $y = 0.88\delta$.](image)

The percent energy is a maximum at the lowest frequency (largest wavelength) for all cases. This indicates that there are structures occurring which are larger than the field of view (4.3$\delta$ in the streamwise direction). The $\beta = 0$ case has a higher spectral energy for $\kappa_x\delta$ values of less than 0.7, which corresponds to wavelengths of greater than 1.4$\delta$. For wavelengths less than 1.4$\delta$ and greater than 0.1$\delta$, the adverse pressure gradient cases had more energy than the zero pressure gradient case. This indicates that the larger structures ($>1.4\delta$) occur more often in the zero pressure gradient case, whereas the adverse pressure gradient cases had smaller structures ($<1.4\delta$) more frequently. This confirms the observations made from the flow visualization images. The energy in the structures decreases at a steeper slope compared to the $\kappa_x^{-5/3}$ curve which is commonly seen in the power spectral density of boundary layer velocity measurements. Here, the $\kappa_x^{-5/3}$ curve is shown for comparison only, as we would not necessarily expect the intensity power spectral density to follow the velocity exactly.

C. Binary Images

To identify and quantify large scale motions, the flow visualization images were converted to binary such that inside the boundary layer corresponds to one and outside the boundary layer is zero. In each horizontal (x-z plane) slice the “islands” which featured the inside of the boundary layer surrounded by the boundary layer edge were identified and their centroids location and areas calculated using the “regionprops” function in MATLAB’s Image...
Processing Toolbox. Figure 11 shows the number of islands and the average area (normalized by $\delta^2$) in each wall-normal slice for all three cases.

![Figure 11](image1.png)

**Figure 11.** Average number of “islands” and average area of the “islands” (normalized by $\delta^2$) for each wall-normal height.

The largest number of islands occurs between about 0.85$\delta$ and 0.95$\delta$ for all three cases. The average area of the islands decreases with increasing wall-normal height as one would expect as shown in Figure 11. The average area of the features in the zero pressure gradient case is consistently larger than the adverse pressure gradient case for just about every wall normal height. This objectively validates some observations from flow visualization showing larger structures in the $\beta = 0$ trial.

D. Conditionally averaged images

Another objective method for analyzing the images is to conditionally average the flow visualization images in which a centroids of one of the islands occur in the inner 25% of the image at a wall-normal height of $y = 0.88\delta$. The instances in which there is a feature at this location whose area was greater than a circle with a radius of 0.1$\delta$, were centered and cropped in the x and z direction such that 25% of the original field of view is kept in the x and z directions. The complete wall-normal dimension is left intact. Table 2 shows the average distance from one island at 0.88$\delta$ to another island at the same wall-normal height. In terms of $\delta$, the average distance between features in the binary images is 1.92$\delta$ for the zero pressure gradient, but 1.81$\delta$ for the two adverse pressure gradient cases. This agrees with observations of the flow visualization images which showed that large scale features seemed to have a larger area and were spaced farther apart in the zero pressure gradient case.

**Table 2.** Distance between the centroids of features in the conditionally averaged binary images at $y=0.88\delta$.

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>Average distance between structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.92$\delta$</td>
</tr>
<tr>
<td>8.1</td>
<td>1.81$\delta$</td>
</tr>
<tr>
<td>9.7</td>
<td>1.81$\delta$</td>
</tr>
</tbody>
</table>

Some select wall-normal slices of the average of the centered and cropped images are shown in Figure 12. The slice in which the feature was selected and centered is in the middle row of the figure. One can see the shift in the center of the feature from upstream (left) at a slice below to downstream at a slice above the centered height. One can also see the difference in the three cases. One main difference is the shape of the conditionally averaged structure. In the zero pressure gradient case, the feature is a more circular shape (similar widths in the streamwise and spanwise directions) where as for the adverse pressure gradient cases, the shape is elongated in the streamwise direction. The coloring for the features in Figure 12 is set from the maximum and minimum of each slice so as to
better highlight the shapes and location of the center of the feature. The intensity is decreasing with increasing wall-normal height.

Figure 12. Conditionally averaged feature centered at the wall-normal slice closest to $0.88\delta$ (center row of figure).

The shape of the conditionally averaged feature can be better compared by plotting the intensity at a cross section through the center. Figure 13 shows the streamwise (a) and spanwise (b) profiles of the intensity at the centered slice normalized to a maximum of unity. The streamwise profiles are similar, with the zero pressure gradient case having a slightly wider spread. The spanwise profiles are significantly different, again, with the zero pressure gradient spreading wider than the other two gradients.
By detecting the center of the feature at different heights, the tilt or average orientation of a structure can be deduced. The x-location of the centroid of the conditionally averaged feature is shown in Figure 14 at different wall-normal heights. By using the two slices above and two below the centered slice a linear fit can be calculated to compare the slopes of the features. The slopes (Δy/Δx) and corresponding orientation from horizontal are shown in Table 3. The adverse pressure gradient cases have a larger angle from horizontal, meaning they are more upright than the zero pressure gradient case. There is a significant increase in the angle for the $\beta = 9.7$ case.

Table 3. Orientation of conditionally averaged feature.

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>slope</th>
<th>angle from horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.08</td>
<td>47.1</td>
</tr>
<tr>
<td>8.1</td>
<td>1.11</td>
<td>48.0</td>
</tr>
<tr>
<td>9.7</td>
<td>1.35</td>
<td>53.5</td>
</tr>
</tbody>
</table>

Figure 13. Streamwise and spanwise cross-sectional profiles of the conditionally averaged structure.

Figure 14. Location of centroid of conditionally averaged feature.
VI. Summary and Conclusions

For a zero pressure gradient turbulent boundary layer and two adverse pressure gradient turbulent boundary layers, three-dimensional flow visualization snapshots of the intensity of the seeded flow were captured. For each trial, 488 volumes were analyzed. Background image subtraction, normalization of the laser sheet intensity, and smoothing filters were used to enhance the intensity images. Objectively determining the boundary layer edge was calculated by using the inflection point of the average smoke intensity of pixels above a set threshold as described by Prasad and Sreenivasan.26

Direct observation of the three-dimensional volumes consistently showed that the structures in the zero pressure gradient turbulent boundary layer were larger, more well-defined, and spaced farther apart than the features at the boundary layer edge in the adverse pressure gradient cases. This was not apparent in every image, but the trend was noticeable. Looking at the power spectral density from the Fourier transformed data showed that the zero pressure gradient case had more energy in the structures with a wavelength of 1.4δ and above, whereas the adverse pressure gradient case had more energy in structures with wavelengths between 1.4δ and 0.1δ. Investigation of the binary slices using the regionprops function in MATLAB showed maximums in the number of “islands” between 0.85δ and 0.90δ for all three cases. The area of the features was largest at just about every wall-normal height for the ZPG cases compared to the APG cases. This helps to confirm that the sizes of the structures are indeed larger in terms of boundary layer thickness for the ZPG case.

The conditionally averaged images with a feature near the center of the image at y=0.88δ showed that the average distance between structures at this location was 1.92δ for the ZPG case, compared to 1.81δ for both APG cases. This also objectively confirms observations seen in the 3D flow visualization images. The average of the volume when a structure is centered at this location showed the shape and profiles of the intensity in the streamwise and spanwise direction. The ZPG case showed similar profiles in the streamwise and spanwise direction, indicating a circular feature, but the APG cases had a much narrower profile in the spanwise direction, meaning the structure are more often elongated in the streamwise direction compared to the ZPG case. The conditionally averaged structure also showed an inclination angle of 47.1 degrees from horizontal compared to 48.0 and 53.5 for the two adverse pressure gradient cases.

References


