

Flying PIV investigation of vortex packet evolution in perturbed boundary layers

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ABSTRACT

A turbulent boundary layer with zero pressure gradient of $Re_\tau=2500$ was perturbed using a single spanwise cylinder array with $H/\delta=0.2$ ($H^+=500$) and aspect ratio $H/D=4$ mounted on the bounding surface. Both fixed location and tracking measurements were performed using particle image velocimetry (PIV) in streamwise-spanwise planes up to 7δ downstream at a wall-normal location of $z^+=300$. The spacing of the cylinder array was varied from 0.2δ to 0.8δ , and the 0.6δ spacing case, which matched the dominant spanwise mode in the unperturbed flow, showed the most stable downstream organization which persisted beyond 7δ in the streamwise direction. The flying PIV method allowed us to track specific vortical structures in the streamwise direction of range $-2 < x/\delta < 7$, corresponding to a time scale of order $12\delta/U_\infty$. The flying PIV results showed that approaching packets lost their organization immediately downstream of the 0.2δ array but regained it 2δ downstream on a time scale of order $3\delta/U_\infty$, suggesting that the outer layer organization propagated inward into the log region. With larger spacing, the cylinders sometimes enhanced the organization of existing packets and generally redirected packets into the spanwise location midway between cylinders. The interactions between packets and cylinder wakes were discussed in three scenarios based on the relative spanwise distance between the cylinder and upstream packet.

1. INTRODUCTION

Since vortex packets are believed to be a key self-sustaining mechanism in turbulent boundary layers, it may be possible to control boundary layer behaviors by manipulating these packets. Many previous studies have shown that the vortex packets are often associated with strong Q2 ejection events (e.g. [2]), within long low-momentum regions (LMRs) extending in the streamwise direction [28]. Hutchins *et al.* [13] compared the spanwise and wall-normal extent of u , v and w two-point correlations at $Re_\tau=690-2800$, and found they all scaled with outer variables, which was consistent with Wark *et al.* [30]. Thus the results in the current study will be discussed using outer units.

Since packets have been found to be prevalent in the logarithmic region of turbulent boundary layers [6, 9, 16], which is also associated with significant energy and wall-normal transport, the log region is of particular interest in the current investigation. It has also been noted that large scale packets in the logarithmic and outer layers make a significant imprint on the near wall region [14]. The current investigation will provide new evidence to that concept.

The spatial scales of the packets have been studied extensively by many investigators. Tomkins & Adrian [28] studied these LMRs in streamwise-spanwise planes at different heights in the log region ($z^+=100-440$) of a turbulent boundary layer at $Re_\tau=2216$ and found low momentum regions extended 2δ or more in the streamwise direction with spanwise width of $0.1-0.4\delta$ which increased with distance away from the wall. Hutchins & Marusic [14] studied these LMRs in turbulent boundary layers with $Re_\tau=1000-6\times 10^5$, and reported length scales over 20δ . Elsinga *et al.* [5] reported spanwise spacing between the LMRs to be $0.5-1\delta$ in a supersonic turbulent boundary layer at $Re_\tau=7080$ using tomographic PIV data, and Gao [10] proposed the typical spanwise spacing of these structures to be larger than 0.5δ in the log layer. Additional results on spatial characteristics of the packets can be found in [1, 3, 4, 5, 10, 13, 14].

Some recent studies also investigated the temporal development of individual hairpins and eddies in the boundary layer. Elsinga & Marusic [7] probed time-resolved tomographic PIV data by examining the invariants of the velocity gradient tensor; they proposed a characteristic lifetime for the energy containing eddies in the outer region of the boundary layer as $14.3\delta/U_\infty$. Elsinga *et al.* [8] examined the streamwise aligned, spanwise vortex elements using the same data and suggested that they interact on a time scale of order $1\delta/U_\infty$. LeHew *et al.* [17] used time-resolved PIV to track the coherent swirling structures and found them to persist more than $5\delta/U_\infty$. The current investigation will use flying PIV data to further the understanding of eddy and packet evolution over time scales up to $12.4\delta/U_\infty$.

Previous studies have demonstrated that perturbations or obstacles strongly affect turbulent boundary layer characteristics (see [11, 15, 27]), and many types of obstacles have been investigated (e.g. [11, 24, 25, 27]). The current study will focus on the perturbation effects of a single spanwise array of cylinders with varying spacing. For individual cylinders, three parameters have been found to influence the wake flow significantly: the aspect ratio AR (height/diameter) [26], the cylinder height with respect to the boundary layer thickness, H/δ [12, 20, 24], and the condition of the incoming boundary layer, laminar or turbulent [29]. The current study used cylinders of $AR=4$ in a turbulent boundary layer, and their height was short compared with the boundary layer thickness ($H/\delta=0.2$, $H^+=500$), extending only through the logarithmic region.

For a spanwise array of cylinders, the spacing seems to be an important parameter. A recent study by Pujals *et al.* [21] investigated the effect of a single spanwise array of cylinders on a turbulent boundary layer at $Re_\tau=370$, with $H/\delta=0.8$ and constant cylinder spacing of

4D for several combinations of diameter and center-to-center distance. Based on the amplitude of spanwise variations in the streamwise velocity, they concluded that the streamwise development of the amplitude would be the same for a constant spacing normalized by the cylinder diameter D . More recently, Ryan *et al.* [23] probed the flow behind a single array of wall-mounted cylinders with $AR=1.5$ in a turbulent boundary layer at $Re_\tau=1200$ using Hot-Wire Anemometry. The cylinder height ($H/\delta=0.15$, $H^+=150$) was chosen such that they extended to the top of the log layer but not beyond. Both 0.25δ and 0.5δ spaced arrays were studied, and the results showed delay in cylinder wake interactions with increasing spacing. Later PIV and V3V measurements by Ortiz-Dueñas *et al.* [19] were performed in a turbulent boundary layer at $Re_\tau=2500$ perturbed by a cylinder array of $AR=4$, $H/\delta=0.2$ ($H^+=500$), with spacings of 0.2δ and 0.4δ . The 0.4δ spaced array was observed to produce relatively stable downstream structures while the 0.2δ case produced rapid wake interaction and pairing as well as greater disorganization of individual eddies downstream.

The current study aimed to build on our previous work to understand the vortex packet evolution in turbulent boundary layers perturbed by cylinder arrays with different spacing. The flying PIV method was employed to observe and quantify the evolution of eddy and packet structures as they propagated downstream over a total distance of 9δ . The impact of instantaneous upstream flow conditions on the development downstream was also investigated based on the tracking measurements enabled by the flying PIV method.

2. EXPERIMENTAL FACILITY AND METHODS

All experiments were conducted in a closed-return water channel facility in the Department of Aerospace Engineering and Mechanics at University of Minnesota. The test section was 8m long and 1.22m wide. It was filled up to 0.39m depth while running under steady conditions. The water was driven by three propellers, and returns to the inlet from the outlet through three pipes underneath the test section. Before entering the test section, the water travels through a 6.35mm honeycomb and three 60% perforated stainless steel screens. A 3mm diameter stainless steel trip was mounted on the bottom wall in the beginning of the test section, and the measurement area started $\sim 6m$ downstream.

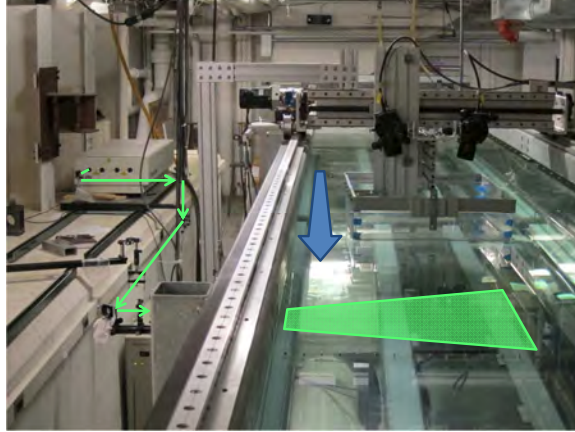


Figure 1: Water channel facility. Blue arrow shows the streamwise direction. Laser path and sheet orientations are shown in green.

The facility has a computer-controlled traversing system mounted on top of the working section which enables tracking measurements. Two rails are laid on top of the side walls throughout the working section, and the traverse can travel in the streamwise direction at speeds up to 1m/s. A platform on the traverse holds the cameras and laser sheet optics. A glass interface box with square bottom of $0.8m \times 0.8m$ was installed below the traversing platform in order to view streamwise-spanwise planes from the top. The setup is shown in figure 1. With the interface box mounted, the boundary layer parameters measured at 6m downstream of the trip are given in table 1.

Re_θ	Re_τ	U_∞ (m/s)	u_τ (m/s)	θ (mm)	δ (mm)
6200	2500	0.508	0.0198	12.1	125.5

Table 1: Turbulent boundary layer parameters 6m downstream of the trip, as determined by Gao [10].

A single spanwise array of stainless steel cylinders with aspect ratio $AR=4$ and height $H/\delta=0.2$ ($H^+=500$) was mounted on the bottom surface of the water channel 6m downstream of the trip. In the remainder of the paper, this location is defined as the origin of the x -axis. Spanwise and wall-normal directions are designated by y and z respectively. Three cylinder spacings: 0.2δ , 0.4δ and 0.6δ were considered for both fixed location and tracking measurements. A 0.8δ case was also investigated at fixed locations.

In the current study, a dual-head Spectra Physics Nd:YAG laser was used with output power of 370mJ/pulse. The laser beam first passed through a set of spherical lenses with $f=500mm$ to reduce divergence, and then a set of sheet optics including one spherical lens with $f=1000mm$ and two convex cylindrical lenses with $f=60mm$. The sheet optics were mounted on a rail attached to the traverse so that the laser sheet was able to travel with the traverse. The laser sheet was approximately 1mm thick and located 15mm ($z^+=300$) above the wall at the center of the field of view (FOV). This height was chosen based on V3V measurements by Ortiz-Dueñas *et al.* [19] and Ryan [22], as a location at which the maximum wall normal velocities were observed.

Two 12-bit TSI PowerView 4MP Plus cameras with resolution of 2048×2048 pixels were used together with Nikon Micro-Nikkor

60mm lenses. Both cameras were equipped with a Scheimpflug adapter for quality imaging. The flow was seeded with silver coated hollow glass spheres from Potters Industries LLC, with a mean diameter of $16\mu\text{m}$ (diameter range of $6\text{--}25\mu\text{m}$).

Two types of measurements were performed: one based on acquiring data at fixed streamwise locations, and the other based on traversing the cameras and laser sheet at the local mean convection velocity. For fixed location measurements, both stereoscopic PIV and planar PIV were performed, referred to as SPIV and PPIV respectively. For SPIV experiments, each camera was oriented approximately 30° to the z -axis, and the FOV was approximately 1.18×1.18 . For PPIV measurements, the angle between each camera and the z -axis was reduced to minimize the overlap, yielding a layout of two side-by-side fields of view with a resulting FOV of 1.18×1.98 in the x and y directions respectively. This was necessary to observe and quantify spanwise variations for the larger array spacings. All fixed location measurements consisted of 1000 image pairs for each FOV with sampling rate of approximately 0.5Hz. The time difference between two laser pulses was chosen to be $\Delta t = 800\mu\text{s}$.

Based on the traversing system and the SPIV arrangement, a method referred to as flying PIV (FPIV) was employed to track the flow evolution in specific runs. For all FPIV experiments, the traverse was first accelerated to a fixed speed before data were acquired over a streamwise range of $-2 < x/\delta < 7$. The traversing speed (0.37m/s) was set based on the mean velocity at the measurement height in the unperturbed (no cylinder) case. Image pairs were captured with a sampling rate of 7.25Hz, and an average number of 40 runs were taken for each case. The time difference between two pulses for FPIV measurements was $\Delta t = 1800\mu\text{s}$.

A dual plane calibration plate was used for all calibrations. For fixed location measurements, a calibration image was taken with the channel running at $U_\infty = 0.508\text{m/s}$. For flying measurements, the traverse moved at 0.37m/s, so the velocity difference was calculated, and the channel was set to run at $U_\infty = 0.138\text{m/s}$ while the calibration image was taken to minimize the error introduced by the interaction between the box and the flowing water (see [10]). A self-calibration [31] was also performed on all cases of SPIV and FPIV measurements to correct for misalignment between the laser sheet and calibration plane.

All vector fields were calculated in DaVis 7.4 from LaVision. For all fixed location data sets, an interrogation window size of 32×32 pixels was used with 50% overlap. The resulting vector spacing was $l = 1.1\text{mm}$ ($l^+ = 21$). For FPIV data sets, the interrogation window size was chosen to be 64×64 pixels with 50% overlap. The corresponding vector spacing was consequently $l = 2.3\text{mm}$ ($l^+ = 45$). The statistical uncertainty of the averaged results was estimated as 0.60%, 0.54% and 0.73% of U_∞ for U , V and W components respectively based on stereoscopic setup, and 1.77% and 1.30% of U_∞ , for U and V component respectively based on side-by-side planar setup.

3. FIXED LOCATION RESULTS

The unperturbed streamwise velocity fields acquired at $x/\delta = 0$ were analyzed using a Fourier transform method to determine the dominant mode of spanwise variations. Details of the method can be found in [32]. Figure 2 shows the result based on PPIV measurements, and the most dominant scale is 0.6δ mode, which is comparable to previous results by Hutchins *et al.* [13]. Note that the span of the FOV is 2δ , so that any components larger than 1.4δ are underestimated due to the limitations of the method.

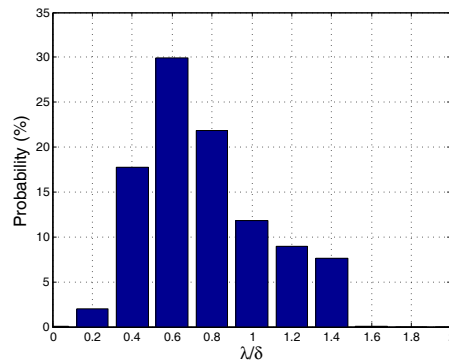


Figure 2: Distribution of dominant spanwise scales for unperturbed flow using PPIV.

In the perturbed cases, all four spacings were studied by fixed location measurements, and all of the averaged measurements exhibited a similar pattern in that the wakes of slow moving fluid behind each cylinder appear to split symmetrically (see [32]). Results of the 0.6δ spacing case are given in figure 3. Neighboring split wakes merge into new slow moving regions at $x/\delta = 3.5$, and then a clear pattern of spanwise variations of streamwise velocity is observed to persist beyond $x/\delta = 7.4$. This splitting pattern moved further downstream with increasing cylinder spacing from 0.2δ – 0.8δ . However, the strongest amplitude of the average streamwise velocity variation was observed for the 0.6δ spacing case, indicating that the perturbation effects were optimally preserved.

The downwash patterns given in figure 3 (b), which did not shift in the spanwise direction, lasted longer with increased cylinder spacing. In the 0.6δ case shown, the downwash lasted throughout the measurement domain. In general, this downwash behavior was related to tip vortices observed by Ryan [22] that brought faster moving fluid from above the cylinders down toward the measurement plane, such that fast-moving regions then developed downstream of each cylinder. Combining the observations of streamwise velocity pattern and the downwash effects, it was concluded that the 0.6δ case yielded the most stable flow organization compared to the other three cases investigated, as might be expected given that it is the most dominant spanwise scale in the unperturbed flow (see figure 2).

4. TRACKING RESULTS

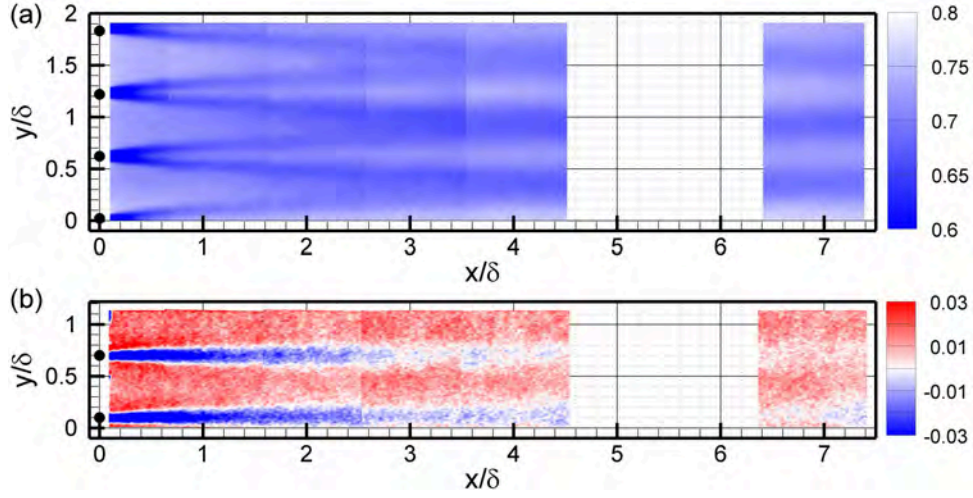


Figure 3: Averaged (a) streamwise (blue is slow, white is fast) and (b) wall-normal (blue is towards the wall, white is zero) velocity field of 0.6δ case, normalized by $U_\infty=0.508\text{m/s}$. Spatial variables are normalized by $\delta=125.5\text{mm}$.

A select run of unperturbed FPIV result is given in figure 4. Contour levels are set to highlight the slow moving regions, and hence the packets. The streamwise velocity is computed relative to the averaged mean velocity without the cylinders, so zero in the plot represents a convection velocity of 0.37m/s .

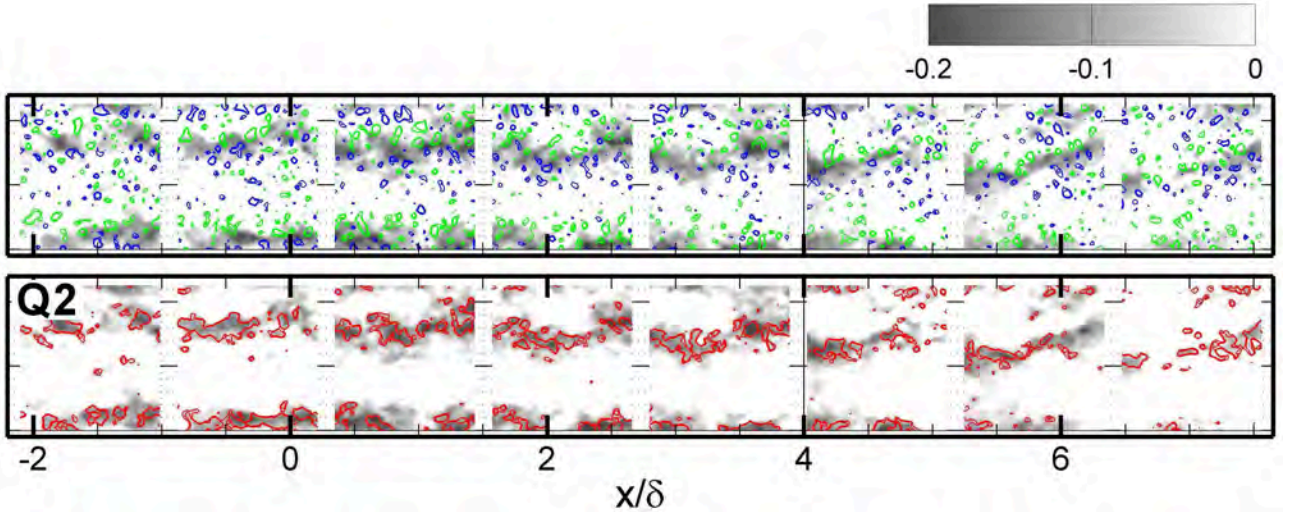


Figure 4: FPIV measurement of (a) streamwise velocity and 2D swirling strength (blue: $\lambda_{CI}>0.6$, green: $\lambda_{CI}<-0.6$, signed by ω_z); (b) streamwise velocity and contour lines (red) of $Q2$ Reynolds stress ($Q2=0.5\sigma_u\sigma_w$). Contour map shows the streamwise velocity relative to $\bar{U}=0.37\text{m/s}$ normalized by $U_\infty=0.508\text{m/s}$. Bold ticks on y -axis are separated by 0.5δ .

Figure 4 shows two distinct packets identified by LMRs in the streamwise velocity contour surrounded by counter-rotating swirling structures that coincident with $Q2$ Reynolds stress. These packets persisted over a streamwise distance of 9δ corresponding to a time scale of $12.4\delta/U_\infty$, and the spanwise spacing between these structures varied in the range of $0.4-0.7\delta$ due to packet rotation as observed in the last four frames. This is comparable to the meandering feature of the packets mentioned in many previous works, as we are providing the Lagrangian view of the development.

A cross correlation was performed for the first and last frame of the streamwise velocity field in each run; and the correlation maps of all 40 runs were averaged as shown in figure 5. The fields are well correlated over the streamwise range, and it is interesting that the strongest contours show a diamond shape, which could be caused partly by spanwise rotation of LMRs. The zero contour lines (marked by white patches) indicate the width of the LMRs to be approximately 0.2δ , which is consistent with observations from [14] and [28].

Figure 6 gives select FPIV runs with 0.2δ spacing array in place. Two distinct packets are observed in the incoming flow in figure 6 (a), identified by the well aligned swirls on both sides of the long LMRs. Immediately downstream of the cylinders, the streamwise velocity is significantly decreased. Individual wake structures interact with their neighbors causing the number of swirl structures to increase and their sizes to become more diverse at this measurement location. This is better illustrated in figure 7. In this case, the incoming vortex packets are broken down to smaller scales, at least at this measurement height. These smaller scale vortices interact with neighboring ones so the flow remains disorganized up to approximately $x/\delta=2$, where these structures start to reorganize themselves towards the status similar to the incoming flow, i.e. two independent LMRs are observed at $x/\delta=2$ (marked by red circles in figure 7), and their spanwise spacing and location are similar to those of the upstream packets.

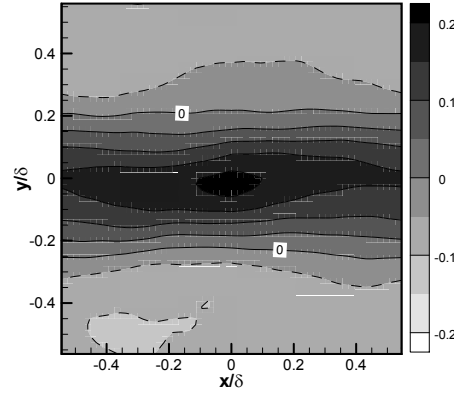


Figure 5: Cross correlation of the first and last frame of streamwise velocity field averaged over 40 runs for the unperturbed case.

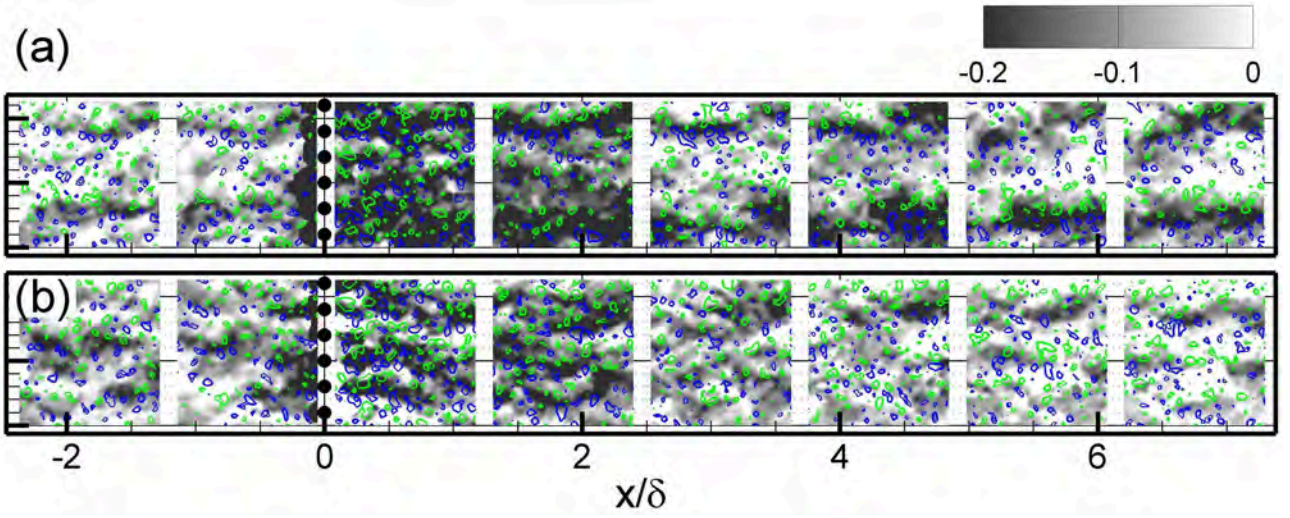


Figure 6: Select runs of 0.2δ spacing case. Contour map shows the streamwise velocity relative to $\bar{U}=0.37\text{m/s}$ normalized by $U_\infty=0.508\text{m/s}$. The 2D swirling strength is given in contour lines (blue: $\lambda_{ci}>0.6$, green: $\lambda_{ci}<-0.6$, signed by ω_z). Bold ticks on y-axis are separated by 0.5δ .

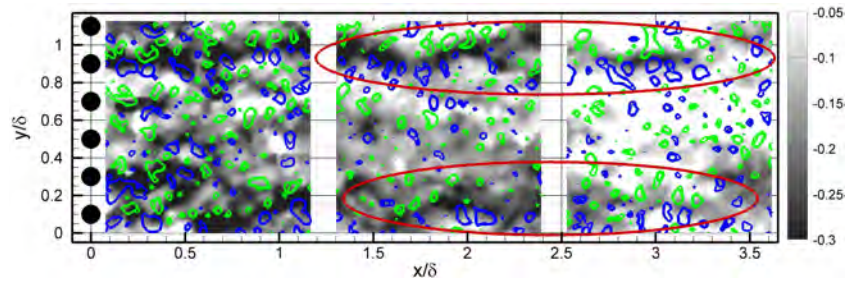


Figure 7: Near field of the 0.2δ spacing case (a). Contour map shows the streamwise velocity relative to $\bar{U}=0.37\text{m/s}$ normalized by $U_\infty=0.508\text{m/s}$. The 2D swirling strength are given in contour lines (blue: $\lambda_{ci}>0.6$, green: $\lambda_{ci}<-0.6$, signed by ω_z).

In figure 6 (b), there are likely three packets in the flow (two stronger ones on top and a weak one at bottom). In this case, the number of the swirl structures is also increased after the cylinder array, and they reorganize at $x/\delta=2$ into three packets, which is again comparable to the incoming condition. This behavior is observed frequently in the 0.2δ case, suggesting that the cylinder array perturbs only part of the existing packets, and the remaining organization in the outer layer significantly affects the development of the flow downstream. This concept is consistent with the idea of Hutchins & Marusic [14] that packets in the outer region make a significant imprint on the near wall region.

The result from the aforementioned cross correlation method for the 0.2δ case is shown in figure 8. The region of highest correlation is elongated in the streamwise direction compared to the unperturbed case, suggesting first that the packet structure and associated LMR persist through the perturbation and second that the spanwise movement of the existing packets is decreased compared with the unperturbed case, leading to the slightly narrower width between the zero value contours lines. The spanwise contour variation is also different in that the negative lobes become more prominent, which could also result from decreased spanwise movement.

When the cylinder spacing increases beyond 0.2δ , the instantaneous downstream flow organization depends more on the upstream

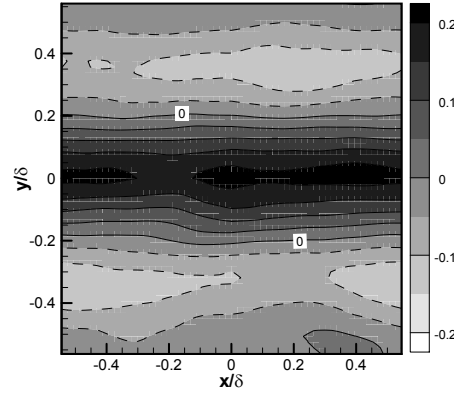


Figure 8: Cross correlation of the first and last frame of streamwise velocity field averaged over 40 runs for the 0.2δ case.

flow conditions. Based on examination of many runs, three scenarios were proposed to explain the wake-packet interactions. In the first scenario, no distinct packets were observed in the incoming flow, and individual cylinder wakes merged or paired into new slow moving regions at spanwise locations midway between the cylinders. In the second scenario, packets in the incoming flow passed between neighboring cylinders and attracted the nearest wake so that the existing LMRs were strengthened and remained coherent in the mid-spacing locations. In the third scenario, the incoming packets impinged directly on the cylinders. The packets were enhanced by the coincident cylinder wakes before shifting gradually toward the mid-spacing locations. Scenario I occurs $\sim 12\%$ of the time, while II and III make up the remainder.

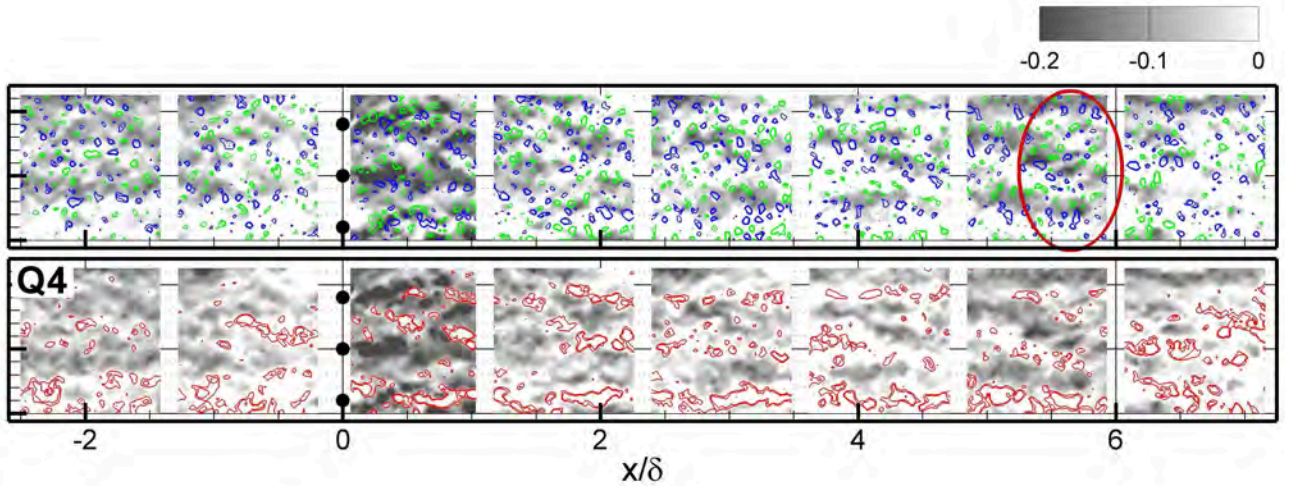


Figure 9: Select run of 0.4δ spacing case representing Scenario I of wake-packet interaction. Contour map shows the streamwise velocity relative to $\bar{U}=0.37\text{m/s}$ normalized by $U_\infty=0.508\text{m/s}$. The 2D swirling strength are given in contour lines (blue: $\lambda_{ci}>0.6$, green: $\lambda_{ci}<-0.6$, signed by ω_z). High Reynolds stress ($-uv$) regions of Q4 events are given in red contour lines ($Q4=0.5\sigma_u\sigma_w$). Bold ticks on y-axis are separated by 0.5δ . The large red circle marks the interaction of LMRs in the far field. [Zoom in for better resolution.]

Figure 9 shows Scenario I in the 0.4δ case where no distinct packets are observed in the incoming flow. The relatively disorganized swirling structures indicate no strong packet structures in the flow as there is no obvious streamwise alignment. In this case, three cylinder wakes are distinct immediately after the cylinder array, and no obvious interactions are observed in the near field ($x/\delta < 0.5$) because the swirls (blue and green contour lines) are well aligned on each side of each cylinder wake. This observation is different from the 0.2δ case where interaction between wakes happened immediately downstream of the cylinders. At $x/\delta=1$, some mixing of opposite signed swirl structures can be observed throughout the span, suggesting a stronger spanwise interaction. At $x/\delta=2$, two independent LMRs are observed at the mid-spacing locations associated with counter rotating swirl structures. By observing the trace of the blue and green swirls, it is evident that the new LMRs are merged from the cylinder wakes. Beyond $x/\delta=2$, these two LMRs maintain a relatively stable spacing of 0.4δ with small scale spanwise movement (of order 0.1δ) before a secondary spanwise movement seen at $x/\delta=5.7$ (marked by the large red circle) which suggests the decay of the flow organization. Indeed, the last FOV no longer shows distinct LMRs.

In this scenario, with larger spanwise spacing where no distinct incoming packets are present, the downwash effects become significant in determining the behavior of the cylinder wakes. In figure 9, strong Q4 Reynolds stress events are observed downstream of each cylinder which are well associated with regions of high speed fluid. Based on continuity, the slow moving regions are expected to shift aside with possible upwash behaviors. These movements also contribute to the streamwise vorticity as observed by Ortiz-Dueñas *et al.* [19] and Ryan [22].

Figure 10 shows Scenario II in the 0.4δ case where two packets present in the incoming flow hit the mid-spacing locations. In this case, the cylinder wakes are attracted immediately by the nearest packet which then stays strongly coherent in the mid-spacing location

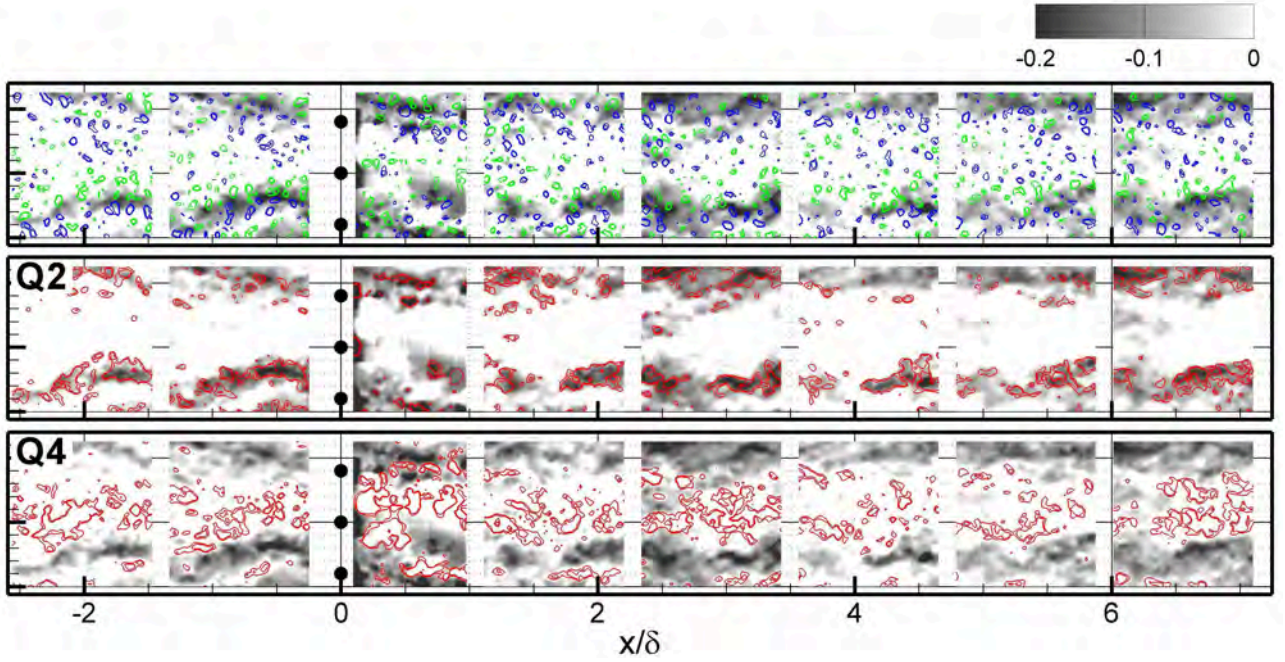


Figure 10: Select run of 0.4δ spacing case representing Scenario II of wake-packet interaction. Contour map shows the streamwise velocity relative to $\bar{U}=0.37\text{m/s}$ normalized by $U_\infty=0.508\text{m/s}$. The 2D swirling strength are given in contour lines (blue: $\lambda_{ci}>0.6$, green: $\lambda_{ci}<-0.6$, signed by ω_z). High Reynolds stress ($-uv$) regions of both Q2 and Q4 events are given in red contour lines ($Q2=Q4=0.5\sigma_u\sigma_w$). Bold ticks on y-axis are separated by 0.5δ .

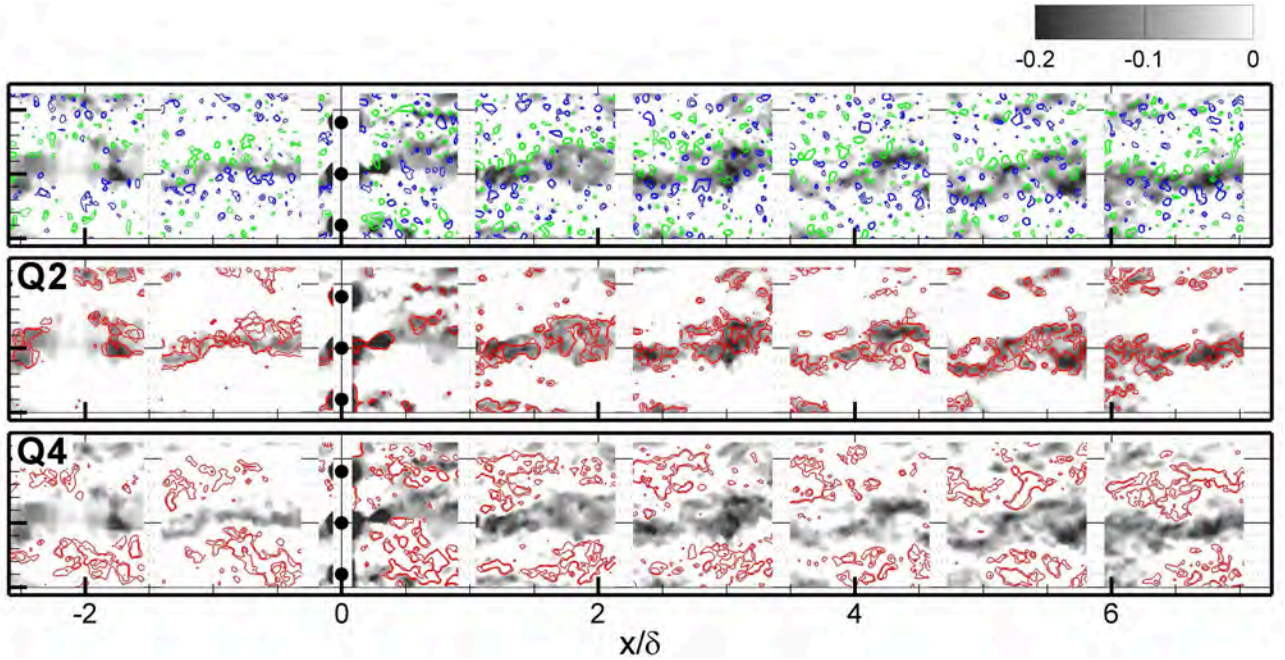


Figure 11: Select run of 0.4δ spacing case representing Scenario III of wake-packet interaction. Contour map shows the streamwise velocity relative to $\bar{U}=0.37\text{m/s}$ normalized by $U_\infty=0.508\text{m/s}$. The 2D swirling strength are given in contour lines (blue: $\lambda_{ci}>0.6$, green: $\lambda_{ci}<-0.6$, signed by ω_z). High Reynolds stress ($-uv$) regions of both Q2 and Q4 events are given in red contour lines ($Q2=Q4=0.5\sigma_u\sigma_w$). Bold ticks on y-axis are separated by 0.5δ .

throughout the measurement domain. By comparing the more prominent Q2 Reynolds stress events to the Q4 events, it was concluded that since the packets dominated the downstream flow and the wake-packet interactions were strong, the tip downwash did not seem to affect the flow development significantly.

Figure 11 shows Scenario III in the 0.4δ case where a packet hits the cylinder directly. Immediately downstream of the cylinder array, the LMR overlaps the cylinder wake, and remains strongly coherent throughout the measurement domain while gradually migrating towards the mid-spacing location. Comparably to Scenario II, the Q2 events in this case are also more coherent than the Q4 events, as has been documented by Ganapathisubramani *et al.* [9] and Longmire *et al.* [18].

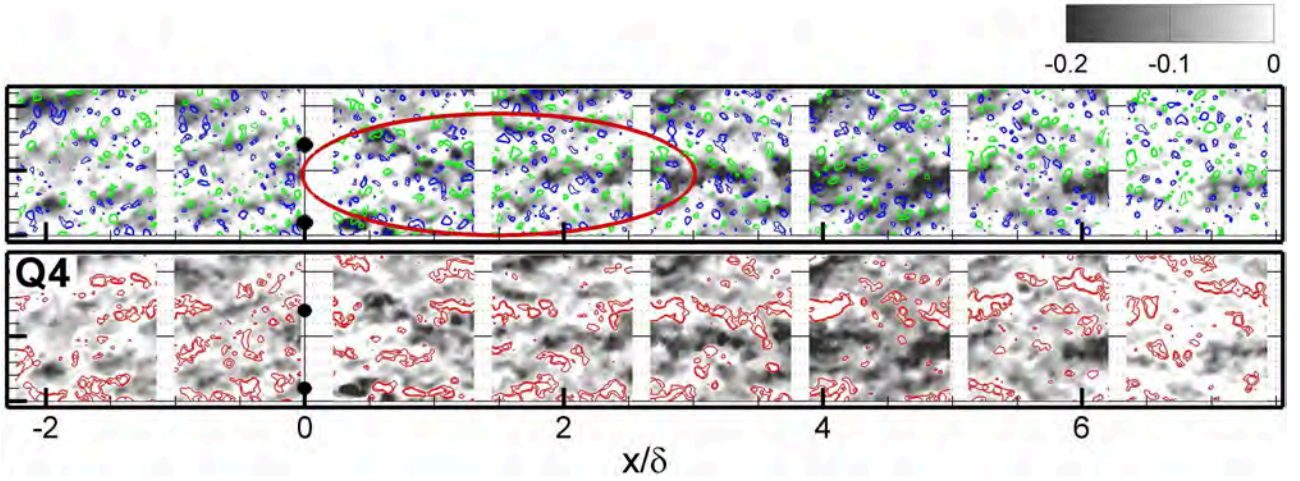


Figure 12: Select run of 0.6δ spacing case representing Scenario I of wake-packet interaction. Contour map shows the streamwise velocity relative to $\bar{U}=0.37\text{m/s}$ normalized by $U_\infty=0.508\text{m/s}$. The 2D swirling strength are given in contour lines (blue: $\lambda_{Ci}>0.6$, green: $\lambda_{Ci}<-0.6$, signed by ω_z). High Reynolds stress ($-uv$) regions of Q4 events are given in red contour lines ($Q4=0.5\sigma_u\sigma_w$). Bold ticks on y -axis are separated by 0.5δ . The large red circle marks merging of the cylinder wakes. [Zoom in for better resolution.]

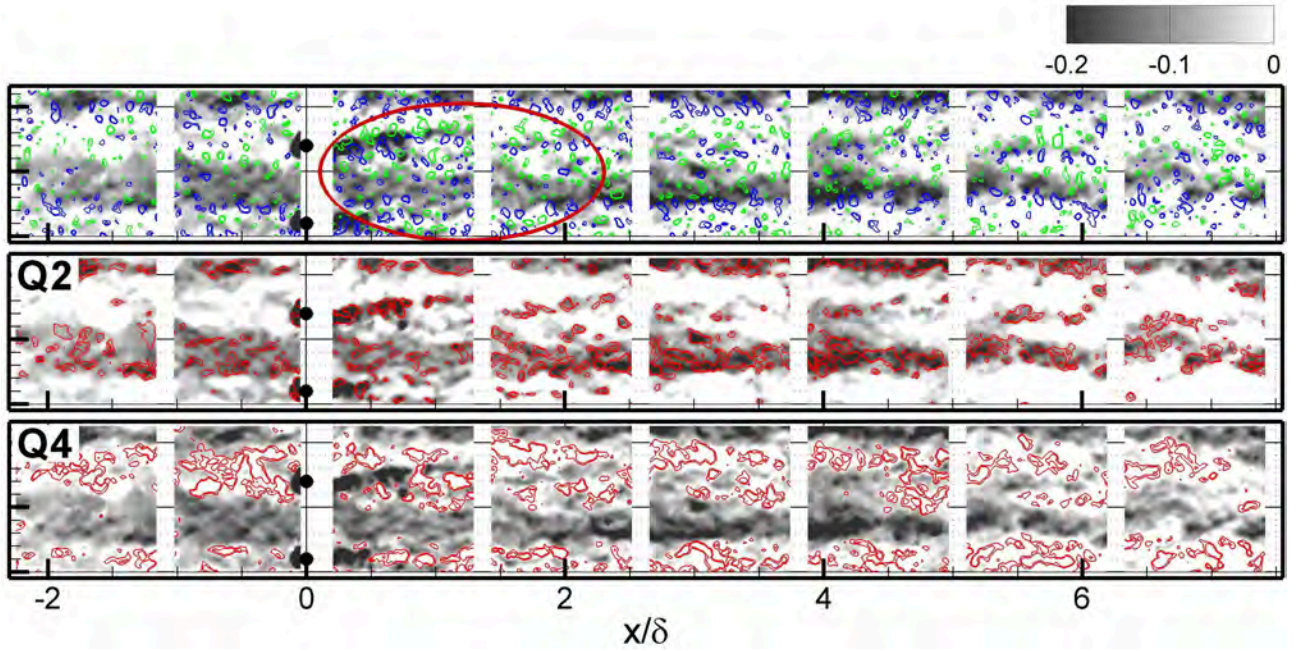


Figure 13: Select run of 0.6δ spacing case representing Scenario II of wake-packet interaction. Contour map shows the streamwise velocity relative to $\bar{U}=0.37\text{m/s}$ normalized by $U_\infty=0.508\text{m/s}$. The 2D swirling strength are given in contour lines (blue: $\lambda_{Ci}>0.6$, green: $\lambda_{Ci}<-0.6$, signed by ω_z). High Reynolds stress ($-uv$) regions of both Q2 and Q4 events are given in red contour lines ($Q2=Q4=0.5\sigma_u\sigma_w$). Bold ticks on y -axis are separated by 0.5δ . The large red circle marks the splitting of the cylinder wake and the merging of lower part into the neighboring packet. [Zoom in for better resolution.]

Figure 12 represents Scenario I in the 0.6δ case where no distinct packets are observed in the incoming flow. This is based on the rather disorganized distribution of swirling structures. Individual wakes downstream of the cylinders appear very unstable and bend in either the positive or negative spanwise direction causing significant interactions between neighboring wakes. An example of the spanwise movement is observed at $x/\delta=1$ based on the tilting of like-signed groups of swirls. By comparing the range of sizes and the number of swirl structures upstream and immediately downstream of the cylinders, it is evident that interactions between individual wake structures are much weaker than the 0.2δ and 0.4δ cases. That makes sense as the 0.6δ array is less disruptive to the flow field, and consequently fewer interactions are observed. Two neighboring wakes merge into a distinct LMR that appears at $x/\delta=2$ in the mid-spacing location between the two cylinders shown (as marked by the large red circle). The new LMR persists throughout the measurement domain. In this case, the spanwise movement of the wakes is initiated by the downwash effects associated with the Q4 Reynolds stress events observed behind each cylinder. These Q4 events are expected to convect faster moving fluid downward from above the cylinders forcing the wake structures to move aside.

In figure 13, a packet in the incoming flow passes between neighboring cylinders, giving an example of Scenario II in the 0.6δ case. In this specific run, the wake of the upper cylinder shown first splits, as part of it remains independent over $7\delta/U_\infty$. The other part of the cylinder wake interacts with the packet immediately downstream of the array. The swirl structures showed clear evidence of the wakes

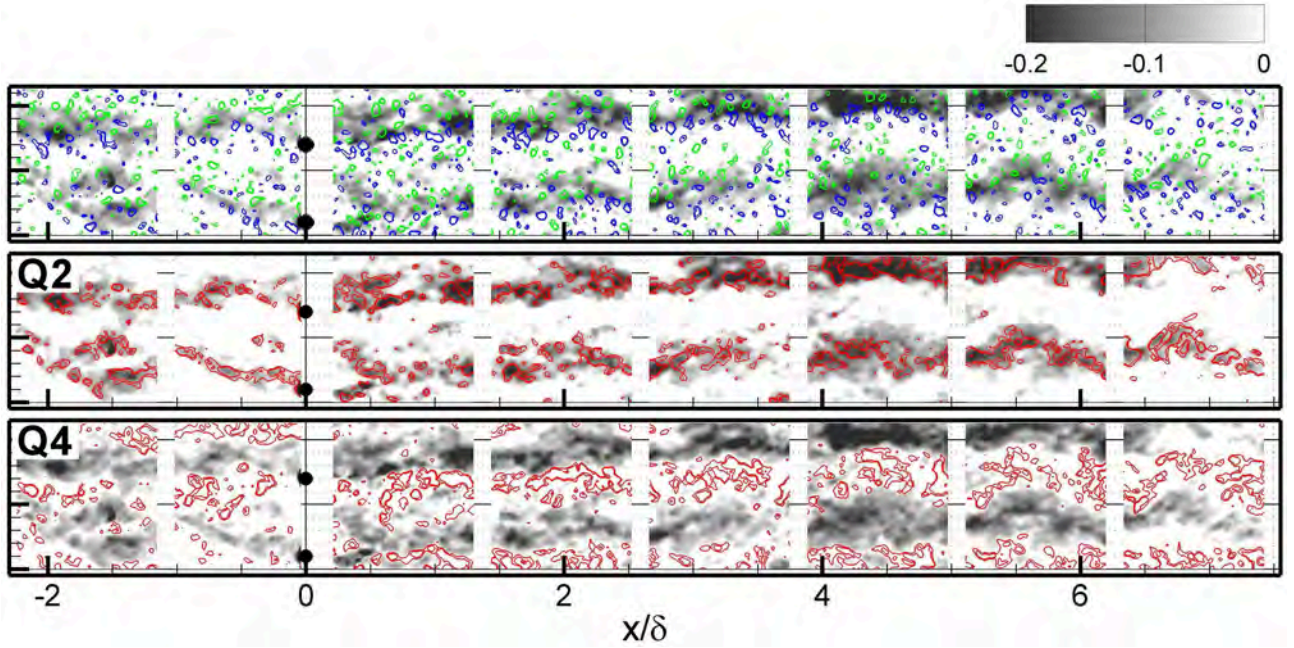


Figure 14: Select run of 0.6δ spacing case representing Scenario III of wake-packet interaction. Contour map shows the streamwise velocity relative to $\bar{U}=0.37\text{m/s}$ normalized by $U_\infty=0.508\text{m/s}$. The 2D swirling strength are given in contour lines (blue: $\lambda_{ci}>0.6$, green: $\lambda_{ci}<-0.6$, signed by ω_z). High Reynolds stress ($-uv$) regions of both Q2 and Q4 events are given in red contour lines ($Q2=Q4=0.5\sigma_u\sigma_w$). Bold ticks on y-axis are separated by 0.5δ .

merging laterally into the packet as marked by the large red circle. In this scenario, the LMR settled at the mid-spacing location and remained coherent throughout the measurement domain with no further strong spanwise movements. The Q2 Reynolds stress events dominated the downstream flow as expected, and in this specific run, it was obvious that the population and strength of Q2 events in the LMR was increased after the attraction of the cylinder wake at $x/\delta=2$, as compared to the Q2 events within $-2<x/\delta<1.5$. The Q4 events induced by the lower cylinder in this run seem to modulate the packet structure by bringing faster moving fluid to the measurement plane and compressing the width of the packet, as indicated by the decreasing width of the LMR. Although, by the fact that there is no spanwise movement observed of the packet (which is also true in other Scenario II cases), we conclude that the action of Q4 events is relatively weak as opposed to the interaction between the packet and nearby cylinder wakes.

Finally, figure 14 illustrates Scenario III in the 0.6δ case where packets impinge directly on the cylinders. The diverging pattern of blue and green swirls just upstream of the upper cylinder suggests that the vortex packet is indeed obstructed by the cylinder. Downstream of the cylinder array, the two packets are enhanced by the wakes as the population of streamwise-aligned swirls increases, and also the population of high Q2 Reynolds stress regions. No spanwise interaction is observed between the neighboring packets, and they move gradually toward the mid-spacing location. The spanwise spacing between them remains about 0.6δ throughout the measurement domain. The spanwise movement of the enhanced packets in this case was induced by downwash directly behind each cylinder, as observed in the Q4 Reynolds stress plot. The difference in Q4 Reynolds stress effects between this specific case and figure 11 where the Q4 Reynolds stress did not show a dominant effect to modulate the packet is the initial condition. In the previous case, the packet location was perfectly aligned with the cylinder, as opposed to the current case where the alignment was slightly off, consequently the effects of the Q4 Reynolds stresses were different.

Since the 0.4δ cylinder array had a spacing different from the most dominant spanwise scale of 0.6δ in the unperturbed (incoming) flow, a mixed scenario (II and III) was frequently observed for that array, resulting in more disorganization of the downstream flow structures due to the different wake-packet interaction schemes for each scenario. For the 0.6δ array, however, the relative packet-to-cylinder position was more likely to be the same for neighboring packets; thence either Scenario II or III would occur and dominate the downstream flow. Consequently, the wake-packet interactions and development of neighboring packets was better organized, helping explain the enhanced flow stability in the 0.6δ case.

5. CONCLUSIONS

A flying PIV method was implemented to study the perturbations caused by a single spanwise array of cylinders immersed in the logarithmic region of a turbulent boundary layer. The implementation of this method allowed us to capture SPIV fields with excellent resolution and accuracy, which enabled tracking measurements of packet structures in specific runs. In the unperturbed flow, features of strong coherent packets were observed to persist throughout the measurement domain over a streamwise distance of 9δ , corresponding to a time scale of $12.4\delta/U_\infty$. Cross correlation results indicated a packet width of $\sim 0.2\delta$, which is consistent with observations from [14] and [28].

This method allows us to directly observe the effects of perturbations on the incoming flow structures. In the 0.2δ array case, the downstream flow recovered relatively rapidly from the perturbation in a time scale of $2.7\delta/U_\infty$. The FPIV results suggested that packet organization in the outer layer persisted through the perturbation and communicated inward to re-establish itself in the logarithmic

region.

For arrays with larger cylinder spacing, three scenarios of wake-packet interactions were observed. In most cases, Q4 Reynolds stresses induced downstream of cylinder tips acted to displace them in either spanwise direction. Depending on the scenario, this encouraged either formation of new packets in the midspan locations or migration of existing packets into the same locations. Packets passing close to a given cylinder tended to ingest the wake from that cylinder, potentially strengthening the swirling structures and the Q2 Reynolds stresses.

The 0.6δ array yielded the most stable organization of LMRs downstream which was not surprising as it matched the dominant spanwise scale in the unperturbed flow. Under this perturbation scale, the relative packet-to-cylinder position was more likely to be the same for neighboring packets; thence either Scenario II or III would occur and dominate the downstream flow, leading to better organized wake-packet interactions and development of neighboring packets in the downstream flow.

Future work will include measurements with different cylinder heights as well as measurements at different wall-normal locations to examine further the importance of the downwash effects, and the importance of outer flow organization to the inner flow downstream of perturbations.

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REFERENCES

- [1] R. J. Adrian. Hairpin vortex organization in wall turbulence. *Phys. Fluids*, 19(4), 2007.
- [2] R. J. Adrian, C. D. Meinhart, and C. D. Tomkins. Vortex organization in the outer region of the turbulent boundary layer. *J. Fluid Mech.*, 422:1–54, 2000.
- [3] D. J. C. Dennis and T. B. Nickels. Experimental measurement of large-scale three-dimensional structures in a turbulent boundary layer. part 1. vortex packets. *J. Fluid Mech.*, 673:180–217, 2011.
- [4] D. J. C. Dennis and T. B. Nickels. Experimental measurement of large-scale three-dimensional structures in a turbulent boundary layer. part 2. long structures. *J. Fluid Mech.*, 673:218–244, 2011.
- [5] G. E. Elsinga, R. J. Adrian, B. W. van Oudheusden, and F. Scarano. Three-dimensional vortex organization in a high-reynolds-number supersonic turbulent boundary layer. *J. Fluid Mech.*, 644:35–60, 2010a.
- [6] G. E. Elsinga, D. J. Kuik, B. W. van Oudheusden, and F. Scarano. Investigation of the three-dimensional coherent structures in a turbulent boundary layer with Tomographic-PIV. In *45th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV, USA, 2007.
- [7] G. E. Elsinga and I. Marusic. Evolution and lifetimes of flow topology in a turbulent boundary layer. *Phys. Fluids*, 22(1):1–9, 2010b.
- [8] G. E. Elsinga, C. Poelma, A. Schröder, R. Geisler, F. Scarano, and J. Westerweel. Tracking of vortices in a turbulent boundary layer. *Journal of Fluid Mechanics*, 697:273–295, 3 2012.
- [9] B. Ganapathisubramani, E. K. Longmire, and I. Marusic. Characteristics of vortex packets in turbulent boundary layers. *J. Fluid Mech.*, 478:35–46, 2003.
- [10] Q. Gao. *Evolution of eddies and packets in turbulent boundary layers*. PhD thesis, University of Minnesota, 2011.
- [11] M. Guala, C. D. Tomkins, K. T. Christensen, and R. J. Adrian. Vortex organization in a turbulent boundary layer overlying sparse roughness elements. *J. Hydraulic Research*, 50(5):465–481, 2012.
- [12] R. Hain, C. J. Kähler, and D. Michaelis. Tomographic and time resolved PIV measurements on a finite cylinder mounted on a flat plate. *Exp. Fluids*, 45:715–724, 2008.
- [13] N. Hutchins, B. Ganapathisubramani, and I. Marusic. Spanwise periodicity and the existence of very large scale coherence in turbulent boundary layers. *Proc. Turbulence and Shear Flow Phenomena IV*, 2005.
- [14] N. Hutchins and I. Marusic. Evidence of very long meandering features in the logarithmic region of turbulent boundary layers. *J. Fluid Mech.*, 579:1–28, 2007.
- [15] I. Jacobi and B. J. McKeon. New perspectives on the impulsive roughness-perturbation of a turbulent boundary layer. *J. Fluid Mech.*, 677:179–203, 2011.
- [16] J. H. Lee and H. J. Sung. Very-large-scale motions in a turbulent boundary layer. *J. Fluid Mech.*, 673:80–120, 2011.
- [17] J.A. LeHew, M. Guala, and B.J. McKeon. Time-resolved measurements of coherent structures in the turbulent boundary layer. *Exp. Fluids*, 54(4):1–16, 2013.

- [18] E. K. Longmire, Q. Gao, M. D. Ryan, and C. Ortiz-Dueñas. Examination of turbulent boundary layers by volumetric velocimetry. In *9th International Symposium on Particle Image Velocimetry*, Kobe, Japan, 2011.
- [19] C. Ortiz-Dueñas, M. D. Ryan, and E. K. Longmire. Modification of turbulent boundary layer structure using immersed wall-mounted cylinders. In *Proc. Turbulence and Shear Flow Phenomena VII*, Ottawa, Canada, 2011.
- [20] C. W. Park and S. J. Lee. Flow structure around a finite circular cylinder embedded in various atmospheric boundary layers. *Fluid Dynamics Research*, 30(4):197–215, 2002.
- [21] G. Pujals, C. Cossu, and S. Depardon. Forcing large-scale coherent streaks in a zero-pressure-gradient turbulent boundary layer. *J. Turbulence*, 11(25):1–13, 2010.
- [22] M. D. Ryan. Planar and volumetric measurements downstream of cylinders immersed in a turbulent boundary layer. Master’s thesis, University of Minnesota, 2011b.
- [23] M. D. Ryan, C. Ortiz-Duenas, and E. K. Longmire. Effects of simple wall-mounted cylinder arrangements on a turbulent boundary layer. *AIAA J.*, 49(10):2210–2220, 2011a.
- [24] H. Sakamoto and M. Arie. Vortex shedding from a rectangular prism and a circular-cylinder placed vertically in a turbulent boundary-layer. *J. Fluid Mech.*, 126(JAN):147–165, 1983.
- [25] W. H. Schofield and E. Logan. Viscous flow around two and three dimensional wall mounted obstacles. In *1st AIAA, ASME, SIAM, and APS, National Fluid Dynamics Congress*, pages 1742–1748, Cincinnati, OH, USA, 1988.
- [26] D. Sumner, J. L. Heseltine, and O. J. P. Dansereau. Wake structure of a finite circular cylinder of small aspect ratio. *Exp. Fluids*, 37(5):720–730, 2004.
- [27] C. D. Tomkins. *The structure of turbulence over smooth and rough walls*. PhD thesis, University of Illinois at Urbana-Champaign, 2001.
- [28] C. D. Tomkins and R. J. Adrian. Spanwise structure and scale growth in turbulent boundary layers. *J. Fluid Mech.*, 490:37–74, 2003.
- [29] H. F. Wang, Y. Zhou, C. K. Chan, and K. S. Lam. Effect of initial conditions on interaction between a boundary layer and a wall-mounted finite-length-cylinder wake. *Phys. Fluids*, 18(6):1–12, 2006.
- [30] C. E. Wark, A. M. Naguib, and S. K. Robinson, editors. *Scaling of spanwise length scales in a turbulent boundary layer*, January 1991.
- [31] B. Wieneke. Stereo-piv using self-calibration on particle images. *Experiments in Fluids*, 39:267–280, 2005.
- [32] S. Zheng. Perturbing spanwise modes in turbulent boundary layers. Master’s thesis, University of Minnesota, 2013.